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CAMILA ANDREA SANDOVAL BUSTOS

**INTEGRATED SURFACE-SUBSURFACE BIM DESIGN
WORKFLOWS FOR TECHNOLOGICAL FACILITIES**

**INTEGRIRANI DELOTOKI PROJEKTIRANJA BIM NAD IN POD
POVRŠJEM TEHNOLOŠKIH OBJEKTOV**



European Master in
Building Information Modelling

Master thesis No.:

Supervisor:
Assist. Prof. Tomo Cerovšek, Ph.D.

Cosupervisors:
Franc Sinur, Ph.D.
Assist. Prof. Dejan Grigillo, Ph.D.

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Avtor:	Camila Andrea Sandoval Bustos
Mentor:	doc. dr. Tomo Cerovšek
Somentorja:	doc. dr. Franc Sinur doc. dr. Dejan Grigillo
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Izveček: Modeliranje topografije, geoloških in geotehničnih razmer v gradbeništvu še ni uveljavljeno. Projekti BIM običajno ne vključujejo modela površja in podpovršja, zaradi česar so pogosto informacije o zemljinah neusklajene v procesu BIM. Z vključitvijo dodatnih informacij o površju in podpovršju v modele BIM, bi lahko procesi projektiranja, gradnje, sanacij ali rušenja omogočili nove načine uporabe BIM, ki bi lahko izboljšali upravljanje informacij v življenjskem ciklu gradbenih objektov.

Zaradi vse bolj pogostega vključevanje zemljin v modele BIM, se pojavlja potreba po standardizaciji tovrstni modeli. Poleg tega se interoperabilnost med progami za geologijo in geotehniko ter BIM nenehno izboljšuje. Zato se naloga najprej osredotoča na primere projektov, na standarde in orodja za modeliranje površja in podpovršja tal. Na osnovi pregleda podajamo predlog digitalnega delotoka za modeliranje površja in podpovršja za zahtevne tehnološke projekte, ki ga tudi demonstriramo na primeru hidroelektrarne Mokrice.

Današnji infrastrukturni projekti izpostavljajo vse večje povpraševanje po BIM, kar posledično zahteva novo strokovno znanje o metodah BIM za modeliranje topografije, geoloških in geotehničnih razmer. Zato ta teoretična študija in aplikativno raziskovalno delo predlaga pomembne delotoke, ki se lahko uporabijo v industriji pri tehnološko zahtevnih projektih. Predlagan pristop odpira številne možnosti za uporabo v digitalnih delotokih, ki lahko zagotovijo prihranke časa in denarja, upravljanje nepredvidenih dogodkov in težav v gradbeni industriji, ki se pojavljajo v življenjski dobi gradbenih objektov.

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BIBLIOGRAPHIC– DOCUMENTALIST INFORMATION AND ABSTRACT

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Author:	Camila Andrea Sandoval Bustos
Supervisor:	Assist. Prof. Tomo Cerovšek, Ph.D.
Cosupervisors:	Franc Sinur, Ph.D. Assist. Prof. Dejan Grigillo, Ph.D.
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Abstract: The modelling of the topography, geological and geotechnical conditions is not yet common in the construction industry, and BIM projects usually do not include surface-subsurface models. Hence, information about the topography, geological and geotechnical conditions is often outdated and excluded from the BIM procedures. If the surface and subsurface information is available and included in the BIM models, the processes of design, planning, construction, rehabilitation or demolition could enable advanced uses and applications of BIM that can improve the construction life cycle management.

With an increasing inclusion of the subsurface in BIM models, the need for standards for this type of models is emerging. Besides, the interoperability between geological/geotechnical software and BIM is continuously improving. Thus, this thesis first explores relevant project case studies, standards and software that enable modelling of the surface and subsurface in BIM. Based on the review, a digital workflow for modelling of surface-subsurface models for demanding technological facilities is proposed and tested on a case study of the hydro-power plant project HE Mokrice. Also, a proposal for standardisation in terms of the level of development for the surface-subsurface models is discussed, as well as some interoperability analysis between the software involved.

Finally, given that the infrastructure projects expose an increasing demand for BIM, consequently, this requires expertise in BIM methodologies for modelling of topography, geological and geotechnical conditions; this theoretical study and practical research work propose valuable workflows that can be implemented in the industry for technological projects. The proposed approach is opening a wide range of possibilities of uses in digital workflows that can generate significant savings in terms of time, costs, management of unforeseen events and problems for the AECO industry in the lifetime of constructions.

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constantemente motivadores en mis sueños.*

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1 INTRODUCTION

1.1 Background and Problem Statement

Geological and geotechnical data in Building Information Modelling (BIM) is usually neglected, as mentioned by M. Berdigylyjov and H. Popa, and G. Morin [1], [2]. More often, BIM models include the foundations, but no additional information that would represent the subsurface. One of the pillars of BIM is cost reduction by a better understanding of the project, and geological and geotechnical information is crucial to accomplish this goal. Hand in hand with topography, they are one of the first studies to get preliminary feasibility of the project, their importance has made appear lately the term GeoBIM that seeks to integrate Geographic Information Systems (GIS) with BIM.

In this thesis, the term GeoBIM will be used as the BIM model generated from the topography, geological and geotechnical information, that will be combined with the facility model for different uses considering that some projects that included the geological model had demonstrated the enormous impact this information can have. The use of the GeoBIM during the complete life cycle of the facilities or infrastructures can be translated directly to cost reduction, less unforeseen and better planning with more efficient alternatives of foundation, retaining structures and others.

Nowadays, the workflow to generate geological or geotechnical models is based on the software of these disciplines based on GIS. These models have particular extensions and are not readable by other programs most of the time; however, most of them now allow an exchange of geometrical information in the drawing file, but still, the data is not transferable. Geological models often were represented in sections and planes in two dimensions (2D); nevertheless, now they are changing to 3D representations. In the same way, geotechnical models usually represented in 2D are changing to 3D models, and the analysis software is improving their capabilities. However, these 3D models are not yet fully integrated into BIM.

Similarly, as infrastructure some years ago and even now, GeoBIM is creating new uses and possibilities in BIM. Infrastructure is evolving faster but is also pulling the surface-subsurface modelling. Governments demanding the use of BIM in any construction project has made the industry change their ways to work. Bridges, dams, roads, among others, with BIM models, had demonstrated the importance of a digital model and the infinite possibilities with time, scheduling, sustainability, management, and others considered in the lifecycle of the projects. While these models grow and are developed further in the common practice, the surface and subsurface interaction is acquiring visibility and consciousness of its importance.

For technological facilities, earthworks' volumes, material's quantities (depending on the soil), among others, make an essential impact in the budget of a project. Given the above, the following document will explore projects that have included the subsurface in BIM models, the current normative for this type of models, and the software available. Also, a proposed workflow will be included considering the requirements for information needed of the other disciplines involved in technological projects as well as the quality assurance parameters for the GeoBIM. The interoperability issues will be discussed as well as the BIM uses. Finally, a case study will test the workflow and allow leaving some new ideas for future works.

1.2 Goals and Aims

This research seeks to develop procedures to include and use GeoBIM in technological facilities. By integrating geotechnical design in the workflow, testing the interoperability between software, comparing the specific scenarios in the design of high-tech facilities considering topography and soil investigation, analysing the relevance of soil profiles, and proposing a workflow including topography, geological and geotechnical data for quantity take-off, clash detection, quality control & assurance, and 4D simulation uses.

1.3 Methodology

The leading research aims to develop procedures to include and use GeoBIM in technological facilities such as hydropower plants and dams, thermal plants, nuclear plants, industrial factories, storage facilities, power plants, infrastructure, and environmental protection projects. Since in the field of geology and geotechnics, there is no standard methodology for BIM projects, first in theoretical research, searching for projects already using BIM for the surface and subsurface, and later, in practical research where a workflow will be developed to include GeoBIM in technological projects.

The existing data collection was based on the field knowledge in papers and conferences about topography, geology, geotechnics, and BIM. Some videos about specific expertise for the software were also consulted to have more updated approaches. The criteria to select the content was primarily the contribution to the background and the current state of the BIM methodology in the subsurface, and then the material that helps develop the workflow.

Finally, after the research and development of a preliminary workflow, this was tested for the different BIM uses purposed to understand the difficulties designers may encounter during the process and proposed different solutions, and lastly validating the proposed workflow with a case study that shows the potential for the industry.

1.4 Thesis Structure

This document consists of seven chapters that included an introduction, the state of the art of geotechnical BIM, standardisation, a technical solution, surface-subsurface importance in technological projects, the case study and the discussions and conclusions.

Chapter 1 Introduction includes the background and problem statement, the goals and aims of the investigation, the methodology of investigation and the structure of the document. Chapter 2 follows with the state of the art of the geotechnical BIM, showing the typical BIM uses companies had used in their projects associated to the surface and subsurface as well as some proposed that can be developed. This chapter also includes the requirements and scenarios that the industry and education community has developed so far. Chapter 3 Standardisation is a brief exposure of the existing normative for geotechnical data and ground investigation. Chapter 4 Analysis of the software for the technical solution describes the software employed for the proposed workflow, the analysis programs used in the HPP Mokrice, some alternative tools for subsurface modelling and an interoperability analysis.

Later, Chapter 5 GeoBIM model using Civil 3D describes the proposed workflow for surface-subsurface modelling, including the information needs for the subsurface in BIM projects, the difficulties, the differences between 2D and 3D geological and geotechnical analysis and the interoperability between the software employed for the proposed workflow. The second part of the chapter will develop the specific workflows for the proposed uses for Geo BIM, and other potential uses. Chapter 6 case study is the application of the workflow in a technological project: the hydropower plant Mokrice, and finally, Chapter 7 is a discussion of the research with the critical evaluation and lessons learned.

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2 STATE OF THE ART OF GEOBIM

The following section will tell the current development of the Geological and Geotechnical BIM models including the topography in the industry (GeoBIM). From the current BIM uses that can be developed to the already classified by BIME initiative. Passing through the general requirements for geological and geotechnical data exchange, the methods and difficulties of modelling the subsurface, and finally arriving at some scenarios that already have included the GeoBIM in projects showing significant benefits in including the surface and subsurface model in BIM projects.

2.1 Typical BIM Uses

The site and ground investigations result in a field report; this report will contain all data required for interpretation of the field exploration recorded by the operator [3]. As described in the BS 5930:1999 (later update in 2015 and with annexes in 2012 and recently 2020), the contains should include a description of the site, geology, fieldwork, boreholes logs, ground conditions and parameters, and engineering interpretation with design, construction expedients, sources of material, failures, and calculations.

The engineering interpretation includes the specific areas of potential uses of a subsurface BIM model, as follow:

- **Design:** spread foundation, piles, retaining walls, basements, ground anchorages, chemical attack, pavement design, slope stability, mining subsidence, tunnels and underground works, the safety of neighbouring structures, monitoring of movements, embankments, and drainage.
- **Construction expedients:** open excavations, underground excavations, groundwater, driven piles, grouting, mechanical improvement of soil below ground level, and contamination.
- **Sources of material:** fill, and aggregates.
- **Failures:** Foundations, landslides, embankments, retaining walls, and pavements.

According to the BIME initiative [4] Table 211 in Model Uses, geotechnical BIM models can include the following General Uses: concrete structure modelling (piles), drainage/hydraulic systems modelling (underground pipes), foundations modelling, infrastructure systems modelling (underground systems), terrain modelling (topographical/site/geological/geotechnical/open-pit). For the Domain Model Uses the following can be considered: 3D detailing, as-constructed representation (after PIT), surveying, demolition planning (underground structures), clash detection, constructability analysis (types of machines requires for excavation), finite element analysis, life cycle assessment, concrete precasting, sheet metal forming, performance monitoring (tie-backs).

In general, GeoBIM is taking importance in the BIM world where some of the common uses are: calculation of soil volume [5], reducing risk and cost during construction [6], more accurate space planning [7], landslide and seismic risk [8] and selection of excavation equipment based on cost and schedule information [5]. Other uses are: structured database, integration of data with other disciplines, profiles updated with the model, reports evoked from the model, analytical models extracted for the analysis, augmented reality (with georeferentiation), excavation difficulties or interferences, foundations and retaining structures design, and pipelines, subways and underground infrastructure.

One of the main BIM advantages is the ability to simulate various options and improve the design to minimize the risks in the construction process. The role of the geotechnical team is to diminish the risk in construction [1], including a better manage and update of the soil data during the site investigation process, including the laboratory test [9].

2.2 Requirements

Nowadays, the geological-geotechnical model is not standardized; therefore, the requirements to develop it are not defined. Following the requirements for a geotechnical exchange format proposed by N. Mokarram [10], that can be a base to standardize the GeoBIM.

Table 1. List of Requirements for a Geotechnical Data Exchange Format
(Source: N. Mokarram [10])

Code	Name	Criteria Definition
G1	Consistent Nomenclature	Is naming convention consistent?
G2	Unit Abbreviation	Are unit abbreviations according to standard units?
G3	Integrability of Data Subsets	Can subsets be integrated back to larger data sets?
G4	Using Accepted Test Procedures	Does data come from well-accepted test standards?
G5	Exchangeability via Email	Can data be exchanged via email?
G6	Acceptance by the Community	Can data exchange be accepted and used by the community?
D1	Data Dictionary	Are all variables defined based on common knowledge in the field?
D2	Unit Validation	Are all values associated with units?
D3	Value Format Validation	Are the values in the right format, e.g., integer, string?
D4	Value Range Validation	Are the values being validated to be in an acceptable range?
D5	Missing Data Recognition	Are missing fields recognized with error messages?
D6	Interoperability	Can exchange data be used in different platforms and operating system?
D7	Wide Support	Is the data format readily supported by non-commercial and commercial tools?

Code	Name	Criteria Definition
D8	Archivability	Can data be indexed for archival and later retrieval?
D9	Machine Searchable Data	Is it possible to search within the data file for a particular value or attribute, using a search engine?
D10	Locatable	Can data be located on interactive maps?
D11	GIS-enabled	Are all objects in data following GIS accepted format, such as GML, so that they can be position in 3-dimensional spaces?
D12	Unique Relationships	Is the exchange format capable of identifying missing objects or objects with non-unique or missing relations?
D13	No Circular Relationship	Is data format free of circular relations between objects which create infinite circular loops?
D14	Random Data Generation	Is it possible to generate random instances of objects for populating data?
D15	Flatable Structure	Can all relationship identifiers be replaced with object attributes to form 2D tables without any relationships?
D16	Data Annotation	Can data exchange format hold annotations (additional information)?
D17	Machine Readable Annotation	Does annotation have the capability of containing structured metadata?

The elements of geotechnical BIM model should carry specific information, e.g. location, cartography, field exploration (boreholes, CPT, downhole), stratigraphy, laboratory test results, geological data, geotechnical data (soils parameters), and GIS data.

Accessibility and flexibility are critical for the adoption of GeoBIM in practice. Besides, appropriate training [9], software, hardware and qualified personnel are also included as requirements for a Geological BIM model.

Furthermore, the requirements of the Code of Practice for the management of geotechnical data for ground engineering project shall complement the requirements set out here in the specific scenario of a data management system (3.4 BS 8574:2014 Code of Practice for the Management of Geotechnical Data).

2.3 Scenarios

From several years the AECO industry has been evolving with the computational developments. Since the CAD revolution, BIM is one of the most significant steps in the industry to better design construct, operate, maintain, and demolish. In such a way that different companies have started to invest in technology and specifically in BIM, seeing enormous benefits. Hereafter some projects that have developed a GeoBIM model and the benefits of having the subsurface speciality in 3D modelling.

Farringdon Station Project by DSP and BFK

The Crossrail Farringdon station required a geotechnical risk management process because of the complex geology, the high degree of risk and uncertain, and the presence of infrastructure and third-party assets. By regularly nourishing the 3D BGS ground model with each excavation phase, it was possible to increase the knowledge and confidence about the subsurface, enhance the predictions about the soil conditions, and implement geotechnical risk managements standards [11].

Study and Development Project to Investigate the Feasibility of 3D Underground Modelling by CH2M

As a investigate and development project to examine the feasibility of 3D subsurface modelling, CH2M defined at the design stage the importance of a 3D that is consistent with the BIM principles, so that the data of the subsoil could help to identify uncertainties or risks, improve the areas on which new investigations should focus and reduce the costs associated with 'unexpected' geotechnical problems during construction [12].

Railway Electrification between Leeds and York by Tata Steel Projects

For the 28 km long railway line between Leeds and York, a geological 3D model with 102 drilling logs was created from the National Archives of the BGS. The top and bottom of the weathered rock, as defined, is shown as layers within the model. The specifications of the conceptual ground model (CGM) were: CGM must extend 30 m below track level, contain surfaces representing the top and bottom of the geological layers, and the model must be in the Bentley (.dgn) 3D model file format (.dgn). The Leeds-York 3D Conceptual Ground Model (CGM) covers an 80 m wide and 28 km long section of the Leeds to York railway line, includes 117 correlated cross sections and 57 geological units, contains 11 coal seams (not modelled as volumes or surfaces). The geological model contributes to a better understanding of the project and full integration into the underground BIM system. [13].

Victoria Station Upgrade: BIM Strategy from Previous Experience by Keller

The Victoria station site was very dense with pipelines, sewers, and power/communication cables, accordingly, since the planning of the project BIM was involved even for ground engineering. The company requirements were automating BIM processes as far as possible, leverage the data source collected during the construction phase of work to fulfil BIM requirements, and tie together previously independent databases. The BIM model of the tunnel was not just used to have confidence in the foundation drilling but as well in the coordination of the stabilization with jet gout columns, allowing to enrich the model while the project advance and more information acquired to end in an as-built model with the drilling data [14].

The Silvertown Tunnel Project by Transport for London (TfL) & Atkins

The Silvertown Tunnel is a connection between Silvertown and North Greenwich to reduce the impact on nearby Blackwall Tunnel and other existing intersections. There were many challenging problems in the area, the route of the tunnel will have to pass through heavily industrialized areas of London; areas which have many different types of soil, roads, foundations, and other underground structures. The approach was combining existing geotechnical knowledge into a geotechnical data management scheme, while simultaneously developing a soil model of the site and soil conditions in 3D. Both were then integrated to create a 3D geotechnical model to refine the geotechnical data and the model throughout the process from preliminary investigation, full site survey, design, and ongoing refinement. The main benefits of a 3D geological model were a better understanding of the site, which enabled them to identify possible construction obstacles. Also, improvements in the estimation of earthworks and contamination size, a noteworthy reduction in the number of new exploratory drillings required through the correct use of historical data in geotechnical databases, and new streamlined workflows that saved time and effort in updating and integrating the data [6].

Bored Tunnel for Combined Sewer Overflow (CSO) by McMillen Jacob Associates

The project includes a centralised and coordinated approach to geotechnics, integration with AutoCAD Civil 3D, rapidly create and visualise cross-sections (profile views). In the software, MJA replaced gINT with HoleBASE SI because it has a close integration with AutoCAD Civil 3D, a centralised geotechnical data management and is relatively easy to use and configure. For the future, data collection with pLog, which is quick and easy. Main benefits were more focused site investigations, faster reaction to a potential issue, complete picture of the sub-ground, better understanding of the soil behaviour and improved communications [15].

A Prototype of an Underground 3D Geotechnical Information Model in Illinois Peoria County

Approximately 136 drill logs were combined in software to create an interactive 3D soil database. The database created is highly interoperable, allowing any personnel (including end users) to update the database. The database provides characterized soil information for the project site and depth, e.g. source factor and uniaxial compressive strength, which can define the volume of the excavation during the earthworks. [5].

BIM for the Subsurface by Keynetix, the British Geological Survey (BGS), Atkins and Autodesk

An initiative from BGS to create a cloud-based database that integrates the geological and geotechnical information with 3D models. Because of misinterpretation, one of the most severe difficulties when incorporating geotechnical data in BIM is that geotechnical teams are hesitant to share interpreted data. This research should help dispel these concerns, improve collaboration and data sharing, leading to an improved understanding of the ground, and more informed decision-making throughout the lifetime of a project [16].

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3 STANDARDISATION

3.1 Context of Standards for Geotechnical Data Management

One of the most used digital standards AGS was first recognized in 1991 as a method of transferring data in a text file (extension .ags). AGS is a digital data transfer format for ground engineering by the Association of Geotechnical & Geoenvironmental Specialist in the United Kingdom. For the geotechnical and geoenvironmental industries, it allows sharing data between more than 25 software with more than 60 users registered. At an epoch where artificial intelligence, cloud computing and BIM regularly make the headlines, in its 25-year history the AGS Data Format is more significant than any time [17] is a standardized text file to collect, report, visualize, transfer and storage geotechnical data. Currently, the standard is in version 4 published in 2010 with the last addendum in 2011 and is represented as AGS4.

Because it is a standardized text file, companies can continue their process and methods without having difficulties in exchange data. It includes the Data Dictionary of the items that can be transferred, including items required by Eurocodes and British standards. Finally, there is already the possibility to convert AGS to Excel with Bentley AGS Toolkit and Keynetix solutions.

Mainly, the geospatial standards are developed by the Open Geospatial Consortium (OGC), an international alliance interested in geospatial location information. The OGC standards are technical documents that detail interfaces or encodings, within which it is possible to emphasize GML, GeoXACML, GeoSPARQL and GeoAPI.

GML (Geography Markup Language) is a XML grammar for expressing geographical features. GML serves as a modelling language for geographic systems and as an open exchange format for geographic transactions on the web. Like most XML-based grammars, the descriptive linguistics consists of two components, the schema (describes the document) and therefore the instance document (actual data). A GML schema is used to describe a GML document [18].

As defined by the OASIS standard “*eXtensible Access Control Markup Language (XACML)*, *GeoXACML provides support for spatial data types and spatial approval decision functions. These data types and functions can be used to define additional spatial constraints for XACML-based policies*” [19].

The OGC GeoSPARQL standard supports the presentation and retrieval of geodata within the linguistics net. GeoSPARQL defines a vocabulary for the illustration of geodata in RFD (Resource Description Framework), and it defines an extension of the search language SPARQL for process geodata. Besides, GeoSPARQL is intended to support systems based on qualitative spatial reasoning and systems based on quantitative spatial calculations [20].

GeoAPI provides a group of programming interfaces for geospatial applications. In many packages or modules GeoAPI 3.0 defines interfaces for data handling and geodetical referencing (map projections). The GeoAPI interfaces closely follow the abstract models jointly published by ISO (International Organization for Standardization) in its 19100 document series and also the OGC (Open Geospatial Consortium) in its abstract and implementation specifications. GeoAPI provides an interpretation and adaptation of those standards to fulfill the expectations of Java or Python programmers [21].

However, the most influential format in terms of geological and geotechnical information is GeoSciML, a model of the earth, ground and geological features usually described and presented in geological maps, cross sections, geological reports, and databases. The model has been developed by the Commission for the Management and Application of Geoscience Information (CGI); version 4.1 is the first version officially presented as an OGC standard. This specification describes a logical model and GML/XML coding rules for the exchange of geological map data, boreholes and information for laboratory analysis [22].

In the BIM context, the IFC (Industry Foundation Classes), is a standardized format, that describes digitally the built environment, mainly buildings but including civil infrastructure. It is an international standard (ISO 16739-1:2018) most known for being open, that is intended to be vendor neutral or sceptical and can be used for a wide range of hardware devices, software platforms and interfaces for various use cases. The specification of the IFC schema is buildingSMART International's most important technical outcome to achieve its goal of promoting openBIM [23].

