POLITECNICO DI TORINO

Master of Science in Civil Engineering

Master Thesis

Technical-economic analysis for a metro project by the integration of BIM modelling and construction schedule

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Abstract

An increasing number of construction projects utilizing building information modeling (BIM) have been witnessed in the past years. Research has shown that several countries worldwide started to request or enforce the adoption of BIM methodologies in construction projects especially publicly funded ones. Therefore, BIM implementing firms are now investigating possibilities to expand the use of BIM to cover more aspects of projects. This study is a real-life BIM application on a metro project to be constructed, with the main aim is to practice the BIM methodologies in integrating both 4D (time) and 5D (cost) into the project three-dimensional geo-referenced model.

Throughout this article a brief background about BIM was studied. Then the BIM methodology followed to prepare a reliable 4D/5D model of the underground metro project was addressed. The methodology included the process of BIM validation, construction scheduling and cost estimation.

The output of this study is separated into the 4D simulation which represents a real-time graphical simulation of construction progress against time, in addition to the 5D simulation which includes the generation of cost budget representations of the model against time. Results interpretation was also divided into two categories time and cost. In order to the interpret the 4D (time) a comparison between the initial project milestones and the final construction schedule was highlighted. However, to comprehend the 5D (cost) a literature review regarding the expected investments for mechanized tunneling was done and then compared with what was achieved during this study.

Based on the output of the BIM methodology in this real case study, it can be concluded that investing in BIM should be taken into consideration by every construction firm due to its numerous advantages in the construction process especially reflecting a better project quality at the lowest possible time and cost.

Keywords: Building information modeling, BIM, 4D, 5D, BIM validation, Construction scheduling, Cost estimation.

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1. Introduction

Building Information Modeling (BIM) implementation is currently one of the most trending applications in the construction industries. “BIM is actually a process for creating and managing all the project information, it allows the project to be built virtually before it is constructed physically, eliminating many of the inefficiencies and problems that arise during the construction process. Some of the greatest benefits of BIM in construction are to allow more effective construction cost estimation in the planning stage, reduce the time of project cycles by improving construction scheduling, and to allow preconstruction project visualization.” (Hall, 2018) This article investigates the application of BIM in a real-life underground project during its bidding phase. The study will include the integration of both time 4D and cost 5D into the project 3D model.

Some construction businesses are still worried about adopting BIM as part of their projects mainly because of the required investment. “These early investments include the time and cost of training and hiring employees to use BIM and the software associated with it, and the need for complementing software and better hardware.” (Tulenheimo 2015) However, the long-term benefit from building information modeling is undeniable since it leads to higher quality projects with less errors, change orders and reduced project cost and time. This study will prove the importance of the implementation of BIM during the bidding phase of a construction project based on a real case study.

The core of this thesis work focuses on technical economic analysis for a metro project by the integration of BIM modeling and construction management. A case study of a metro project to be constructed was considered, and construction management applications were applied to finally reach a complete building information model of the project incorporating both time and cost.

This report starts with a brief literature review about building information modeling (BIM). Then in the next chapter an introduction about the case study was reported. The case study is an underground metro project with a total length of approximately 7 km including 7 different stations, the construction methodology of different sections of the project was also reported. Later, in chapter four the methodology followed starting from a 3D BIM model and reaching a reliable 4D/5D BIM model was declared. The methodological process was subdivided into five different steps and each step was elaborated in a separate chapter. The first step of the methodology was BIM validation, it is the process of validating the 3D model against the 2D cad drawings to assure reliable model output. Then, the construction schedule was prepared, respecting the project milestone, which was used later in addition to the validated 3D model in the third step which is the creation of the 4D model simulation. Moving on, the process of cost estimation composed the fourth step of the methodology, in this step different offers where compared and summary sheets were prepared. Finally, using the cost estimates and the 4D model the cost was integrated into the model hence achieving a 5D simulation. At this stage of the thesis the BIM application have been tested on the real-life example and hence results had to be interpreted. In chapter 8 the results interpretation was done considering both time and cost, hence proving the importance of BIM in the construction field for the consistent output that can be attained.

2. BIM Background

“The concept of BIM can be traced back to the earliest days of computing in the 1960s and solid modeling programs began to emerge in the 1970s and 1980s. The development of the ArchiCAD software program in 1982 in Hungary is viewed by many as the real beginning of BIM and the development of Revit software program in 2000 saw a real shift toward effective BIM implementation.” (Bergin, 2012)

“BIM emerged in the last few years as a revolutionary concept and is being looked upon as the future revolution of the Architectural, Engineering and Construction (AEC) industry.” (Kassem et al., 2012) The adoption of BIM methodologies in many foreign countries (Northern Europe and US among others), together with the tendering reform approved by the European Parliament (European Union Public Procurement Directive, EUPPD) indicates a growing demand for the use of BIM methodologies in designing operations in the public construction sector.

“BIM is mainly a three-dimensional digital representation of a structure and its essential features. It is composed of intelligent building elements which include data attributes and parametric rules for each object.” (Hergunsel, 2011) It is an information-based system that builds long-term value and advances innovation. It also improves how projects get designed and built. The user can view and interact with the model in three-dimensional views as well as orthographic two-dimensional plan, sections, and elevation views of the model. As the model is developed, all other drawings within the project will be correspondingly adjusted.

“BIM involves more than just 3D modelling and is also commonly defined in further dimensions such as 4D (time), 5D (cost) and even 6D (as-built operation). 4D links information and data in the 3D object model with project programming and scheduling data and facilitates the simulation analysis of construction activities. 5D integrates all of this information with cost data such as quantities, schedules, and prices.” (Smith, 2015)

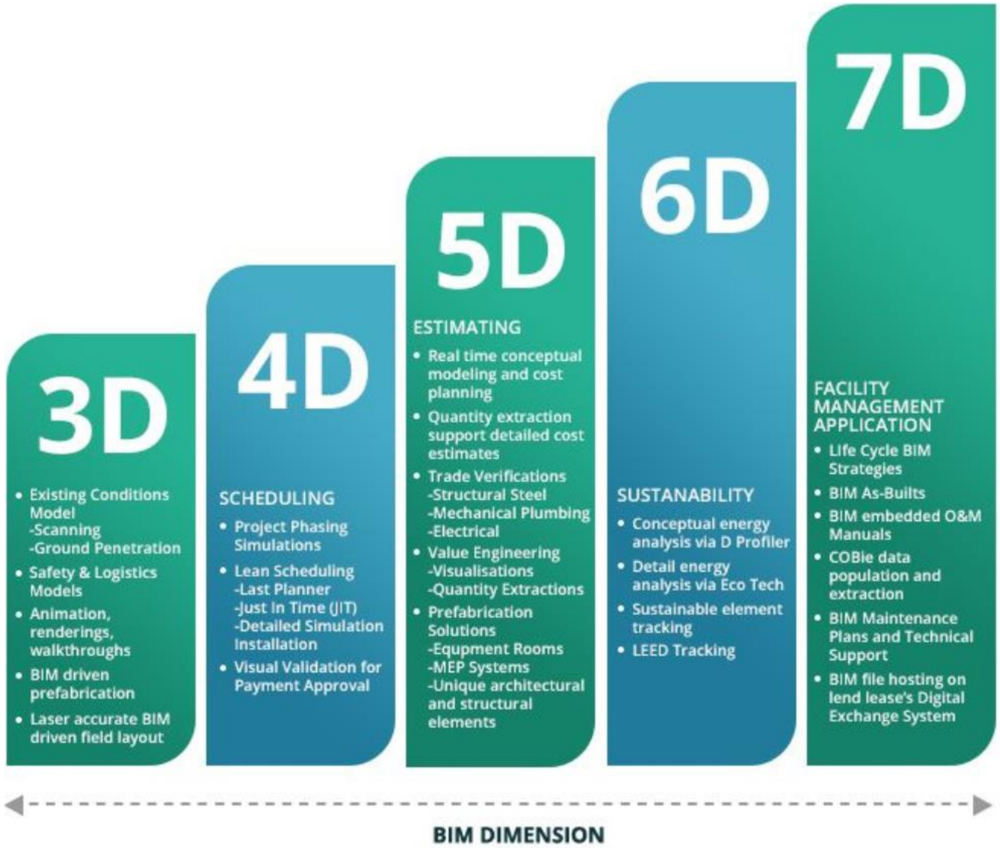


Figure 1 BIM Different Dimensions. Source: Excelize Software Pvt. Ltd.

“4D is a planning process to link the construction activities represented in time schedules with 3D models to develop a real-time graphical simulation of construction progress against time. Adding the 4th dimension ‘Time’ offers an opportunity to evaluate the buildability and workflow planning of a project. Project participants can effectively visualize, analyze, and communicate problems regarding sequential, spatial, and temporal aspects of construction progress. As a consequence, much more robust schedules, and site layout and logistic plans can be generated to improve productivity.” (Kameedan, 2010, p. 285)

“Integrating the 5th dimension ‘cost’ to the BIM model generates the 5D model, which enables the instant generation of cost budgets and genetic financial representations of the model against time. This reduces the time taken for quantity take-off and estimation from weeks to minutes, improves the accuracy of estimates, minimizes the incidents for disputes from ambiguities in CAD data, and allows cost consultants to spend more time on value improvement.” (Kameedan, 2010, p. 285)

BIM specification standards during the various stages of development of a project are important for project cost managers and other construction professionals to assist them in defining their information requirements during these various stages. A Level of Development (LOD) Specification was developed that has potential global application. It is a reference that enables professionals to specify and articulate with a high level of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process. The LOD Specification utilizes the basic LOD definitions developed by the American Institute of Architects. It defines and illustrates characteristics of model elements of different building systems at different Levels of Development. "This clear articulation allows model authors to define what their models can be relied on for and allows downstream users to clearly understand the usability and the limitations of models they are receiving." (BIM Forum, 2013, p.8) The intent of this Specification is to help explain the LOD framework and standardize its use so that it becomes more useful as a communication tool.

The table below shows how the American Institute of Architects define LOD. There are six levels of LOD:

Table 1 Level of Development "LOD" Source: AIA

LOD 100	The Model Element may be *graphically represented* in the Model with a **symbol or other generic representation**, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.
LOD 200	The Model Element is *graphically represented* within the Model as a **generic system, object, or assembly with approximate quantities, size, shape, location, and orientation**. Non-graphic information may also be attached to the Model Element.
LOD 300	The Model Element is graphically represented within the Model as a **specific system, object or assembly in terms of quantity, size, shape, location, and orientation**. Non-graphic information may also be attached to the Model Element.
LOD 350	The Model Element is *graphically represented* within the Model as a specific system, object, or assembly in terms of quantity, size, shape, orientation, **and interfaces with other building systems**. Non-graphic information may also be attached to the Model Element.
LOD 400	The Model Element is *graphically represented* within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation **with detailing, fabrication, assembly, and installation information**. Non-graphic information may also be attached to the Model Element.
LOD 500	The Model Element is a **field verified representation in terms of size, shape, location, quantity, and orientation**. Non-graphic information may also be attached to the Model Elements.

3. Case Study

3.1 Geodata

This thesis work was conducted at Geodata's headquarters in Torino, Italy.

Geodata is a geoengineering company engaged since 1984 in the design of underground works. It has designed and supervised the construction of over 4,000 km of tunnels and more than 3,500 projects worldwide in:

- area of metros
- traditional and high-speed railways
- roads and motorways
- dams and hydroelectric plants
- geology and environment

Geodata has designed and constructed a number of the largest and most technically complex public transport infrastructure projects worldwide. These projects are located in Italy, Brazil, Turkey, India, Venezuela, Singapore, Peru, Russia, Portugal, Iran, France, and Greece.

3.2 Metro Project

3.1.1 Project Introduction:

This metro project is still in the bidding phase hence in order to respect geodata's regulations the name, location, station names and costs of this project will not be reported. The main reason for such regulations is due to the fact that several contractors are competing to be awarded the project, thus such data is highly confidential, and it would reduce geodata's chances in winning the bid in case it was published.

Metro project was introduced thanks to the demands of the infrastructure plan for public transport. The layout of the metro line has an extension of 25.8 kilometers and is planned to pass in seven different cities.

Considering the above and the constructive methodology, the Project has been segmented into three sections, which differ geographically, according to the following:

Section 1: Seven different stations

Section 2: Six different stations

Section 3: Seven different stations

In this report Section 1 of the metro was only considered in the bidding phase. It has a total length of approximately 7.9 km, comprises from the maneuver Queue which is about 280m. In this section there are 7 stations considering a Construction Shaft that contains the junction with the branch to workshops and garages.

Stations tunnels, shafts galleries, maneuvering tail tunnel and unique works will be built using the Sequential Excavation Method, also called NATM, while for the tunnel between stations it will be built, with Tunnel Boring Machine "TBM".

The TBM method allows to excavate tunnels to full section, ensuring the restraint of the walls through the placement of the definitive casing made of prefabricated concrete as it progresses (Segmental rings), leaving at the end, a concrete tunnel completely finished in terms of its civil works.

The works that have to be performed as part of the project were reported as codes instead of the real names for confidentiality and are the following:

- Ventilation Shaft (B.9).
- B.1 Station and Maneuver Queue.
- Ventilation Shaft (B.10).
- B.2 Station.
- Construction shaft (B.3).
- B.4 Station.
- Ventilation Shaft (B.11).
- B.5 Station.
- Ventilation Shaft (B.12).
- B.6 Station.
- Ventilation Shaft (B.13).

- B.7 Station.
- Ventilation Shaft (B.14).
- B.8 Station.
- Interstation tunnel from the eardrum of the B.1 station tunnel to the north (West Limit of Initiation of the Section 1 Contract. PK – 0+000).
- Interstation tunnel from the eardrum of the tunnel station B.1 south to eardrum north tunnel station B.2.
- Interstation tunnel from the southern eardrum of the B.2 station tunnel south to B.3 and Branch to workshops and garages.
- Interstation tunnel from the southern eardrum of B.3 heading south to eardrum north tunnel B.4 station.
- Interstation tunnel from the southern eardrum tunnel B.4 station south to eardrum west tunnel station B.5.
- Interstation tunnel from the eardrum east tunnel station B.5 east to eardrum west tunnel B.6 station.
- Interstation tunnel from the eardrum east tunnel B.6 station to the east to eardrum west tunnel B.7 station.
- Interstation tunnel from the eardrum east tunnel B.7 station east to eardrum west tunnel walker B.8.
- Access and Services Galleries.
- Tunnels station.

Therefore, to summarize the scope of work of the project it is distributed between tunnels, stations, and shafts. The total tunneling length is 7.9 km, of which approximately 14% will be excavated using the conventional method NATM while the remaining 86% will be mechanized excavation by the TBM. In addition, a total of 7 station should be constructed, 4 of which are cut and cover stations while the rest are shaft plus tunnel stations. Finally, 7 shafts are required, 6 are ventilation shafts and the remaining 1 is a construction shaft. The chart below shows a top view of metro section 1 including all the parts of the work that should be performed.

