Article

From Geotechnical Data to GeoBIM Models: Testing Strategies for an Ex-Industrial Site in Turin

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Abstract: Over the years, the use of Building Information Modelling (BIM) methods has changed the workflows of various actors, providing better integration across different domains and allowing for new ways of working. This paper outlines the interest towards the integration of BIM with geotechnical/geological modelling (GeoBIM), which still represents a major challenge in several respects. The present study aims to provide a flexible method for assessing various integration strategies and to establish a preferred workflow based on the selected requirements and preference parameters. This integration is designed to provide a final federated model that can also be archived in the as-built documentation. Four alternative processes were selected to analyse the specific types of data and transformations required in the process. Each process was applied on a real case study in order to test the developed assessment framework using the Analytical Hierarchy Process (AHP). Due to technological advances, modelling and integration workflows change rapidly; however, our results show that the proposed evaluation framework is universal and adaptable to any new integration approach. Further research efforts must be undertaken to reduce attribute data losses and enhance the interoperability between systems and professionals.

Keywords: BIM; geomodelling; interoperability; visualisation; database; assessment

1. Introduction

The integration of geotechnical/geological data with BIM (GeoBIM) is critical for managing various natural calamities such as earthquakes, landslides, and avalanches, as well as hydrogeological disasters (e.g., debris flow, floods). Accordingly, the use of digital information models is of paramount importance in the analysis and study of future possible scenarios. Climate change, which is affecting the frequency of natural events and their impact on the landscape, has made this requirement more pressing in recent years. As a result, the focus of digitalisation in the Built Environment should be on how to integrate and manage heterogeneous data from different data sources. However, such integration becomes difficult in the case of geotechnical and geological digitisation. In this publication, GeoBIM [1] refers to an environment in which subsoil layer information is used to define a digital information model that may interact with and play a role in Building Information Modelling (BIM) processes.

The initial research on the integration of geodata with BIM was conducted on the merging of BIM and GIS, establishing a basis for collaboration between the two systems [2,3]. Several unresolved issues were identified in those studies, including differences in their modelling methods, the heterogeneous levels of detail and development of BIM and GIS at different scales, and the different uses of BIM and GIS [4–6]. Several authors have analysed the current status and prospects of using BIM, machine learning and computer vision techniques as support tools to reinforce the efficient and effective planning, development and management of underground construction [7–11].

All of these studies aimed to create communication between such systems by employing different approaches to integration [12–18]. One of the key aspects of this topic is related to the analysis of different representation methods for 3D geological models, such as BIM-based, voxel-based and hybrid models [19,20]. Due to the flexibility offered by parametric design, other approaches that involve the use of Visual Programming Languages (VPLs) and dynamic 3D modelling for geology for the design and execution of large-scale infrastructure projects have recently been developed [21]. To provide sufficient integration, several actions that manage/modify the subsoil and its geo-related data and hydrogeological and geotechnical objects and properties must be performed [22,23]. This type of integration would make relevant data available at any stage, and drastically decrease data loss between the two domains. Some studies have analysed the role of BIM in the different phases of geotechnical investigation [24] and proposed methods for optimising the procedures of geotechnical surveys [25,26]. In some studies, investigations for the design and management of civil infrastructures have been performed that incorporate the use of non-destructive survey data, such as Mobile Laser Scanner (MLS), Ground-Penetrating Radar (GPR) and satellite-based information [27]. Most of this research has been performed in support of the development of innovative modelling methods for tunnelling projects, where the information related to the subsoil is even more relevant [28–30]. The core of Geo-BIM is a versatile and comprehensive database [1] that is capable of handling geotechnical data, which are collected digitally and seamlessly transferred throughout the whole design process of underground infrastructure projects, with no manual transformations. This process requires the geo-model to have an "unbroken digital information supply chain", and its elements need to be directed towards the design process in a way that designers can readily use [1]. Setting up a proper database for an efficient data exchange process is crucial in this approach.

The data collection process begins with the collection of geotechnical data. This phase aims to gather relevant information in order to create suitable soil models and provide appropriate design solutions (e.g., the selection of an appropriate foundation system for the structure, the choice of the improvement technique or environment to be used, etc.). A geotechnical model is, for all intents and purposes, a "computational model" in which each element is characterised by parameters that allow the definition of an appropriate soil behaviour model (e.g., thickness of layers, geo-structural features, mechanical and hydraulic parameters). Building a soil model requires a preliminary interpretation of in situ and laboratory tests, as well as the collection of these data in a database. To provide comprehensive interoperability and integration with the superstructures, the database should not only allow the construction of the geometrical model, but also the extraction of all of the information and data in each layer. During this phase, the key challenge is to combine the results of tests performed in order to identify the stratigraphic model and hydromechanical parameters. This process is rather complex, especially when the site is characterised by high lateral variability or when stratigraphic profiles must be reconstructed by merging the results of several types of test (e.g., boreholes, CPTs—Cone Penetrometer Tests). To pick an adequate representation of the soil model based on proper soil classification, a comprehensive 3D stratigraphic model will involve the combination, correlation, and simplification of all tests [31]. This is an important step that must be completed while keeping in mind that the 3D model is derived via interpolation methods. As a result, each option must be chosen carefully to generate a simple yet complete representative model of soil without losing crucial strata or information. In this context, the term classification is employed to describe the procedure of sorting soil into distinct classes, with the assumption that materials within the same class will exhibit similar behaviour [32]. It is worth noting that several classification systems are currently in use: (i) the Unified Soil Classification System [33] adopted by the AGI (Italian Geotechnical Association); and (ii) the HRB-AASHTO system (American Association of State Highway Officials), codified in Italy by UNI EN 13242 [34].

Another crucial part of the integration of geo-related data and BIM is the information interchange and processing standard, which allows successful management of the built

environment and connectivity between BIM and geo-models. Several research groups have attempted to define appropriate standards for the incorporation of geological models into BIM processes. Building Smart International (bSI) has already introduced an open standard for describing the built environment, known as IFC (Industry Foundation Classes). The "BuildingSMART rooms" [35] research group suggested updating the IFC open standard by including geological models for planning as use cases for the standard "IFC-Tunnel". This standard aims to expand the IFC data model to allow for the precise description of the semantics and geometries of the different elements that make up tunnels, such as geotechnical subsoil conditions and treatments, civil engineering components, and the functional systems that equip them [36]. Geotechnical analysis tools already enable IFC input, but this data format does not allow for further analysis once the features have been imported as IFC. Furthermore, only a few IFC Classes are implemented in some tools, severely limiting the options inside the exchange scenario.

Other extant digital spatial data and information standards related to 3D geometries include those developed by the Open Geospatial Consortium (OGC): (i) CityGML, an open-data model and XML-based format for storing and exchanging virtual 3D city models; (ii) GeoSciML and GroundWaterML2, which are targeted towards geology and hydrogeology, respectively. GeoSciML is a logical model, and GML/XML encodes rules for exchanging geological map data, geological time scales, boreholes, and metadata for laboratory analyses [37]. GroundWaterML2 introduces extra concepts including hydrogeologic units, fluid bodies, discharge, and recharge [36]. OGC developed the LandInfra/InfraGML format, which focuses on land use, topographic modelling, and infrastructure parts such as roads and rainwater management works [38]. Even though all these standards are excellent, there is still a lack of actual integration between geomodelling and BIM systems.