Nevertheless, for the surface and subsurface description, this standardized schema is not enough developed. In the latest version 4.2.0.0 published in April 2019 (candidate when consulted, now withdrawn and replaced for 4.3.0.0 published in April 2020 now candidate consult in 11.1 Appendix 1) for geological and geotechnical purposes, the following are the IFC definitions:

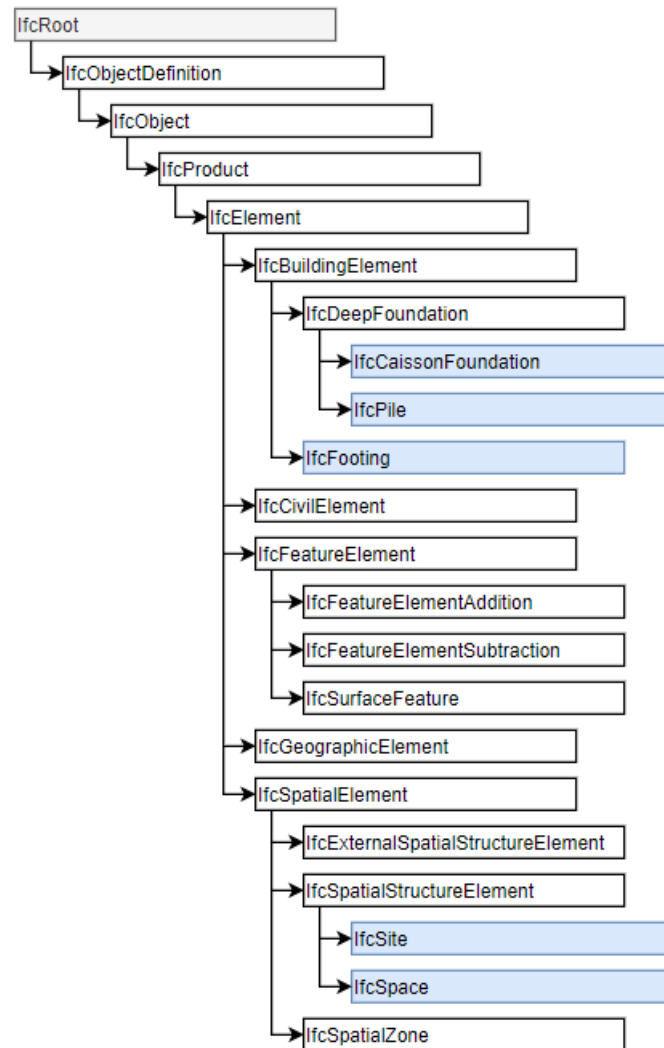
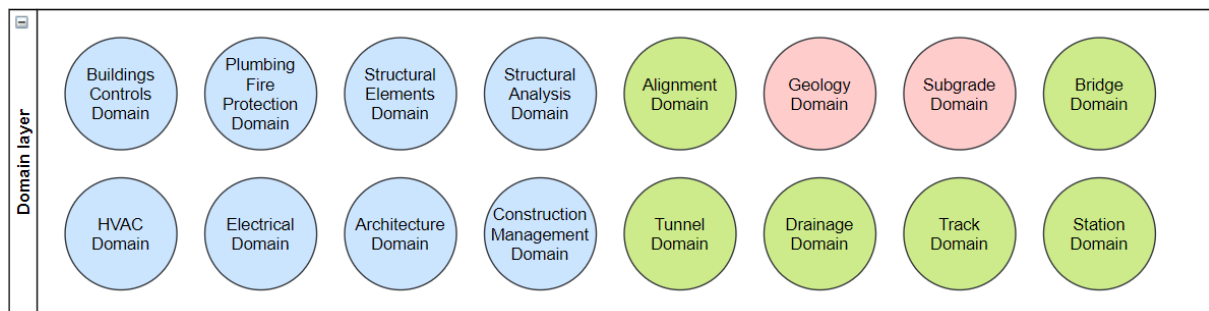


Figure 1. IFC Inheritance for Geological and Geotechnical Elements without PredefinedType
(Source: BuildingSMART International [23])

The most significant advance for subsurface BIM standards had been made by China Railway BIM Alliance (CRBIM) [24] where they extended the IFC4 standard Domain Layer in eight disciplines (Figure 2): Alignment, Geology, Subgrade, Bridge, Tunnel, Drainage, Track and Station as shown in Figure 3 and Figure 4 for geology and subgrade domains respectively.



Note: In blue the existing domains, in green and red the proposed by CRBIM.

Figure 2. IFC4 Domain Layer
(Source: China Railway BIM Alliance (CRBIM) [24])

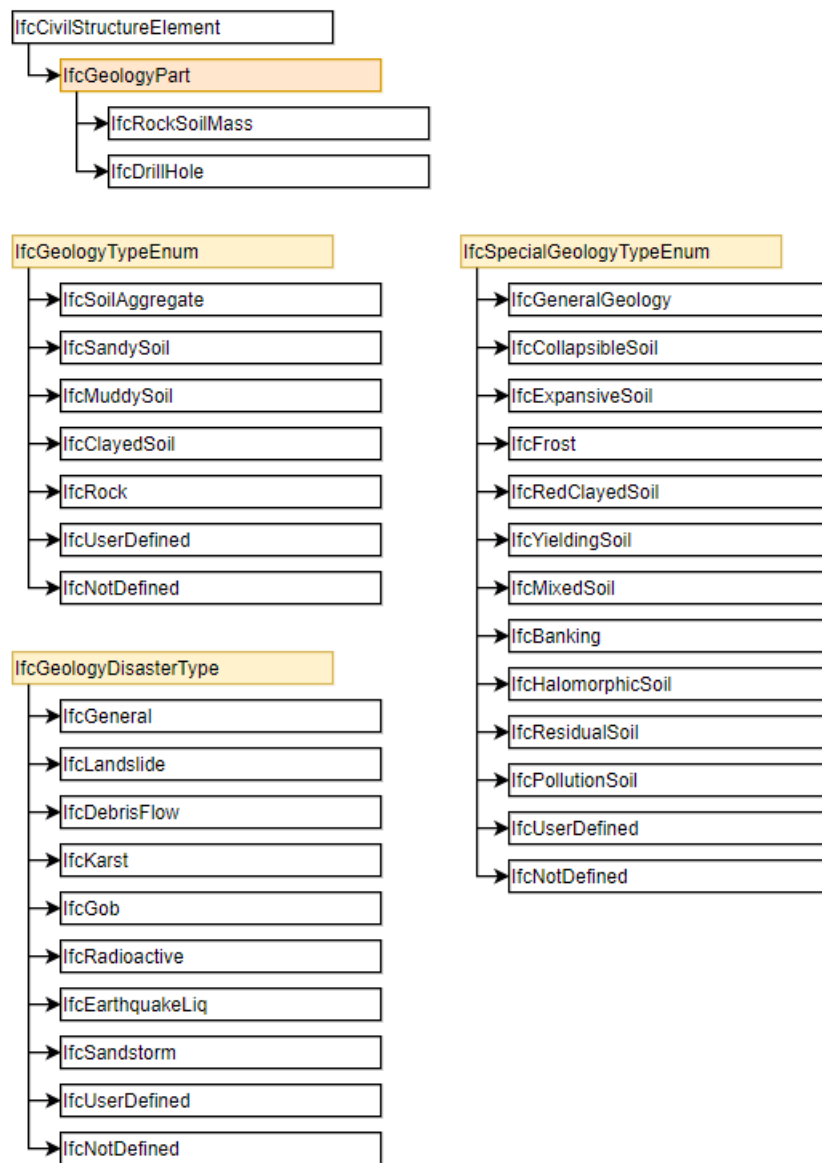


Figure 3. IFC Inheritance for Geology Domain
 (Source: China Railway BIM Alliance (CRBIM) [24])

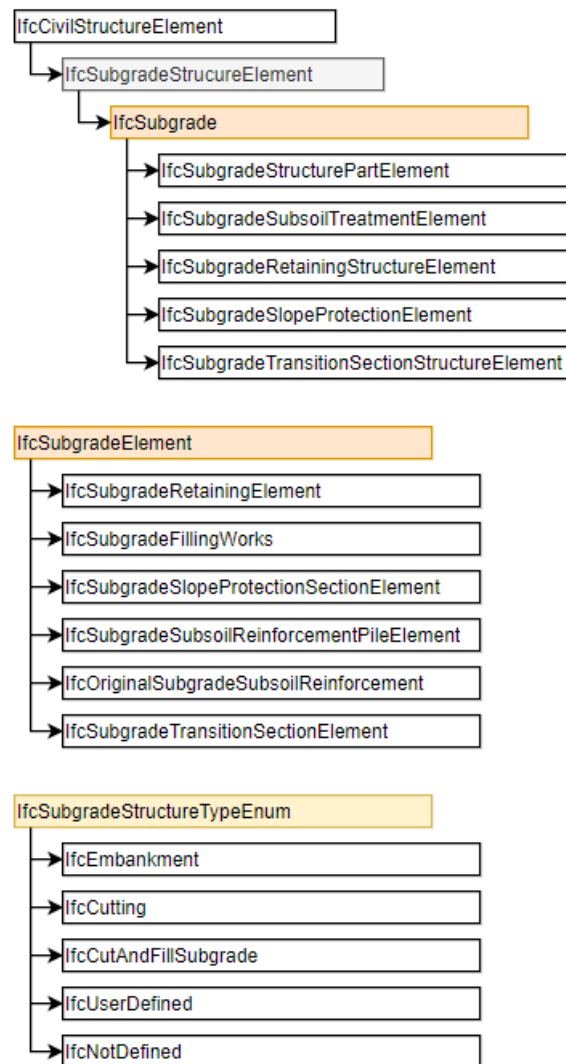


Figure 4. IFC Inheritance for Subgrade Domain without PredefinedType
 (Source: China Railway BIM Alliance (CRBIM) [24])

This contribution in the syntax of the IFC format will allow better development, editing and interoperability in the field of geotechnics regarding the BIM world.

3.2 ISO Series

The ISO series such as BS EN ISO 14688-1:2002, BS EN ISO 14688-2:2004 and BS EN ISO 14689-1:2003, are requirements, unlike the British Standard that are codes of conduct taking the form of guidelines and recommendations [3].

Following the ISO series referring to geotechnical information:

Table 2. ISO Series for Geotechnical and Geological Information
(Source: Own, based on ISO standards)

Series	Title
ISO 14688	Geotechnical investigation and testing - Identification and classification of soil
ISO 14689	Geotechnical investigation and testing - Identification and classification of rock
ISO 22476	Geotechnical investigation and testing - Field testing
ISO 17892	Geotechnical investigation and testing - Laboratory testing of soil
ISO 18674	Geotechnical investigation and testing -Geotechnical monitoring by field instrumentation
ISO 22475	Geotechnical investigation and testing — Sampling methods and groundwater measurements
ISO 22476	Geotechnical investigation and testing — Field testing
ISO 22477	Geotechnical investigation and testing — Testing of geotechnical structures
ISO 23469	Bases for design of structures — Seismic actions for designing geotechnical works
ISO 22282	Geotechnical investigation and testing — Geohydraulic testing

It should be noted that all these documents are referring to investigation, testing and design, but they do not deepen in data management and modelling.

3.3 BS 5930:2015 Code of Practice for Site Investigations or Ground Investigations

As mentioned before, most of the existing standards were written without thinking in BIM, interoperability, and data management. The BS 5930:2015 [25] standard for geotechnics follows the progression of a ground investigation on site, from initial considerations through the planning, implementation and reporting of an investigation programme, to the further investigation all along and after construction.

This standard is divided into eleven sections as follow: Preliminary considerations, Desk studies and field reconnaissance, Planning ground investigations, Fieldwork, Geophysical field investigations, description of soils and rocks, Field tests, Field instrumentation, Laboratory test on samples, Reports and interpretation and Reviewing during and after construction.

To assess suitability for the development of constructing works and civil engineering, this Code of Practice obtains with the investigation of sites expertise of the characteristics of the ground that have an impact on the design, construction and safety of adjacent land and property. Though, the data management and interoperability problems related to BIM are addressed in the following section (3.4).

3.4 BS 8574:2014 Code of Practice for the Management of Geotechnical Data

For organizational and project level, this British Standard provides guidelines for the duration of the life cycle of civil engineering and constructing projects for the management of geotechnical information. It additionally offers suggestions for the collection, storage, archiving, sharing and transfer of logical data. The BS is aimed at geotechnical data managers, engineering geologists, IT managers, geotechnical and environmental engineers, and project managers [26].

Given that each engineering project requires multiple actors who in turn collect information from different sources, process it with various programs and transmit it in multiple formats, the management and presentation of information of a project during the life cycle is a central factor to consider when talking about BIM as the central repository of information. Therefore, a data management system and usage policies must be defined so that all project information can be consulted, analysed, and reused.

The BS 8574, proposed procedures to facilitate the management of geotechnical data in a BIM project following PAS 1192 and is applicable for geotechnical and environmental investigators, monitoring and asset management, and specific activities including earthworks in all scales. This document includes terms and definitions, data management principles and data management systems.

The data principles of the Code of Practice for the data collection should be performed at the source, once and preferably electronically, if it is recorded manually, then it should be digitalised. The time of collection, data transfer and type of data entered should be stated in the data management plan. In terms of storage, it should be stored securely, including version control, in consistency depending on the different systems and locations and with the status recorded. Also, the management plan should ensure long-term readability. Finally, to ensure quality, each record should use a unique reference, that helps trace the verification and validation process.

For the data management system, the British standards recommend having policy, strategy, manual and plans. The policy is the framework for data management by setting the objectives. The strategy defines the goals and resources of the system and may include key performance indicator (KPIs) and the critical success factors (CSFs). The manual proposed is based on the PDCA (plan, do, check, act) method of continual improvement. Finally, the plan should include the aim, the items required and the breakdown of the tasks of each work item.

3.5 Level of Development (LOD) and Level of Accuracy (LoA)








The BIM world has introduced in the models since 2004 introduce the term Level of Detail (LOD) in the United States by Vico Software. Then, several countries had adopted the concept in different terms and meanings. In 2007, the term Information Level appeared in Denmark, later in 2009 in Australia the terms used were Object Data Levels and Level of Detail, while in the UK the term used was Component Grade and Level of Detail. Evolving through the years, other countries like Hong Kong, Singapore, Canada, Germany, Taiwan, Australia, China, France, Netherlands and Belgium had referred to the concept in different ways, Lately, in 2015 in the UK as Level of Detail (LOD) and Level of Information (LOI) by BIMForum and the United States as Level of Accuracy (LOA) and Level of Development (LOD) by USIBD.

Semantic information (non-geometric properties) which include types and relationships among elements complemented and 3D shapes of all building elements and the enclosed spaces, constitute a BIM model. During the design, construction and operation of the building, BIM unites a database to change graphically and non-graphically information in a 3D environment for multiple disciplines [27].

According to BIMToolkit in the UK, reference libraries of definitions are required to illustrate information delivery. Geometry (levels of detail) or information (levels of information) requirements construe the levels of definition [28].








Level of Development states to the reliability and content during each phase of the construction process from concept design till as-built. In contrast, Level of Detail is the evolution of the graphical representation (quantity, the proportion of detail), and the non-graphical information is part of the Level of Information. Nowadays, a general term to refer to all varieties is Level of X (LoX) that collect all the current terms and future variations.

Table 3. Comparison of the Intended Coverage of LoX Systems
(Source: M. Bolpagni [29])

Source	LoX system	Whole Model	Model Element	Geometric data/info	Non-Geometric data/info
 ABEB-VBA 2015	Level of Development (LOD)		x	x	x
 D&R 2015	Level of Development (LOD)	x		x	
 BIMForum 2015	Level of Development		x	x	x
	Element Geometry		x	x	
	Associated Attribute Information		x		x
 NBS BIM Toolkit 2015	Level of Detail (LOD)		x	x	
	Level of Information (LOI)		x		x
 AEC (UK) 2015	Level of Definition		x	x	x
	Level of Information (LOI)		x		x
	Grade/Level of Detail (LOD)		x	x	
 SZGWS 2015	LOD	x		x	x
 USIBD 2016	Level of Development				
	Level of Accuracy	x	x	x	

Note: Updated July 22, 2016.

Table 4. Comparison of Classification Systems within Different LoX Systems
(Source: M. Bolpagni [29])

Source	Title	Authorship	LoX System	Levels
 ABEB-VBA 2015	LOD Description	-	Level of Development (LOD)	- - - 100 200 300 350 400 500 -
 D&R 2015	-	-	Level of Development (LOD)	-100 0 - 100 200 300 - 400 500 -
 BIMForum 2015	LOD 2015 Element Attributes Tables	Model Element Author (MEA)	› Level of Development (LOD) › Level of Detail › Element Geometry › Associated Attribute Information	- - - 100 200 300 350 400 500 -
 NBS BIM Toolkit 2015	NBS BIM Toolkit	Responsibility	› Level of Detail (LOD) › Level of Information (LOI)	- - 1 2 3 4 - 5 6 7
 AEC (UK) 2015	-	-	› (Level of Definition) › (Level of Information (LOI) › Grade/Level of Detail (LOD)	- - 1 2 3 4 - 5 6 -
 SZGWS 2015	-	-	LOD	- - - 100 200 300 - 400 500 -
 USIBD 2016	-	-	Level of Development Level of Accuracy	- - - 100 200 300 - 400 500 - 10;20;30;40;50

Note: Updated July 22, 2016.

Under the category site, some of the times the surface and subsurface can be found. For BIM Forum the LOD specification [30] closest to the GeoBIM is the G10 (Uniformal) 21-07 10 (Omniclass) Site Preparation category that includes G1070 21-07 10 70 Site Earthwork, G1070.10 21-07 10 70 10 Grading and G20 21-07 20 Site Improvements. Moreover, for USIBD [31] under G10 (UniFormat) Site Preparation can also be found G1070 Site Earthwork. While in the NBS BIM Toolkit the activity Uniclass2015 - Ac_15_75_50 Geotechnical ground investigating [32] is defined but not as a model, even geological activities and laboratories exist but without definition yet. Hong Kong has led the development of a LOD for geological models, the Construction Industry Council (CIC) of Hong Kong developed a LOD Specification for the geological model for soil, fill, rock (Table 5). Also, the Airport Authority Hong Kong (AAHK) in their construction specification had indicated the LOD 400 and 500 for Geological Model (Table 6).

Table 5. CIC Hong Kong LOD Specification for Geological Model
(Source: The Construction Industry Council (CIC) [33])

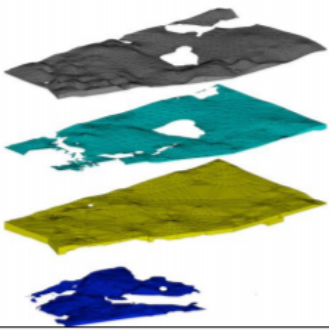
LOD	Description	Data	Example Image
100	N/A		
200	3D model showing approximate layers of soil, fill, decomposed rock and hard rock.	m ³	
300	3D model of layers of soil, fill, rock etc. based on bore hole logs from site investigations.	m ³	
400	N/A		
500	N/A		

Table 6. AAHK LOD Specification for Geological Model (400 and 500)
(Source: Airport Authority Hong Kong (AAHK) [34])

#	CAT Code	LOD	AAHK's Requirements	Remarks/ References
i	GEO		Geological Model (seabed, fill, marine deposits, alluvium, colluvium, completely and highly decomposed granite, bedrock)	
		400	<p>The model shall be trimmed by the constructed ground model.</p> <p>Geometric information include:</p> <ul style="list-style-type: none"> - Borehole - Layers of soil, fill, rock, etc. based on borehole logs or AGS from site investigations. - The model represented in TIN surface with project-specific surface styles for displaying contours, triangle, and etc. - The topography model displayed in the plan view with the form of contours with project-specific intervals. - Site boundary marked based on the surveyors setting out information. <p>Non-graphic information include:</p> <ul style="list-style-type: none"> - GI data information (such as GI data file name, survey date, survey company, data type and the like) - Excavation volume for each types of geological layers. 	
		500	Refer to <i>LOD 400</i> and the model shall be trimmed by the as-built ground model.	

4 ANALYSIS OF THE SOFTWARE FOR THE TECHNICAL SOLUTION

When implementing GeoBIM model for technological projects, this thesis proposes some BIM uses and its workflows (based on the software used by the company IBE). However, some alternatives can be developed for other companies that use different software.

The main workflow is developed by the Keynetix solution Geotechnical Module, incorporated in the program Civil 3D for infrastructure design. Revit, Navisworks, Solibri, AutoCAD, RS2 (Phase2), RS3, Plaxis 2D and Plaxis 3D are other software used in the proposed workflow. Finally, some other software alternatives for subsurface modelling are mentioned at the end of the chapter too.

4.1 Authoring/Modelling Programs

For the BIM context, an authoring tool is a software that helps to develop a virtual representation of existing and future conditions for a construction project. In this environment, the user can create, edit and export to other software for different purposes.

4.1.1 Civil 3D

Autodesk tool Civil 3D® is CAD software that supports BIM (Building Information Modelling) for civil engineering design, including features to improve design, drafting, and construction documentation [35]. This software is oriented to civil infrastructure design, focus on collaboration and for workflows until production stage. Under the civil design features, it includes corridors, rail track, point clouds, surface creation and modelling, grading, parcel design and gravity pipe networks. Besides, it includes features of drafting, documentation, visualization, analysis, and collaboration.

In the interoperability headland, offer better predictability with Navisworks, enhance the civil design with Revit and made it possible to import/export AutoCAD solids to IFC files. Additionally, it includes the visual programming tool Dynamo and can be upgraded with the geotechnical module for subsurface modelling. Initially, it includes the productivity pack 1 that allows the user to create AutoCAD 3D solids from surface models in 2015. Nowadays, in the tab Surface tools is possible to Extract Solids from Surface and Extract Objects.

Keynetix developed the geotechnical module for Civil 3D, a company concentrated on geotechnical and geoenvironmental data management, that have created an intelligent data management software that is focused in two golden rules “*only enter data once and get someone else to do it*” [36]. HoleBASE SI Standard works as a database that permits to produce logs, data and reports easier and quicker. With various import formats and customisable data entry profiles, the data is entered only one time, either on the office or in the field [37]. The main features are data entry, desk study, data management, report production, integrated GIS, and security.

The geotechnical module or the HoleBASE SI Extension for AutoCAD Civil 3D offers in a BIM environment the management and modelling of subsurface modelling. Currently available from version 2016 to version 2020, this Civil 3D module (see Figure 5) includes four sections: the data management, that allow connection, import, update and export of data by creating projects and uploading the boreholes information. The export tool allows exporting the plan boreholes, 3D boreholes and fence diagrams in a DWG file.

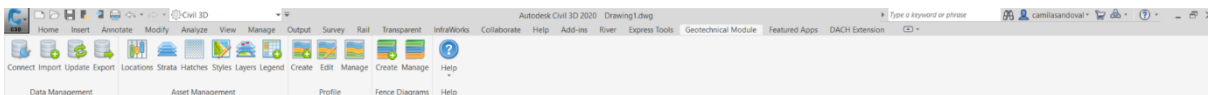


Figure 5. Geotechnical Module Civil 3D
(Source: Autodesk Civil 3D)

In asset management, the tools, locations, strata, hatches, styles, layers, and legends can be personalized. The profile section allows to create, edit and manage the profiles of the geotechnical data imported and the surfaces of the project. Finally, the Fence diagrams allow us to create and manage this type of profiles.