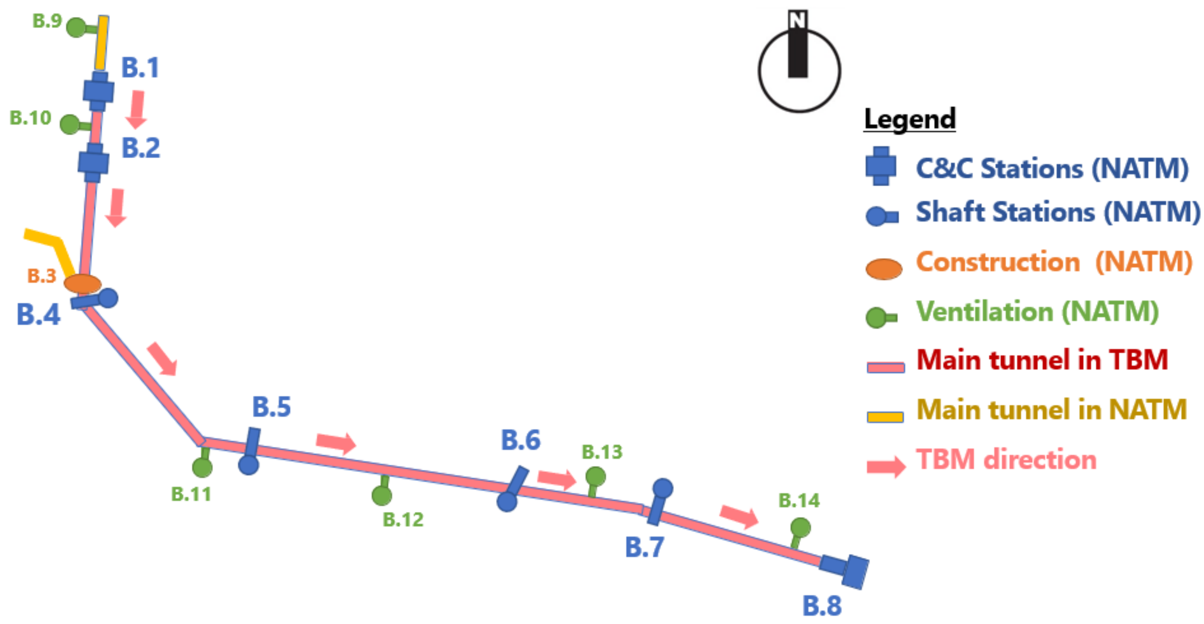


Figure 2 Metro Section 1 Scope of Work. Source: Geodata

3.1.2 Construction Methodology:

The construction methodology of the cut and cover stations, shaft plus tunnel stations, ventilation shafts, TBM tunnel and NATM tunnel will be discussed throughout this section of the report.

3.1.2.1 Cut and Cover station:

Starting with a cut and cover station, B.1 station will be considered for instance.

B.1 Station consists of the materialization of a rectangular section shaft whose dimensions and depth are indicated in the project plans.

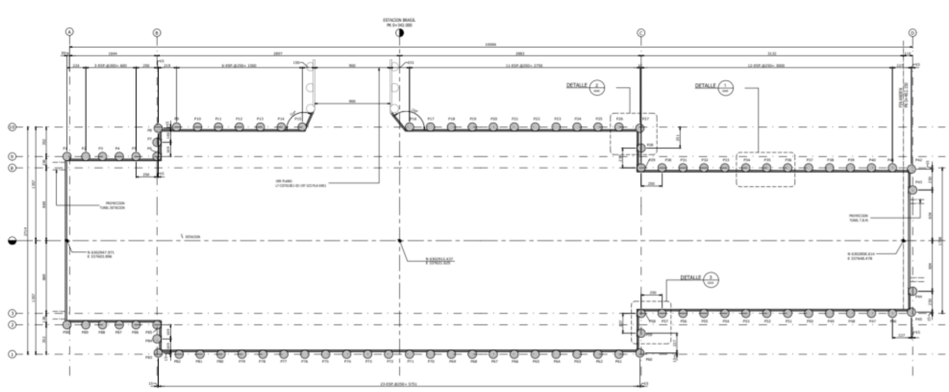


Figure 3 B.1 Station Rectangular Shaft Plan View. Source: Geodata

In B.1 station shaft, the shaft's own work facility will be located, plus the installation of tasks necessary for the segment plant and for the assembly TBM operation. The shaft will be built with vertical excavation, from reinforced concrete piles.

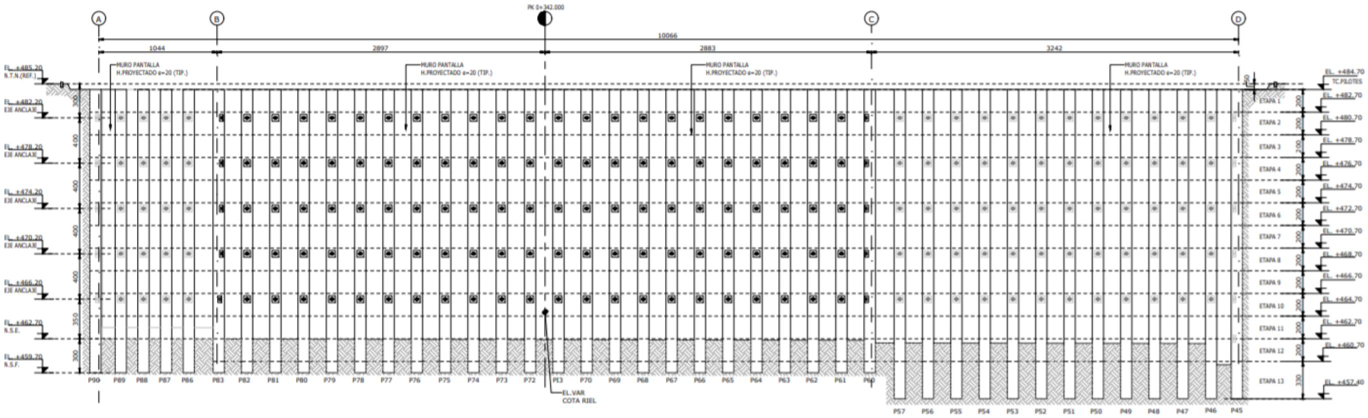


Figure 4 B.1 Shaft Side View – Piles and Soil Nailing. Source: Geodata

Once the piles have been executed, the excavation will advance until reaching the final depth considering the execution of sheeting, anchors, and soil nailing as indicated in the documents of the project and subsequent demolition of the temporary shotcrete.

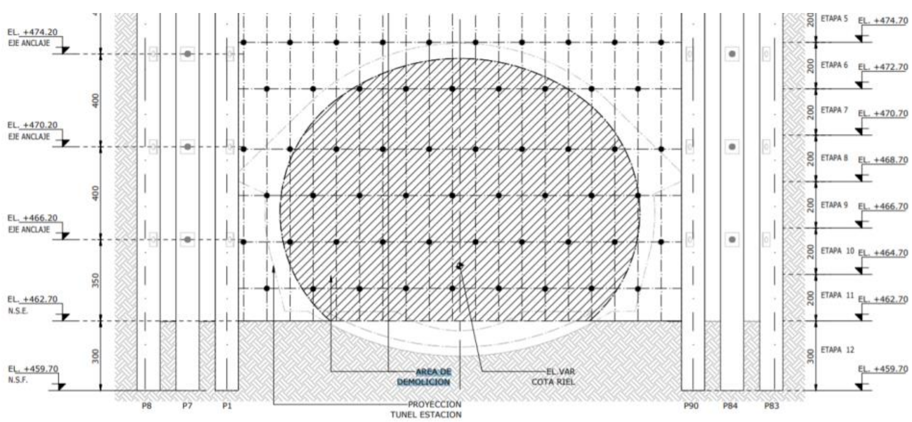


Figure 5 B.1 Shaft Temporary Shotcrete Example. Source: Geodata

The shaft also considers the generation of the access ramp, which will be key for the operation of the tunnel boring machine and to exploit the tail tunnel. This, in its section the initial slope is executed considering variable height slope until reaching a maximum height of approximately 5.4 meter.

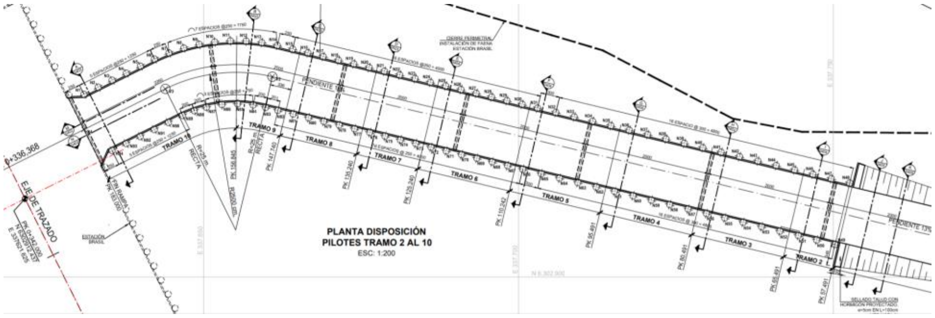


Figure 6 B.1 Station Access Ramp. Source: Geodata

After the final design depth is reached, excavation and construction of the shaft to level from the base of the station tunnel vault at the north end, it is possible to continue with the execution of the station tunnel and later the maneuvering tail tunnel, which will be executed using the NATM Method (New Austrian Tunneling Method). The station tunnel is approximately 21 meters from the station to the north and then continues with approximately 282 meters tail tunnel excavation.

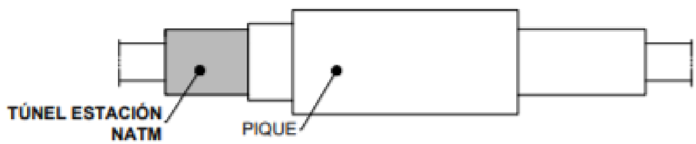


Figure 7 B.1 NATM Station Tunnel. Source: Geodata

NATM method consists mainly of excavating respecting the sequence and progress indicated in plans and technical specifications, placing shotcrete and reinforcements such as meshes welded steel frames, cross-linked steel metal frames and protection according to the project. The fortification of the tunnel walls, both in vault as in counter vault, will be through shotcrete, lattice frames and reinforcing trusses, to finish with slabs and their previous fillings, next to the concreting of platforms.

The excavation of the tunnels will be done using mechanized equipment such as excavators According to the section to be excavated, the material will be transported by front loaders, or trucks being driven to the B.1 shaft for transportation and unloading.

In this specific case of the Tunnel Station (B.1 Station), given its geometry and size, it will be built in four stages, respecting, and complying with what is specified in plans and project documents as shown below.

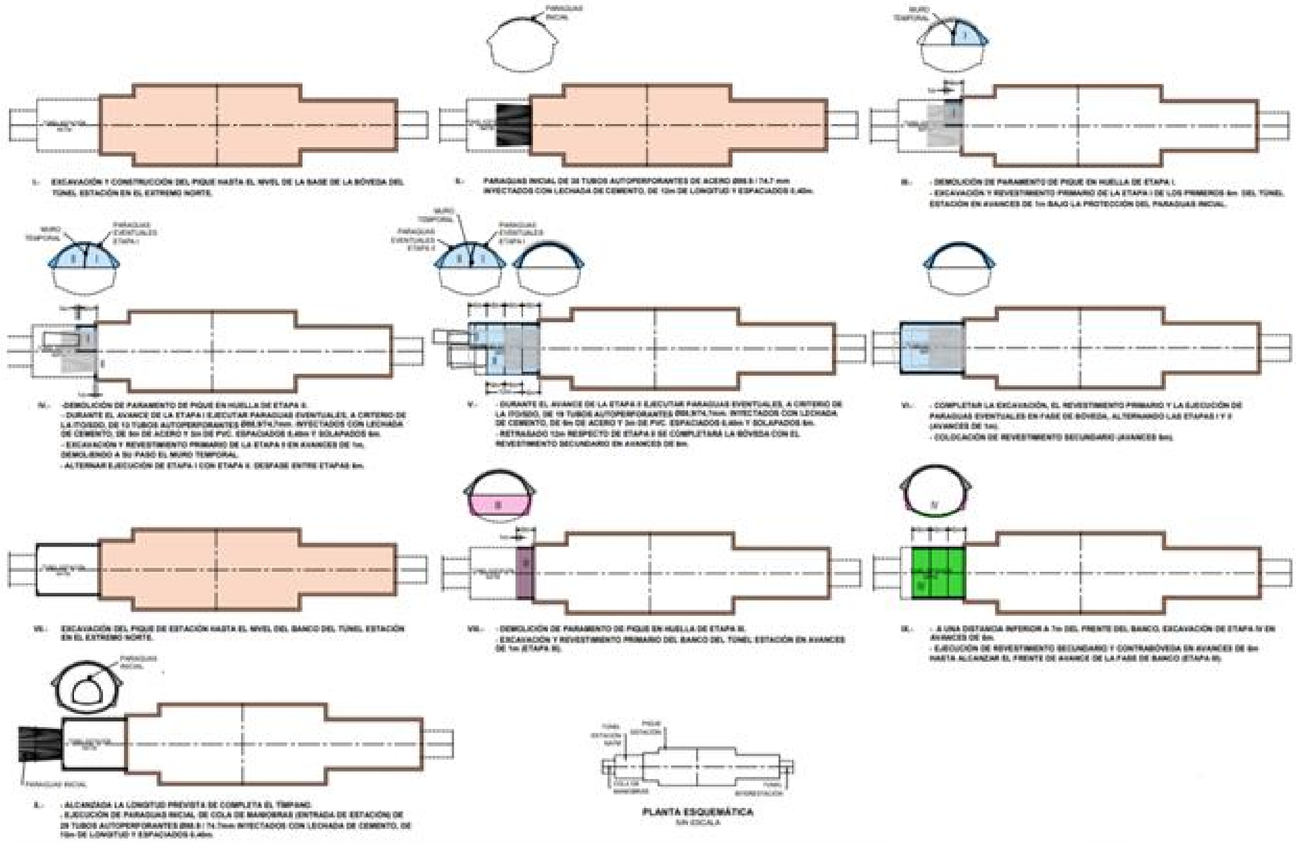


Figure 8 NATM Excavation Sequence in B.1 Station. Source: Geodata

For the construction of the tail tunnel, it is considered full face excavation in successive advances of 1.0 m placing 5 cm sealing and the rest of the primary lining consisting of frames, mesh, reinforcing steel and shotcrete. At a maximum distance of 4 m the counter vault will be executed, in 4 m advance. Finishing with the execution of the secondary coating, at a distance greater than or equal to 20 meters.

Also, after the final design depth is reached in the shaft, construction at the south end of the shaft will proceed with the execution of protection umbrellas, mounting cradle and drag, TBM assembly, reaction structure assembly and all what is required and specified in the project to proceed with the excavation with TBM. From the shaft south end, the Interstation tunnel is executed with a TBM for approximately 476 m, until it intersects with the B.2 north station tunnel.

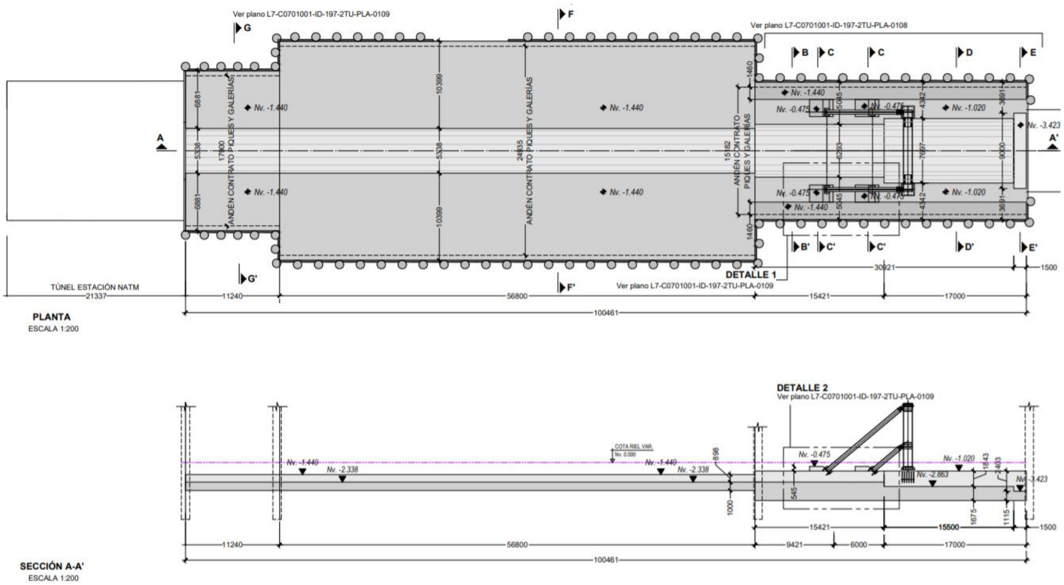


Figure 9 Cradle for TBM in B.1 Shaft. Source: Geodata

To start the excavation with the TBM, it is necessary to assemble the tunnel boring machine, including the TBM trailers. The assembly will be carried out in a shaft built overhead to the layout, which later will become part of the future B.1 Station.