Due to the limitations outlined, integration between geotechnical and geological modelling and BIM procedures is currently specified in different workflows. Each of them is characterised by distinct tools and standards, which frequently impede the effectiveness of the integration process. The present study aims to examine several feasible workflows for integrating and managing geotechnical and environmental project data within BIM procedures. This integration is designed to provide a final federated model, which is also archived in the as-built documentation. Four alternative processes were selected for this purpose to analyse the specific types of data and transformations required in the process. The methodologies were applied to a real case study. The originality of the paper lies in the definition of a framework for assessing several GeoBIM integration methods, considering specific parameters for evaluation. Each process was evaluated by assigning different levels of interoperability based on data integration. The Analytical Hierarchy Process (AHP), one of the Multi-Criteria Decision Approaches (MCDAs), was used to conduct the evaluation in order to use both quantitative and qualitative indicators for the assessment. This enabled the effective coordination and interchange of data for the purposes of information integration, which were then used to construct a "multidisciplinary model" of the case study, incorporating data from many sources.

2. The Case Study

The present study was established with the aim of creating a GeoBIM model for the underground area where the new Headquarters of the Piedmont Region was built and where the new hospital "Parco della Salute" will be in Turin (Italy).

The project site was included in the requalification and urban development plan for the ex-industrial site Nizza Millefonti, located in the southeast part of Turin city. The whole area is 313.725 m^2, and it is divided into three lots (Figure 1). The first lot will be converted into the "Parco della Salute, della Ricerca e dell'Innovazione", where a hospital including several healthcare facilities and research centres will be built. Lots 2 and 3 were selected for the construction of the new Headquarters of the Piedmont Region, which was officially opened on 14 October 2022. The skyscraper, which stands 205 m tall and has 42 storeys, serves as the Headquarter of the Piedmont Region. The BIM model of this tower,

developed in previous years by the drawingTOthefuture lab at the Polytechnic of Turin [39], is integrated with the federated model of the case study in the present research.
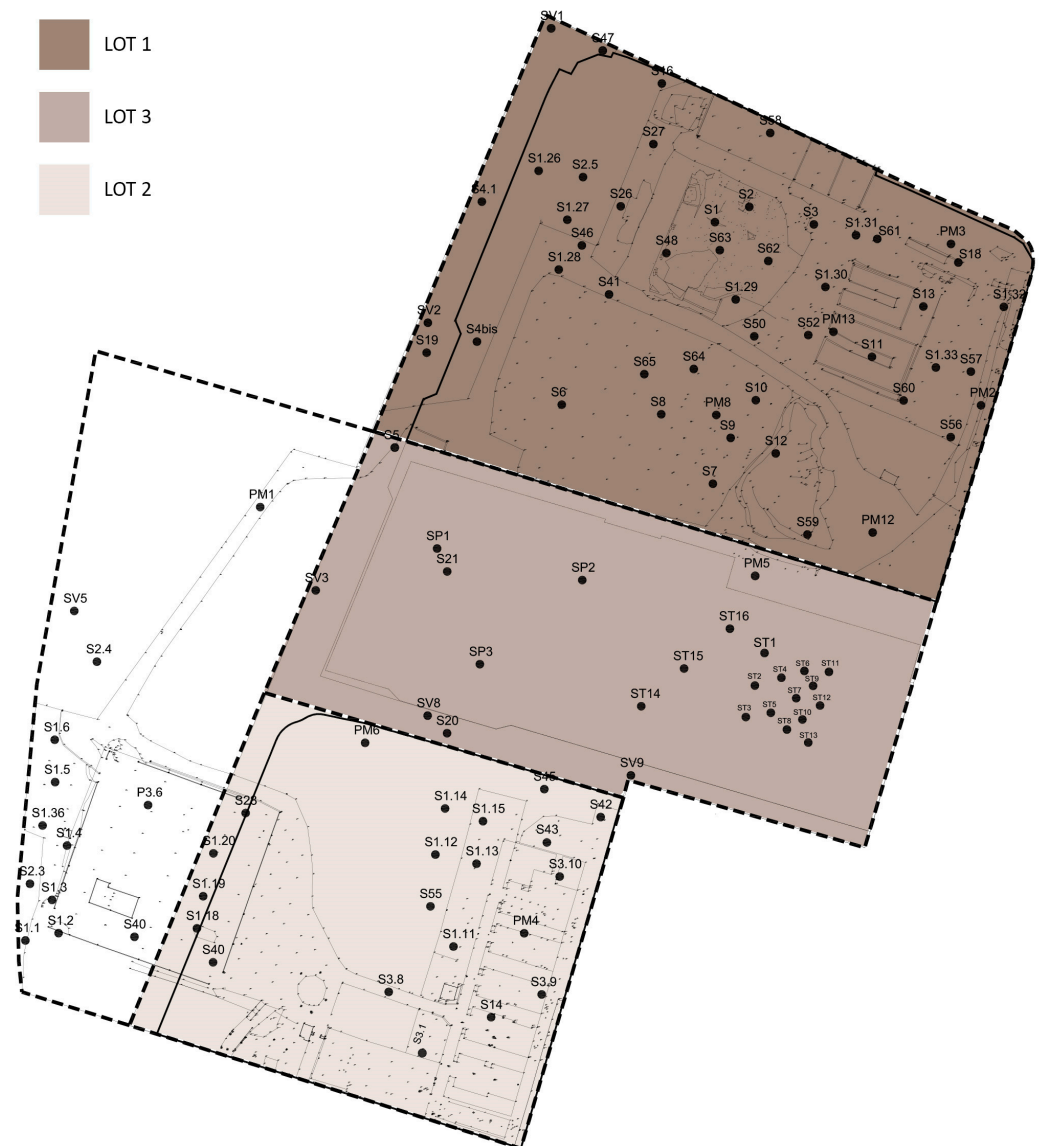

Figure 1. The three lots and localisation of in situ tests.

Many investigation campaigns have been performed over the years, making it possible to collect several sets of subsoil data, including hydro-mechanical properties.

Figure 1 shows the localisation of the in situ tests. Specifically, two different investigation campaigns were performed on lots 1, 2, and 3: an environmental survey on the first two lots and a geotechnical investigation on lot 3. Due to their classification as ex-industrial sites, the investigations carried out on lots 1 and 2 in 2004–2005 aimed to identify chemical pollutants (electromagnetic investigations, georadar reliefs, electrical tomographies, piezometric surveys, and water and soil analyses). The depth of the boreholes used in this area was limited to 15–17 m due to the nature of the site investigation. In contrast, the survey campaign performed on lot 3 in 2007–2008 was carried out to establish a geotechnical model for the design of the tower. Several geotechnical tests were executed, both in situ (SPT: standard penetrometer tests; PMT: pressuremeter tests; Lafranc permeability tests; cross-hole tests; and measurement of piezometer levels) and in the laboratory (grain-size distribution tests, Atterberg limits, triaxial tests, and oedometer tests). Boreholes in this lot

were employed at two different depths: up to 80 m in the zone where the skyscraper was built, and up to 40 m in the area nearby.