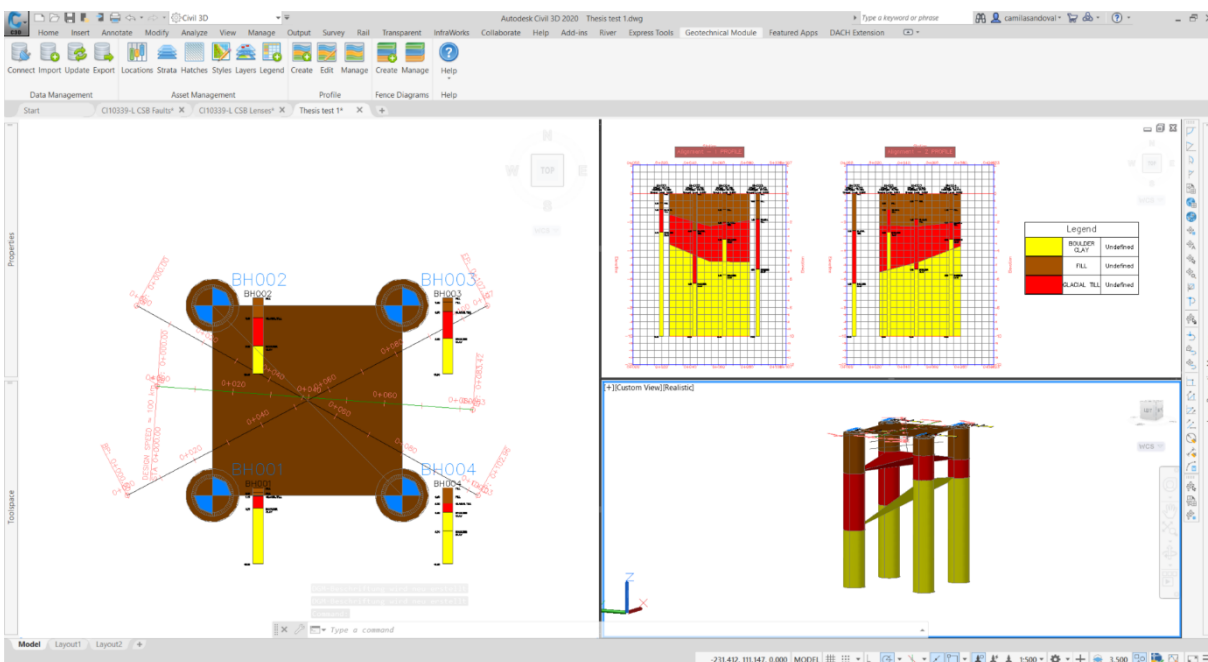


Figure 6. Geotechnical Module Civil 3D Thesis Test 1
(Source: Own in Autodesk Civil 3D)

Civil 3D uses the TIN (triangulated irregular network) methodology to create surfaces, which has two significant conditionings: a surface will not have a thickness; therefore, it cannot be treated as a solid (no operations can be performed); and on the other hand, vertical planes cannot exist because two points on the triangular surface cannot have the same elevation, hence, vertical surface such as walls cannot be automatically represented. For vertical surfaces, breaklines must be used.

4.1.2 Revit

According to Autodesk, Revit is a multidisciplinary BIM software for higher quality, coordinated designs [38]. In the interdisciplinary interface, it offers features for Architectural design, Structural engineering and fabrication, MEP engineering and fabrication, and construction. This software allows multiple disciplines to participate in the project lifecycle from design to construction and even rehabilitation or demolition, all in a 3D modelling interface, where teams can collaborate.

The top features are generative design, parametric components, work-sharing, schedules, interoperability and IFC, annotation, global parameters, Dynamo for Revit and add-ins (extend functionality with API and third-party solutions).

4.1.3 Dynamo Interface for Civil 3D or Revit

Dynamo is a visual programming tool including in Revit that allows script development for repetitive or complex tasks. Based on nodes, programming is more intuitive; libraries of codes can be consulted to search the appropriated node needed and can be enhanced by packages of third parties that develop new nodes for specific disciplines. It can automate tasks, can be used as a searcher of the different data included in the model, might be used for optimization and multiple design options, and can simulate the building performance.

Also, the Dynamo scripts can be executing in Revit only with Dynamo Player. Revit user does not need to know to program; the script can be developed and share inside a company or project to improve tasks. The script of Dynamo can be quickly launched in Revit with Dynamo Player, allowing to enter the information requested and receiving the output without passing to the programming interface.

4.2 Viewers or Specialized Programs

The viewers are tools that can import models from authoring tools for visualization purposes. Some of the viewers are also specialized in other BIM uses like time simulation, cost estimation, clash detection, model checking, among others.

4.2.1 Navisworks

Navisworks for architecture, engineering and construction is a 3D model review software in a BIM environment. It combines the design and construction models to control schedules/time (4D) and cost estimation (5D) simulations. This tool can also be used for clash detection purposes, data aggregation and support over 60 file formats [39].

4.2.2 Solibri

Solibri [40] is a Nemetschek solution for quality assurance. It includes an IFC model's viewer, a combination of IFC files for coordination, clash detection, quantities take-off, customizing rules for quality control, and autorun.

4.2.3 Bexel Manager

Bexel Manager [41] is specialized in 3D, 4D, 5D, and 6D BIM. Some of the functionalities are: IFC models visualization, design reviews, generate clash detection and quantity take-off reports, create schedules, time simulations, construction tracking, cost estimation, and include some features for facility maintenance and asset management.

4.3 Analysis Programs

These are software that can create or import models for analysis purposes. In the case of geotechnical analysis, this can be used for designing excavations, supports, slope stability, and others.

4.3.1 Rocscience – RS2 and RS3

RS2 (previously known as Phase2) and RS3 are software for excavations, design supports and groundwater flow. RS2 is 2D, and RS3 is 3D, both are finite element programs for soil and rock. The applications mention by Rocscience of the software are dams, embankments, excavations, groundwater, mining, retaining walls, settlement, rock slopes, soil slopes, tunnels [42], [43].

4.3.2 Plaxis 2D and 3D

Plaxis is the geotechnical finite element analysis software from Bentley Systems. It allows performing design and analysis of soil and rock, as well as deformation, stability and soil-structure interaction, and groundwater. The software has different versions, basic, plaxflow, dynamics and the package of all the previous, suite. Also, Bentley offers MoDeTo for monopile design [44].

4.4 Others Geotechnical Modelling and Data Management Software

Geotechnical and geoenvironmental software is evolving in the market; the following are the most popular solutions besides the Geotechnical Module for Civil 3D. The final sections quickly mention other possible solutions or software developers for geological or geotechnical modelling.

4.4.1 Leapfrog

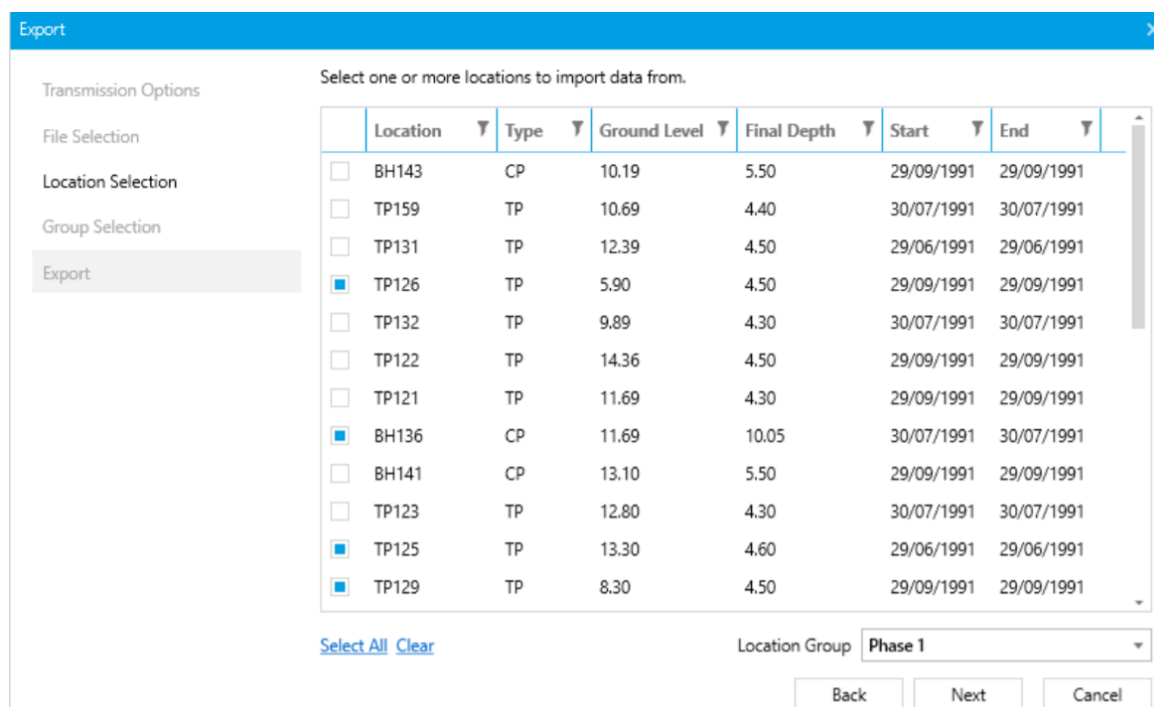
According to Seequent [45], "*Leapfrog Geo is a workflow-based 3D geological modelling tool. Leapfrog Geo's advanced implicit modelling engine bypasses time-consuming wireframing and allows build models directly from various sources including drill holes, points and surfaces.*" This software is specialized in geological modelling software that can describe in a better way the subsurface, including specific features such as fault system, lithologies, surface chronology and output volumes.

4.4.2 SoilVision

SoilVision innovative geo-modelling software with their geotechnical and hydrogeological software with modules SVDesigner, SVSlope, SVSeismic, SVSoils, SVFlux, SVSolid, SVHeat, SVChem, SVAir and SVHeave for creating geotechnical/hydrogeological 3D models, slope analysis in soil and rock, earthquake analysis, estimate hydraulic properties, calculate groundwater flow, determine deformations, calculate heat conductivity of soils, and more.

4.4.3 OpenGround

Included in Bentley's collection of geotechnical applications, OpenGround can be used to collect, report, manage, visualize, analyse, and access the ground data acquired in the field or laboratories [46].



Note: Similar interface than Civil 3D Geotechnical Module.

Figure 7. Data Export in OpenGround
(Source: Bentley Systems [47])

Also, the platform of OpenGround is very similar to the Geotechnical Module in Civil 3D because the developer Keynetix is the same for both, making it easy to learn how to use the tool for the user who has mastered one of the two tools.

4.4.4 gINT

Developed by Bentley Systems, gINT [48] offers centralized data management. The products include Professional, Professional Plus, Logs, and Collector. Each of them focusses on the report and manage subsurface data, create custom reports, manage boring and wells logs, and single report platform for field workers.

4.4.5 HoleBASE SI

From the developers of the Geotechnical Module for Civil 3D, HoleBASE SI is a Geotechnical Management System that helps analyse, control and customize field data. With the Civil 3D extension it allows to integrate geotechnical data within the BIM process, easy access to historical data for the lifecycle of the building or even the area, and also allows dynamic data analysis with Excel [37] [49]. Also, important to highlight, from Keynetix the product KeyLogbook and KeyLAB are interesting evolutions for managing geotechnical data from the field and the laboratory respectively. Making the collection of data digital in every instance and instantly available for all the team [50], [51].

4.4.6 Others

Following some other software solutions for geological/geotechnical data:

- Emerson Electric solutions
- Intrepid Geophysics with the software GeoModeller
- Dassault Systèmes products, Solidworks and Geovia
- Mira Geoscience products
- Maptek Pty solutions for Exploration & Geology, Planning & Design, and Operations & Production
- Promine mining & surveying software products essentials, modelling, engineering, and live survey
- Schlumberger geology and geophysics software
- RockWare software for geology, geophysics, hydrology, and structural & geotechnical
- The MOVE suite of Petroleum experts
- The British Geological Survey no-cost BGS Groundhog Desktop geological software
- GEOTIC products such as GeoticLog, GeoticField, GeoticGraph, GeoticCAD, and GeoticMine

- Environmental modeling solutions software for Geology, Hydrogeology & Remediation like GeoModeller
- DecisionSpace by Halliburton Landmark cloud-based software with applications for geology, geophysics, geosciences, earth modelling, well construction, among others.
- Micromine mining software Geobank, Micromine and Pitram.
- Datamine products for exploration, geological data, resources & reserves, underground planning, open pit planning and operations.

4.5 Interoperability from Authoring to Analysis Software

Interoperability is the capacity between software to share information, not just geometrical but as well as semantical. The GeoBIM information is divided into geometrical and metadata, following the possibilities to exchange information between the authoring to the analysis software and vice versa.

4.5.1 Exchange Geometry

Nowadays exchange of geometry is possible from modelling software to analysis software in a bidirectional way. As shown in the tables below, both modelling and analysis software can import and export in various format, .dxf and .dwg stand out as the most used. However, in Table 7 and Table 8 below the interoperability can be achieved in other formats. It is noteworthy that although the format is read in the different programs, most of the time it is required to prepare the geometry of the modelling program with the specific requirements of the analysis program to be used. Each analysis software handles different ways of reading the DXF file, and not all of them read DXF in 3 dimensions.

Another highlight to achieve interoperability in the BIM context is that Plaxis 3D can import .ifc files geometry of certain types but cannot export yet. For Civil 3D both import and export can be done for the industry foundation classes format making the initially CAD solution also a BIM alternative, same way Leapfrog can export .ifc files to achieve bidirectional interoperability of geometry between modelling and analysis software.

Table 7. Interoperability in Terms of Import/Export for Modelling Software
(Source: Own)

	Software	Import	Export
Modelling	Civil 3D	Drawing (*.dwg, *.dxf) Autodesk Point Cloud Project (*.rcp, *.rcs) DWF Files (*.dwfx, *.dwf) Industry Foundation Classes (*.ifc) Navisworks files (*.nwc, *.nwd) All MicroStation DGN Files (*.dgn) InfraWorks files (*.sqlite, *.imx)	AutoCAD Drawing (*.dwg) AutoCAD DXF (*.dxf) 3D DWF/DFWx (*.dwf, *.dwfx) Industry Foundation Classes (*.ifc) Metafile (*.wmf) ACIS (*.sat) Lithography (*.stl)
	Leapfrog ¹	Leapfrog Files (*.pl3, *.ara, *.msh, *.ara, *.lfpl, *.txt) CSV Files (*.csv) ASCII Text Files (*.asc) DXF Files (*.dxf) Gocad Files (*.pl, *.ts) Surpac Files (*.str, *.dtm) Gemcom Files (*.tri, *.asc) Datamine Files (*.asc, *.pt.asc, *.tr.asc) Micromine Files (*.MMpt.dat, *.MMtr.dat, *.str, *.asc) DXF Polyface Files (*.dxf) Alias Wavefront Object Files (*.obj) Vulcan Files (*.00t) (with Maptek Link) MineSight Polylines (*.srg)	Leapfrog Files (*.msh, *.lfpl) CSV format (*.csv) DXF format (*.dxf) Drawing File (*.dwg) Industry Foundation Classes (*.ifc) Bentley Drawing (*.dgn) Gocad Files (*.ts, *.pl) Surpac Files (*.dtm, *.str) Gemcom Files (*.tri) Datamine Files (*.pt.asc, *.tr.asc, *.asc) Micromine Files (*.MMpt.dat, *.MMtr.dat, *.str, *.asc) Alias Wavefront Object Files (*.obj) Bentley Drawing Files (v8) (*.dgn) MineSight Polylines (*.srg)
	SoilVision	SoilVision Model Format (*.svm) Comma Separated Values (*.csv, *.xyz) Microsoft Excel (*.xls, *.xlsx) USGS DEM File (*.dem) ESRI Grid File (*.asc, *.dat, *.grd) ESRI Shapefile (*.shp) Table File (*.tbi, *.tbl, *.tdb) 3D Studio File (*.3ds) AutoCAD DXF File (*.dxf) Existing Model (*.svm) ACUMESH Results (*.dat) file Cross-Sectional Data CLARA-W (*.clw) Surpac DTM File (*.dtm) Wavefront OBJ (*.obj) Conceptual model (*.svp) Volume Mesh (*.node, *.smesh) LandXML (*.xml) Stereolithography (*.stl) JPGIS (GML) (*.xml)	SoilVision Model Format (*.svm) Comma Separated Values (*.csv, *.xyz, *.txt) AutoCAD DXF File (*.dxf) XML (*.xml)

Note: ¹GIS Data, Maps and Images, Drillhole Data, Points Data, Structural Data, Meshes, Polylines, Geochemical Data.

Table 8. Interoperability in Terms of Import/Export for Analysis Software
(Source: Own)

	Software	Import	Export
Analysis	RS2	Autodesk Files (*.dxf) Rocscience Files Slide2 (*.sli)	Autodesk Files (*.dxf)
	RS3	RS Geometry Object (*.rsgeomobj) OBJ Files (*.obj) STL Files (*.stl, *.stlbin) Autodesk Files (*.dxf, *.dwg) DTM Files (*.dtm) STEP Files (*.step, *.stp) IGES Files (*.iges, *.igs) TIN Files (*.tin) OFF Files (*.off) ASC Files (*.asc) LAS Files (*.las) LUSAS Files (*.mdl)	Autodesk Files (*.dxf) Rocscience Files RS2 and Slide2 (*.fea/*.fes, *.sli) <i>Planar sections</i>
	Plaxis 2D ¹	DXF: AutoCAD interchange files TXT/CSV: text files (tab-separated values or comma-separated values) BRep: Open CASCADE BRep file format STEP/STP: Standard for the Exchange of Product model data files GEO/STI: Delft GeoSystems M-Series geometry files SVM: SoilVision model geometry	STEP/STP: "Standard for the Exchange of Product model data" files DXF: AutoCAD interchange files
	Plaxis 3D	STEP/STP: "Standard for the Exchange of Product model data" files BRep: Open CASCADE BRep file format DXF: supports only parametric geometry IFC: Industry Foundation Classes files ² Point cloud data in *.txt format	STEP/STP: "Standard for the Exchange of Product model data" files DXF: supports only parametric geometry STL: Stereo Lithographic data format

Note: ¹with a Geotechnical SELECT Entitlements [VIP] licence; ²IFC types: roof, slab, footing, pile, beam, plate, wall and column

4.5.2 Exchange Metadata

More importantly, to avoid errors and double work, the interoperability of modelling and analysis software should be achieved for properties also, while the 3D shapes already work in bidirectional interoperability with .dwg, .dxf and .ifc formats, the metadata associated to them cannot be exchange. In the case of Rocscience, it is possible to use the soil parameters of previous projects, but it is not possible to read the metadata included in the files coming from the modelling tools. For Plaxis a script can be created using Python to read the properties of the file; nevertheless the export of any additional data (graphical and non-graphical) of the stability analysis results such as anchors, bolts, geosynthetics, filters, and others has to be exported in the .dxf file because Plaxis does not support .ifc export. Then the analysis software (RS and Plaxis) can have bidirectional interoperability just with geometry, for metadata these tools had to develop an export that allows the exchange of non-graphical information.

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5 GEOBIM MODEL USING CIVIL 3D

BIM projects usually focus only on architectural, structural and MEP disciplines, so the subsurface is often neglected. The Singapore BIM Guide [52] includes a civil discipline where they consider elements like the digital terrain model (DTM) and the geology report, and even Existing Conditions Information Model and Site Analysis Model are considered in the BIM Processes Map of Penn State CIC Research Team [53]. However, the Geological-Geotechnical Model is not standard in projects or documentations.

The subsurface can have a considerable impact on technological projects, the geotechnical report is done in the early design stage, and the Geotechnical BIM model can benefit the design, planning and construction in different ways. Hereunder the proposed workflow to create a GeoBIM model, the interoperability formats and BIM uses.

5.1 Proposed Workflow of GeoBIM

The authoring tool for the proposed workflow is the Autodesk software Civil 3D with the Geotechnical Module developed by Keynetix.

5.1.1 Procedure

The GeoBIM model will be composed by the surface and the subsurface models, in Figure 8, the proposed workflow to create it. The documents necessary as inputs are the LIDAR data for surface information, the geotechnical report with the properties of the soil and water table and the bore logs to create the strata. The data from LIDAR in Slovenia can be obtained in LAZ format; however, the most common format is the LAS. After converting the data, the cloud model can be generated in Recap and imported in Civil 3D to create the surface of the actual terrain.

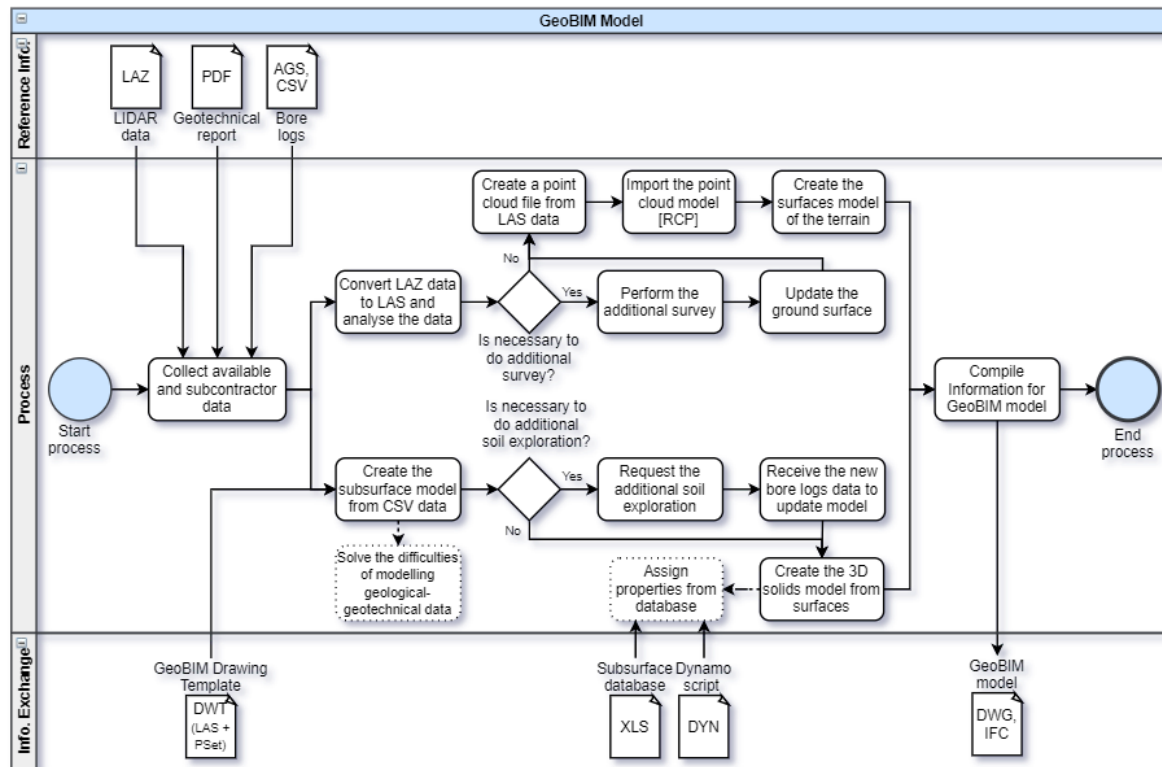


Figure 8. GeoBIM Proposed Workflow
(Source: Own.)