The storage area of B.1 station will house the segment manufacturing plant and the assembly and testing of the TBM. The shaft of the B.1 station will also extract all the Excavation material from the tunnel Interstation by conveyor belts.

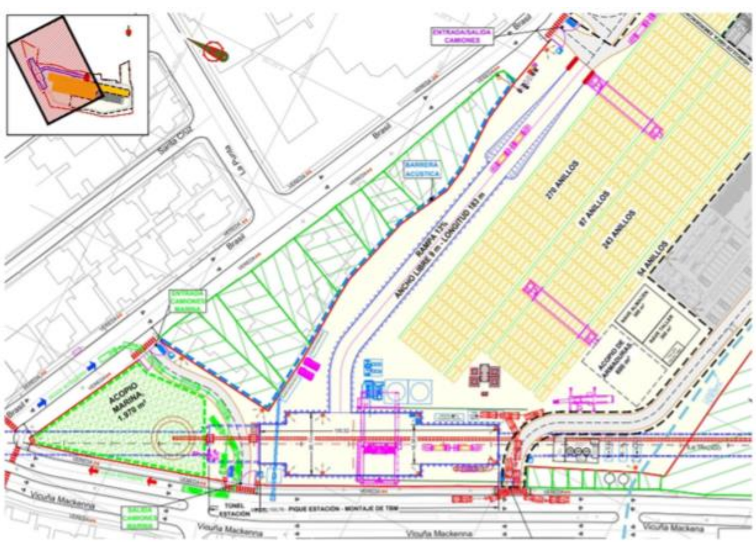


Figure 10 TBM assembly area, access ramp and segment storage. Source: Geodata

The concrete and metal structures must be built support (called cradle) to be able to mount the TBM inside the shaft and enable its subsequent dragging to the starting point of the excavation.

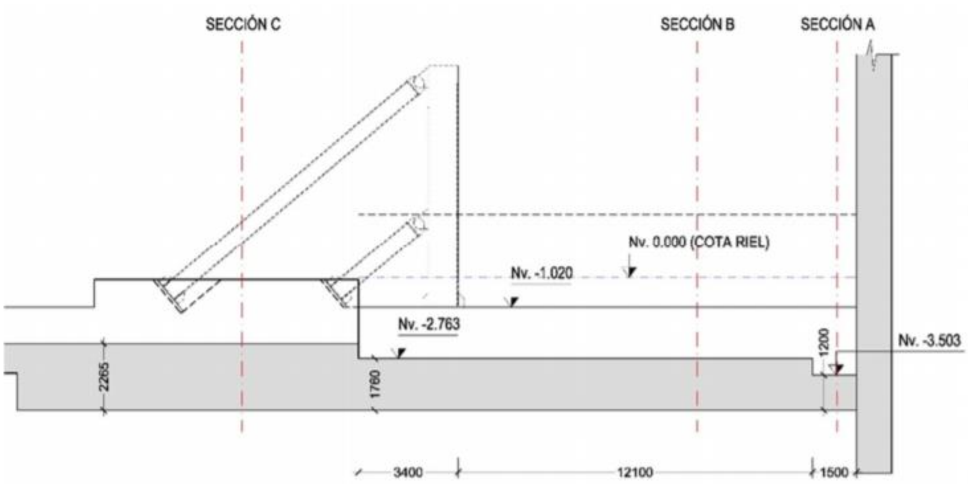


Figure 11 Longitudinal layout of the cradle in the TBM assembly area. Source: Geodata

Once the cradle is finished, the shield will be lowered and assembled and the cutting wheel of the tunnel boring machine, by means of a gantry crane and mobile cranes. Once the tunnel boring machine is in position, the reaction structure will be installed. The first complete ring must be placed after the dragging of the tunnel boring machine in the segments of base, until there is space to mount this ring between the TBM and the reaction structure. This ring will serve as a connection between the first ring that will be possible to assemble normal shape from inside the TBM and the reaction structure, mounted on the exterior of it. The start of the excavation of the eardrum is produced by pushing the jacks on the different elements prepared for such effect.

3.1.2.2 Shaft plus Tunnel station:

Moving on to a Shaft plus Tunnel station, let us consider B.6 station for example.

B.6 Station consists of the materialization of a circular section shaft whose dimensions and depth are indicated in the project plans.

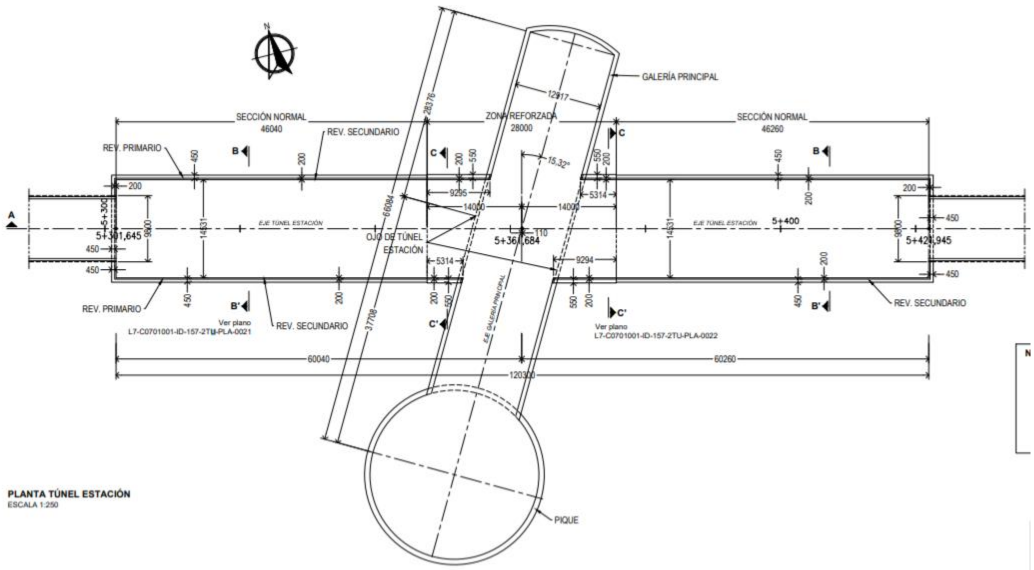


Figure 12 B.6 Station Plan View. Source: Geodata

In addition to the construction of the access gallery, from this gallery there will be built 120 meters of tunnel with the NATM method, approximately 60 meters of tunnel station towards the west (from the axis of the access gallery), where the arrival of the TBM will be awaited which has been running the Interstation tunnel and 60 meters of the station tunnel to the east. Inside the station tunnel, the tunnel boring machine will be dragged and then continue to build with TBM to the east approximately 1,336 meters of Interstation tunnel.

The circular shaft will be built with vertical excavation, from a curb beam of cast concrete. Once the curb has been executed, the excavation will continue with approximate depths of 2 meters, as indicated in the project drawings, dividing the plant into sections, and working alternately. Fortifying the walls of the Pit using shotcrete and welded reinforcement mesh.

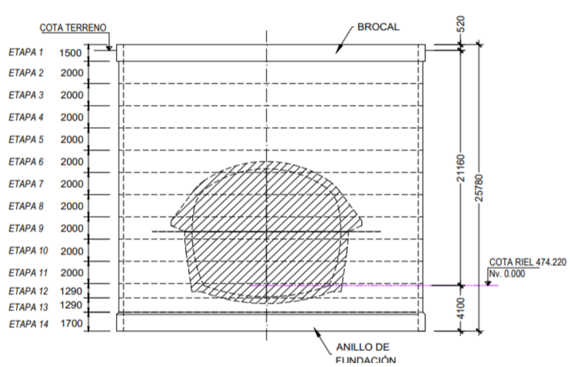


Figure 13 Circular Shaft Excavation Steps. Source: Geodata

After the completion of the excavation of the circular shaft, the excavation on the access gallery can commence using the NATM method. The access gallery must be executed in accordance with what is indicated in the construction sequence plans, considering the execution in stages of the excavation and eventual umbrellas with 6m overlap. The figure below demonstrates the excavation sequence that should be followed in the construction of the access gallery.

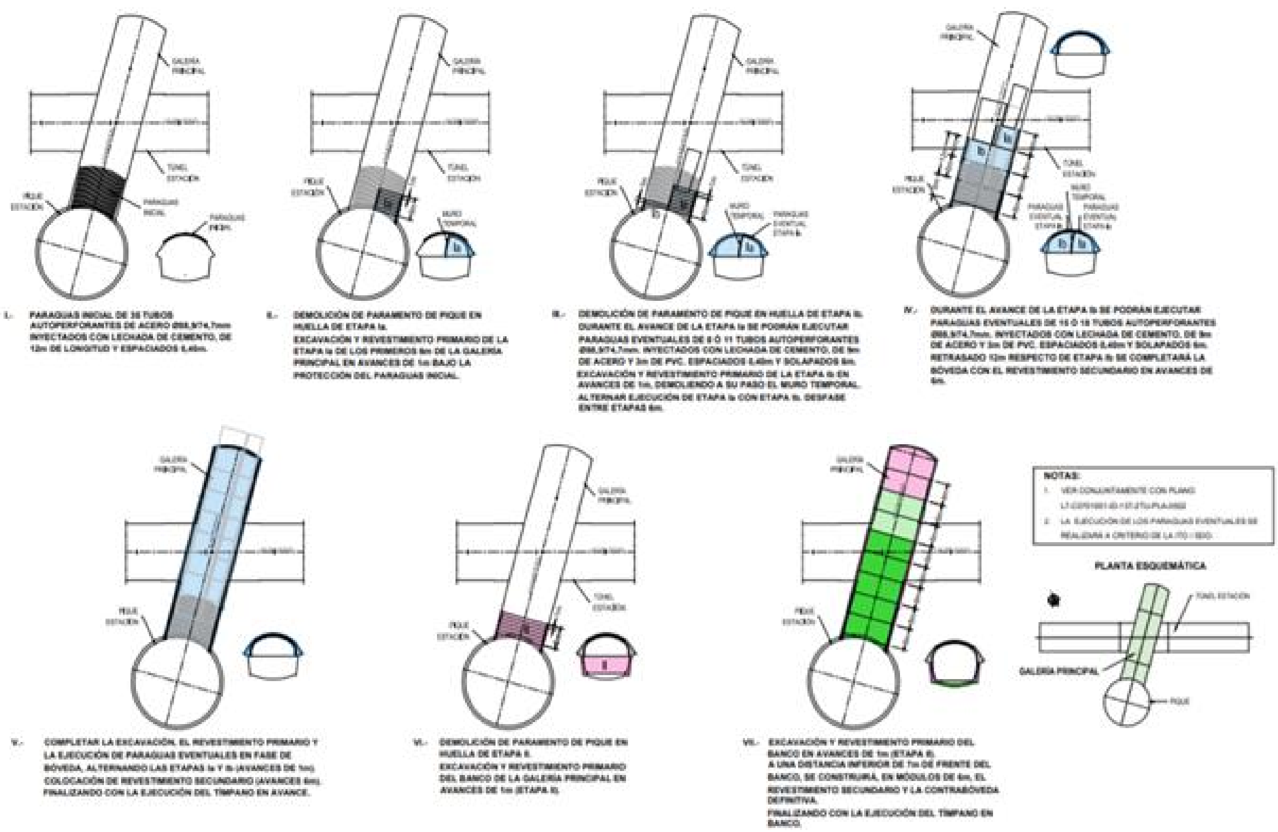


Figure 14 Access Gallery NATM Excavation Sequence. Source: Geodata

Once the access gallery is excavated, the excavation of the western side tunnel may start following the construction sequence plans and then when 24 meters are excavated the eastern side tunnel excavation begins following the same construction sequence. The figure below demonstrates the construction sequence plans for both the western and eastern side of the station tunnel.

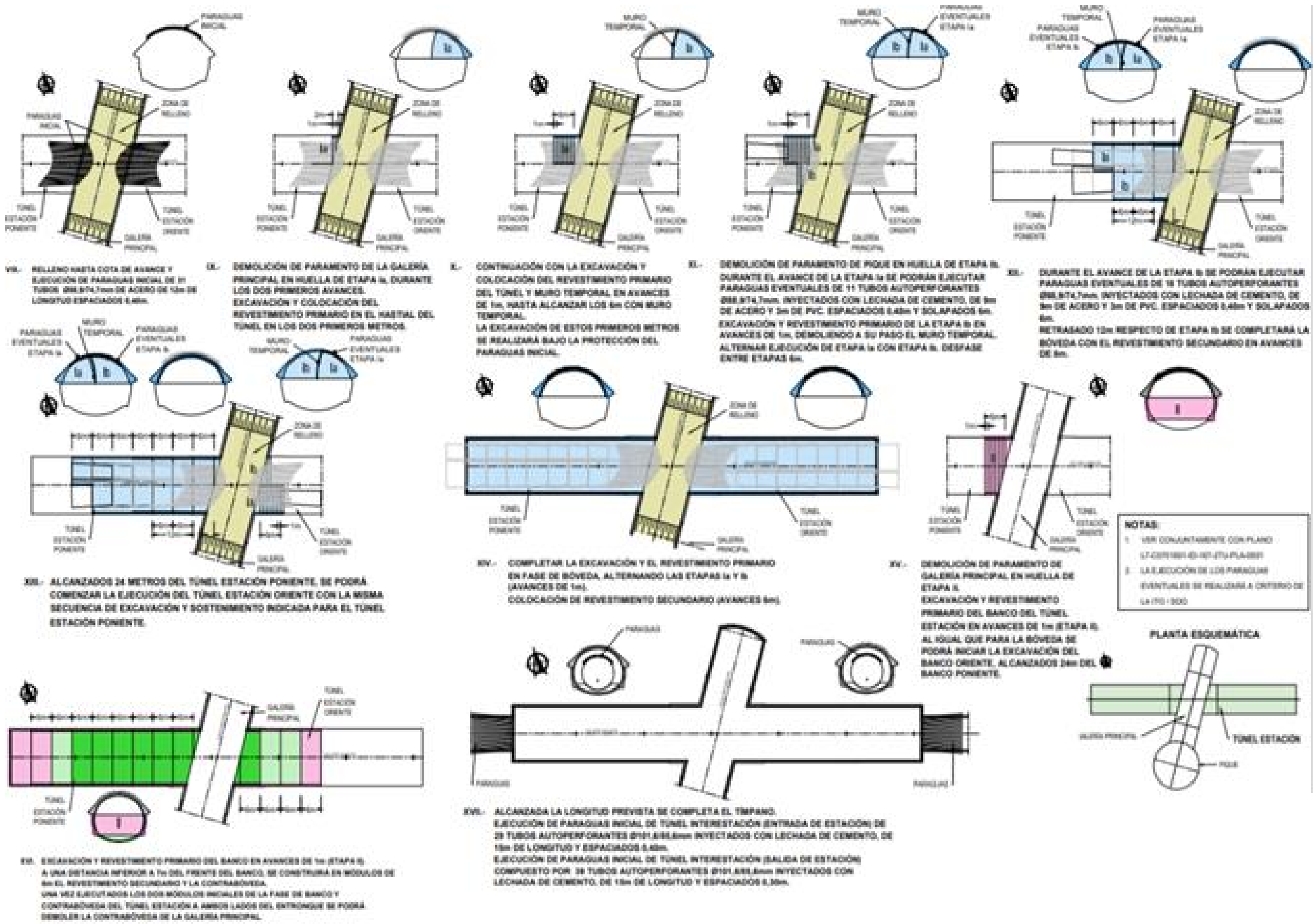


Figure 15 Station Tunnel Excavation Sequence. Source: Geodata

Inside the station tunnel, the necessary works must be carried out to drag the TBM (cradle assembly of the reaction structure) and everything required and specified in the project to proceed with the excavation with TBM in the Interstation tunnel.