The following factors influenced the selection of the case study: (i) the presence of many lots with specific characteristics; (ii) investigation campaigns carried out for different purposes and at various depths; and (iii) the broad availability of geotechnical and geo-environmental data from heterogeneous tests. All these factors made the site appropriate not just for testing various geotechnical data and GeoBIM model integration approaches, but also for performing interoperability tests. Lot 3 was subjected to the methodology and the interoperability tests outlined below. Once the appropriate tools in terms of interoperability were identified, data from the investigations of lots 1 and 2 were processed and integrated with those from lot 3 to create a federated model of the whole underground area, as detailed in Section 4.3.

3. Methodology

3.1. Geo-Modelling–BIM Integration Methods

There are currently several workflows specifying methods for integrating geo-modelling and BIM, which are based on a combination of tools and software that frequently impede the good integration process. Different approaches can be selected in accordance with an ideal methodological framework that is capable of achieving a high degree of integration, which may be developed starting from the semantic concepts established in the IFC-Tunnel project [17]. A specific taxonomy was defined in this project to clarify the context in which the geological/geotechnical data and models should be exchanged. The taxonomy can be divided into two main categories:

(a)　GeoDocu (Factual or Base Data), including data related to site investigation, laboratory/in situ tests, borehole data, and tunnel documentation;

(b)　Interpreted models (GeoModel, HydroModel, and GeotechModel), providing input for further analysis and application. Each taxonomy element requires geometric representations, which can be divided into the following dimensions: 0D point, 1D line, 2D area/surface, 2.5 elevation grid or 3D surface, and 3D volume [36].

For instance, in the case of interpreted models, the element "geological/geotechnical units" must be represented as 3D solid models or 3D surfaces, with a top and/or a bottom layer, such as Faceted BRep, NURBS, or TriangulatedFaceSet [36].

Based on this semantic concept, methodological frameworks are defined, considering the specific types of data required at each stage of the process. These methods are developed with the following objectives in mind: (i) analysing data to be used as the "input" in the first phase, to better understand how to organise the existing data sets; (ii) processing the data by using different methods and tools for the definition of soil modelling; and (iii) determining the results in terms of information models that can be integrated within a BIM environment procedure, as a repository of information and database for geotechnical/geological domain that may also interact and be transformed into BIM features.

In detail, the data input phase includes the following major activities: (i) data pre-processing to adopt the appropriate classification codes chosen for the collected information; (ii) data digitisation, which is helpful for further data elaboration; and (iii) data setup, to manage the import phase. It is important to note that an efficient workflow involves information about the points (e.g., Cartesian points and annotations), surfaces (e.g., triangulated and parametric surfaces), and volumetric representations (e.g., faceted BRep and NURBS).

As stated in the IFC-Tunnel project [36], the data processing step involves the use of factual data to generate interpreted models. This phase can be divided into four major activities: (i) modelling, which requires the use of specific customised commands; (ii) parameterisation, which involves linking information contents to the modelled objects; (iii) data visualisation, filters, and customised views, for organising the data hierarchy; and (iv) export, which necessitates proper management of the associated settings. The content of factual data in this context is highly dependent on existing data and standards (e.g., AGS or GeoSciML), and, eventually, new project-specific site investigation results. In this respect, it is important

to highlight that the accuracy of data gathering is largely dependent on the activities of the previous phases. This emphasises the significance of the data pre-processing described in Section 4.1.1. Interpreted models describe the predicted ground conditions, including uncertainty, and may operate as the basis for the design, structural analysis, and definition of construction measures, as well as the representation of contract-relevant predictions of ground conditions [36].

Finally, the data output phase includes the following activities: (i) visualisation of stratigraphies, along with their properties; (ii) model production; (iii) extraction of views in the form of 3D views, cross-sections, etc.; (iv) extraction of information contents related to the properties and characteristics of objects; and (v) setting the model to coordinate it with other discipline-related models with the goal of creating a data repository. At this stage, the results serve as the input for subsequent analysis and/or design processes, due to the creation of a digital repository collecting all necessary information produced to ensure integration with BIM processes. Following this methodological framework, several workflows combining many tools and software solutions for geo-modelling–BIM integration can be developed. These integration approaches must ensure an adequate level of interoperability, which can be evaluated throughout all data processing steps. Several tests can be adopted to assess the interoperability of the different approaches. The method described by Fjeldsted et al. [5] was employed in this study.

3.2. Assessing Workflow Alternatives Using the AHP Approach

Different integration approaches can be characterised on the basis of their advantages and disadvantages. Especially within the context of the present research, where different approaches have been developed in recent years, it is of paramount importance to provide a tool to support decision making regarding the selection of one method over another. The innovative scope of the present study is to define the best methods for achieving the aim of integrating and managing geotechnical and environmental project data within BIM processes and to develop a data repository for such information. In this respect, integration procedures must guarantee: (i) time saving, ensuring rapid replicability for application in different contexts; (ii) high levels of interoperability in terms of the type and number of file formats that can be imported/exported, in order to make the procedure flexible; (iii) exchange of information content, i.e., "a set of information organized according to a specific scope for a systematic communication of a set of knowledge within a process" [40], that is effective and efficient; and (iv) a good level of process customisation according to the different characteristics of the specific application. These characteristics define metrics that make the definition of an "ideal" process possible; providing appropriate indications regarding the type of data to be collected, the type of integration that should take place, and the possible outputs.

Based on these metrics, an original framework for assessing integration processes is proposed here. The interoperability tests performed by applying the selected modelling workflows enable a database of 'values of performance' to be defined, which is necessary for the development of a framework for assessment. In order to evaluate the performance of the different workflows towards the research goal, a set of Key Performance Indicators (KPIs) was identified and evaluated on the basis of the previously performed interoperability tests.

Since the use of KPIs to assess the efficiency of workflows for modelling purposes represents a novelty, the authors identified specific indicators for their evaluation, providing for each KPI a unit of measurement, a description, and a measurement method, as follows:

(a) Workflow execution time [min]: time required to execute the whole workflow. Measurement method: Quantitative.
(b) Number of formats supported for import/export (Data exchange) [n.]: sum of the total number of file formats allowed for import and export of data. Measurement method: Quantitative.
(c) Information content share (Modelling) [%]: percentage of information preserved through appropriate levels of interoperability. Measurement method: Qualitative.

(d) Customisation share [%]: percentage of the workflow with the ability to be customised according to specific user requirements (e.g., the ability to produce different views—3D, cross-sections, etc.—or the ability to achieve a given objective simply by combining different tools). Measurement method: Qualitative.

The first two indicators' values are determined by assessing the time required to execute the integration approach and the interoperability tests on a computer, and for the final two on the basis of the subjective experience of the operator.

These indicators can be used to perform a quantitative comparison of different approaches and to determine which one is superior based on the parameters considered. The Analytical Hierarchy Process (AHP), one of the Multiple-Criteria Analysis (MCA) decision-making techniques, is used as the assessment method in the present study. Multi-criteria analysis first appeared in the 1960s as a decision-making method for evaluating alternative projects by comparing and assessing many criteria simultaneously. Several evaluation methods are available, but the AHP method [41] appears to be the best suited for this study owing to its ease of application and the ability of compare multiple options by giving priority ratings to distinct criteria/sub-criteria to be used for comparison.