From the boreholes data (Figure 9 below), the subsurface model can be created in Civil 3D with the Geotechnical Module. Previously the process had considered a Drawing Template that will contain the Layers (LAS) that are needed and the Property Set for the solid model after. Then the difficulties addressed below in numeral 5.1.3 Difficulties Modelling the Subsurface have to be solved. Always, the model can be updated with new information, additional borehole campaigns. After from the surfaces, the 3D solids can be created, and with the database of the properties obtained from the field test and laboratory tests, the properties can be assigned with a dynamo player that includes the script to speed up this step in the process and avoid human error in retyping information. Finally, the GeoBIM compile information of the surface and subsurface in 2D with surfaces and 3D with volumes shown below in Figure 10.

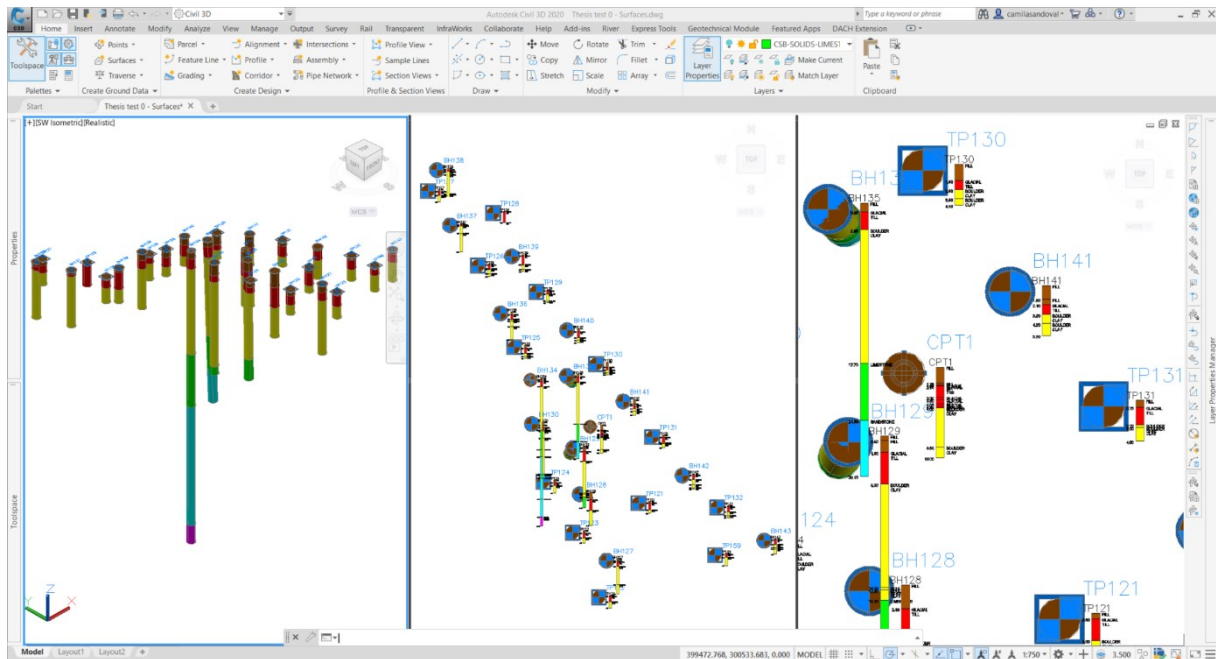


Figure 9. Bore Logs Data (AGS/CSV) in Civil 3D with the Geotechnical Module
(Source: Example Data of the Geotechnical Module in Civil 3D)

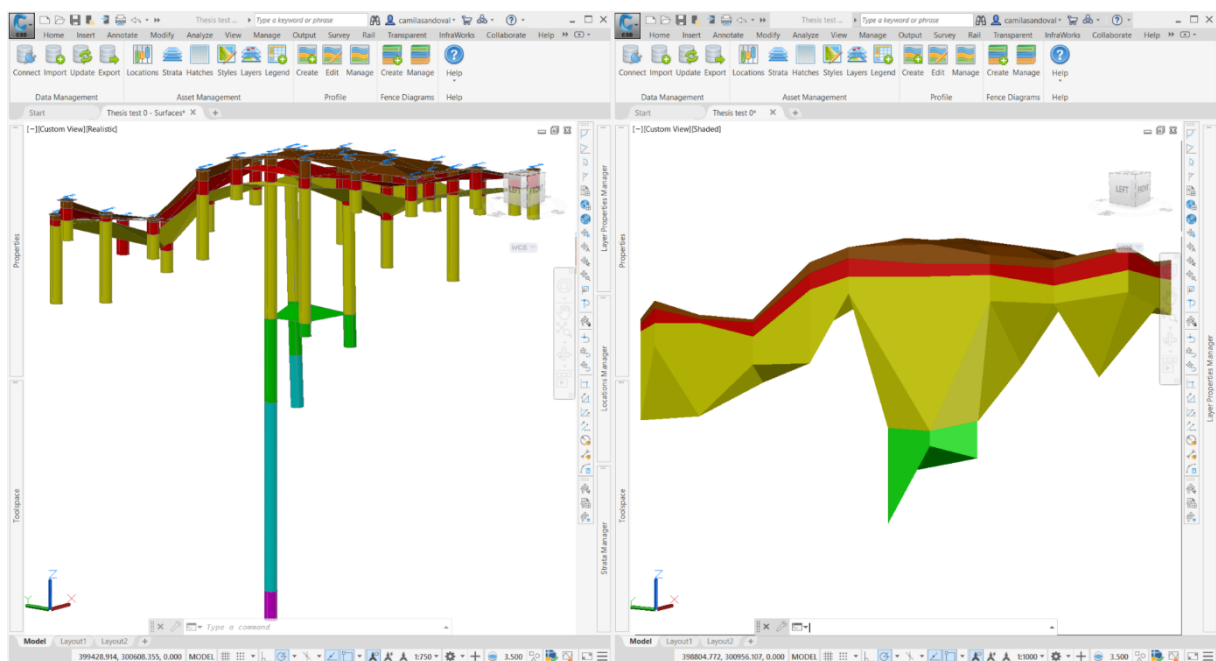


Figure 10. Bore Logs Data (AGS/CSV) in Civil 3D with the Geotechnical Module
(Source: Example Data of the Geotechnical Module in Civil 3D)

Further, this model can be used to create the sections along an alignment and decided the critical sections to analyse in 2-dimensions; but even beyond, it can be used to create a mesh to analyse in 3-dimensions software. Following the workflow proposed to import the geometry of the GeoBIM to the analysis software.

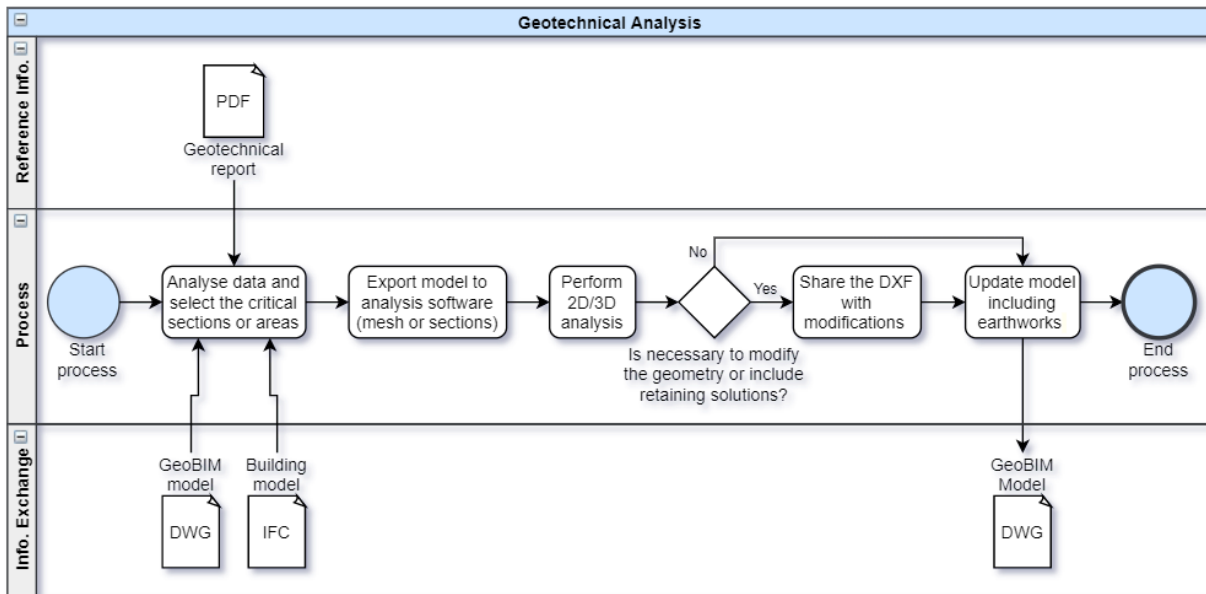


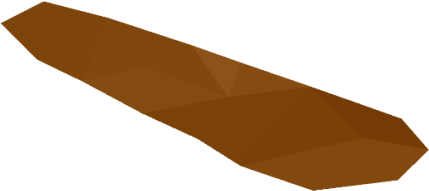
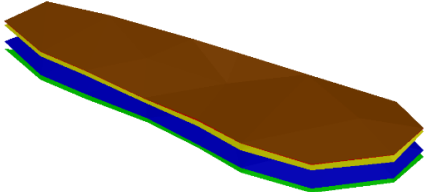
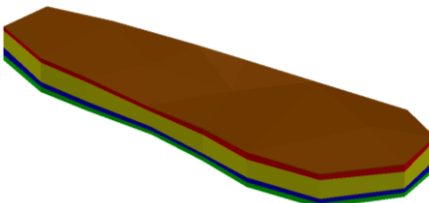
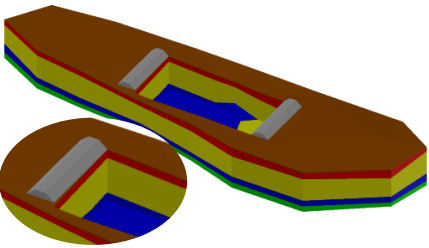
Figure 11. Geotechnical Analysis Proposed Workflow
(Source: Own)

5.1.2 Requirements

The BEP of the project defines the minimum requirements of the GeoBIM model, as well as the other disciplines like architecture, structure, and MEP. Nevertheless, the property sets of the model depend on the analysis software, if the properties assigned to model match the properties required by the analysis software the interoperability could be achieved non just for geometry but even for the metadata. The level of development usually divided into the level of geometry (graphical information) and the level of information (data) can be set as the minimum requirements for the surface-subsurface BIM model. Further, the property sets (PSet) according to the analysis can be defined and assign with the dynamo player that runs the script that is linked to the geotechnical database of the bore logs and could include the laboratory data below in Figure 12.

The BEP of the project defines the minimum requirements of the GeoBIM model, as well as the other disciplines like architecture, structure, and MEP. Nevertheless, the property sets of the model depend on the analysis software, if the properties assigned to model match the properties required by the analysis software the interoperability could be achieved non just for geometry but even for the metadata. The level of development usually divided into the level of geometry (graphical information) and the level of information (data) can be set as the minimum requirements for the surface-subsurface BIM model. Further, the property sets (PSet) according to the analysis can be defined and assign with the dynamo player that runs the script that is linked to the geotechnical database of the bore logs and could include the laboratory data below in Figure 12.

Table 9. Proposed LOD for GeoBIM
(Source: Own)

LOD		Graphically	Information	Example
2	100	Symbolic 2D graphical representation of the terrain surface.	Approximate position/coordinates	
3	200	Conceptual 2D representation of the soil/rock strata based on borehole logs, including the topography.	Previous plus elevation	
4	300	Generic 3D representation of the soil/rock strata based on borehole logs including the topography.	Position/coordinates, elevation, bore logs data, material, material classification	
-	350	Specific and coordination 3D representation of the soil/rock strata based on borehole logs, including the topography and earthworks zones.	Previous plus excavation and fill areas. Material properties to export to analysis software such as unit weight, cohesion, friction angle, among others (required by each analysis software).	--
5	400	Specific and coordination 3D representation of the soil/rock strata based on borehole logs, including the topography. Construction and fabrication representation of earthworks stages and support elements or ground improvements.	Previous plus excavation and fill volumes of each material might include the unit cost of excavation in soil or rock. Proctor data for fills.	
6	500	Specific and coordination 3D representation of the soil/rock strata based on borehole logs, including the topography. As-Built representation of earthworks stages and support elements or ground improvements.	Previous plus construction report (date, material, drawbacks, etc.) of each support element or ground improvement with 3D representation in the model.	--

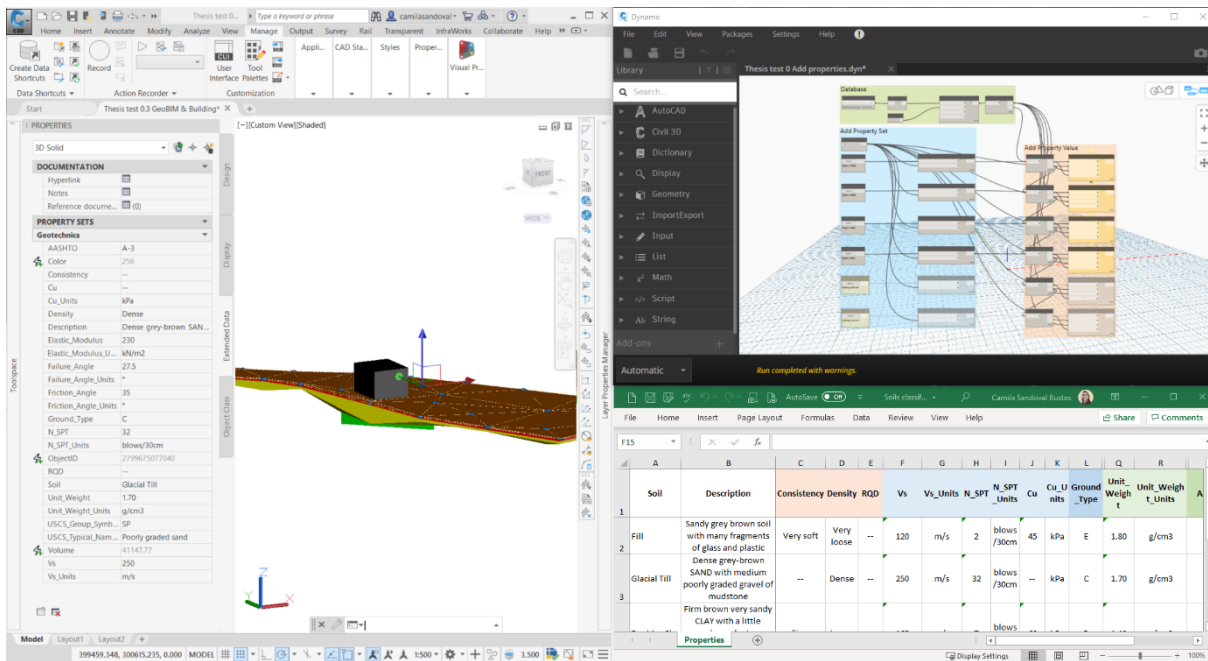


Figure 12. PSet Assignment to GeoBIM Model from a Database with Dynamo
(Source: Own)

Questions of Table 1 must be answered to have an efficient geotechnical exchange format. From G1 to G6, BIM already has a naming convention; units abbreviations are standard. Also, different property sets assigned can be used as subsets or combine to have more extensive data sets. The data included should be the data required for the calculation software as well as the data defined by the geotechnical specialist from the field and laboratory data. Furthermore, information can be exchanged via mail (however, more updated, data can be treated as a database a consulted everywhere at any time). Finally, data can be exchanged in different formats accepted by the engineering community, as a database in .csv or .xlsx; or as the model in .dwg or .ifc.

From D1 to D10, the variables are common knowledge in the field; nevertheless, a data dictionary can be implemented. Units of every variable are defined as a property; values' format is defined by the input database and maintained in Civil 3D. The input of data from databases to the model can be improved by validating the value in an acceptable range. The script in Dynamo can be further developed to recognized missing fields and display error messages. The interoperability, broad support and achievability are assured using standardized open formats to exchange information. Inside the modelling tool is possible to search for a particular property as well as in the database. Finally, the database can be included on online interactive maps to make the information not just locatable but for companies to have 3D databases of their projects.

5.1.3 Difficulties Modelling the Subsurface

When modelling the subsurface, some characteristics can generate difficulties in automating the process. The following are common difficulties and solutions:

Soil Lens

As shown in Figure 13, the raw data from the boreholes cannot produce a GeoBIM of quality automatically always. In this case, some boreholes do not have the clay lens (blue) so the surface generated is not correct. Thus, some surfaces had to be adjusted to create a lens, after a modification process incorporating polylines, feature lines, breaklines and boundaries, the profile in Figure 14, has the correct limits of the clay lens (blue) above the gravel (yellow) and the sand (cyan).

Geological Faults

Geological faults are common in geological profiles, and these can occur in different ways. Normal and reverse faults can be represented with "wall breaklines" as shown in Figure 15. However, for more complicated profiles, especially in rock, other modelling tools can be a better solution to create the 3D geometrical model. Then, it is possible to add the metadata in the same software it will be not necessary to use Civil3D; otherwise the geometrical can be imported, and the information can be added in Civil3D with the Dynamo script.

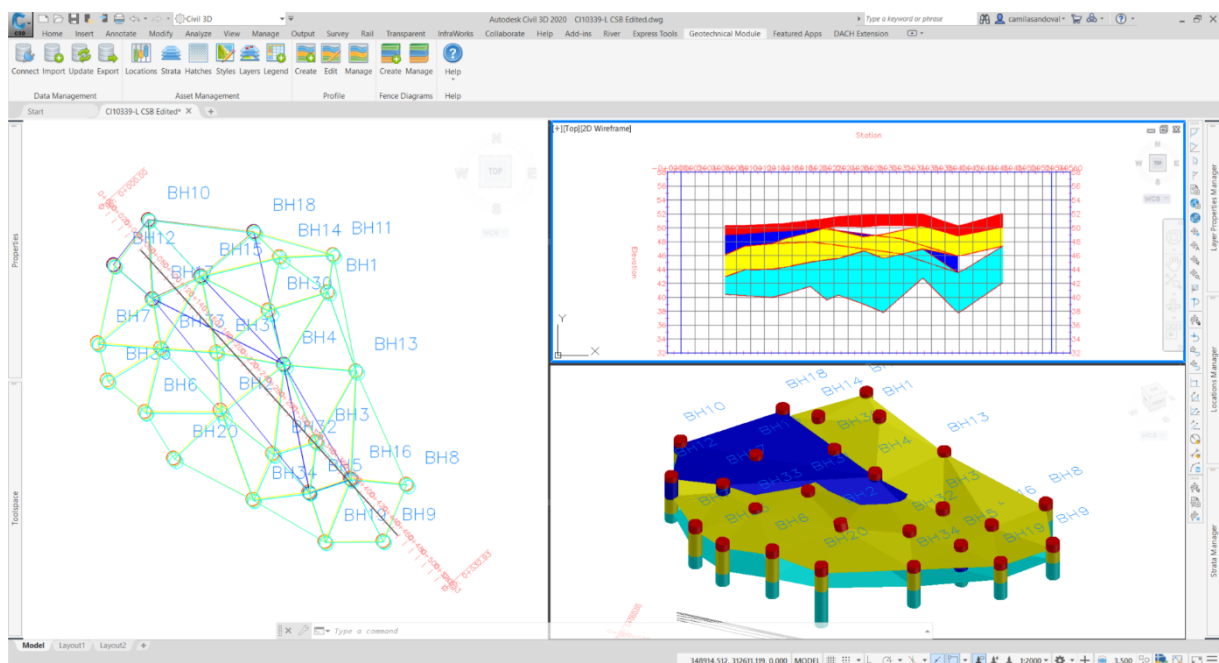


Figure 13. Raw Data from Boreholes Imported to Civil 3D
(Source: Own with data from [54])

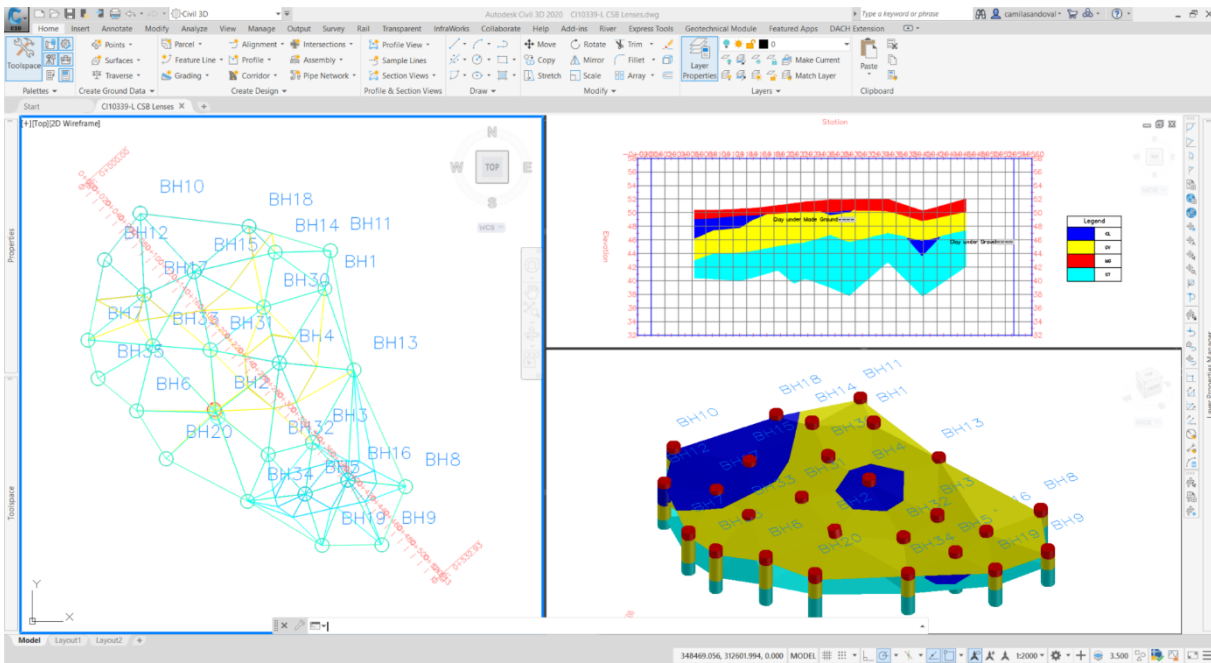


Figure 14. Corrected Surfaces with Proper Representation of the Clay Lens
(Source: Own with data from [54])

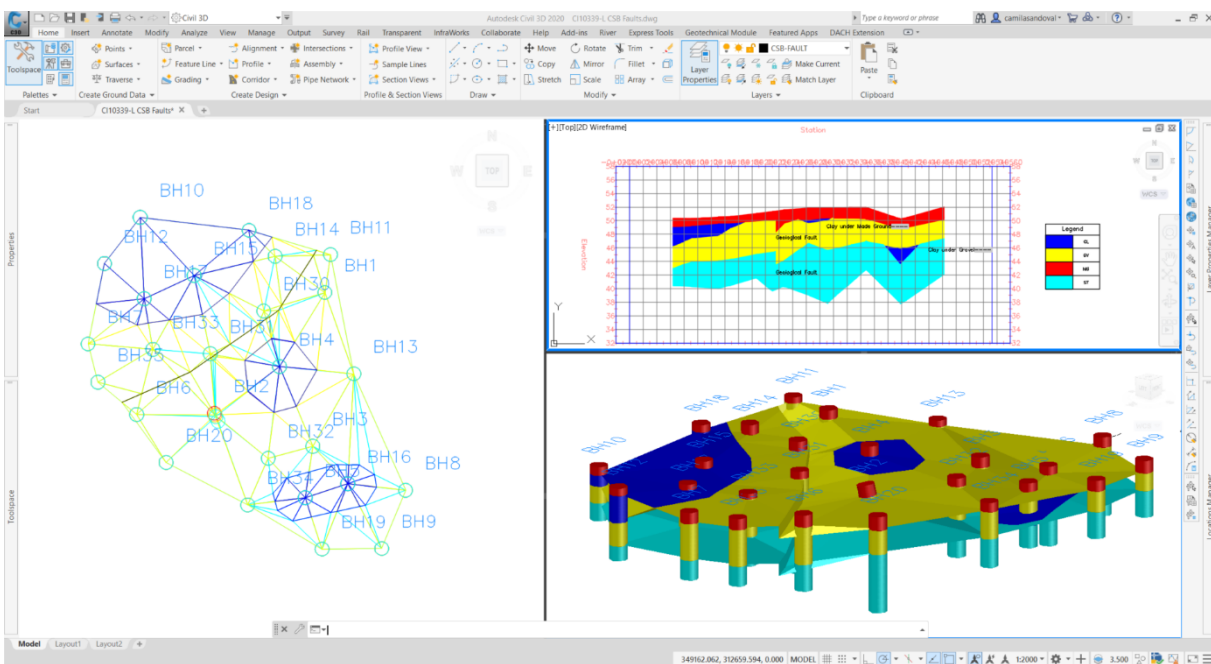


Figure 15. Modelling a Geological Fault
(Source: Own with data from [54])

5.1.4 Interoperability Analysis

Civil 3D has the authoring format DWG and also offers the exchange format DXF. Moreover, for BIM projects, the IFC format can be used to export twenty-one different objects. Following the SWOT analysis of these format for interoperability purposes.