Once the TBM has passed through the station tunnel, it is feasible to proceed with the execution of the civil works of the platforms and execution of the mezzanine bridge.

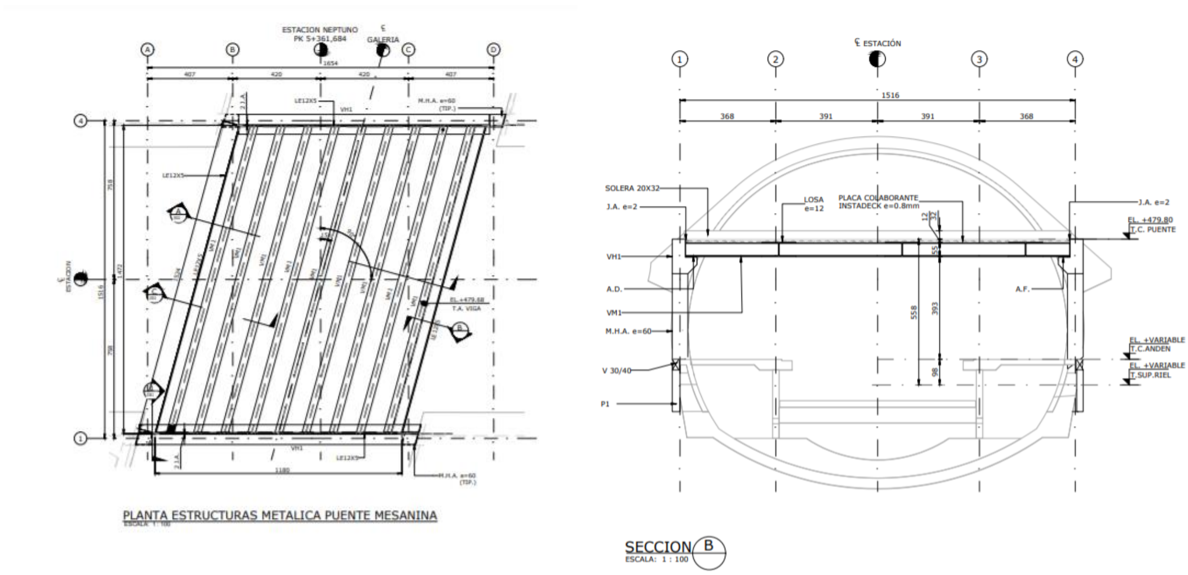


Figure 16 Mezzanine bridge. Source: Geodata

The material extraction, as a whole, must be carried out according to what is indicated in the EIA. The material will be conducted towards the Pit, from where it will be extracted towards the surface through at least two independent and simultaneous material extraction systems.

3.1.2.3 Ventilation Shafts:

Moreover, ventilation Shafts are also part of the project scope, so the construction methodology of one ventilation shaft B.10 will be tackled.

B.10 corresponds to a circular section shaft, of dimensions, depth, and gallery (ventilation lunge) specified according to the details of the project plans.

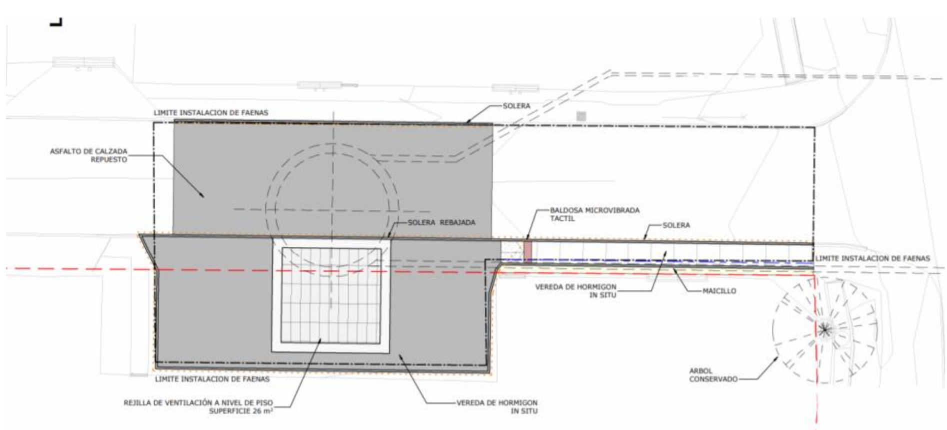


Figure 17 B.10 Plan View. Source: Geodata

This circular shaft will be built with vertical excavation, from a curb beam of cast concrete. Once the curb has been executed, the excavation will continue considering the depths and stages, working alternately, according to what is indicated in the project excavation sequence plans. The walls of the shaft will be fortified using shotcrete (sealed, 1st and 2nd layer), with electro welded mesh and reinforcement defined in the project. Reached the upper level of the ring foundation will proceed to the execution of this as indicated in the project, to continue later with the execution of the base slab.

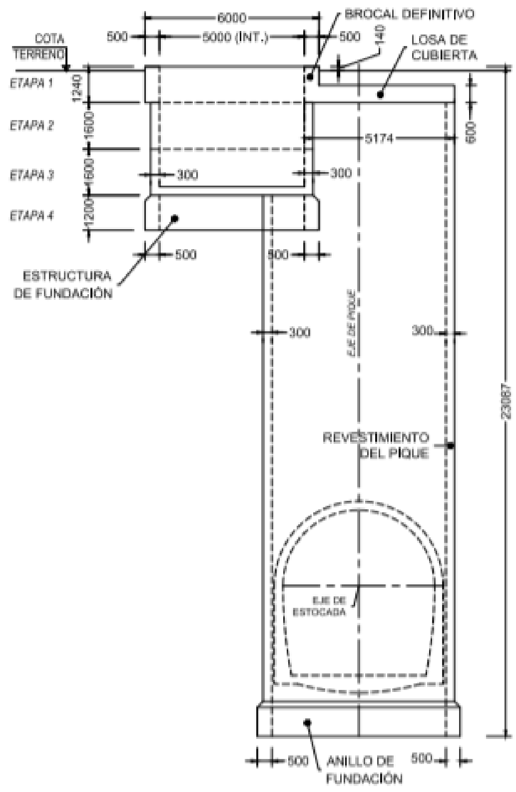


Figure 18 Circular Shaft Vertical Excavation Sequence. Source: Geodata

Subsequently, umbrellas are installed to start with the execution of the ventilation lunge. The vent lunge will be constructed using NATM, it will be excavated full section ventilation, in advances of 1m, the execution of the primary coating in offset of a forward pass with respect to the excavation. With a phase shift of 12m with respect to the primary coating, the excavation and construction of the counter vault and execution of the secondary lining in advance of 6m. The figure below demonstrates the ventilation lunge excavation sequence:

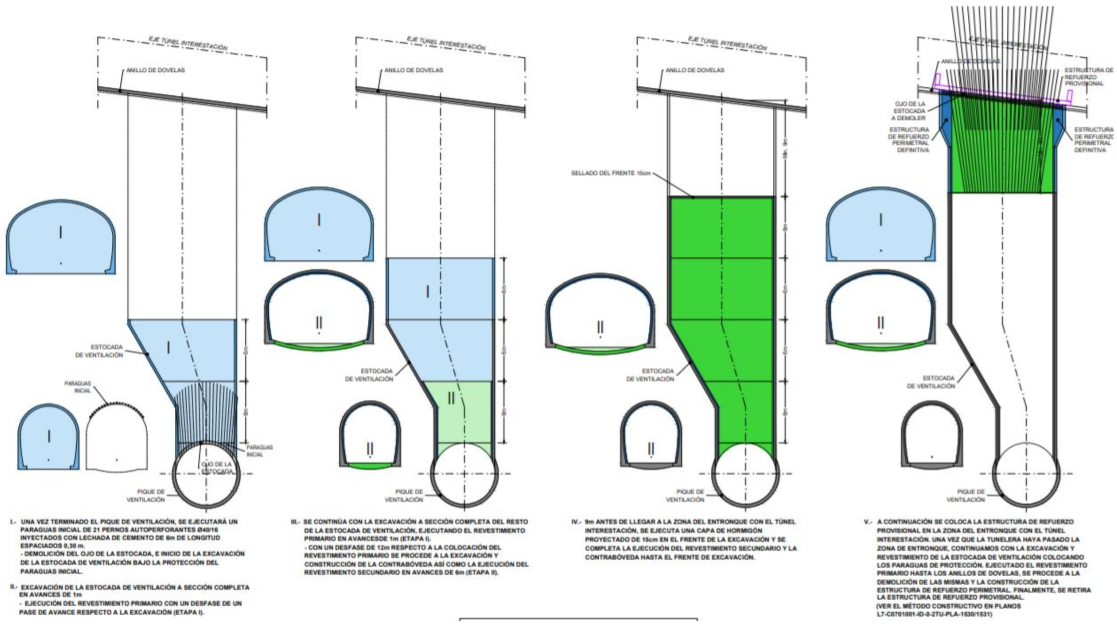


Figure 19 B.10 Ventilation Lunge Excavation Sequence. Source: Geodata

According to the project requirements, it is necessary to assemble a structure of temporary reinforcement in the area of the junction with the Interstation tunnel, before proceeding with the demolition of the lunge eye. Later, after it is excavated and the final reinforcement structure in the area is constructed the temporary reinforcement structure can be removed.

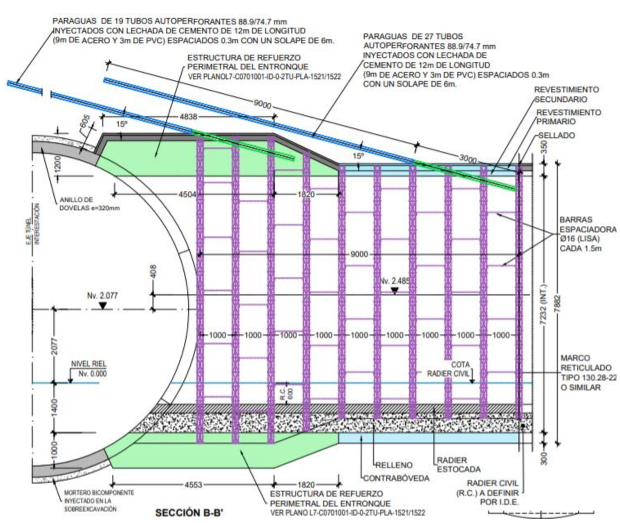


Figure 20 Ventilation Shaft intersection with interstation tunnel Design. Source: Geodata

Subsequently, the civil works of the upper structure of the shaft must be carried out as roof slab, definitive curb, excavation and placement of sealing, 1st and 2nd layer of lining, and excavating and concreting the foundation.

Regarding the material extraction, it must be carried out according to what is indicated in the EIA. The material will be directed towards the Pit, from where it will be extracted towards the surface through at least two independent and simultaneous material extraction systems (tower or mobile cranes, skip, gantries).

3.1.2.4 Tunnel Boring Machine:

The interstation tunnels will be executed by means of a TBM, starting the excavation in the south end of B.1 Station, and ending at the western end of B.8 station; with an interstation tunnel length of 6,704 m. The tunnel excavation diameter will be approximately 9.8 m. Its lining will be made up of rings of precast segments 32 cm thick and 1.7 m long, to be placed during excavation with the TBM, and the internal diameter of the tunnel finish will be 8.83 m. The gap between the excavated ground and the back of the rings, which will be around 16.5 cm, must be filled by injecting a two-component mortar.

The excavation with the tunnel boring machine is achieved by applying a force and a rotation to the cutting head that causes the tools rubbing and cutting to break the terrain of the forehead.

The EPB shield exerts pressure against the forehead, which is stabilized by the material product of the excavation to which conditioning agents are injected that are added to the excavated ground. The system for the conditioning of the excavated material will be located inside the shield and must allow the injection into the excavation chamber of foams necessary for the material to be easily transported and, eventually polymers and restructuring agents. To do this, the system for conditioning of the material will have the pipes and injection nozzles necessary. Conditioning agents must be environmentally friendly in terms of ecotoxicity and biodegradability, also all excavated material must meet the same conditions to be transferred to the final dump. The material product of the excavation is extracted from the bottom of the chamber by means of a screw conveyor; depositing it on a conveyor belt located in the trailer system to be transported outside the tunnel.

3.3 Contract Documents

To have a good background about the project, the project contract documents in addition to the presentations prepared by Geodata were reviewed.

One of the essential contract documents is under the title "Detail Engineering of Shafts, Stations and Tunnels/Technical Tender Section 1". This document started with an introduction and an overview of the works that will be part of the scope of the tender. These works covered all shafts, stations and tunnels excavated with both mechanized and conventional methods. Moreover, the general scope of the project was addressed including contractor's responsibilities and rights towards different aspects such as, but not limited to:

- Modifications to services
- Relationship with other contractors
- Soil background
- Environmental impact assessment

In addition to that, the core of the document clearly stated the works to be executed by the contractor including:

- Underground Works
- Indoor Civil Works, Surface Works, and Terminations
- Road and Sidewalk Replenishment Works
- Traffic Diversion Works
- Signage Works
- Electrical Works
- Interface management

Later, the technical construction methodology of all parts of the project was provided in detail. Therefore, this document was very important to understand all the project aspects in depth and clearly comprehend the contractor's responsibilities that should be part of his bid.

Another way to understand the construction methodology of all shafts, stations and tunnels was to go over all the binders provided by the client/consultant. The binders are detailed 2D drawings that cover the structural and architectural base design of different sections, with the construction sequence. Binders are also used to prepare the project 3D BIM model.

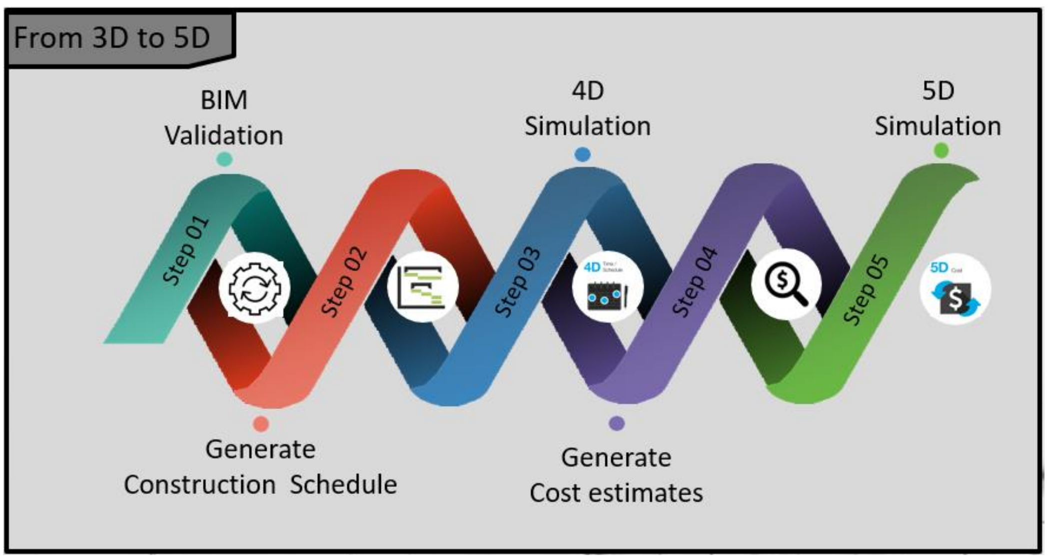
Moving on, the bill of quantities "BOQ" is one of the contract documents provided by the client which is crucial for the contractor tender. The bill of quantities provides project specific measured quantities of the items of work identified by the drawings and specifications in the tender documentation.