The approach is divided into four stages: (i) top-to-bottom breakdown, creating a structure with unidirectional hierarchical links across levels; (ii) pairwise comparison, in which the decision elements are compared pairwise in terms of their importance for their control criterion. This comparison is based on the "Saaty's Fundamental Scale", a 9-point scale that determines the relative importance of one choice when compared to another; (iii) judgment synthesis to define weights for each decision element; and (iv) evaluation and checking of judgment consistency.

Pair matrixes are formed on the basis of the numerical judgments established at each level of the hierarchy: if n is the number of criteria in a given level of the hierarchy and m is the number of options, a square matrix (n × m) can be constructed at that level.

4. Results

4.1. Modelling Workflows

The present study addresses the previously highlighted need for integration between geomodelling tools and the BIM environment by implementing and testing an innovative approach aimed at establishing the best alternative workflows in consideration of specific prerequisites and assigning different weightings to specific criteria. Following the architecture outlined in Section 3.1, four workflows were selected on the basis of the key tools and software currently available for integrating geo-models into the BIM environment. Each modelling workflow is divided into three main steps: data input and pre-processing, data processing, and data output. The data analysis and pre-processing process serves as a starting point for the integration procedures; hence, this stage is common to all modelling workflows.

The selected modelling workflows were applied to the described case study.

4.1.1. Data Pre-Processing

Before being used in the procedures for the integration of geo-modelling with the BIM environment, the data collected for the three lots (Section 2) were examined and pre-processed. As a result, the available data were organised into Excel tables to create a ready-to-use database. To obtain stratigraphic information, a more thorough process was coupled with data digitalisation. The borehole logs only provided a qualitative geological description of the strata; therefore, a nomenclature code was developed to uniquely identify the different lithographic types. The lack of quantitative information in several of the strata precluded the use of conventional nomenclatures, such as the Italian one proposed by the AGI (Italian Geotechnical Association). Accordingly, layers were classified by combining the available qualitative information with the small amount of quantitative data.

Two different classifications were adopted, due to the different degrees, purposes, and types of investigation performed on the two districts. Because the investigation for

lots 1 and 2 targeted environmental remediation, the classification of soils in these districts was based on their hydraulic conductivity. The soil classification used for lots 1 and 2 is as follows:

- R = Fill;
- P = Flooring;
- PI = Flooring and underground structures;
- UG1 = High permeability soil to water;
- UG2 = Low permeability soil to water.

The soil classification of lot 3, on the other hand, was based on the hydro-mechanical behaviour of the strata. Figure 2 shows an example of the classification adopted for this lot, as well as the strip-log of some boreholes.
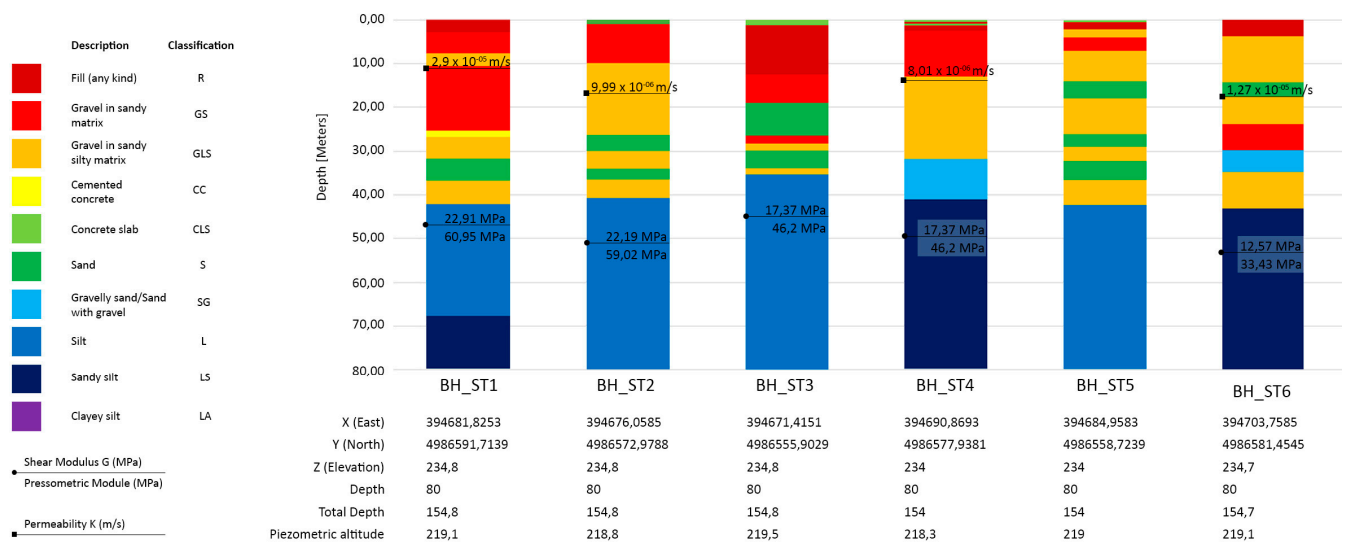
Figure 2. Stratigraphic classification of seven boreholes of lot 3 and the results of Lefranc tests, wave velocity tests, and pressumeter modulus (PMT).

The figure also shows some parameters derived from in situ tests, such as shear modulus, pressumeter modulus, and hydraulic conductivity. Other parameters from in situ and laboratory tests are available upon request. The lot 3 factual data were used as the input data for the interpreted models described in the following workflows.

4.1.2. Data Processing and Output

The four different modelling workflows were tested to examine their differences in terms of output and data integration regarding the case study. Each workflow required the use of a specific combination of tools and formats for data processing and exchange. The interoperability test was performed for each approach as described in Section 3.1. Grid and model dimensions are strictly related to the borehole data, and were set as reported in Table 1.

Table 1. Grid and model dimensions.

	Minimum	Maximum	Spacing	Nodes	Unit
X	394,600	394,700	100	2	m
Y	4,986,500	4,986,600	100	2	m
Z	80	240	10	17	m

The first workflow involved the use of ArcGIS software 10.x, a geographic informative system (GIS) developed by Esri for creating and managing maps, and useful for exchanging geographic data. It is divided into two applications: ArcView, which includes ArcMap (for

maps production and geographic analysis) and ArcCatalog (for data management), and ArcScene, which is used to visualise 3D data. ArcCatalog was used to import the factual data into ArcScene, and ArcMap was used to build the Triangular Irregular Network (TIN) topographical surface. The topographic surface and stratigraphic layers were adequately combined and georeferenced using the same reference system WGS84/UTM 32N.