Table 10. SWOT Analysis of Civil 3D Formats Regarding Interoperability
(Source: Own)

Formats	Strengths	Weakness	Opportunities	Threats
DWG	Drawing file extension for most of the CAD programs in 2D and 3D	A binary format that is not open for some programs	High-quality information widely supports by developers	Drawing exchange format file that allows direct interoperability with most of the analysis software
IFC	Open standard format for exchange in BIM programs	A binary format that can lose information when opening in a non-authoring tool that does not support specific definitions	Exchange open standard format	Text formats that can be easier to use and more open to developers
DXF	Exchange text format for drawing files	A format that can lose information when opening in a non-authoring tool that does not support specific definitions	Exchange open format	Not all the properties are standards of the format

Each format has its limitations when exchanging information, DWG can be used to import geometry to some analysis software but not for all. IFC is not supported in the analysis software to import geometry, even in Plaxis 3D where it is supported, the IFC schema is not defined then not supported for export geometry. DXF is the most interoperable format between modelling and analysis programs; however, it needs some manual preparation for the programs to understand the geometry entry.

Finally, none of the formats can be used to import metadata automatically in the analysis software; this still a manual entry or in the case of Plaxis a script must be developed but as mentioned before the metadata cannot go back from the analysis software to the modelling software or even exported in a format that can be used in a federated coordination model.

5.1.5 Modelling Geological and Geotechnical Data in 2D and 3D

In the industry, usually 2D slope stability analyses are performed; however, 3D analyses are opening their way with the educational and investigative sectors support that pushes the industry and software developers towards 3D analysis. With the eruption of BIM in the AECO industry, three-dimensional models are making every discipline involved in a construction project develop new tools to integrate the design in this methodology. Therefore, the geological and geotechnical disciplines are increasing the demand in the 3D analysis.

According to SoilVision article [55], the majority of the industry has adopted a two-dimensional approach of the slope stability analysis, based on backward analysis of failed slopes to calibrate the models and obtained the accepted factor of safety between 1.3 and 1.5 even if the real failure occurs in three dimensions represented by an ellipse surface. Also, differences between 2D and 3D analysis can vary from 15% to 50% according to documented research. The popularity of 2D is based on the facility and acceptance of the methodologies; however, nowadays, 3D analyses are easier and faster to do. Even some 3D software allows performing both analyses in the same model allowing the engineer to discover which scenarios are important to represent in 3D.

Finally, three-dimensional analyses represent better the existing conditions while 2D analysis simplified the models with some initial conditionings that affect the overall result. Some of the scenarios that have potential in the three-dimensional analysis according to Dr Murray Fredlund, (geotechnical advisor for Bentley [56] and SoilVision [55]) are levee analysis, deep foundations, tailing facilities, heap leach analysis, earth storage and back analysis, and to Dr Robert Pyke [57] rock slopes, dams or landfills, and problems involving constant section over a relatively long length.

5.2 BIM Uses of Proposed Workflow

The following are the BIM uses intended for the GeoBIM; however, more uses can be added and developed.

5.2.1 Quantity Take-Off (QTO)

The volume of the GeoBIM is going to be done in terms of volume of the solids. In Civil 3D, the solids can have a property Volume and when defining the excavation (right side Figure 16). This property can be export in a database, for example, an excel file with Dynamo if necessary. The workflow for the QTO BIM uses below in Figure 17. Other ways to get schedules of the volume property is with software for scheduling like Navisworks or Bixel Manager.

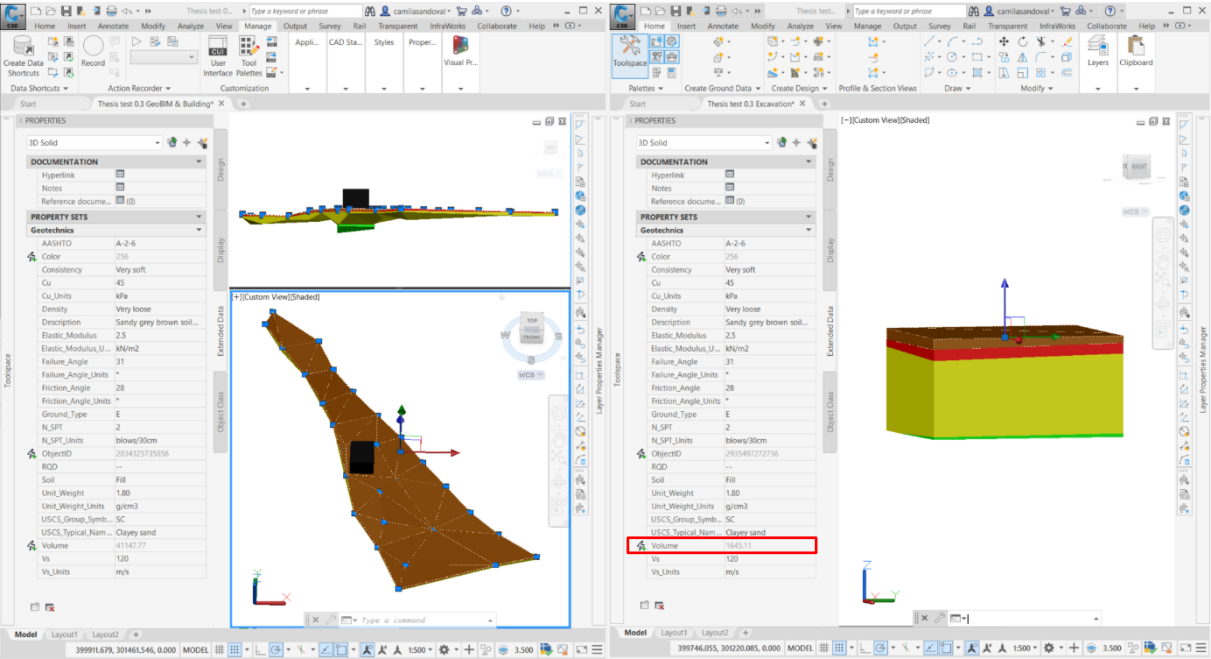


Figure 16. QTO of GeoBIM
(Source: Own)

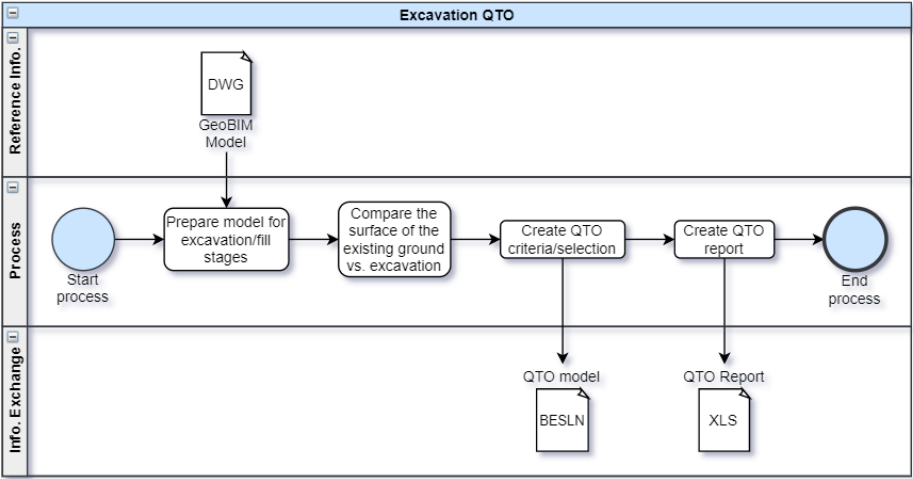


Figure 17. Excavation Quantity Take-Off Proposed Workflow
(Source: Own)

5.2.2 Clash Detection

For clash detection, the GeoBIM will be checked in Solibri Model Checker with rulesets explicitly created for this new discipline. The workflow is shown below in Figure 18. From the IFC model created in Civil 3D, the checking of the rules is performed, and a report can be generated, the clashes are reported, solved and the checking is done again if the model meets the requirements the process end.

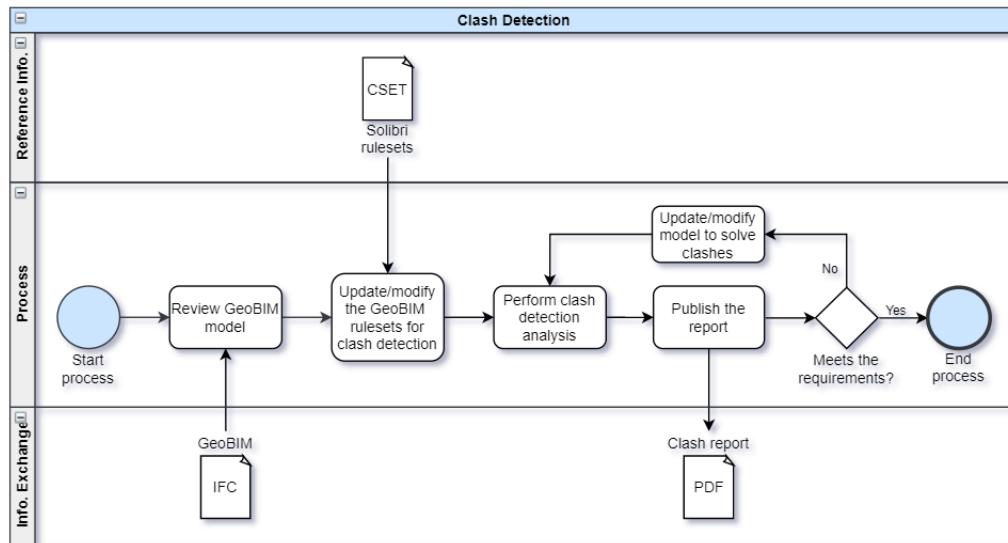


Figure 18. Clash Detection Proposed Workflow
(Source: Own)

The Solibri rules for Geo BIM include not overlapping or intersection between the elements of the model, like the lenses difficulties solved on page 37. Also, the rules check intersection with the structural and architectural model. Figure 19 shows the model checking and the interferences from the building with the subsurface.

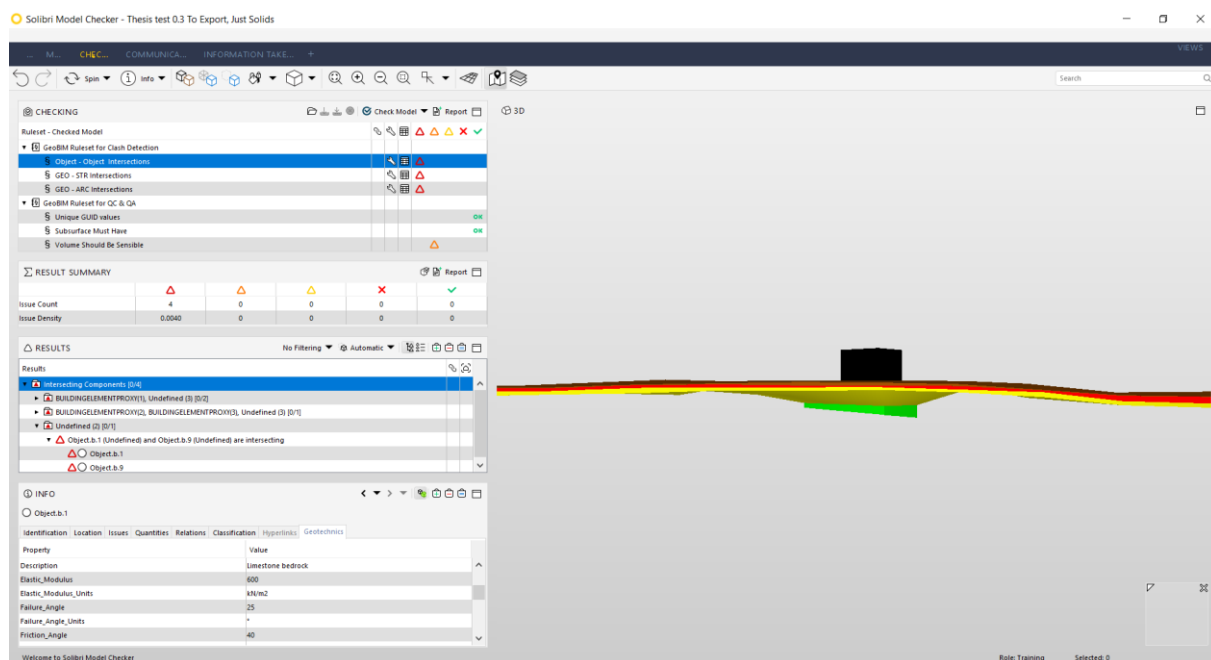


Figure 19. Solibri Checking for Clash Detection and Quality
(Source: Own)

5.2.3 Quality Control & Quality Assurance (QC & QA)

For quality assurance and control, the process is like clash detection but with different rules. According to the Singapore BIM Guide [52], modelling guidelines, dataset validation and interference check should be considered when determining a quality assurance plan. The following is the proposed workflow based on the previous requirements:

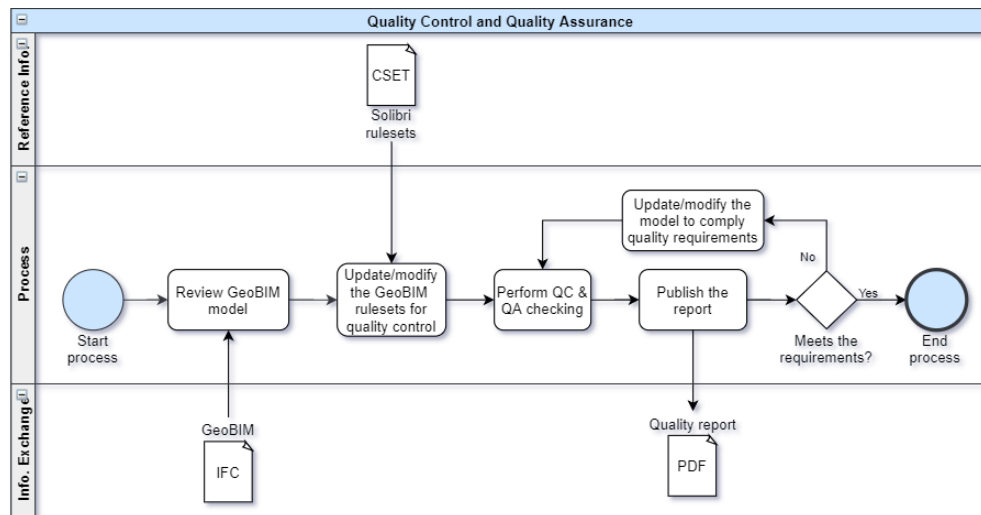


Figure 20. Quality Proposed Workflow
(Source: Own)

The ruleset created for Solibri, ensure the model is created with unique GUID values, that the subsurface has the property sets required by the project and the interferences are solved in the previous check for clash detection, complying with the Singapore recommendations. Following the ruleset manager for Clash Detection, and QC & QA.

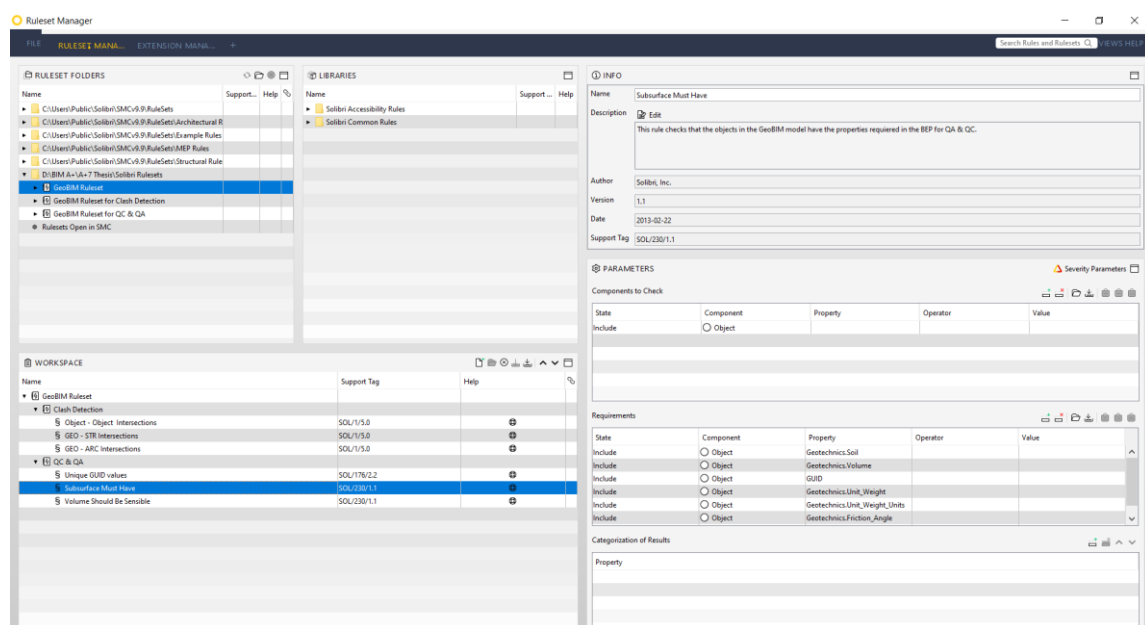


Figure 21. GeoBIM Ruleset Manager for Clash Detection, and Quality Control & Assurance
(Source: Own)

5.2.4 4D Simulation

The earthworks simulation was generated from the GeoBIM, with the definition of the excavation and infills. The solids were operated to generate different phases of excavation according to the excavation surfaces. For this process, an excavation schedule must be defined to associate the different parts of the model being "demolished" in Navisworks, other simulation software can be used like Bixel Manager.

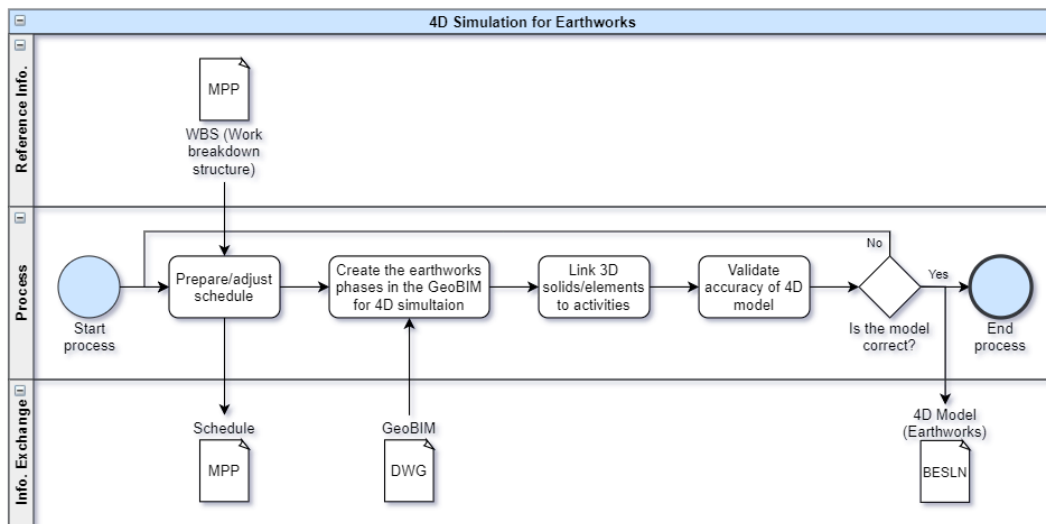


Figure 22. 4D Simulation Proposed Workflow
(Source: Own)

5.2.5 Other Potential Uses

Other uses can be explored with the GeoBIM, for example, 5D cost simulation. Since the cost of rock (most of the times requiring blasting) is considerably higher than soil, depends on the equipment, machinery and personnel required, the projects can be plan better and with a more accurate budget. When possible, also projects can avoid excavation in the rock by changing elevation or even had alternatives to analyse terms of excavation and fill costs.

The model can also be used to check the anchorage length; in this case, anchorage design usually provides a minimum length but a conditional of reaching a specific material that can warranty the support of the excavation. More accurate lengths of anchors according to the subsurface model, can help to create more accurate budgets as well as better planning.