4. Workflow Methodology

Throughout the thesis the broad goal was to achieve a 4D/5D model of Metro Santiago project. A methodology was followed during the entire process in order to achieve the global objective. This methodology was divided into five different steps that are listed below:

1. BIM Validation
2. Construction Schedule Generation
3. 4D simulation preparation
4. Cost estimation
5. 5D simulation preparation

The workflow during this report is summarized based on the steps as shown in the chart below.



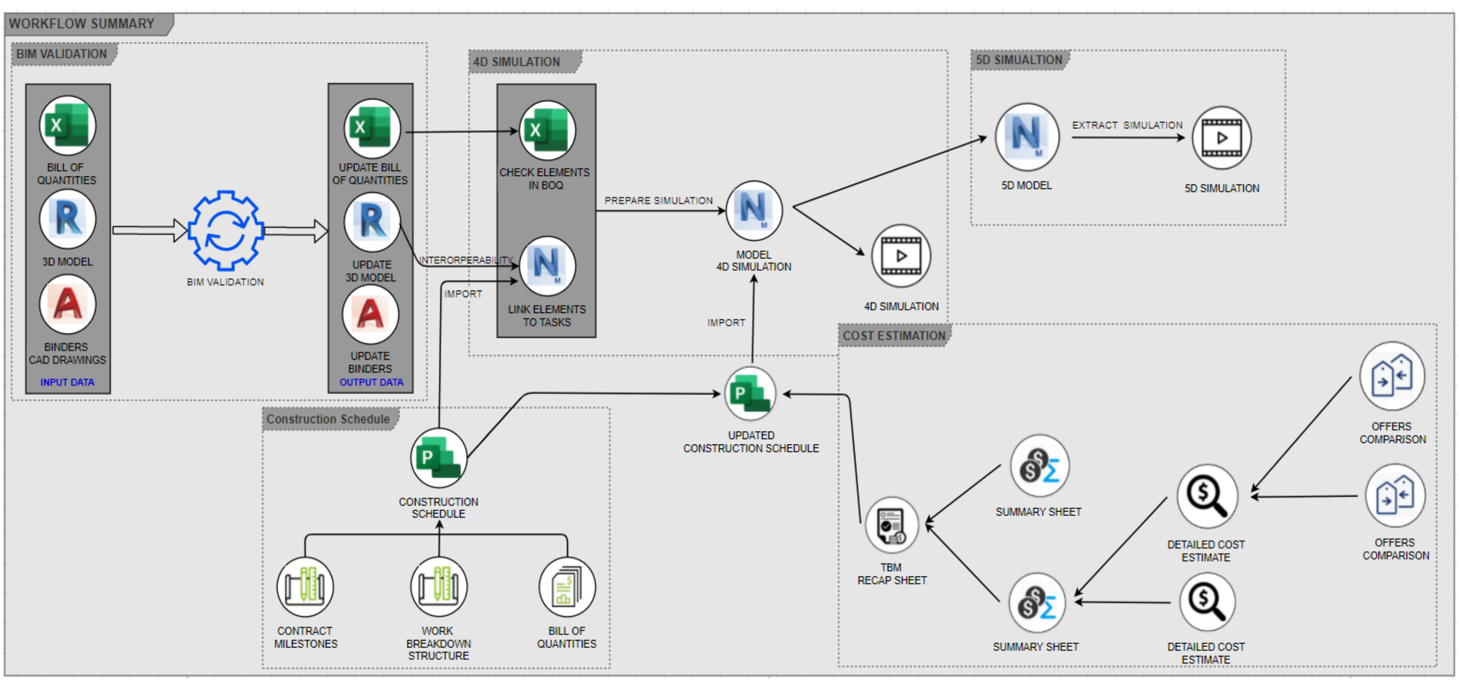
First, 3D models of different sections in the project were prepared by Geodata's BIM department based on the 2D CAD drawings and bidding documents. However, before being able to move those models in 4D "time", they had to be validated. The validation process is mainly a tool to confirm the consistency between the prepared 3D models, 2D files and the bill of quantities. Once all the inconsistencies in the model are sorted out then the model is considered reliable and can be used in further stages of the project.

Second, when models are validated quantity take offs could be extracted to be used in the preparation of the Construction Schedule. Scheduling was done while respecting the main project milestones specified by the client and using as a base the work breakdown structure which was part of the bidding document. The work breakdown structure was further elaborated to go more in detail in the project scheduling.

Later, using both the validated 3D BIM models and the construction schedule it was possible to add time into the model, hence have a simulation of the construction process vs. time. The real-time graphical simulation of construction progress against time is what is known as the 4D Model.

Moving on, the cost had to be added to the model thus based on the available resources and offers comparison. The price of different activities in the construction schedule was subdivided between labor, equipment, material, and subcontractors.

Last but not least, using the 4D model and the cost estimates, cost was added to the simulation hence the cash flow variation during the construction process was reported as time progresses. The instant generation of cost budgets and genetic financial representations of the model against time is what is known as the 5D Model. The flow chart below summarizes the work methodology during this thesis starting from the 3D BIM models and moving toward a 5D Model of the metro project.



The main software used to during the project are:

- Autodesk Revit 2020
- Autodesk AutoCAD 2020
- Autodesk Navisworks 2020
- Microsoft Office 365: Excel, Word
- Microsoft Project
- Film Forth

The Level of Development of the BIM model used was enough to be considered as reliable in this stage of the project. Based on the American Institute of Architects level of development specifications, the models used were with an LOD 350 and LOD 400.

Elements in LOD 350 are usually developed in Construction Document stage. The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation. and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.

Therefore, the models prepared by geodata's BIM department were considered reliable with an LOD 350. However, in order to add the time and cost into the model and hence move it into 4D/5D the LOD of the model was moved to LOD 400.

LOD 400 is similar to LOD 350 but the only difference is that the element fabrication, assembly, and installation information are added into the model.

5. BIM Validation

As soon as enough information about the metro project was collected, the "BIM Validation" process started.

5.1 Definition

To guarantee reliable results, an initial pre-check should be carried out, the so-called BIM Validation. This way, any possible flaw is highlighted in advance and can be sorted out. Therefore, using BIM validation we will be able to control the model quality and thus confirm its agreement with the early call for tender requirements. Based on the publication of the Italian ministry of economy and finance (Agenzia Entrate, n.d.), the validation of the model must be a combined effort between both the designer and the client, thus reducing the number of project modifications required during the work execution and increasing the process transparency. "Model Checking leads to an automated validation of 40-60% of the design, by following specific checks rather than sample checks. Checking the informative context of the model is required in many phases, the so-called checkpoints." (Agenzia Entrate, n.d.). Hence, it is important to assign enough time for BIM validation and modification creation in addition to considering it as a standard routine in the construction process due to its reimbursements.

In a BIM validation phase, a check of the model informative content is done before moving to more advanced analyses, thus ensuring reliable results in the following phases. During this phase, a quality assurance process is followed to make sure that the model elements contain the correct information such as name, classification, and alphanumeric attributes that will be used later in the process. After the validation is done and necessary modifications are applied, accuracy and reliability of the documents coming from the Building Information Model are assured. Usually, BIM validation is applied to single discipline models first, separate station or shaft model in our case, and later to the merged model, containing several shafts and stations.

Based on the publication of the Italian ministry of economy and finance (Agenzia Entrate, n.d.), after a BIM validation two types of error may be discovered:

- Modelling Related Error
- Design Related Error

5.2 Application in Case Study

In order to perform BIM validation in the metro project consistency between CAD drawings, client BOQ and BIM 3D Model had to be verified. The validation was applied to each single discipline model separately, which means validation was performed to 17 different models. The models where distributed between 6 shafts, 7 stations, 2 NATM tunnels and a TBM tunnel.

During the BIM validation different information regarding each element were checked. The information checked were element name, element mark, cost mark, and quantity take off comparison with that of the BOQ.

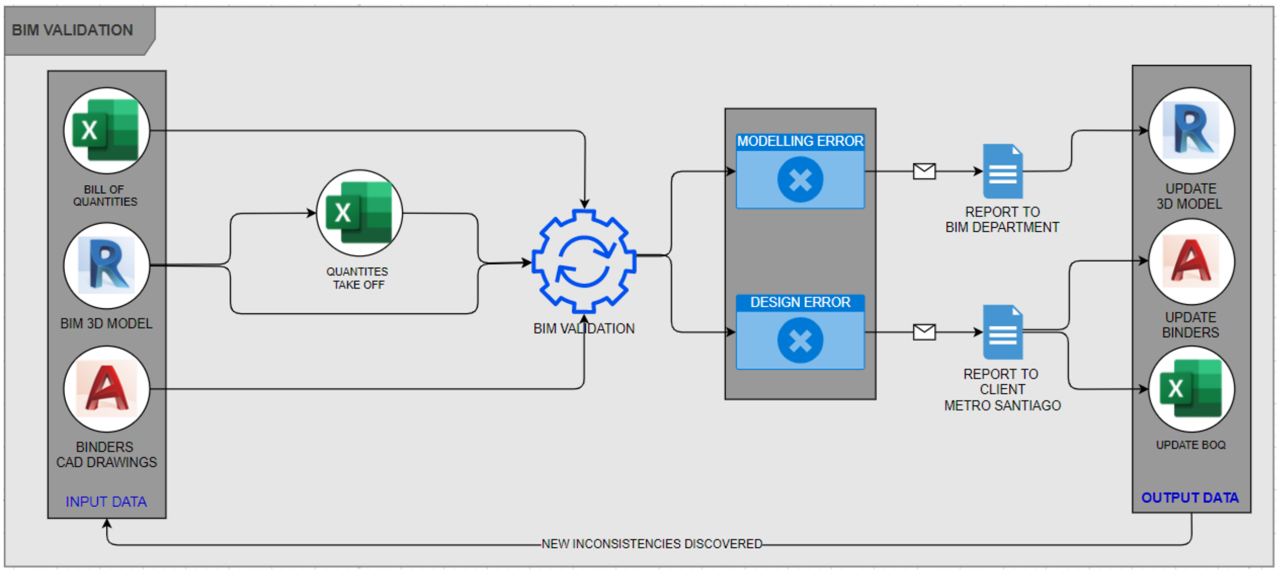
The first step of the BIM validation process was to prepare the necessary documents. First using the Revit 3D model, prepared by Geodata's BIM department, a quantity takeoff document was extracted which contains all necessary information. Then using the bill of quantities provided by the client "Metro Santiago" the data related to the model under verification was also extracted. Hence the available data to be compared now are Revit quantity take off, bill of quantity data, the model binders "2D CAD files" and the Revit 3D model. Comparing these input data several inconsistencies were discovered. The causes of the inconsistencies were either due to an error in modelling or due to a design error.

On the one hand, to solve model errors, a document was prepared containing all different errors in the model being verified. This document was discussed in a meeting with Geodata's BIM department, and to be more specific the engineer who prepared the model. After the meeting, the model was updated by the engineer and hence ready to move to the next stage.

On the other hand, regarding design errors, such errors had to be reported to the client to be corrected or clarified. Hence, the mean of communication between Geodata and the client was through a document sent every two weeks. Therefore, to resolve such design errors I was given the possibility to report them in the client communication document.

Finally, at the end of the BIM validation all flows in the model are sorted out and we are able to ensure reliable results in the coming stages.

To make it clearer a workflow chart of the BIM validation process discussed before will be stated below:



The software used are:

- Autodesk Revit 2020
- Autodesk AutoCAD 2020
- Microsoft Office 365: Excel, Word

Some examples of errors found in different models, after the BIM validation, are presented in the coming paragraph.

5.2.1 Modeling Errors Examples

One of the modeling related errors, found in B.1 station model, was related to the shaft projected concrete screen wall. The binders of this station showed that areas in the screen wall, where the TBM and NATM tunnels will start excavation, should be part of the concrete wall and would be demolished at a later stage of the project. However, in the model those areas where not considered to be part of the concrete screen wall so there was an inconsistency between the concrete quantities in the BOQ and that in the Revit file quantity take off. This error was solved by adding those areas to the concrete wall as shown in the figures below.

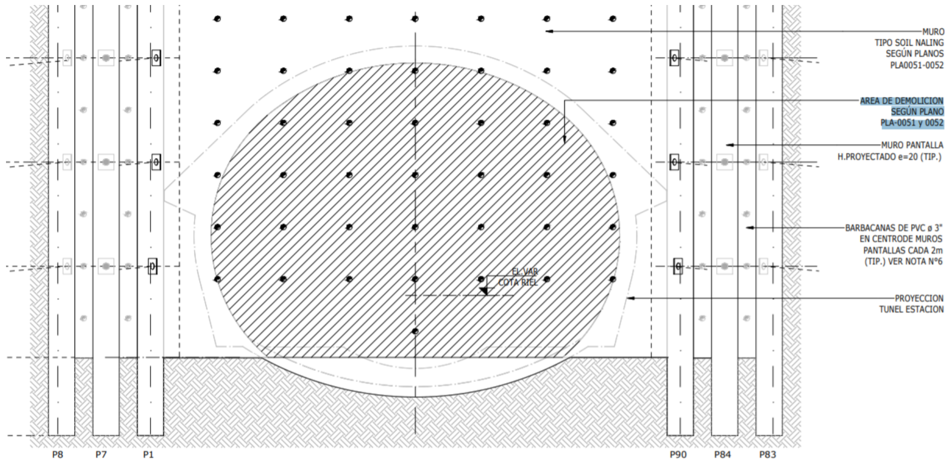


Figure 21 Binder data, NATM Demolition Area. Source: Geodata

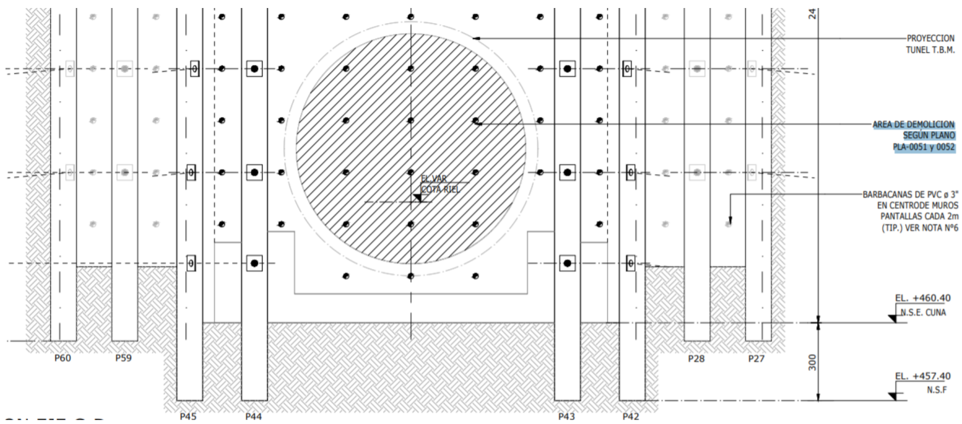


Figure 22 Binder data, TBM Demolition Area Source: Geodata

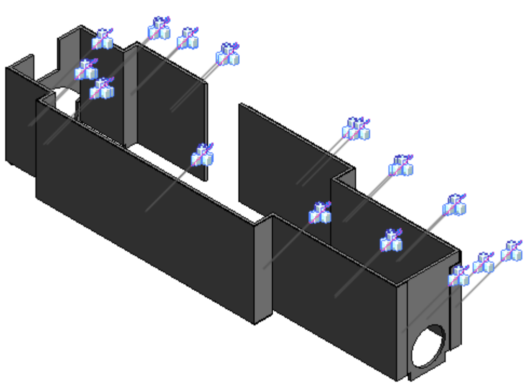
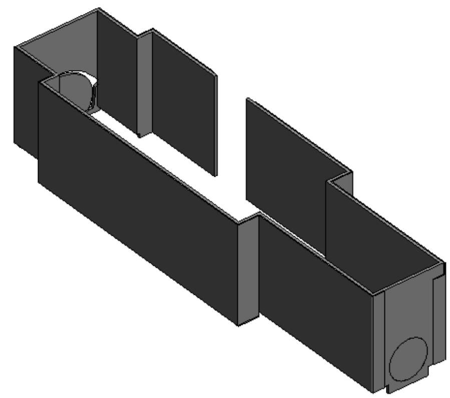