This approach produced an incomplete model (Figure 3), and an export file format suitable for interoperability could not be identified; therefore, the outcome did not fulfil the requirements regarding integration with BIM processes.
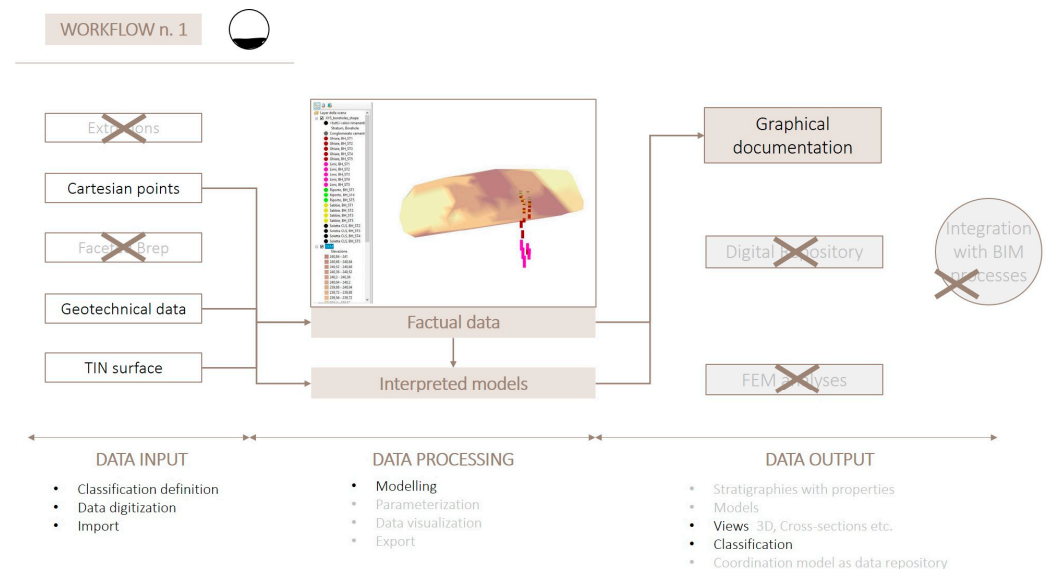
Figure 3. Results for modelling workflow n. 1.

The software RockWorks 2023 was used in the second integration modelling technique. RockWorks is a software package for modelling underground stratigraphy; it allows the visualisation of boreholes, topographic surfaces, and subsoil layers, as well as the generation of full stratigraphy, maps, cross-sections, and volumes.

Factual data were organised for management within the "Borehole Manager", which allows boreholes to be geolocalised, properties to be specified, and data to be updated during the process. RockWorks enabled the precise and thorough 3D visualisation of input data, resulting in a geo-model with distinct lithographic layers (Figure 4). Following the generation and visualisation of 3D representations of the strip logs, stratigraphic volumes of geo-model were constructed using interpolation methods. Several interpolation algorithms can be used to produce an interpreted model, depending on the nature of the data and the soil. The most significant limitation of this approach is the inability to customise the modelling process, meaning that the user cannot update the three-dimensional model. Furthermore, if a lithographic type occurs many times at different depths in the same stratigraphy, the software treats it as a singular layer, losing the real soil arrangement. The RockWorks model was exported in the form of DXF and DAE files, and their interoperability with other BIM-oriented programmes was examined. While the DXF file imported into Autodesk Civil 3D preserved the geometry and all attributes, the DAE file brought into the object-oriented environment of Autodesk Revit via Autodesk 3ds Max highlighted the preservation of only the geometries of the model, without attributes.
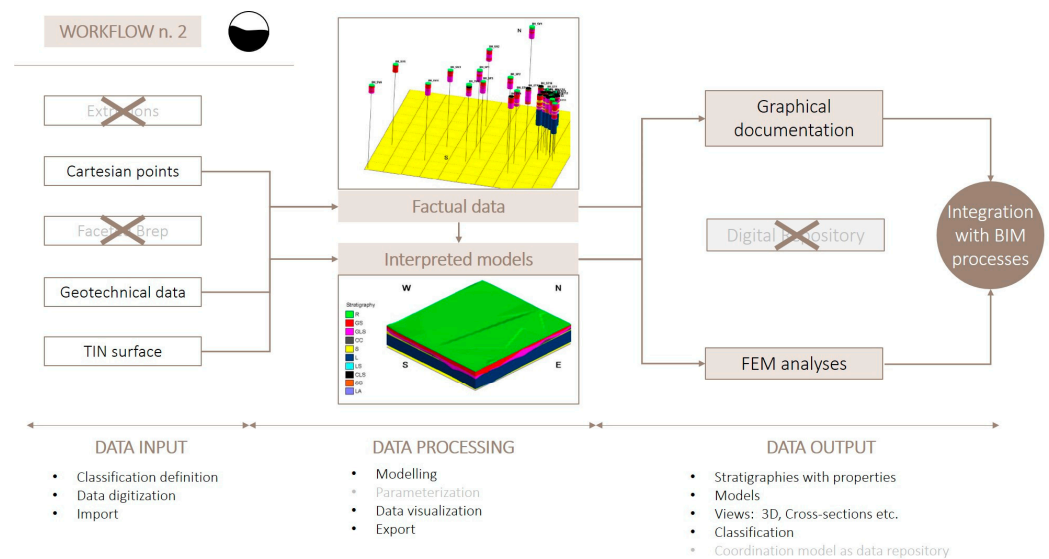
Figure 4. Results for modelling workflow n. 2.

The third method involved the use of the "Geotechnical Module" tool, designed by Keynetix for Autodesk Civil 3D software 2023 exclusively for geological/geotechnical soil modelling using in situ borehole data. This approach, like the previous one, did not allow intermediate layers to be distinguished with respect to the same unit; only a suitable coding of the layers allowed this limitation to be overcome. To denote the order depth of layers with the same unit, a smart solution was found, in which an integer number was included at the beginning of the name. The processing step included surface modelling based on soil stratigraphy and topography using Triangular Irregular Network (TIN) surfaces. The three-dimensional solid model was automatically generated once the upper (Top) and bottom (Base) surfaces for each stratigraphic unit had been defined (Figure 5). During this stage, the tool revealed some criticalities. Due to the complexity of the sequential variability within the geological units, the realisation of the stratigraphic surfaces, including the visualisation of the cross-sections, was inaccurate. The surface generated by the rough model showed several points of discontinuity; therefore, the errors had to be fixed manually. A disadvantage of this tool was the inability to update the models. Only by including the HoleBASE SI database in the workflow, allowing the collection and organisation of environmental survey data, could the model be updated. In terms of data output, Civil3D supports three main formats: CAD files (DWG/DXF), which only export the geometry, and therefore provide a low level of interoperability; open standard IFC; and LandXML formats, which can export both geometries and attributes, as well as properties, thus ensuring a high level of interoperability.