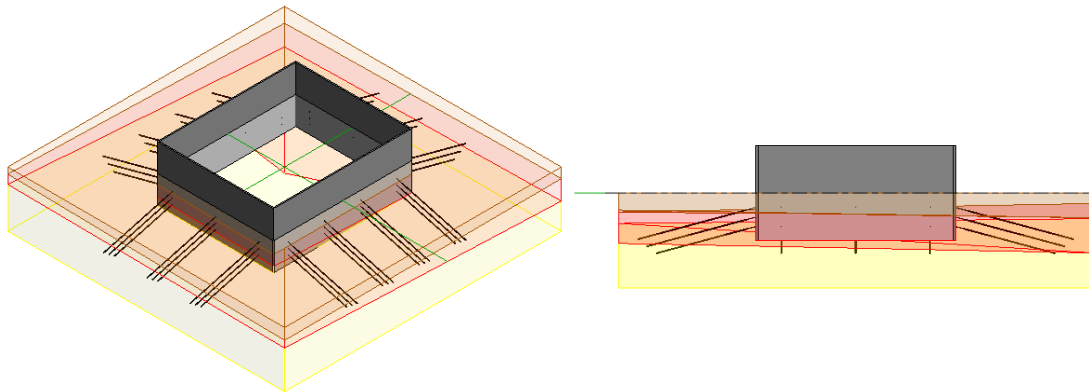


Figure 23. Anchors Design Using GeoBIM
(Source: Own)

In some projects, the excavation can be automatized when the soil profile can be associated with a single slope of excavation. The following is a first trial to automatize the excavation using dynamo. The user defines a polygon representing the excavation, then select the slope, height of the excavation and the width of the berms

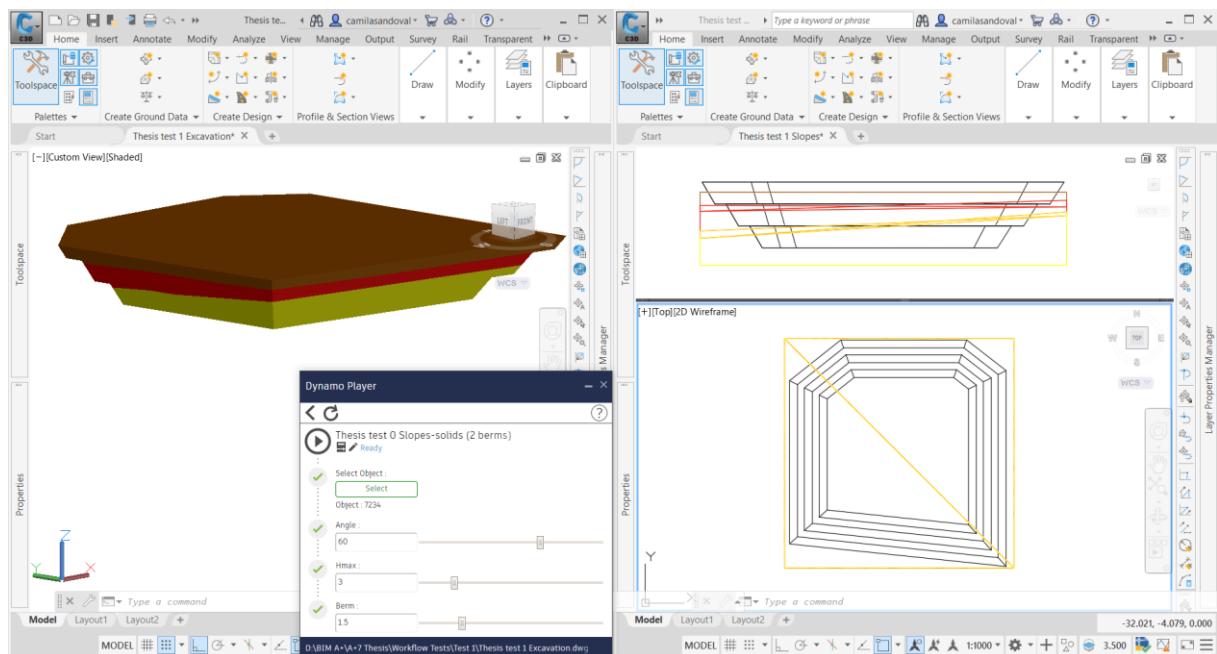


Figure 24. Automatization of Slopes Definition with Dynamo
(Source: Own)

Many other applications can be developed if the GeoBIM start to be used regularly. Like the other disciplines in BIM, this will allow companies, universities, and investigators to face new challenges and resolve them with the help of a ground 3D model.

5.3 Dynamic GeoBIM Model

An application focus on the construction phase of the projects implies to convert the GeoBIM in a dynamic model taking images of the earthworks with UAV (unnamed aerial vehicles) or terrestrial stations. For technological projects, terrestrial stations can create field difficulties; UAVs do not need a particular space to be installed or to take care in the field and can be programmed with certain regularity before starting, between or at the end of the working shifts to reduce the human or machinery interference in the images.

5.3.1 Technical Solution

According to the International Society for Photogrammetry and Remote Sensing (ISPRS), *“Photogrammetry is the science and technology of extracting reliable three-dimensional geometric and thematic information, often over time, of objects and scenes from image and range data.”* [58] and according to other definitions and in other words, photogrammetry is the science or art of using photographs to describe the real world in shape, dimensions, and position. In civil engineering, it had been used for topography mapping, slope stability analysis, monitoring of mass movements and archaeological excavations. The products extracted from photogrammetry with UAV can be DEM (digital elevation model), DTM (digital terrain model), DSM (digital surface model), orthophotos, 3D building models, contour maps, among others.

Recent developments in the photogrammetry field had a solution for the main problems of topographic data measurement that is the necessity of a specialized supervisor and expensive technologies. The alternative for DEM produced from airborne/terrestrial laser scanner data is known as Structure-from-Motion (SfM) photogrammetry, a 3D data acquisition that is fast, automated, and low-cost. The implementation of this method may vary, by generally as traditional methods of photogrammetry, multiples images of an object/site are taken from different positions. The difference is that in an arbitrary three-dimensional coordinate system, the spatial relationships between the original images locations and the common feature points on the images are identified automatically with feature detectors and image matching algorithms (e.g. scale invariant feature transform SIFT, among others). Nowadays, fully automation in internet-based platforms is the most common in SfM processors; nevertheless, local software SfM has better quality [59]. Ground-control points (GCPs) with known object-space coordinates are needed to convert SfM image-space coordinates from the arbitrary coordinate system to an absolute coordinate system. The GCPs are physical targets with a defined centroid and high contrast [60].

The primary product of SfM photogrammetry is a sparse point cloud. Besides, using dense image matching algorithms such as MVS (Multi-View Stereo) [61], a dense point cloud is produced. By using the SfM/MVS photogrammetry and modelling techniques, a dynamic GeoBIM model can be created. A fascinating application of SfM/MVS photogrammetry techniques was made in the Dig Tsho moraine-dam complex in the Khumbu Himal, Nepal. To obtain a fully georeferenced DEM (Figure 25), was necessary to deploy 35 GCPS in around 10 hours (shorter time is usually employed; nevertheless, this project was challenging because of the high altitudes topography and its effects) and acquire 1649 images in approximately 4 hours [60].

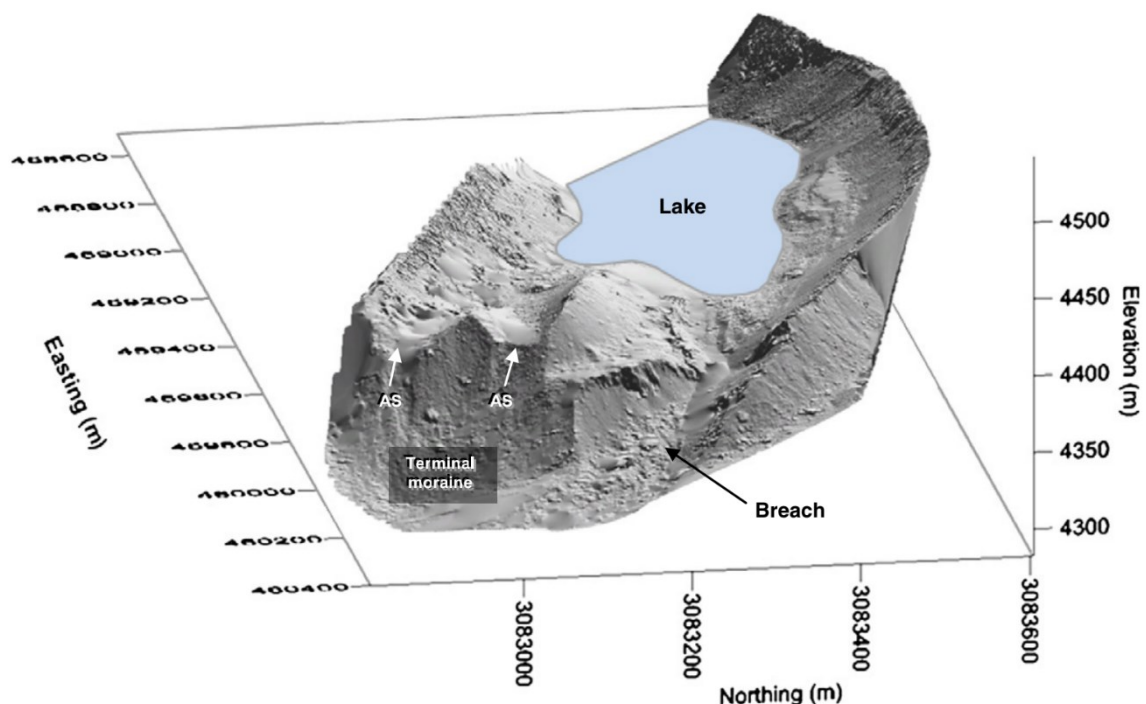


Figure 25. Dig Tsho SfM DEM
(Source: [60])

The GeoBIM model created from the data obtained by SfM/MVS photogrammetry can be used for surveying, logistics, time management, detection of progress, derivations and performance analysis (As-built vs As-planned) [62]. Initially, the UAV survey can take the surface as the starting point for the GeoBIM, and that will be complemented with the geotechnical exploration and geological data. Then, when knowing the terrain, logistics of earthworks can be planned to balance the volume of excavations with fills to reduce the transport of material. Furthermore, detection of progress can be achieved; the UAV survey can be done for monthly payments of earthworks. Then the performance analysis comparing the design of the earthworks with the actual development on the field can give to the companies some lessons learned for future projects, where they can analyse the differences and propose better solutions based on the previous experience.

However, use of UAVs for surveying has some limitations, local regulations of usage, professional operators for the construction industry, flight reliability affected by weather conditions, flight time usually limited to 20 minutes, payload when upgrading to more sensors [62]. Some countries had already laws that prohibited drones flight without a permit and depending on the UAV the skills to pilot might need to be singular for construction projects, especially technological projects in open areas where the strong winds can make the flight difficult. Other limitations in terms of weather are rain and snow, rain can affect the camera lens, so the quality of the images is not optimal, and snow can produce light reflections making the images unfeasible for photogrammetry purposes. Finally, for large projects, the time of flight can be too short, also when upgrading the UAV with additional sensors, the flight time can be significantly reduced.

5.3.2 Information Needs

Quality of data in SfM/MVS photogrammetry depends on image quality, scale, geometry, and geo-referencing [59]. Ideally, the images should be all-in-focus, avoiding shading, shadowing, blur and out of focus. Also, the images should be of high quality and high resolution [61]. Are also crucial the number of images and the image overlap, higher the appearance of points or objects in images, more accurately can be calculated the 3D point coordinates reducing errors [63]. For construction purposes, the dynamic GeoBIM is advisable to aim for highest accuracy as shown in Figure 26; the requirements are: high-resolution cameras, performing of on-the-site camera calibration, use of convergent images, a large number of tie points per photo, most of the tie points appear on least eight images, and a large number of GCPs that are evenly distributed.

	Camera Resolution	Camera Calibration Method	Point Angles *	Photo Orientation Quality	Photo Redundancy	Targets
Lowest Accuracy 1 part in 100	Low (eg Video) 640x480	No calibration ↓ Inverse Camera	15 degrees or less	Few points per photo, low point coverage	Points mostly on only 2 photos	No circular targets, all user marked points
Average Accuracy 1 part in 5,000	Medium (eg basic/older digital camera) 8MP 3264x2468	PhotoModeler Camera Calibrator (good solution)	20-90 degrees	15+ points per photo, up to 60% coverage	Most points on 3 or more photos	Some points marked on naturally lit targets at key locations
Highest Accuracy 1 part in 30,000+	High (eg good quality digital camera) 20MP+ 5400x3600 or higher	Field Calibration	Close to 90 degrees	35+ points per photo, up to 60% coverage	Most points on 8 or more photos	Many points marked on standard target points All points marked on well-defined targets

Figure 26. Photogrammetry Accuracy Factors
(Source: PhotoModeler Technologies [63])

The target for the dynamic GeoBIM will be to achieve a spatial resolution of images of 2 cm (similar to DTM). The spatial resolution of images also referred as ground sample distance (GSD) of \pm GSD horizontally and ± 1.5 GSD vertically can be achieved according to Sanz-Ablanedo et al. [64] if you use the adequate number of GCPs, evenly distributed over the area. The GSD can be calibrated modifying the height above the ground of the flight depending on the UAV.

5.3.3 Process Model

Starting from the GeoBIM, and with the use of SfM/MVS photogrammetry, excavation and fill models can be produced periodically for better earthworks planning. Quantities can be calculated for periodic payments, and vehicles can be better coordinated optimizing the trips, an as-built model can be produced, 4D and 5D simulations from design to as-built can be generated precisely according to actual work, instability problems can be easily and faster recognize and control, to mention a few.

Some of the main advantages of UAV photogrammetry is that it is a fast process; it can be performed while the excavation is being executed without disturbing, among others. Some of the difficulties are that weather conditions can affect the UAV survey and the quality of the images and that traditional survey has higher accuracy. In Figure 27 below, the process to create the dynamic GeoBIM is explained, processing the UAV data with the SfM/MVS photogrammetry and modelling techniques.

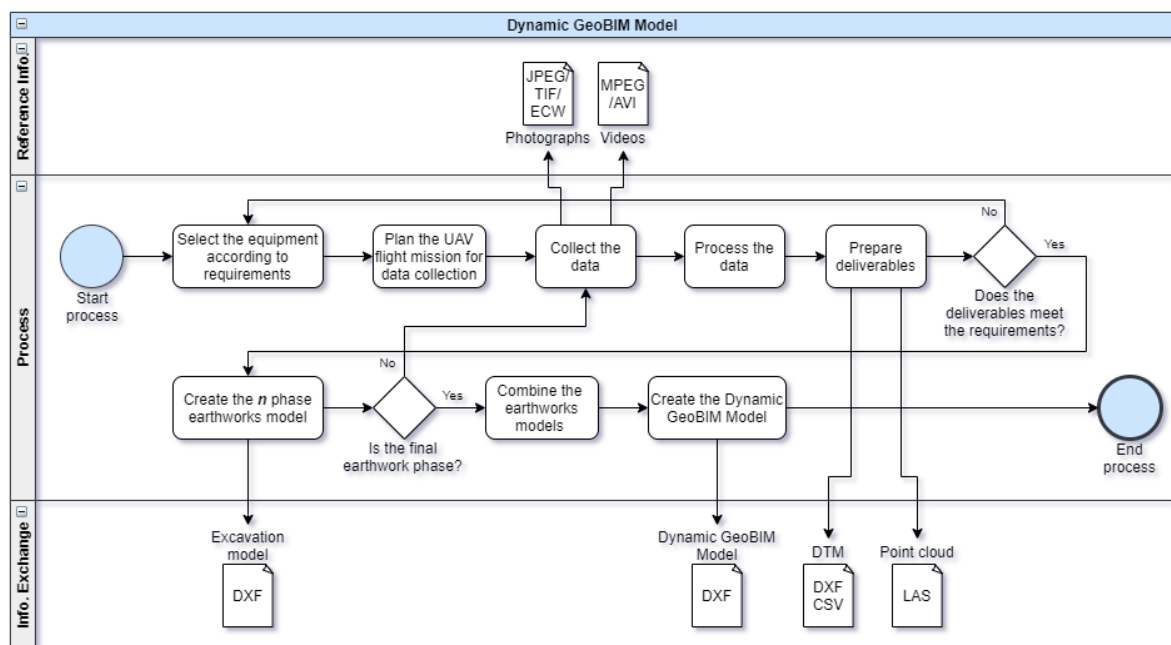


Figure 27. Dynamic GeoBIM Model Workflow
(Source: Own)

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6 CASE STUDY

6.1 Hydro Power Plant Project Overview

The Hydro Power Plant (HPP) Mokrice is a public project by HESS d.o.o. as investor and IBE d.d. as designer. HESS (Hidroelektrarne na Spodnji Savi) describes the HPP Mokrice as follows: *“The HPP Mokrice will be the last on the lower Sava River of six hydroelectric power plants with a capacity of 28.05 MW. It is a hydroelectric power plant of the run-of-the-river and reservoir type, with three bulb-type generating units with a combined rated discharge of 500 m³/s, five spillways and average annual production output of 131 GWh.*

The zone of influence of the HPP Mokrice covers the area from the confluence of the Sava and Krka rivers to the Croatian border. In this area, measures are taken to ensure optimal use of electricity while ensuring that the current natural conditions do not deteriorate in any way. Due to its natural characteristics, the confluence of the two rivers poses a particular problem that requires special care and attention. Sustainable regulatory works for convergence have been planned, which will help to preserve the Krka ecosystem and the natural landscape of the last section of the river before its discharge into the Sava” [65].

This power plant is going to be fully automated, unmanned and remotely operated from the control centre, following the image of the future Mokrice HPP (Figure 28) and the Revit model produced by IBE (Figure 29).



Figure 28. Mokrice HPP
(Source: HESS [65])

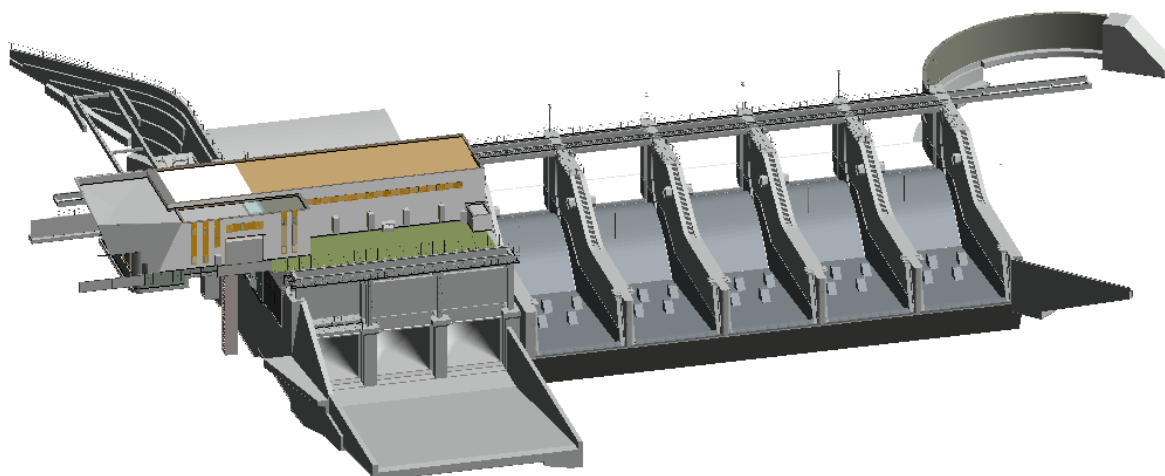


Figure 29. Mokrice HPP Model in Revit Courtesy by IBE
(Source: IBE)

According to HESS and IBE, the Mokrice HPP is a multifunctional strategic state project, which simultaneously fulfils several goals:

- It completes the HPP chain on the lower Sava river and enables energy exploitation of the Sava river basin. The concluded chain of hydropower plants on the lower Sava River will ensure the optimal accumulation and flow regime of the entire chain operation. The chain will produce 800 GWh annually, representing a share of more than 6% of electric energy in Slovenia.
- The Mokrice HPP is the last power plant in the chain and is designed to compensate flows in a way to ensure the so-called natural flow from upstream HPPs at the border profile with the Republic of Croatia.
- Completes flooding protection of the entire concession section, including in the area of influence of HPP Mokrice, from 20 years water (Q20) for all agricultural land and 100 years water (Q100) for all settlements and facilities, including tourist complex Terme Čatež. Flood protection will be built in such a way that the water regime does not deteriorate at the border with the neighbouring country and at the same time all settlements on the section will be protected.
- An additional 28 MW of rated capacity of new green generation from renewable sources, with an estimated annual production of 131 GWh, which, under EU directives and national legislation, must be connected to the transmission network, thereby improving the electricity conditions in Posavje. Mokrice HPP will also provide system services for primary and secondary control of the system.
- Stabilization of levels of declining groundwater in the Dobova and Čatež fields with permanent enrichment of drinking water aquifers under the Krško-Brežice basin.

- More efficient and sustainable farming in the Dobova and Čatež fields due to the optimization of groundwater rise at low Sava flows (summer) and irrigation possibilities.
- Ensure the navigability of the Sava River.
- Development of tourism, recreation and sports on the surface of the reservoir of the Mokrice HPP and on and along the embankments of the accumulation lake.
- Construction of new and modernization of existing local infrastructure, such as a traffic connection will be made between the towns of Dobova and Mokrice (bridge).
- Improving economic growth. Slovenian companies are 90% involved in construction. At the time of the building of the HPP, it contributes 0,3% to the growth of domestic GDP.

6.2 IBE Workflows

The following are the IBE workflows simplified for the thesis for the Mokrice HPP for modelling existing conditions, architectural design, geotechnical analysis, and excavation quantity take-off.