Figure 23 B.1 Station Model Before Update



B.1 Station Model After Update

Another example of modeling error is an error found in B.6 station Model. The volume to be excavated from the main gallery to the temporary wall was not completely highlighted therefore there was a difference between the volume to be excavated in the BOQ and that of the Revit model quantity take off. Below is the image of the volume to be excavated in the model before and after the update:

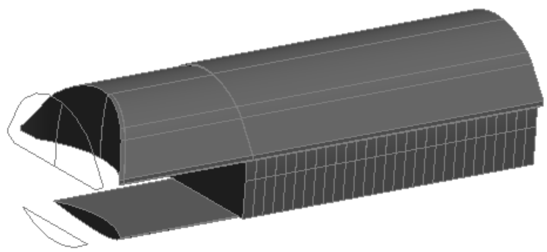
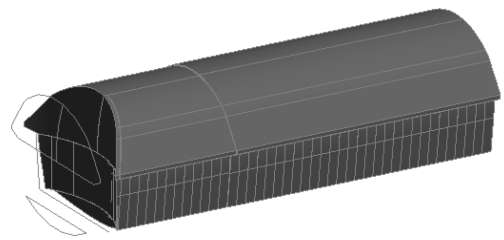


Figure 24 B.6 Station Model Before Update



B.6 Station Model After Update

Moreover, a modelling error found in B.10 was in assigning opposite marks for to different elements in the model. As part of the surface works to be done in B.10 Shaft are asphalt pavement and concrete sidewalks. During the modeling process the alphanumeric marks of these two elements were flipped which led to an inconsistency with the BOQ data. The figures below show the mark assigned to the asphalt pavement before and after the model update.

Table 2 BOQ Surface Works Marks

2849	B.10.4.2	Superficies	Surfaces
2850	B.10.4.2.1	Asfalto calzada	Asphalt driveway
2851	B.10.4.2.2	Baldosa microvibrada táctil	Microvibrated tactile tile
2852	B.10.4.2.3	Maicillo	Maicillo
2853	B.10.4.2.4	Veredas de Hormigón In Situ	In Situ Concrete Sidewalks

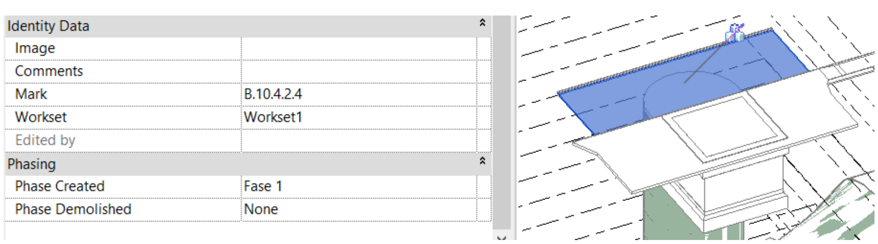


Figure 25 B.10 Shaft Model Before Update

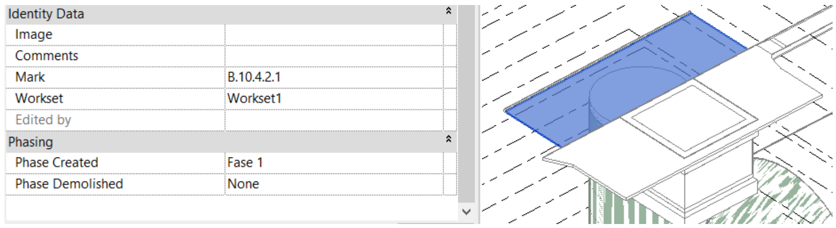
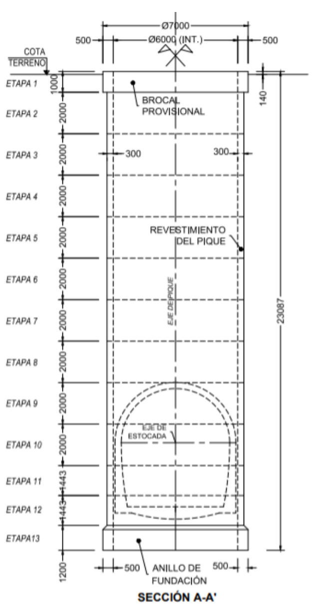


Figure 26 B.10 Shaft Model After Update

5.2.2 Design Errors Examples

Moving on to Design related errors, one was found in B.10 shaft, the design of this shaft was updated by the client, but an update to the BOQ was not applied. In the first design of B.10 shaft only the shaft was considered thus only one foundation at the end of the shaft walls was needed. However, in the updated design a new excavation section was added under the curb hence two foundations were needed, one under the curb and the other under the shaft walls. The updated foundations design was not considered in the updated BOQ and hence an inconsistency was found between the 3D BIM model foundations volume and the BOQ foundations volume. This error was part of the communication report sent to the client every two weeks.

The figure below represents the two different designs of the shaft that caused the inconsistency.



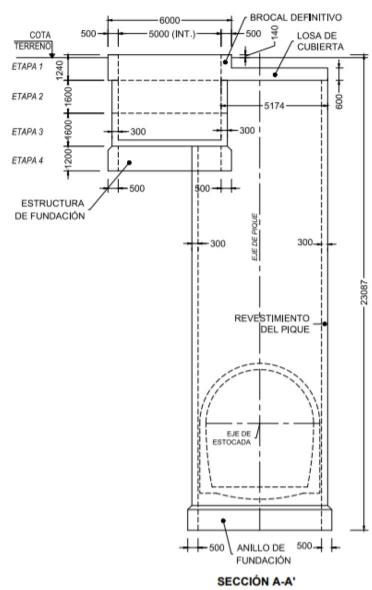


Figure 27 Client Preliminary Shaft Design Client Updated Shaft Design Source: Geodata

Another Design error was in B.6 station. In the first revision of the BOQ “R0” the construction of the entire main gallery was considered together however in the later BOQ revision “R1” the construction of the main gallery was devided into two parts. The first section from the start of the main gallery to the temporary tunnel face and the secod section was from the temporary tunnel face till the end of the main gallery. Those changes led to an error in the marks assigned to the elements in the BOQ since the modifications in the elemnts were not consistent with the modifications in the marks. The tables below show the section of the BOQ that had wrong marks and how they were reasigned correctly.

Table 3 BOQ with Error in Elements' Marks Source: Geodata

B.6.3.3.3.4	**Manguitos de conexión de enfierraduras tipo Lenton o equivalente**
B.6.3.3.3.4.1	Manguitos Fe 12, Tipo Roscado Lenton A2
B.6.3.3.3.4.2	**Muro Temporal**
B.6.3.3.4	**Hormigones**
B.6.3.3.4.1	Hormigón Proyectado G30
B.6.3.3.4.1.1	Demolición Hormigón Proyectado Temporal
B.6.3.3.4.1.2	**Malla ACMA**
B.6.3.3.4.2	Malla ACMA C-443 Acero AT 56-50H o equivalente
B.6.3.3.4.2.1	**Marcos Reticulados**
B.6.3.3.4.3	Marco Metálico Tipo 70.28-22
B.6.3.3.4.3.1	**Contrabóveda**
B.6.3.3.5	**Hormigones**
B.6.3.3.5.1	Hormigón Proyectado G30
B.6.3.3.5.1.1	**Malla ACMA**
B.6.3.3.5.2	Malla ACMA C-443 Acero AT 56-50H o equivalente
B.6.3.3.5.2.1	**Enfierradura**
B.6.3.3.5.3	Acero A 630-420 H
B.6.3.3.5.3.1	**Tímpano**
B.6.3.3.6	**Hormigones**
B.6.3.3.6.1	Sello de hormigón proyectado G30 e_{min}=5 cm
B.6.3.3.6.1.1	Hormigón Proyectado G30
B.6.3.3.6.1.2	Demolición Hormigón Proyectado Temporal
B.6.3.3.6.1.3	**Malla ACMA**
B.6.3.3.6.2	Malla ACMA C-443 Acero AT 56-50H o equivalente
B.6.3.3.6.2.1	**Enfierradura**
B.6.3.3.6.3	Acero A 630-420 H
B.6.3.3.6.3.1	**Sello temporal avance**
B.6.3.3.7	**Hormigones**
B.6.3.3.7.1	Sello de hormigón proyectado G30 e_{min}=3 cm
B.6.3.3.7.1.1	**Paraguas de protección**
B.6.3.3.8	Paraguas protector tubo Acero N80 (API 5CT) 88,9/74,7 mm, (e=7,1 mm), l=12 m (inyectado)
B.6.3.3.8.1	**Inyecciones**
B.6.3.3.8.2	Inyecciones de colmatación
B.6.3.3.8.3	Cemento en inyecciones

Table 4 BOQ with updated Elements' Marks Source: Geodata

B.6.3.3.3.4	**Manguitos de coneхión de enfierraduras tipo Le**
B.6.3.3.3.4.1	Manguitos Fe 12, Tipo Roscado Lenton A2
B.6.3.3.3.4.2	
B.6.3.3.4	**Muro Temporal**
B.6.3.3.4.1	**Hormigones**
B.6.3.3.4.1.1	Hormigón Proyectado G30
B.6.3.3.4.1.2	Demolición Hormigón Proyectado Temporal
B.6.3.3.4.2	**Malla ACMA**
B.6.3.3.4.2.1	Malla ACMA C-443 Acero AT 56-50H o equivalente
B.6.3.3.4.3	**Marcos Reticulados**
B.6.3.3.4.3.1	Marco Metálico Tipo 70.28-22
B.6.3.3.5	**Contrabóveda**
B.6.3.3.5.1	**Hormigones**
B.6.3.3.5.1.1	Hormigón Proyectado G30
B.6.3.3.5.2	**Malla ACMA**
B.6.3.3.5.2.1	Malla ACMA C-443 Acero AT 56-50H o equivalente
B.6.3.3.5.3	**Enfierradura**
B.6.3.3.5.3.1	Acero A 630-420 H
B.6.3.3.6	**Tímpano**
B.6.3.3.6.1	**Hormigones**
B.6.3.3.6.1.1	Sello de hormigón proyectado G30 e..=5 cm
B.6.3.3.6.1.2	Hormigón Proyectado G30
B.6.3.3.6.1.3	Demolición Hormigón Proyectado Temporal
B.6.3.3.6.2	**Malla ACMA**
B.6.3.3.6.2.1	Malla ACMA C-443 Acero AT 56-50H o equivalente
B.6.3.3.6.3	**Enfierradura**
B.6.3.3.6.3.1	Acero A 630-420 H
B.6.3.3.7	**Sello temporal avance**
B.6.3.3.7.1	**Hormigones**
B.6.3.3.7.1.1	Sello de hormigón proyectado G30 e..=3 cm
B.6.3.3.8	**Paraguas de protección**
B.6.3.3.8.1	Paraguas protector tubo Acero N80 (API 5CT) 88,9/74,7 mm, (e=7,1 mm), l=12 m (inyectado)
B.6.3.3.8.2	Inyecciones de colmatación
B.6.3.3.8.3	Cemento en inyecciones

Several more errors where fond during the BIM validation prrocess of all the project models. Appendix A will contain the BIM validation Excel file for each model in the project.

The BIM Validaton was an important task and was given reasonable time, since it helped eleminate a lot of errors that may lead to nonreliable and non reasonable results in the 4D and 5D simulations later on, if not resolved.

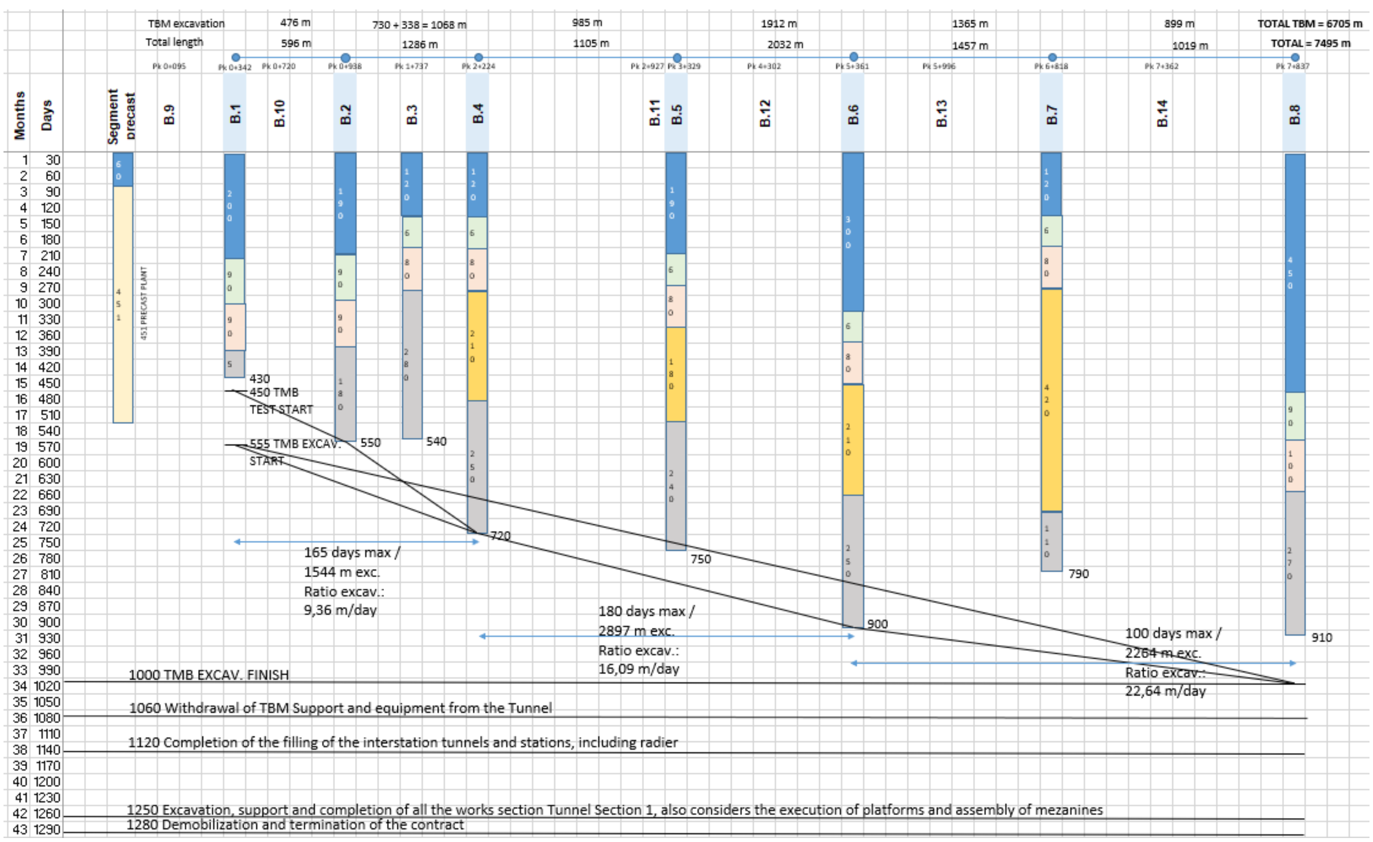
6. 4D Time

6.1 Construction Schedule

6.1.1 Methodology

Construction schedule appears to be one of the most challenging features of the project. The construction schedule of the metro project was prepared based on the contract documents provided. The main contract document for its preparation is with the title "Contract Milestones". This document provides deadlines that should be firmly respected by the contractor otherwise penalties will be applied. Such milestones include dates of the land delivery, that means the day from which the construction sites are available for work. Other milestones include TBM excavation start date, segments construction for the first 250m of the tunnel, each station major milestones, and the effective delivery day of all contracted works.