The last method involved the use of the software Novapoint 21, by Trimble. Novapoint is a BIM-authoring platform for infrastructures that is frequently used in combination with Trimble Quadri, a collaborative platform that allows professionals to work on the same project. In contrast to the previous approaches, this method aims to explicitly simulate the geotechnical model within a BIM platform. In terms of data input, the adopted approach involves the use of the "Civil 3D Connector", a tool that allows data interchange between Novapoint and Civil3D. To this end, the borehole properties were imported into Civil3D before being exchanged within Novapoint. To represent the complete stratigraphy, it is necessary to organise the data related to the geometric locations of the boreholes using DWG files. Therefore, each borehole was discretised into points, with different materials being assigned to different depths and geolocated in the WGS84/UTM32N reference system. Customised software functions were used to process the data and generate a 3D soil model. The linkage between nearby layers was obtained with surfaces that connected points of the same lithographic type. Because the software only supports triangular interpolation, layers with fewer than three points cannot be represented. Then, by connecting consecutive

surfaces, stratigraphic volumes were created, each of which was associated with its specific properties (Figure 6). It was not possible to distinguish volumes based on materials, and the tool only allowed for two distinctions: cut volumes and fill volumes. Different materials could not be graphically displayed; this was possible only through the attribute tables. The 3D boreholes were imported into the geo-model from another geotechnical software package, in this case, RockWorks.
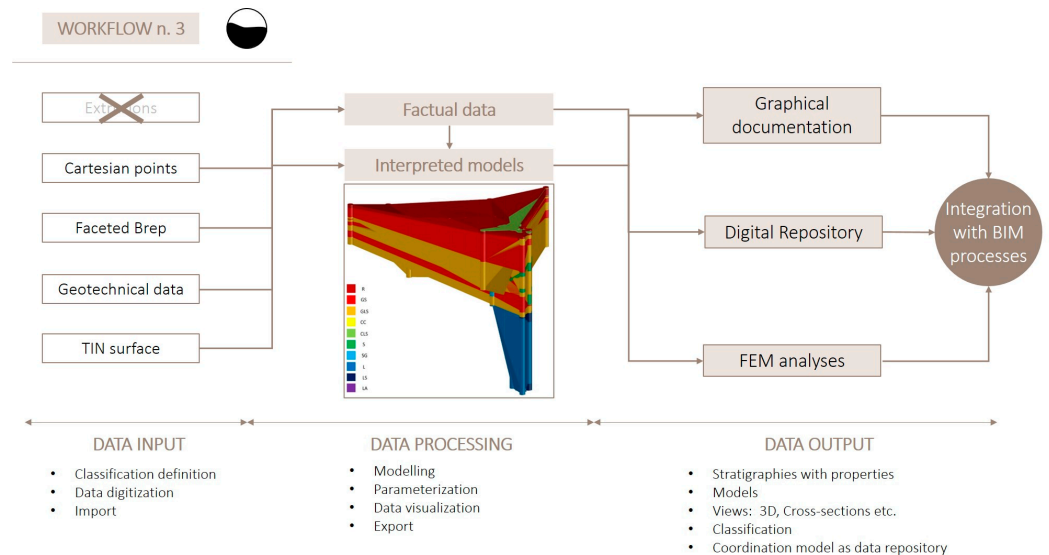

Figure 5. Results for modelling workflow n. 3.
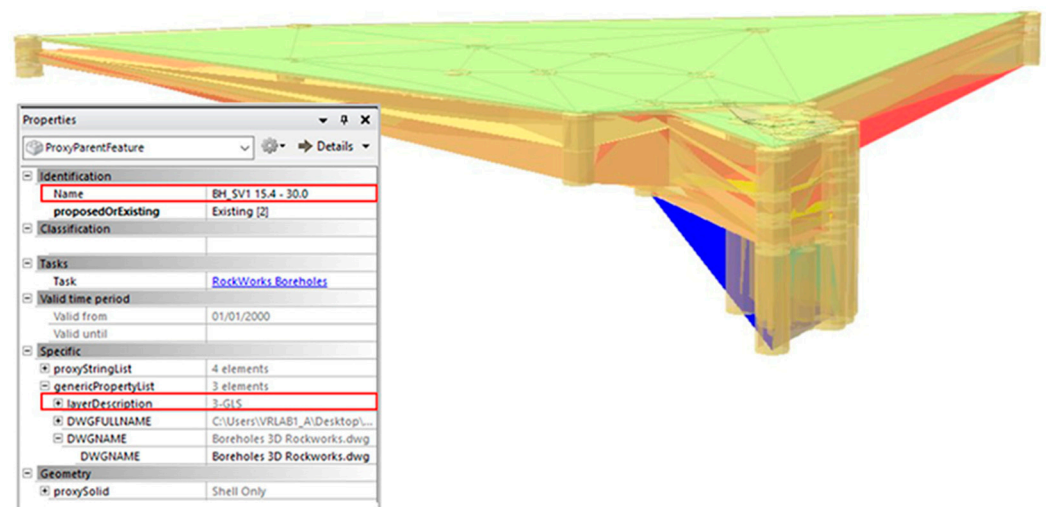
Figure 6. Stratigraphic surfaces and volumes of lot 3 created using workflow n. 4.

In terms of data output, the stratigraphic model can be exported in either the DWG or the IFC format, so this latter approach provides a high level of interoperability. For this reason, Novapoint was employed as a collaboration platform for model coordination.

Figure 7 shows the overall process for workflow n. 4. Figures 3–5 and 7 also show that each procedure was analysed within each step of the methodology, highlighting the specific strategies adopted for data integration following the methodology proposed in Section 3.1. It is evident from the figures that the first workflow does not allow for acceptable levels of integration for BIM processes (the only possible output is graphic documentation), while the other three approaches guarantee increasing levels of integration.
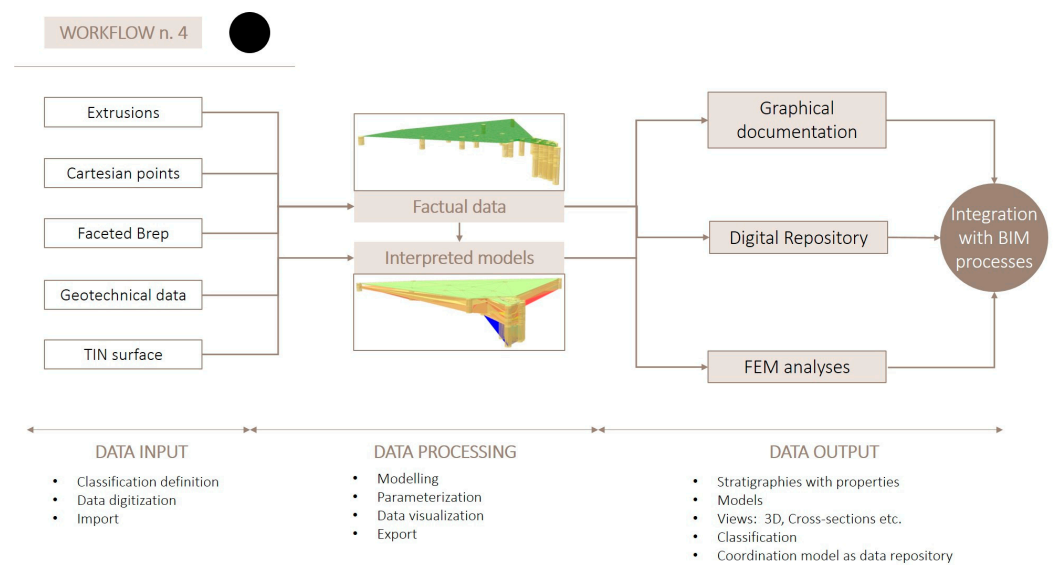
Figure 7. Results for modelling workflow n. 4.