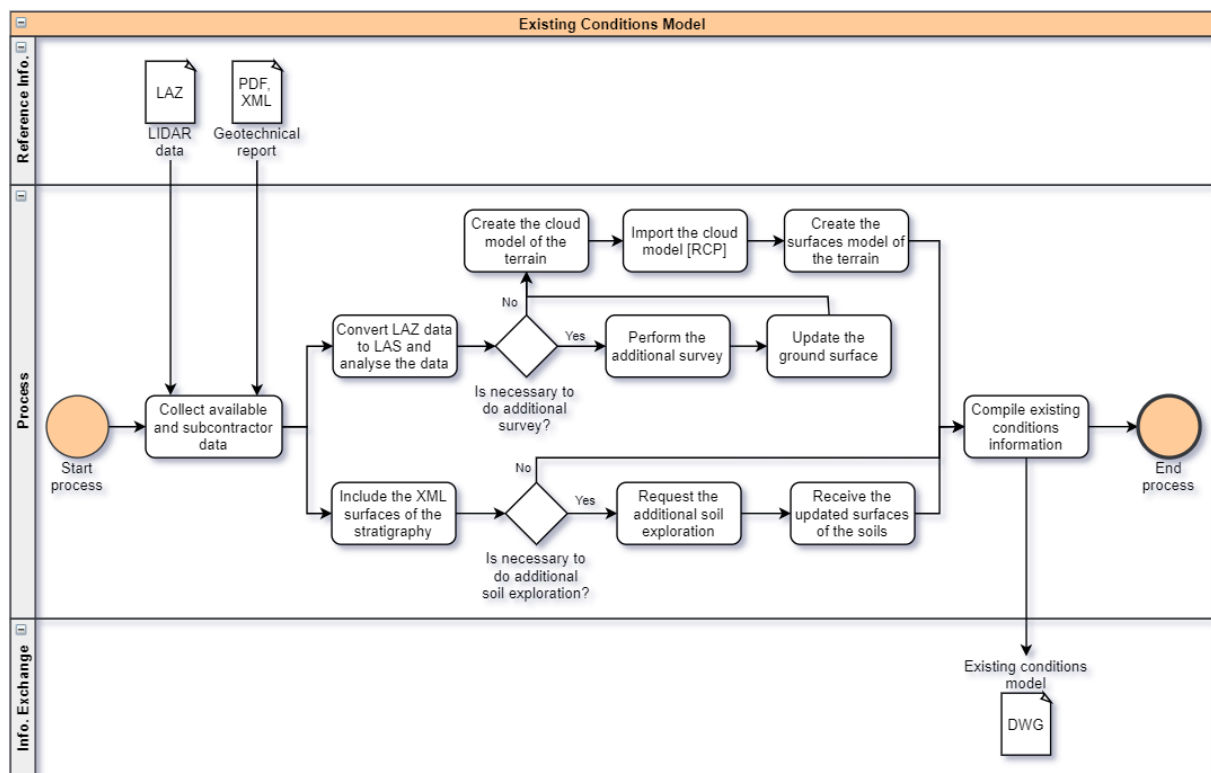


Figure 30. IBE Existing Condition Workflow
(Source: Own)

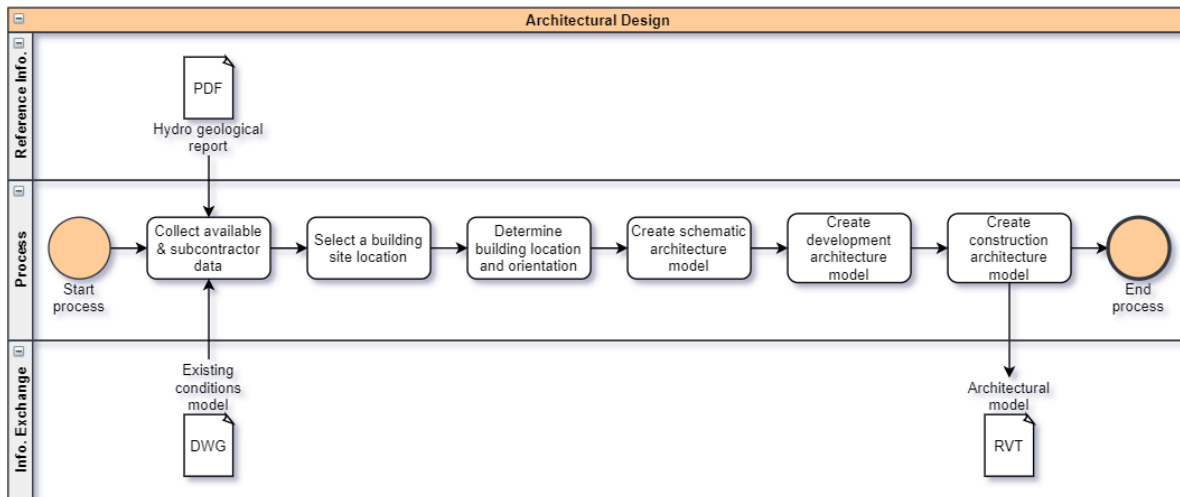


Figure 31. IBE Architectural Design Workflow
(Source: Own)

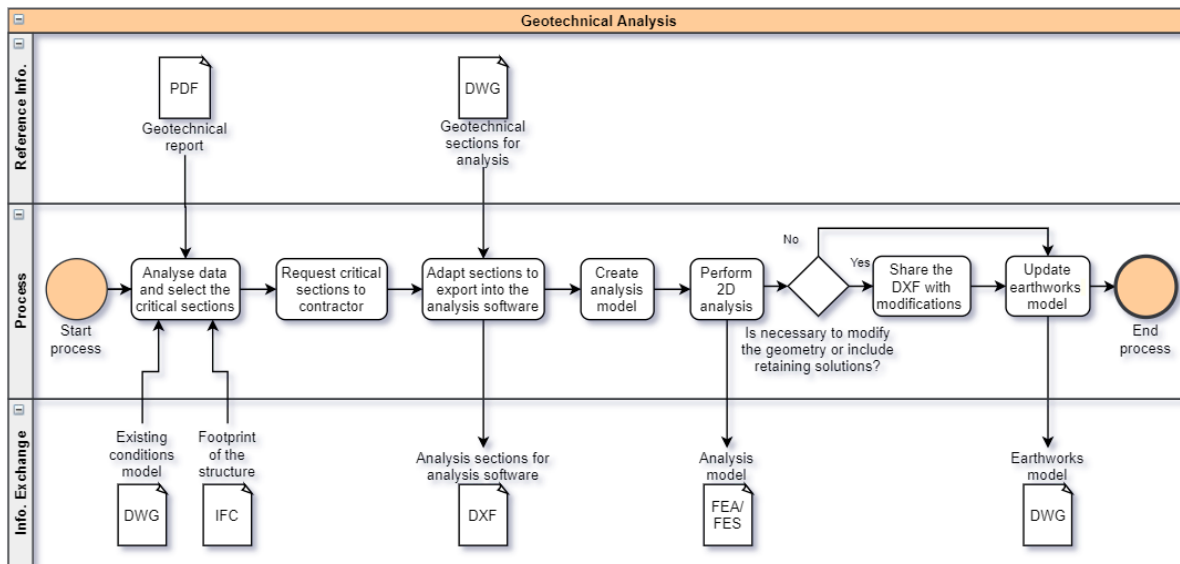


Figure 32. IBE Geotechnical Analysis Workflow
(Source: Own)

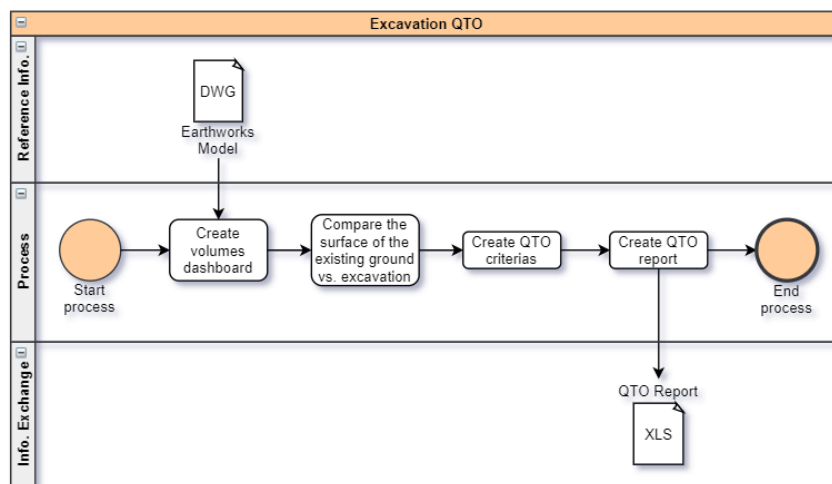


Figure 33. IBE Excavation QTO Workflow
(Source: Own)

6.3 Preparation of the Data Sets

For the Mokrice HPP, the geological and geotechnical reports were subcontracted. The reports received also had three (3) surfaces .XML; OT existing ground (brown), MELJ surface to excavate (red), PROD waterproof/impermeable material (blue). Common difficulties while working in BIM with federated models are the coordinates and location of the project, for this case, two (2) surfaces were located in the coordinates around 168.403 east and 24.781 north; nevertheless, the impermeable surface was around 552.006 east and 81.539 north as shown below in Figure 34.

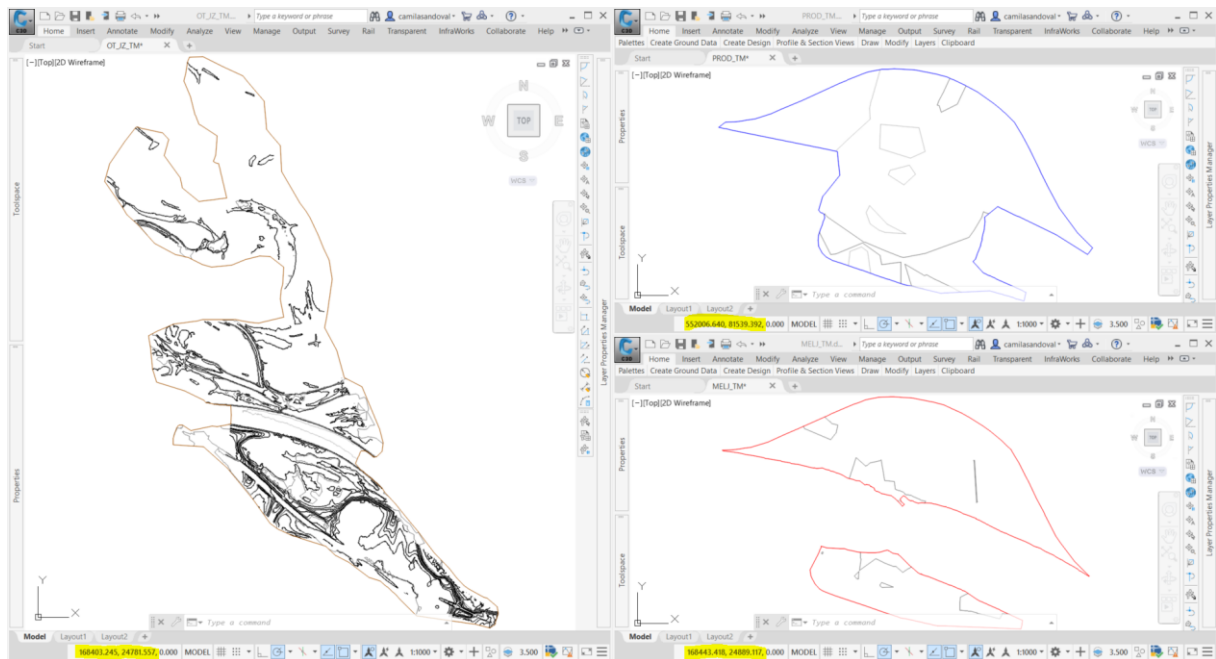


Figure 34. XML Surfaces Provides by the Subcontractor
(Source: IBE)

The impermeable surface was adjusted (Figure 35) to the excavation and existing ground surfaces to use the geological/geotechnical data provided by the subcontractor. The surfaces were trimmed into the area of interest, and the solids had to been created. However, the surfaces of excavation and existing surfaces overlapped, then it is not possible to create the solids (Figure 36), besides the excavation surface ended suddenly, as shown above in Figure 35.

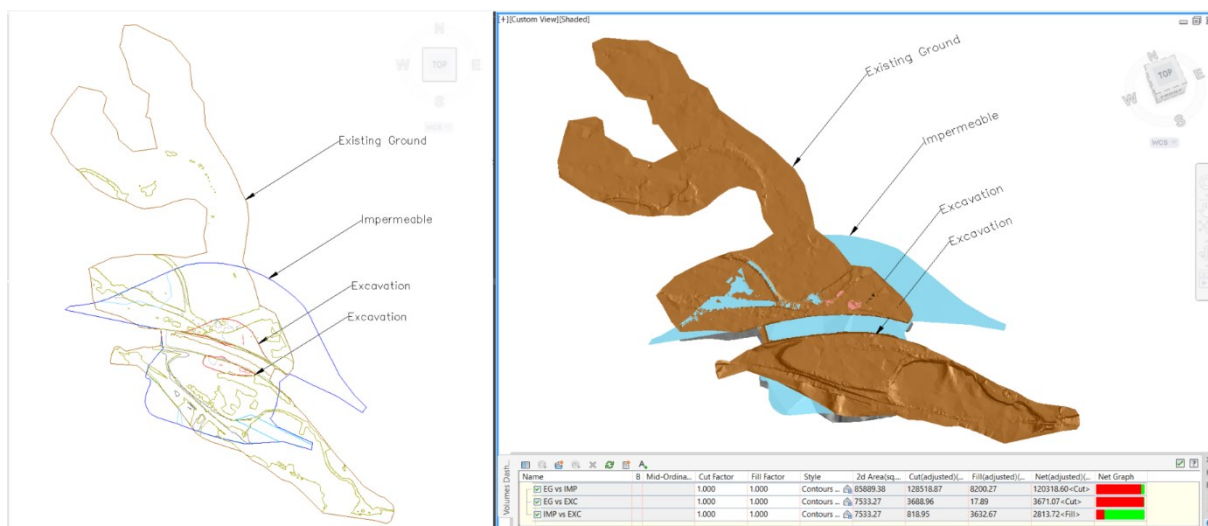


Figure 35. Adjusted XML Surfaces Provided by the Subcontractor
(Source: IBE)

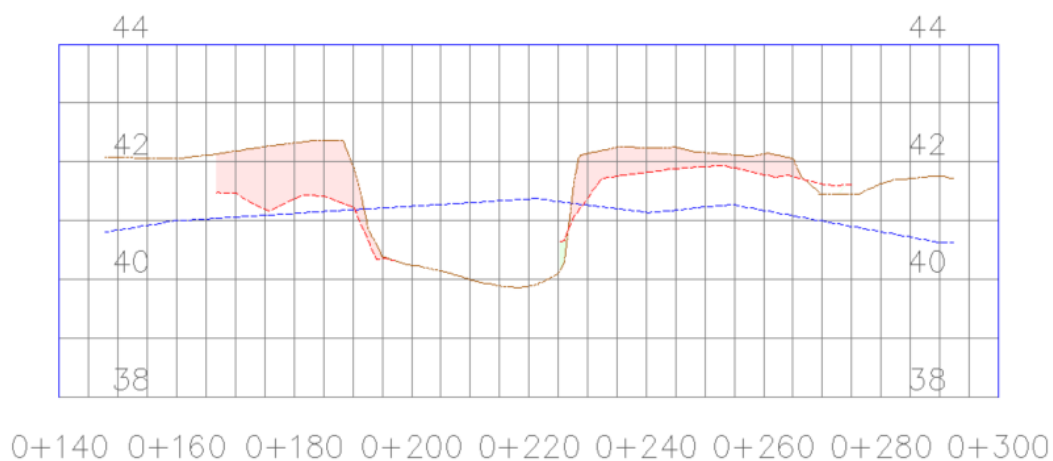
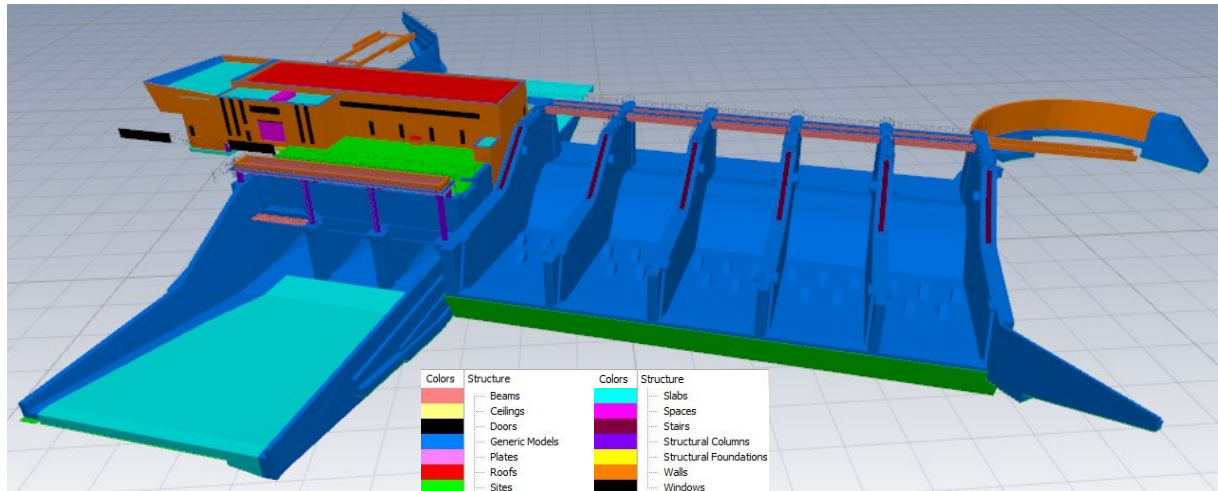


Figure 36. Profile of Surfaces Provided by the Subcontractor
(Source: IBE)



Figure 37. Mokrice HPP Model in Solibri
(Source: IBE)

The dam model was done in Revit with 25% of the elements classified as Generic Models., another 25% of the elements are pipes and 12% walls. These main categories are shown in Figure 38 in blue and orange (pipes are under, no shown). This model (Figure 37) has a high level of development; nonetheless, as said at the beginning of this work, like most of the projects, the subsurface is neglected, not included.



Note: Main elements of the model coloured.

Figure 38. Mokrice HPP Model in Bixel Manager
(Source: Own)

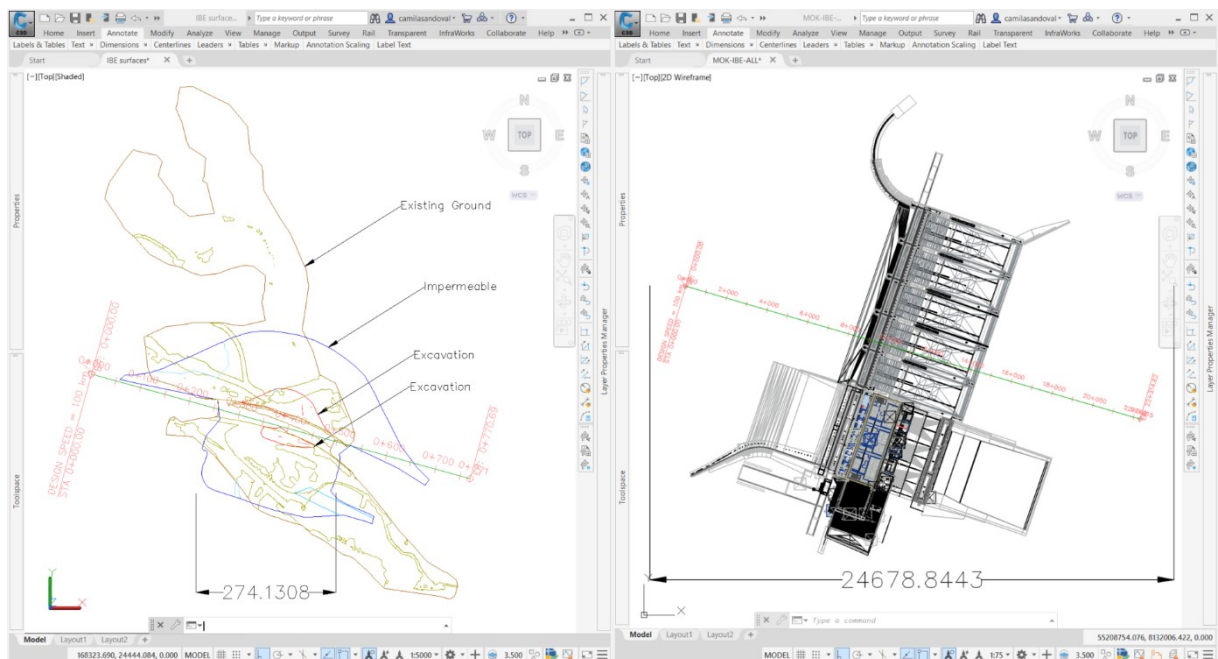


Figure 39. Scale Comparison between Surfaces and IFC Model
(Source: IBE)

After importing the IFC model in Civil 3D, another usual problem appeared when working with different authoring tools, the Revit model was in cm while the Civil 3D Template to import the model was in m. When importing an IFC in Civil 3D is important to have the same units in the Template where the drawing is going to be created that in the original model, else the imported IFC will have scale problems as shown in Figure 39, where the IFC model of the dam imported in Civil 3D was 100 times bigger than the surfaces of the existing ground.

After adjusting the scales of the models, the GeoBIM can be created for the uses described in chapter 405.2. In this case, the surfaces information was not enough to create the GeoBIM, then some boreholes were created, to import in the Geotechnical Module of Civil 3D to create the GeoBIM. From the model created by surfaces, the GeoBIM was created in 3D to be able to use for QTO, clash detection, QA/QC and 4D simulation.

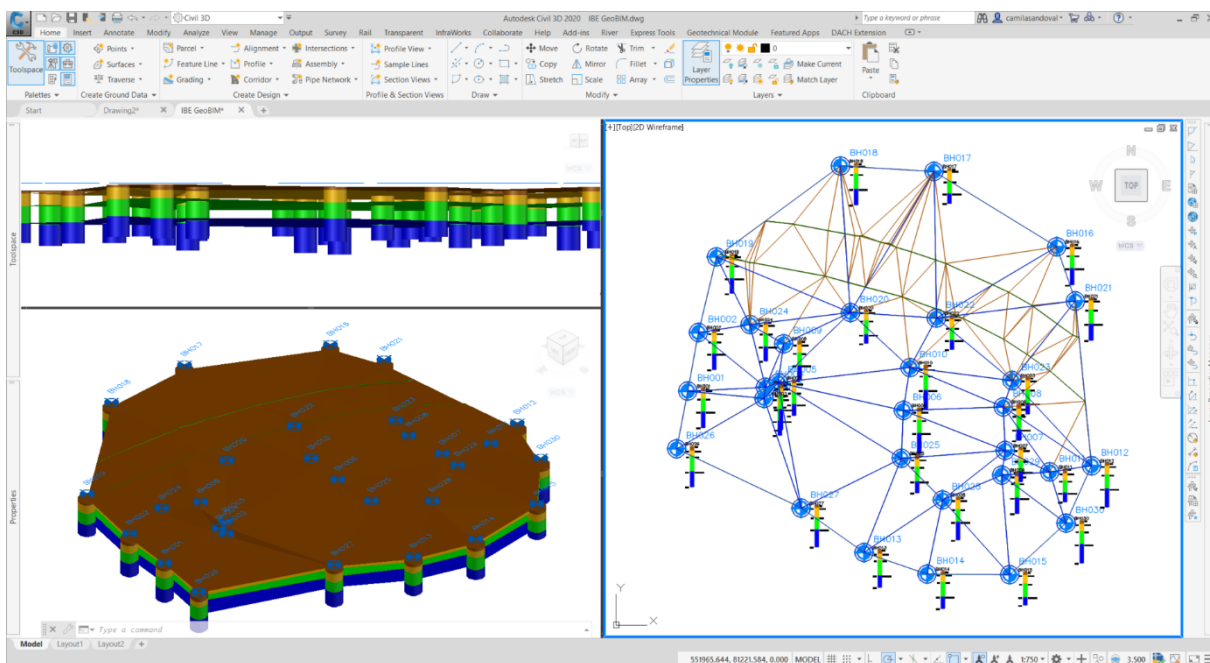


Figure 40. Geotechnical Model for Mokrice HPP
(Source: Own)

6.4 Validation of the Approach

With some excavation surfaces and the GeoBIM, the excavation model was created for 4D simulation. For the first use, Quantity Take-Off each excavation phase has the corresponding volume of excavation of each soil as shown in the following Figure. To report the quantities, Navisworks cannot read the properties added as extended properties in Civil; thus, Bexel Manager was used for making the report of the property volume of each excavation phase. For this case, it was necessary to add a property "Excavation_Phase" to identify the "Generic Models" of the materials involved. Another option to get a report is by using Dynamo.

Then the GeoBIM can be used for clash detection report to assure the excavation is correctly modelled and the objects fit in the excavation voids. Also, infills can be modelled for the same purposes. At the same time, the model was evaluated for quality control and quality assurance. The following is Phase 1 of excavation with the corresponding dam structure, on the bottom of the excel report by Solibri for the GeoBIM Rulesets created for clash detection and quality assurance & control.