The following chart was provided by my supervisor, it illustrates the major milestones found in the contract documents of the project in addition to the TBM advance rate between different stations.



Legend	
Deliver of the lands from Metro	
Shaft start	
Shaft fihish	
Cradle finish, considers the completion of the civil works associated with the cradle, to allow the displacement of the TBM	
Main tunnel finish	

Figure 28 Project Scheduled Milestones. Source: Geodata

Following the construction milestone another document was used as a foundation for the preparation of the construction schedule with the title "WORK BREAKDOWN STRUCTURE (WBS) CONSTRUCTION PROGRAM". In this document the client assigns the minimum breakdown details that should be used in the preparation of the timeline, however additional levels of activities under each WBS were added to track the construction process more accurately.

Later, using the construction milestones, WBS program and BOQ, the duration of each activity in the project in addition to its planned start and end date were estimated by geodata's construction management department. The activities considered in the construction schedule were at a monthly level of detail. Since the goal was to prepare a timeline for the entire project, a monthly interval was sufficient.

To achieve the thesis goal and add time to the 3D BIM model, thus move it to 4D, an excel file for each of the models, after being validated, was prepared. This file contained the activities performed during the model construction, and its duration in monthly increments. This excel file was imported into Microsoft project, a software used to prepare construction schedules. In Microsoft project different activities were linked using engineering sense to create the construction Gantt Chart for each model. The sequential relationships among activities could be finish to start (FS), stat to start (SS), finish to finish (FF), and start to finish (SF) with an appropriate lag.

Finally, the construction schedules and Gantt charts of all models in the project were prepared in the same procedure elaborated in the previous paragraph.

6.1.2 B.1 Station Schedule Example

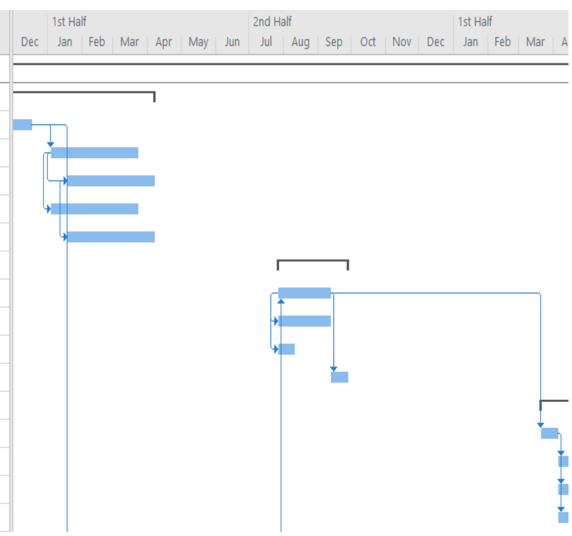
A section of the excel import file and the construction timeline for B.1 station will be reported below:

Table 5 B.1 Station Excel import File to Microsoft Project

Item code	WBS	ACTIVITY ID	Duration
B.1	A.1	**PIQUE STATION**	
B.1.1	A.1.1	**Pique Rectangular Cenital**	
B.1.1.1	A.1.1.1	Piles and Piles	3
B.1.1.2	A.1.1.2	Earth movements	2.5
B.1.1.3	A.1.1.3	Concrete	2.5
B.1.1.4	A.1.1.4	Soil Nailing	2.5
B.1.1.5	A.1.1.5	Wire Mesh	2.5
B.1.2	A.1.2	**Cuna and Radier Estación (Pique and Tunnel)**	
B.1.2.1	A.1.2.1	Concretes	1.5
B.1.2.2	A.1.2.2	Enclosure	1.5
B.1.2.3	A.1.2.3	Metal Structure	0.5
B.1.2.4	A.1.2.4	Demolition of Concrete Structures	0.5
B.1.3	A.1.3	**Andenes Pique Rectangular and Tunnel Station**	
B.1.3.1	A.1.3.1	Concretes	0.5
B.1.3.2	A.1.3.2	Enclosure (Vigas-Pilares-Muro Aajo andén-Losa)	1.5
B.1.3.3	A.1.3.3	Stamps and Gaskets	
B.1.3.5	A.1.3.5	Galvanized ducts	
		Tunnel	
B.1.4	A.1.4	**Maneuver Queue Tunnel (INDICATE PK TO PK)**	
		Vault	
B.1.4.1	A.1.4.1	Land Movement	6
B.1.4.2	A.1.4.2	Primary Coating	6
B.1.4.3	A.1.4.3	Secondary Coating	6
B.1.4.3.2	A.1.4.3.2	Wire Mesh	6
B.1.4.3.3	A.1.4.3.3	Enclosure	6
B.1.4.4	A.1.4.4	**Contravault**	6

Table 6 B.1 Station Construction Schedule in Microsoft Project

Task Mode	WBS	Task Name	Duration	Start	Finish	Text1
	A.1	**PIQUE STATION**	**20 mons**	**September 15, 202**	**June 6, 2023**	**B.1**
	A.1.1	**Pique Rectangular Cenital**	**6.5 mons**	**September 15, 202**	**April 7, 2022**	**B.1.1**
	A.1.1.1	Piles and Piles	3 mons	September 15, 2021	December 17, 2021	B.1.1.1
	A.1.1.2	Earth movements	2.5 mons	January 3, 2022	March 22, 2022	B.1.1.2
	A.1.1.3	Concrete	2.5 mons	January 19, 2022	April 7, 2022	B.1.1.3
	A.1.1.4	Soil Nailing	2.5 mons	January 3, 2022	March 22, 2022	B.1.1.4
	A.1.1.5	Wire Mesh	2.5 mons	January 19, 2022	April 7, 2022	B.1.1.5
	A.1.2	**Cuna and Radier Estación Brasil (Pique and Tunnel)**	**2 mons**	**July 27, 2022**	**September 27, 2022**	**B.1.2**
	A.1.2.1	Concretes	1.5 mons	July 27, 2022	September 12, 2022	B.1.2.1
	A.1.2.2	Enclosure	1.5 mons	July 27, 2022	September 12, 2022	B.1.2.2
	A.1.2.3	Metal Structure	0.5 mons	July 27, 2022	August 11, 2022	B.1.2.3
	A.1.2.4	Demolition of Concrete Structures	0.5 mons	September 12, 2022	September 27, 2022	B.1.2.4
	A.1.3	**Andenes Pique Rectangular and Tunnel Station**	**2 mons**	**March 20, 2023**	**May 22, 2023**	**B.1.3**
	A.1.3.1	Concretes	0.5 mons	March 20, 2023	April 4, 2023	B.1.3.1
	A.1.3.2	Enclosure (Vigas-Pilares-Muro Aajo andén-Losa)	1.5 mons	April 5, 2023	May 22, 2023	B.1.3.2
	A.1.3.3	Stamps and Gaskets	1.5 mons	April 5, 2023	May 22, 2023	B.1.3.3
	A.1.3.5	Galvanized ducts	1.5 mons	April 5, 2023	May 22, 2023	B.1.3.5



The construction Schedule for the remaining stations and shafts will be reported in appendix B of the Thesis.

Therefore, the preparation of the construction schedule is a challenging task that requires a lot of experience in the field of underground construction. Especially due to the fact that, mechanized tunneling “EPB machine” will be used for the excavation of the metro and it is on the critical path of the schedule. A more detailed explanation on the process of estimating the advance rate of a single shielded EPB machine will be reported later in this document.

It is important to note that the construction management department shared with me at a later stage of the thesis the final revision of the construction schedule in Microsoft project. This file contained the schedule of the entire project and was used to prepare the 4D/5D simulation at the project level.

6.2 4D Simulation

Now that the Revit models of the shafts and stations have passed the BIM Validation step and their construction schedule is ready in Microsoft project, it was possible to add the time to the models. Therefore, at this point in the thesis the goal was to move the models from BIM 3D to 4D.

6.2.1 Importance

BIM 4D is a very powerful design tool for schedule visualization. Hence using proper planning and scheduling is an effective way to reduce the risk of the project delay. (Shah et al., 2008) found from a survey that 29% of projects were delayed due to poor planning and scheduling. "4D models help in detecting defects in schedules in terms of inconsistencies and impossible activity sequences. This integration also helps anticipating potential time-space conflicts and accessibility problems, thus facilitating interface management, especially in complex projects. In addition, Griffis and Sturts (2003) reported that using 4D models resulted in an average of 5% savings in cost growth, 4% savings in schedule growth and 65% reduction in rework." (S. M. Ahmed, H. H. Eman And P. Farrell, 2014)

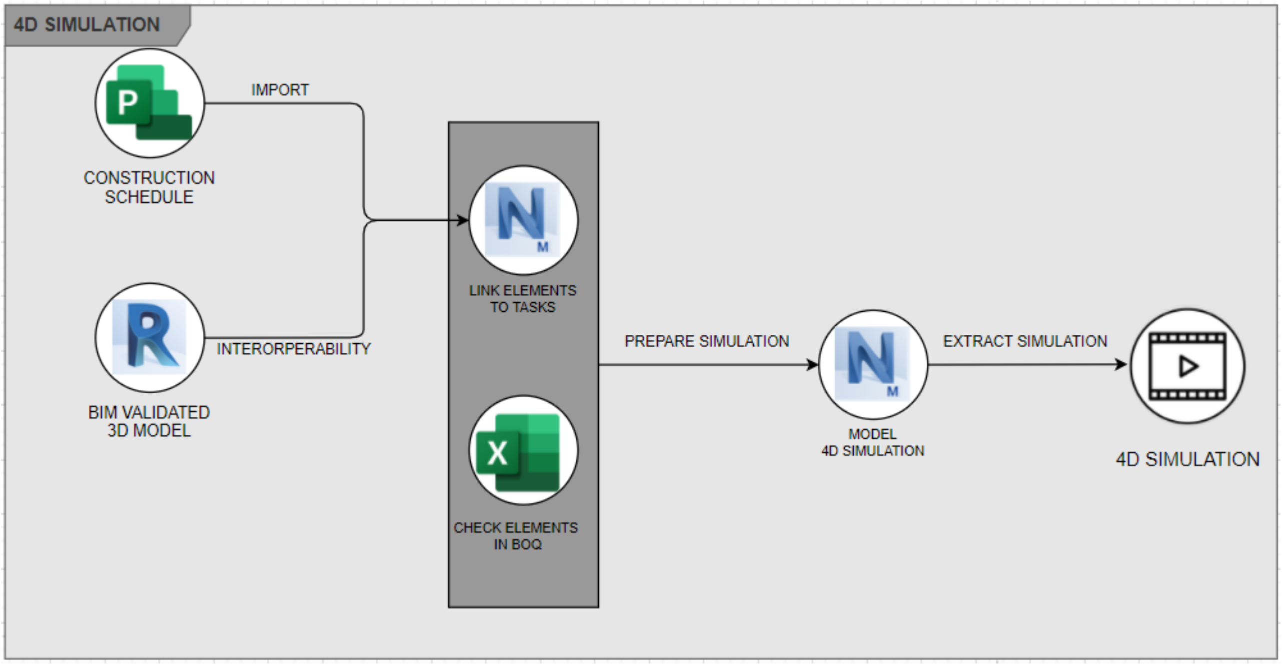
6.2.2 Application in Case Study

To integrate project timeline into the 3D model an Autodesk software was used "Naviswork 2020". This process was applied to each model separately "6 shafts, 7 stations, 2 NATM tunnels and a TBM tunnel" and later all models were appended into one single model which became the 4D simulation of the entire metro project.

As a first step the validated Revit 3D model was moved into Naviswork software using BIM interoperability. Then the prepared construction timeline was imported from the Microsoft project file into the Naviswork model. At this stage, a link between all elements in the model and the activities in the timeline had to be created in order to simulate the construction process.

Each activity in the timeline was linked to its corresponding elements in the model by creating elements sets in Naviswork. To do so the Naviswork file and the BOQ were used in parallel to assure that all the elements in the BOQ are accounted for in the simulation and thus considered in terms of time and cost.

A flow chart of the work done to add the time schedule into the Revit 3D model and thus move it into a 4D model will be reported below:



6.2.2.1 B.1 Station Example and Output

An example of the link between one activity in the B.1 station construction timeline and its corresponding elements in the model will be given. For instance, let us consider an activity with the title "Projected Concrete Screen wall" and WBS "A.1.1.3.1". The type of the activity could be Construct, Temporary or Demolish. In this case Concrete type is Construct and this data is entered into the Naviswork timeline. Moreover, for this activity to be performed it requires two elements in the BOQ which are "Projected Concrete Screen Wall G25", and "Sprayed Concrete Grade G25 (Soil Nailing)" with item marks "B.1.1.3.1" and "B.1.1.3.2" respectively. So, a set is created in Naviswork containing those two elements, as shown in the figure below, and this set is linked to the correct activity automatically based on its WBS code. The same procedure is repeated to all the activities in the timeline and hence a 4D construction simulation can be performed.

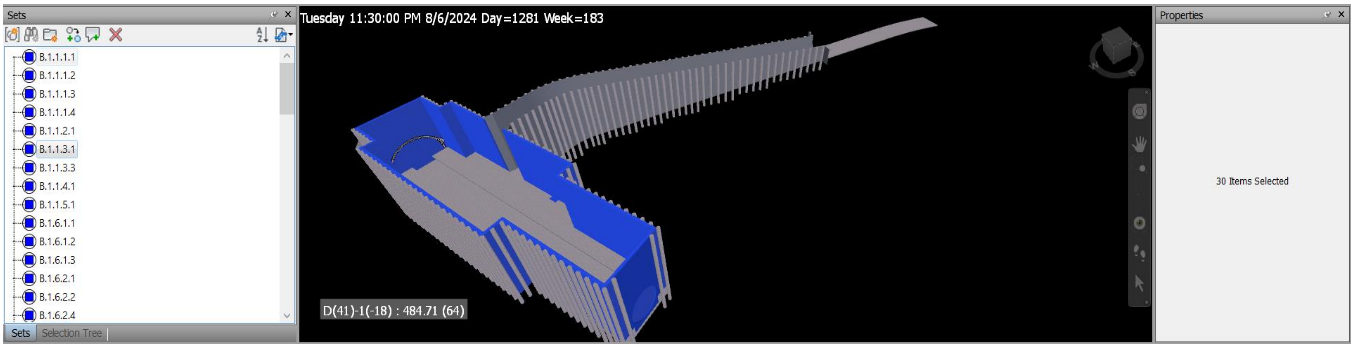
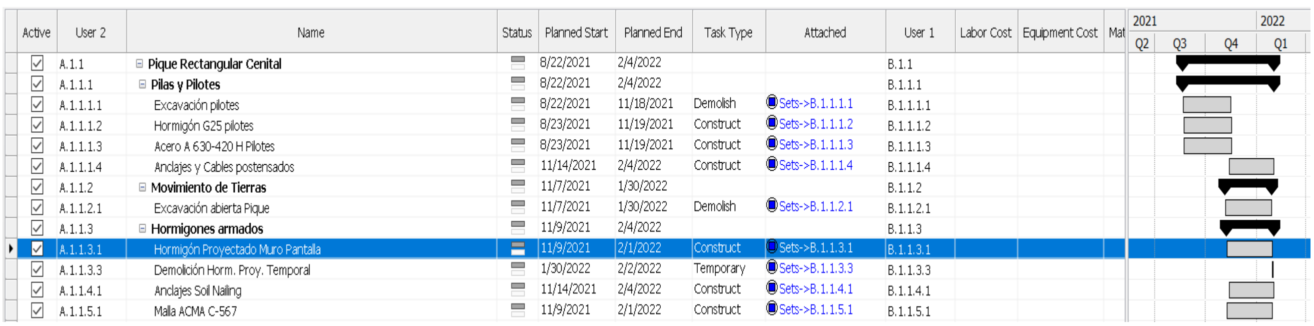


Figure 29 The Set of elements attached to activity A.1.1.3.1

The figures below show some activities in B.1 station timeline and their corresponding sets and elements in the BOQ. The marks of the elements in the BOQ are given different colors to show how the elements are grouped in sets and thus make sure that no elements are left out, not assigned to any activity.