Although the different workflows share some methods (e.g., the TIN—Triangulated Irregular Network—surface), the results differ substantially. All approaches presented different results, both in terms of visualisation (views, sheets, geological cross-sections, etc.) and information exchange. Some file formats merely exchange geometry, while some open standards exchange alphanumeric data and information related to modelled elements that can be integrated into specific databases. Depending on the results obtained during the data processing phase, the four examined workflows achieved different levels of interoperability. The results of the interoperability tests for each workflow are indicated by a marker in Figures 3–5 and 7. The degree to which the marker is filled in indicates the level of interoperability.

4.2. Workflow Assessment with AHP

Following the AHP approach described in Section 3.2, values of the four selected performance indicators were assigned to each workflow as follows:

(a) Workflow n. 1:

- Workflow execution time [min] = 30
- Number of formats supported for import/export (Data exchange) [#] = 1
- Information content share (Modelling) [%] = 0.1
- Customisation share [%] = 0.01

(b) Workflow n. 2:

- Workflow execution time [min] = 90
- Number of formats supported for import/export (Data exchange) [#] = 2
- Information content share (Modelling) [%] = 0.4
- Customisation share [%] = 0.3

(c) Workflow n. 3:

- Workflow execution time [min] = 210
- Number of formats supported for import/export (Data exchange) [#] = 4
- Information content share (Modelling) [%] = 0.4
- Customisation share [%] = 0.5

(d) Workflow n. 4:

- Workflow execution time [min] = 350
- Number of formats supported for import/export (Data exchange) [#] = 5
- Information content share (Modelling) [%] = 0.5
- Customisation share [%] = 0.7

The values of the indicators were first normalised before selecting whether to maximise or minimise them. For example, the indicator "Workflow execution time" was minimised, because larger values of time indicate worse performance in the tool under consideration. Subsequently, a pairwise comparison of options was performed to establish the weights to be assigned to each criterion in the comparison (Table 2). The "Data exchange" criterion was considered more essential than the "Workflow execution time" criterion, using "Saaty's Fundamental Scale". Therefore, the value allocated to "Data exchange" over "Workflow execution time" was arbitrarily set at 7. This suggests that the first criterion is far more relevant than the second, and that the "Data exchange" criterion has a far greater impact on the decision than the element "Workflow execution time".

Table 2. Pairwise comparison among criteria.

	Workflow Execution Time	Data Exchange	Modelling	Customisation	Resulting Weight for Each Criterion
Workflow execution time	1.000	0.143	0.143	0.333	0.050
Data exchange	7.000	1.000	5.000	3.000	0.524
Modelling	7.000	0.200	1.000	5.000	0.3
Customisation	3.000	0.333	0.200	1.000	0.126

The pairwise comparison among criteria using Saaty's scale allowed weights to be calculated for each criterion. The results of this procedure are shown in the last column of Table 2. The priority ratings attributed to the criteria were as follows, listed from least to most important: Workflow execution time, Customisation, Modelling, and Data exchange. Because the primary aim of this evaluation was to assess the interoperability performance and different integration levels of the various approaches with BIM-oriented tools, Data exchange, as measured by the indicator "Number of formats supported for import/export", was chosen as the most important criterion in the approach comparison.

To establish the final priority of each alternative workflow, the normalised matrix of criteria was multiplied by the weights vector acquired from the pairwise comparison. The final priorities for each alternative workflow were as follows:

- Workflow 1: 0.022
- Workflow 2: 0.198
- Workflow 3: 0.338
- Workflow 4: 0.441

The AHP analysis showed that options 3 and 4 received the highest scores in terms of integration with BIM processes.

4.3. Aggregated Model and Digital Repository

The two workflows selected on the basis of the previous assessment (workflows 3 and 4) were used to complete the case study presented in Section 2. The third proposed approach was adopted to define the GeoBIM model of lots 1 and 2 (Figure 8), while the fourth method was employed for lot 3 (Figure 6). Regarding lot 3, it is important to remember that this area was investigated using boreholes with two distinct depths: up to 80 m in the zone in which the skyscraper was built; and up to 40 m in the nearby area. For this reason, the area was separated into two sub-areas to avoid any potential errors in the generation of volumes with a large amount of stratigraphic information owing to the creation of surfaces the dimensions of which are too diverse. The models were obtained independently using workflow n. 4 and then combined.
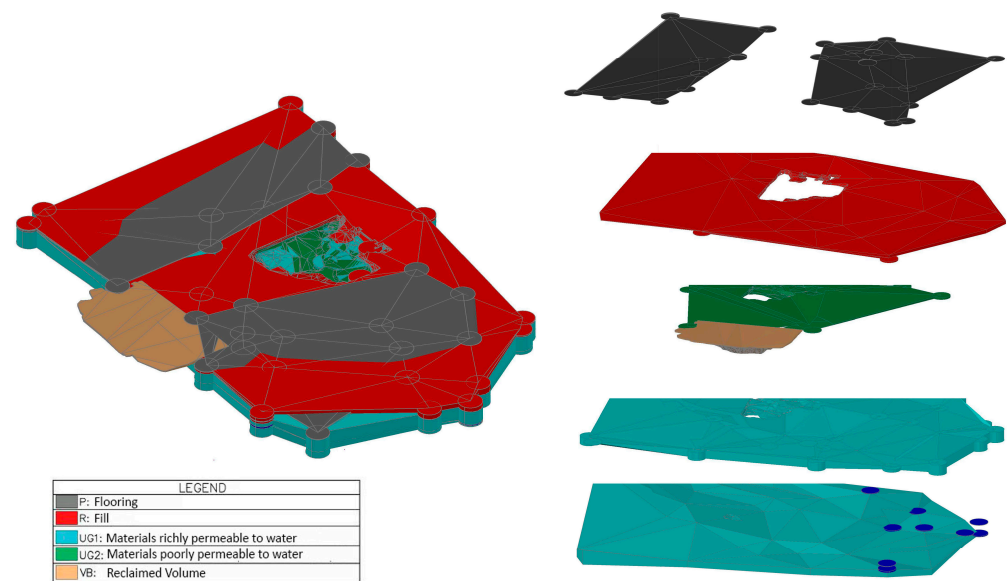
Figure 8. Interpreted models of lots 1 and 2 obtained with workflow n. 3.

The model of lot 3 was combined with the models of lots 1 and 2 by importing the resulting IFC files into a collaborative platform and assembling the area's aggregated model. In this study, Autodesk Navisworks Manage was employed. The model was completed by importing the skyscraper's BIM model.