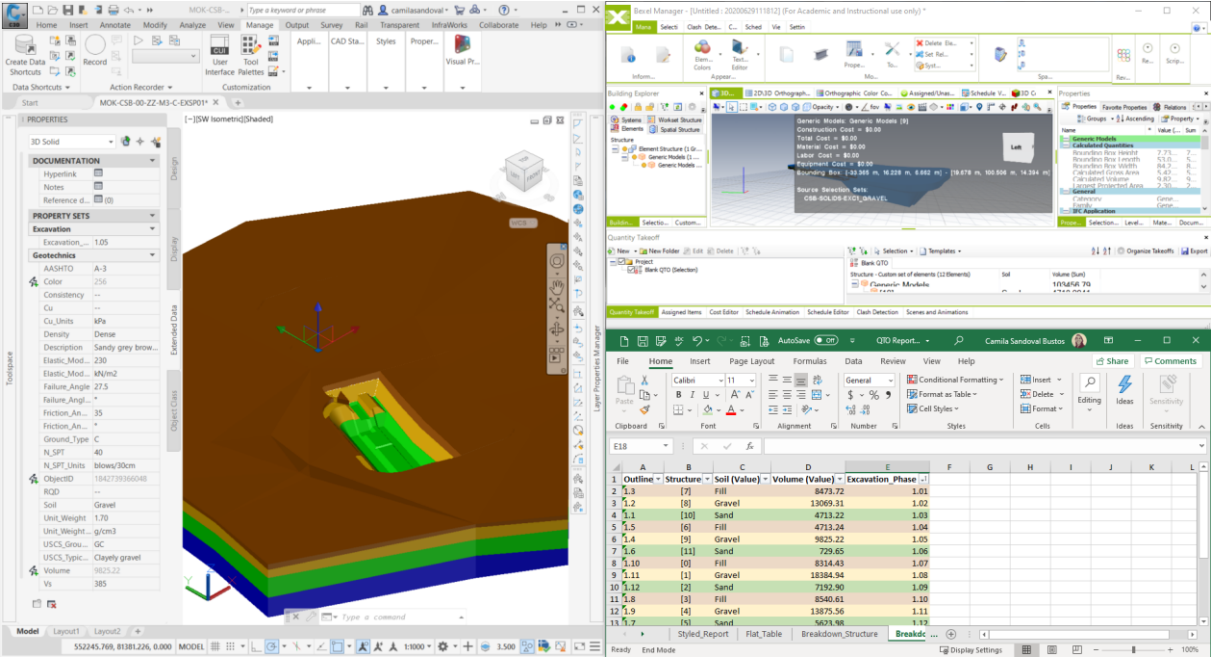


Figure 41. GeoBIM for Quantity Take-off (Source: Own)

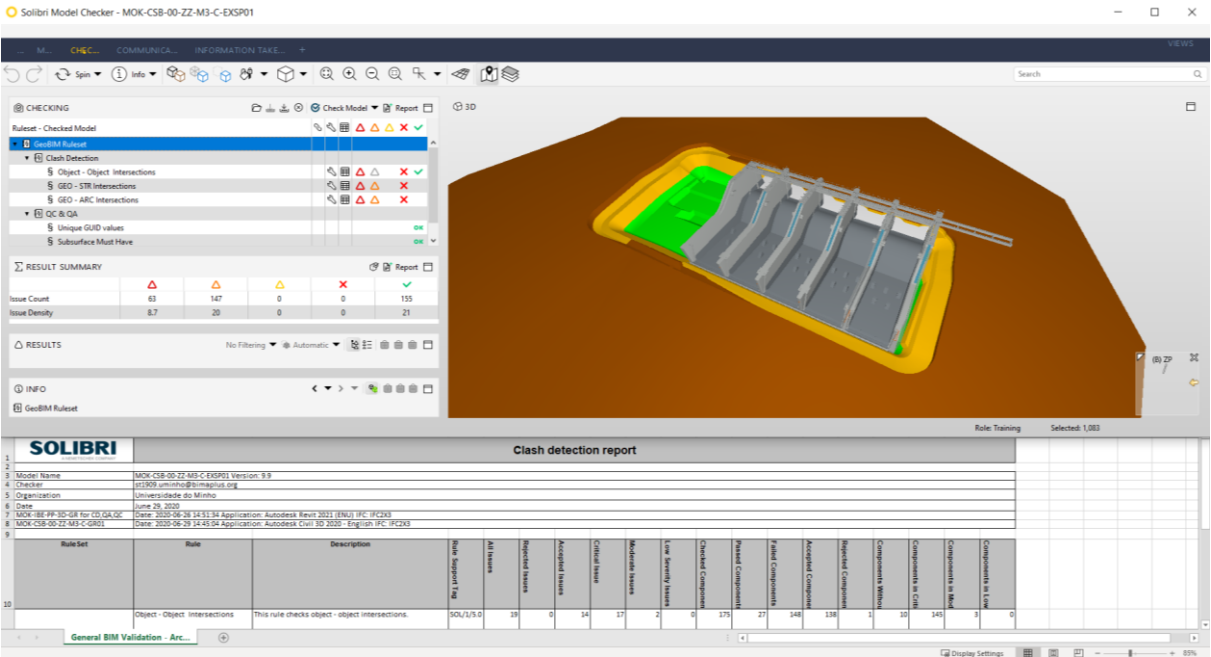


Figure 42. GeoBIM for Clash Detection and QA & QC (Source: Own)

Furthermore, the model was used for a 4D simulation of the excavation and infill. The different phases of excavation were assigned according to an excavation schedule.

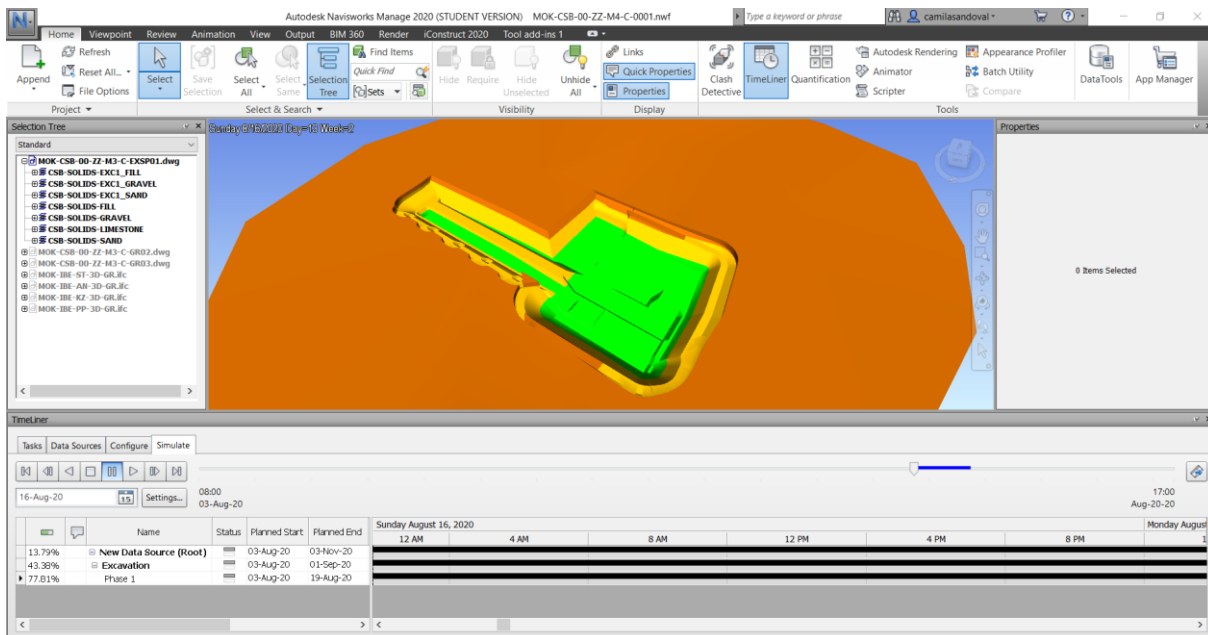


Figure 43. GeoBIM for 4D Simulation
(Source: Own)

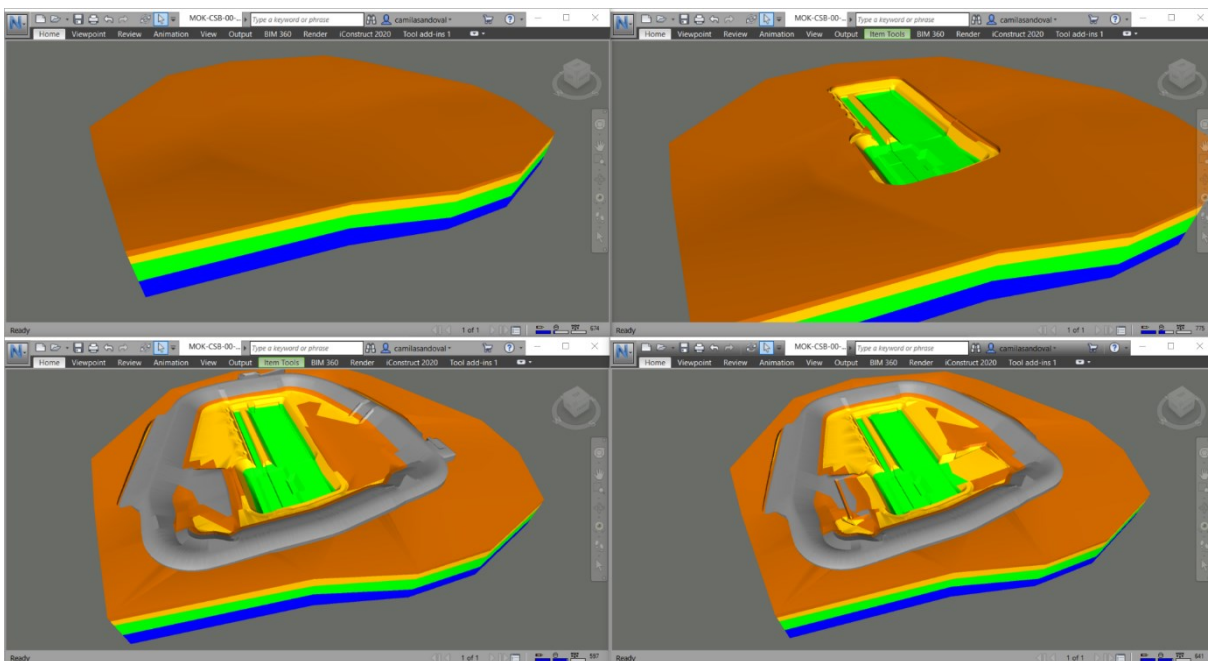


Figure 44. GeoBIM Excavation Stages
(Source: Own)

Finally, the excavated GeoBIM was combined with the hydropower plant model to show the coordinated model. Also, this excavated model can be used to check the supports of the retaining wall and a more precise length of the anchors to reach the adequate soil.

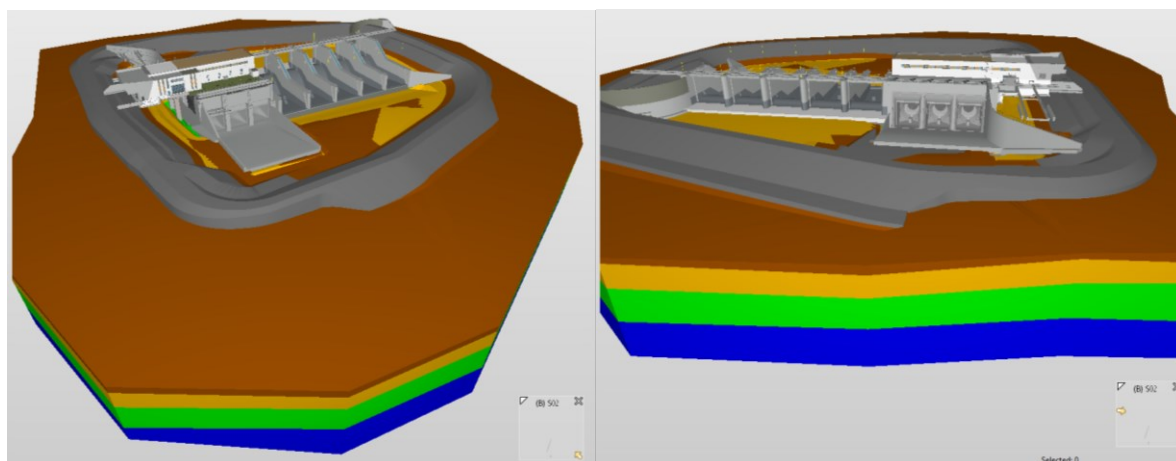


Figure 45. Coordinated Model of the Mokrice HPP Including GeoBIM
(Source: Own)

6.4.1 Schematic Proposal for Dynamic GeoBIM

Considering the excavation of 143.427 m^3 , 80.607 m^3 of fills, a maximum height of 15 m of excavation and 10 m of fills, and an earthworks area of 100.000 m^2 for Mokrice HPP, the following (Figure 46) is the UAV flight mission proposal to be performed weekly to produce a dynamic GeoBIM. The primary characteristics of the flight are nadir images (90 degrees), a front overlap of images of 80%, a side overlap of images of 70%, and a GSD of minimum 2 cm/px (by adjusting the height of flight to 70 m above the ground).



Figure 46. UAV Flight Mission Proposal for Mokrice HPP with 3Dsurvey Pilot
(Source: Own using 3Dsurvey Pilot)

The following are the characteristics of the UAV that can be used (Table 11). To be noted that various UAV exists on the market, and to satisfy the requirements is recommended to see Figure 26.

Table 11. Phantom 4 Pro and Mavis 2 Pro DJI Drones Specifications
(Source: DJI [66])

	Phantom 4 Pro V2.0	Mavic 2 Pro
Design	Iconic Phantom Series Design	Foldable, Portable
Weight	1375 g	907 g
Dimensions	251×398.78×172.72 mm	214×91×84 mm (folded)
Stabilization	3-Axis Gimbal	3-Axis Gimbal
Video	4K/60fps at 100 Mbps	4K/30fps at 100 Mbps
Camera	1-Inch CMOS, 20 MP, Mechanical Shutter	1-Inch CMOS, 20 MP
Max Transmission	8 km	8 km
Max Flight Time	30 Minutes	31 minutes
Obstacle Sensing	5 Directions	Omnidirectional (6 Directions)

The dynamic BIM model can be used for controlling earthworks payment, to compare planning with execution, for preventing landslides, and at the end for the As-Built model, among others. It is crucial to tell that the earthworks have not started yet for the Mokrice HPP, then the workflow proposed could not be tested in the project. The previous proposal can be improved according to the earthworks planning and the progress on the field focusing on a critical area or interest areas in specific moments.

7 DISCUSSION AND CONCLUSIONS

Hereafter, the discussion, and conclusions will be divided into three: a critical evaluation, lessons learned and plans for future work.

7.1 Critical Evaluation

Overall, the thesis consults the actual context of the geological and geotechnical specialities in the BIM world, showing the difficulties in the actual stage of development, definitions, and standards. Considering the context and with the tools used by the company, the thesis proposed a GeoBIM, a surface-subsurface model and a LOD definition to standardize the discipline. Furthermore, some workflows were developed to show the different uses the GeoBIM can have; however, these uses do not limit other potential uses discussed. Finally, for the case study, the Mokrice hydroelectrical power plant in Slovenia, a GeoBIM model was created, and the workflows were tested accomplishing the uses described before.

The work developed is a valuable contribution to the BIM field, specifically to the geo disciplines. The workflows, the LOD definition, the interoperability analysis and the study case are firm steps to include the ground in BIM. Including in any project, and especially in technological projects the GeoBIM has the following benefits: a better understanding of the project, integration of the ground with the projects in the collaborative process, better and faster decision making for explorations and laboratories, more accurate slope stability analysis based on the quality of the model, better quantity take-off for earthworks, quality control can be performed, time simulation of the earthworks can be done, a real-time or dynamic model can be created, more precise anchors design and automatization of excavation, among others.

The case study is evidence that technological projects are benefited by the GeoBIM. Moreover, the scenarios in chapter 2.3 show the AECO industry is becoming aware of the incredible benefits of the surface-subsurface model, like in the Farringdon station project where the complex geology represents significant challenges for the designers. Also, governments are interested in 3D databases that can facilitate the understanding of the projects and provide the information explorations performed. For each of the BIM uses the workflows tested were successful, accomplishing the specific goal of each one for the GeoBIM model.

7.2 Lessons Learned

Geological-geotechnical models can be used for different purposes like the BIM uses proposed in this thesis, quantity take-off, clash detection, quality control & assurance, 4D simulation, and even 5D simulation, dynamic earthworks model, anchors design and automatization of excavation. Even the uses described by BIME initiative can be explored more in-depth. These uses mentioned before are translated in material benefits to the project such as time reduction, cost reduction, better planning of underground works, better understanding of the geotechnical risks, less uncertain, improvements in earthworks estimations, centralized data collection, among others.

The workflow was developed with the tools that the company used or are thinking to implement. Other tools can be used to develop similar workflows, and even more powerful software can complement the workflow for specific purposes or scenarios. When modelling the subsurface some of the difficulties are the different faults and heterogeneities the profile can have, some of these complications can be solved with Civil 3D; nevertheless, some specialized software for geological or geotechnical modelling can be an alternative to have a more powerful modelling tool capable of describing precisely complex soil profiles.

The importance of 3D underground models has been demonstrated, these types of models have powerful applications for the AECO industry and can make projects more feasible, different alternatives can be tested to find the more convenient for investor, constructors, and designers. For technological projects, multiple applications can be developed, the ones explored in this thesis can motivate the companies to develop GeoBIM and dynamic Geo BIM models and further explore other uses interesting for the company depending on the focus it has.

7.3 Plans for Future Work

While developing the thesis, some ideas that have potential were discussed. Considering the author's experience in a geotechnical firm, and with the example of the BGS, 3D geological and geotechnical databases can be developed, either by governments or by companies. Usually, the archive of the companies had the most valuable information of the company, the experience gained during the years, sometimes this information is not easily accessible and not even classified correctly. By developing 3D databases of projects, explorations, laboratories, and others, companies and governments will get the advantage of historical data and produce higher quality models.

The workflow with bidirectional interoperability with the analysis software can be developed so that the analysis software should read the properties assigned to the model from the database of the field and laboratory results. If the developers of the software do not develop the bidirectional interoperability, an API or extension can be developed to achieve the bidirectional interoperability.

As shown in chapter 5.2.5, the GeoBIM can be potentially used to automate the excavation considering the parameters of the soil that provide from the database that is feed with field and laboratory data. A preliminary essay was done; nevertheless, the automatization can improve considering different cases in the same pit. Also, the automatization can consider the results of the analysis software and translate the results into the GeoBIM.

Also, optimization of excavation and fill areas can be developed using tools as Refinery for Dynamo. A script can be developed to give options of implantation levels and areas, considering the surface (topography) and the subsurface (stratigraphic profile) the solution can give the best options in level an area to balance the excavation and fill. Besides, the optimization can include the soil or rock excavation cost, considering the differences in compaction of the types of soils excavated and give an analysis in terms of budget.

Finally, developing further the dynamic GeoBIM model, including testing of the procedure proposed in a real project. When testing the proposed workflows on the project, many difficulties were discovered, and the workflows were improved and adapted; in this case, the proposed is an initial procedure that can be optimized after testing it and face difficulties that were not considered.

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10 LIST OF ACRONYMS AND ABBREVIATIONS

AAHK	Airport Authority Hong Kong
AECO	Architecture, Engineering, Construction and Owner
AGS	Association of Geotechnical & Geoenvironmental Specialist
AGS	AGS text file extension for transferring data
BEP	BIM Executive Plan
BESLN	Bexel Manager native file format
BIM	Building Information Modelling
BGS	British Geological Survey
CGM	Conceptual ground model
CIC	Construction Industry Council (of Hong Kong)
CSET	Checking set of native rulesets format for Solibri Model Checker
CSF	Critical success factors
CSV	Comma-separated values text file extension
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
DWG	Drawing format, a proprietary file format for some CAD software
DXF	Drawing Exchange Format
FEA	Finite Element Analysis format for Rocscience
FEZ	Zipped (compressed) Finite Element Analysis format for Rocscience
GCPs	Ground-Control Points
GeoSPARQL	Semantic query language for geospatial databases for the semantic web
GeoXACML	Geospatial eXtensible Access Control Markup Language

GIS	Geographic Information Systems
GML	Geography Markup Language
HESS	Hidroelektrarne na Spodnji Savi (<i>Hydroelectric power plants on the Lower Sava River</i>)
HPP	Hydropower plant
IFC	Industry Foundation Classes
ISPRS	International Society for Photogrammetry and Remote Sensing
KPI	Key performance indicator
MPP	Microsoft Project File
MVS	Multi-view Stereo
NBS	National Bureau of Standards
NWD	Navisworks Document
LAS	LIDAR Data Exchange File
LAZ	Compressed light detection and ranging (LIDAR) data format
LOA, LoA	Level of Accuracy
LOc	Level of Coordination
LOD	Level of Detail
LOD, LoD, LOD	Level of Development
LOI, LOi	Level of Information
LOG	Level of Geometry
LoX	Level of X (All varieties of the level of development, detail, information, accuracy, others.)
PDCA	Plan, do, check, act (method of continual improvement)
PDF	Portable Document File
PIT	Pile integrity test
RCP	Recap Project File Format (contain RCS files)

RCS Recap File Format (contain the actual spatially indexed point cloud data)

RDF Resource Description Framework

RVT Autodesk Revit project files

SfM Structure-from-Motion (photogrammetry)

SIFT Scale Invariant Feature Transform

UAV Unmanned Aerial Vehicle

USBID US Institute of Building Documentation

XLS Excel Spreadsheet

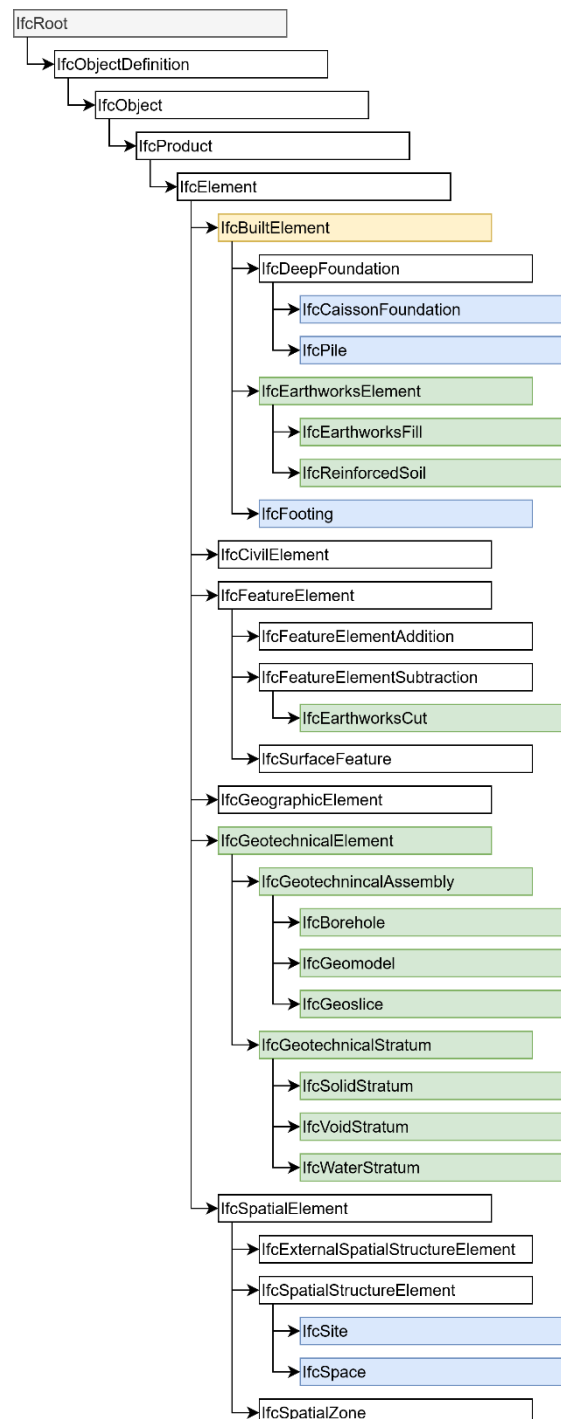
XLSX Microsoft Excel Open XML Spreadsheet

XML eXtensible Markup Language

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11 APPENDICES

11.1 APPENDIX 1 - IFC Definition and Inheritance for Geotechnical Elements According to Version 4.3.0.0 Published in April 2020 (Candidate)



Note: Not including PredifinedType. In green additions and in yellow changes. Blue previous definitions involving the fields of geotechnics and geology.

Figure 47. IFC 4.3.0.0 Inheritance for Geological and Geotechnical Elements
 (Source: BuildingSMART International [67])