A multidisciplinary aggregated model was obtained within a BIM environment for coordination and model-checking purposes (Figure 9). The aim of creating a data repository was achieved in two ways: (i) by using 3D models that included all the attributes assigned during the modelling phase; and (ii) by adding the results of some geotechnical tests to the aggregated model in XLSX format as "Attachments", enriching the model with all data, which were always accessible.
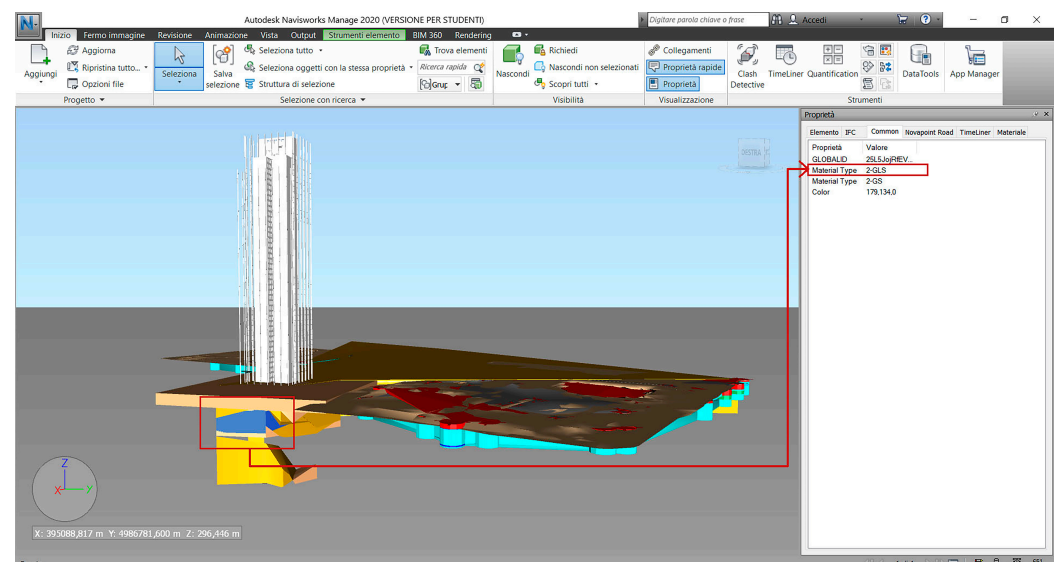

Figure 9. Coordination model showing that properties linked to the objects within the BIM authoring platform are maintained within the IFC standard.

Figure 9 shows two main sections: (i) the navigation view, in which the aggregated model with its graphical features can be visualised; and (ii) the properties view (the red square in Figure 9), which represents the information contents link between the modelling tool and the coordination platform. Figure 9 shows a perfect correspondence of all im-

ported models in terms of their geolocalisation. This was obtained through the proper configuration of shared coordinates. The link to the related properties of elements ensures an "unbroken digital information supply chain", as advocated by Svensson et al. (2017).

As shown in Figure 9, the model maintained both the classification of the layers and the parameters defined within the BIM authoring platform during the import of the IFC files into the BIM tool for coordination. This implies that data can be structured and implemented so that the model can be used as a repository of information on mechanical, physical, or other types of properties on modelled features. A data repository of this type could be enriched with relevant information based on future demands and requirements, acting as a dynamic database that can be updated over time.

The purpose of this study was to obtain a better understanding of the current state of the art of the different available methods and tools for using BIM as a support tool and a source of information for reinforcing the efficient and effective planning, management of underground construction. Within this framework, this pattern of the results is consistent with the previous literature [7–11]. Whereas previous researchers focused on the development of new integration approaches [12–18] or on the optimisation of geotechnical investigations through the connection to the BIM environment [24–26], the present study shows the possibility of developing a tool that is able to support designers and technicians towards the selection of the most appropriate procedure based on the specific requirements of the project.

5. Conclusions

A study on the interoperability between geotechnical and environmental data and BIM-based processes with a view to their integration was presented. The research was tested on a case study in a Turin area involving a requalification plan. Using currently available tools and software, four distinct workflow approaches for the integration of geological/geotechnical data in a BIM environment were defined.

Interoperability tests were performed to assess the advantages and disadvantages of each approach. These tests helped the researchers to evaluate each procedure based on the three primary steps that characterise the integration process: data input, data processing, and data output. The application of the integration procedures to the case study revealed that all of them required an initial phase in which the geotechnical and geological information was thoroughly analysed to enhance its utility in producing GeoBIM models.

The results highlighted that it is not possible to determine a priori which method will provide the best outcome, because the requirements and objectives of a GeoBIM model are defined on the basis of the specific project. In this respect, the adoption of a customizable method allowed the performance of the approaches to be assessed. KPIs were selected, and one of the multi-criteria analysis tools was adopted to define the best alternative workflow. The AHP was applied to the case study, and the results showed the great adaptability of such an assessment approach. Indeed, these indicators not only allowed a quantitative analysis to be performed in which a metric for qualitative parameters was defined, they also provided a framework through which it is possible to draw up a classification and assign a weight for each comparison criterion. The weights can be assigned adequately to emphasise the importance of some criteria over others, depending on the finality of the GeoBIM model.

Accordingly, as explained in Section 4.2, the authors designed a pairwise comparison in which weights were assigned to each criterion to reflect its relative importance to the decision. As the main objective of this evaluation was to assess the interoperability performance and different levels of integration of the various approaches with BIM-based procedures, the data exchange, measured using the indicator "Number of formats supported for import/export", was taken as the most important criterion in the approach comparison. The calculation of the final priorities showed that workflow n. 4 obtained a higher result (0.441) than workflows n. 1 (0.022), n. 2 (0.198) and n. 3 (0.338). However,

workflow n. 4 was selected as the optimum approach due to the weighting decided by the authors within the pairwise comparison.

For this reason, no "ideal" workflow exists that perfectly suits any case, and the most important step when performing the assessment is to decide the priorities of the criteria in order to establish the most efficient workflow based on the given priorities. Therefore, the results of the assessment could differ greatly when giving priority to some criteria instead of others. This means that the most efficient workflow for achieving a specific aim depends on a lot of factors, which must be defined and sorted in order of importance before performing the assessment itself. Due to its flexibility and scalability, the proposed framework serves as a guide for practitioners in need of a clear and straightforward identification of the best-performing workflows, and it is extremely adaptable in its application.

Finally, a coordinated model of the case study was obtained. This represents a data repository model that collects heterogeneous data. This demonstrates how the integration of geotechnical–geological modelling in a BIM environment is crucial to the increasing requirement to create Digital Twins not just for structures or infrastructures, but also for larger areas in territorial contexts. This is critical, for example, in the context of Risk Management for the prevention of floods, fires, and other natural disasters, as well as for defining territorial resilience. Geothermal energy is another sector in which the integration of geo-models and BIM may be quite beneficial (e.g., GeoFIT, in the Horizon 2020 project). It should be noted that the integration of heterogeneous data from different disciplines into BIM can create new challenges within the new bounds of Artificial Intelligence with the application of machine learning techniques (ML). Appropriate solutions might incorporate ML algorithms to address complex issues that require simulations of different scenarios.

Although the findings of this study demonstrate significant benefits for data integration and provide a highly replicable method for multiple contexts, interoperability remains a challenge. However, one limitation of this study is that the critical criterion of the data collected via the interoperability tests could change over time, and is strictly dependent on the user who performs these tests. This requires constant updating of the assessment and necessitates the creation of a clear procedure for performing interoperability tests in order to avoid interpretation mistakes in the process. Furthermore, issues such as the definition of classifications and standards for integration remain to be solved. In terms of future research, it would be useful to extend the current findings by addressing these gaps, decreasing data losses in terms of attributes, and enhancing interoperability between the two systems and among specialists.

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