Active	User 2	Name	Status	Planned Start	Planned End	Task Type	Attached	User 1	Labor Cost	Equipment Cost	Mat
☑	A.1.1	Pique Rectangular Cenital		8/22/2021	2/4/2022			B.1.1			
☑	A.1.1.1	Pilas y Pilotes		8/22/2021	2/4/2022			B.1.1.1			
☑	A.1.1.1.1	Excavación pilotes		8/22/2021	11/18/2021	Demolish	Sets->B.1.1.1.1	B.1.1.1.1			
☑	A.1.1.1.2	Hormigón G25 pilotes		8/23/2021	11/19/2021	Construct	Sets->B.1.1.1.2	B.1.1.1.2			
☑	A.1.1.1.3	Acero A 630-420 H Pilotes		8/23/2021	11/19/2021	Construct	Sets->B.1.1.1.3	B.1.1.1.3			
☑	A.1.1.1.4	Anclajes y Cables postensados		11/14/2021	2/4/2022	Construct	Sets->B.1.1.1.4	B.1.1.1.4			
☑	A.1.1.2	Movimiento de Tierras		11/7/2021	1/30/2022			B.1.1.2			
☑	A.1.1.2.1	Excavación abierta Pique		11/7/2021	1/30/2022	Demolish	Sets->B.1.1.2.1	B.1.1.2.1			
☑	A.1.1.3	Hormigones armados		11/9/2021	2/4/2022			B.1.1.3			
☑	A.1.1.3.1	Hormigón Proyectado Muro Pantalla		11/9/2021	2/1/2022	Construct	Sets->B.1.1.3.1	B.1.1.3.1			
☑	A.1.1.3.3	Demolición Horm. Proy. Temporal		1/30/2022	2/2/2022	Temporary	Sets->B.1.1.3.3	B.1.1.3.3			
☑	A.1.1.4.1	Anclajes Soil Nailing		11/14/2021	2/4/2022	Construct	Sets->B.1.1.4.1	B.1.1.4.1			
☑	A.1.1.5.1	Malla ACMA C-567		11/9/2021	2/1/2022	Construct	Sets->B.1.1.5.1	B.1.1.5.1			

Figure 30 Section of B.1 Station Task Timeline in Naviswork

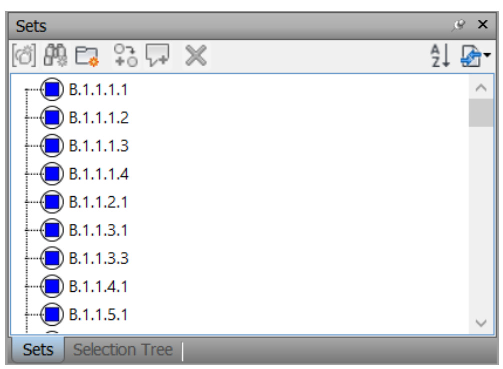


Figure 31 Few Sets of B.1 Station

B.1.1	**Pique Rectangular Cenital**	**cut and cover box**			
B.1.1.1	**Pilotes**	**Piles**			
B.1.1.1.1	Excavación pilotes	excavation piles	5.2.3.5	m3	1,864.00
B.1.1.1.2	Hormigón G25 pilotes	G25 concrete piles	5.2.4.9	m3	1,864.00
B.1.1.1.3	Armadura A630-420H pilotes	Reinforcment bars A630-420H piles	5.2.5.6	kg	352,190.00
B.1.1.1.4	Anclajes y Cables postensados (se incluye destensado)	Post-tensioned Anchors and Cables (tensioned included)	5.2.6.6	un	480.00
B.1.1.2	**Movimiento de Tierras**	**Earth movements**			
B.1.1.2.1	Excavación abierta Pique	Open Excavation Pit	5.2.3.1	m3	52,924.40
B.1.1.3	**Hormigones**	**Concrete**			
B.1.1.3.1	Hormigón Proyectado Muro Pantalla G25 e_{min}=20cm	Projected Concrete Screen Wall G25 emín = 20cm	5.2.4.4	m3	5,230.00
B.1.1.3.2	Hormigón Proyectado Grado G25 (Soil Nailing)	Sprayed Concrete Grade G25 (Soil Nailing)	5.2.4.4	m3	87.80
B.1.1.3.3	Demolición Hormigón Proyectado Temporal	Temporary Shotcrete Demolition	5.2.4.5	m3	78.90
B.1.1.4	**Anclajes Soil Nailing**	**Soil Nailing Anchors**			
B.1.1.4.1	Anclajes Soil Nailing	Soil Nailing Anchors	5.2.6.4	un	162.00
B.1.1.5	**Malla ACMA**	**wire mesh**			
B.1.1.5.1	Malla ACMA C-567 Acero AT 56-50H o equivalente	wire mesh C-567 Steel AT 56-50H or equivalent	5.2.5.2	m2	10,461.00

Figure 32 Section of B.1 station BOQ used to create sets.

After applying the above procedure to all the tasks in the construction schedule of B.1 station a 4D simulation of the construction phases of the station was created.

Below are figures from the simulation as time passes from the start till the end of the construction process. To keep track of the time at different stages in the simulation, the data at the upper left corner of the simulation show the month and the year at which the work is being done. Moreover, elements marked in green are elements being constructed, elements marked in red are being demolished, and elements marked in yellow are temporary elements.

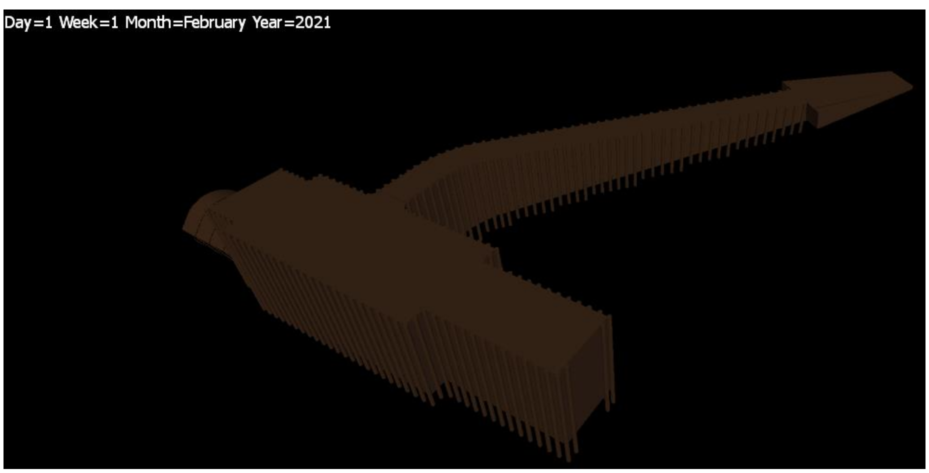


Figure 33 B.1 station at Week 0 (Feb. 2021)

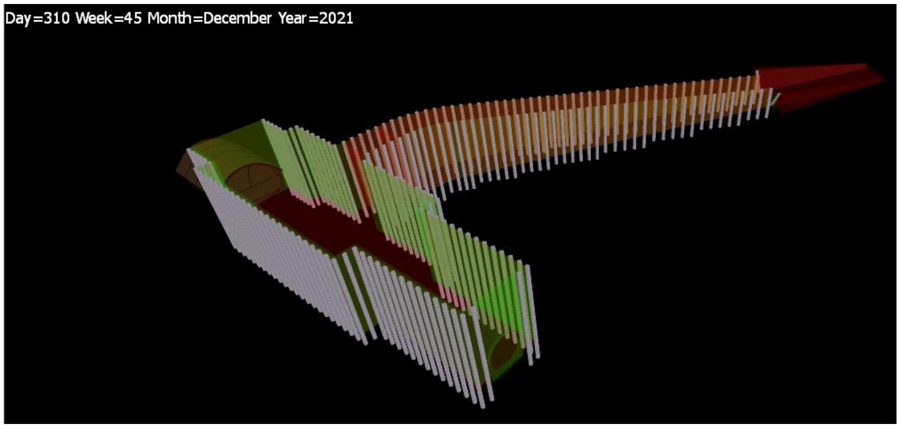


Figure 34 B.1 station at Week 45 (Dec. 2021)

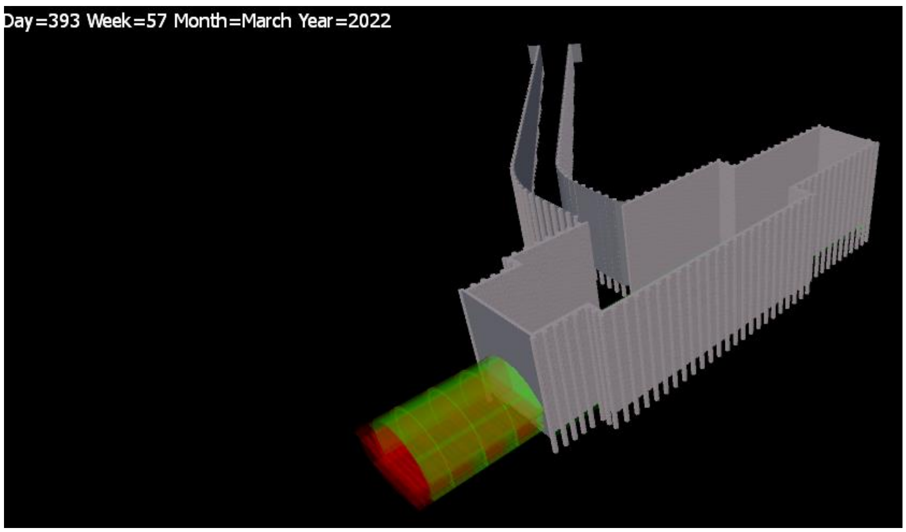


Figure 35 B.1 station at Week 57 (Feb. 2022)

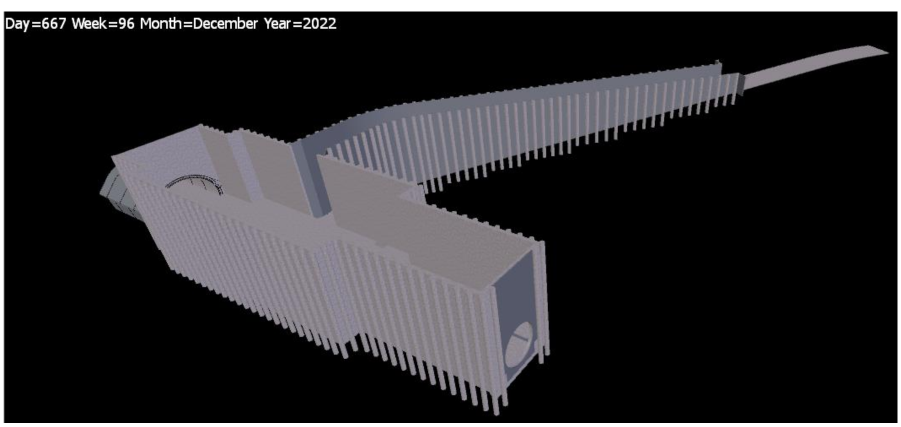


Figure 36 B.1 station at Week 96 (Dec. 2022)

6.2.2.2 Other Output

Similarly, for the remaining shafts, stations and tunnels a 4D simulation was prepared.

In the Shafts rendering was performed to illustrate the surface works that are the responsibility of the contractor. For example, rendering of prefabricated sill, micro-vibrated tactile tile, in situ concrete sidewalks, grass, asphalt, and steel floor grill were performed.

Below are figures taken from the simulations of different stations, shafts, and tunnels.

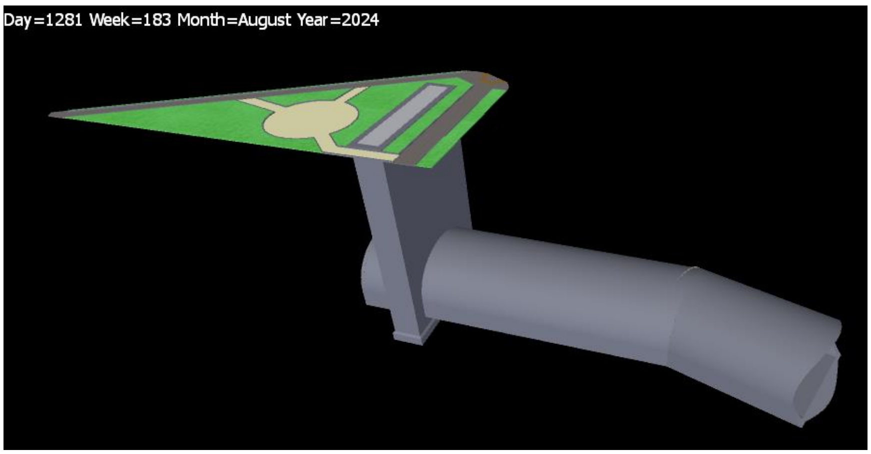


Figure 37 B.9 Ventilation Shaft at the end of the simulation

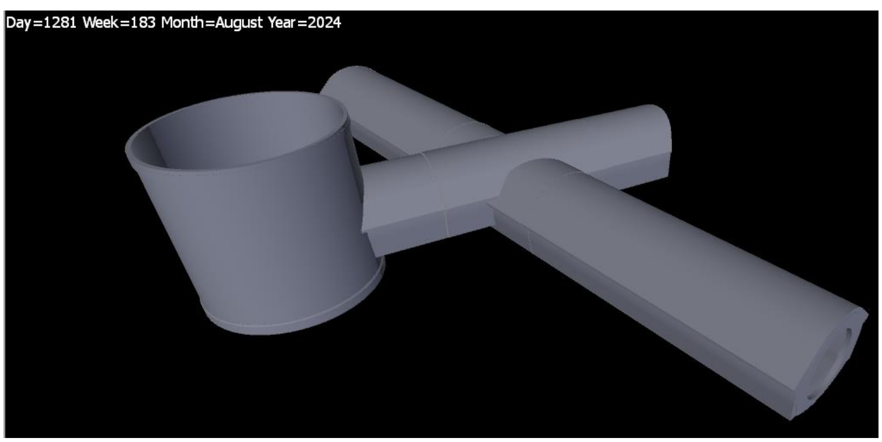


Figure 38 B.6 Station at the end of the simulation

Figure 39 B.3 Construction Shaft at the end of the simulation

Figure 40 NATM Tunnel at the end of the simulation.

Finally, when all the models of the projects were moved to 4D, it was possible to append all the models in one Naviswork file to create a 4D simulation at the project level.

Some figures from the 4D simulation of the whole project are reported below:

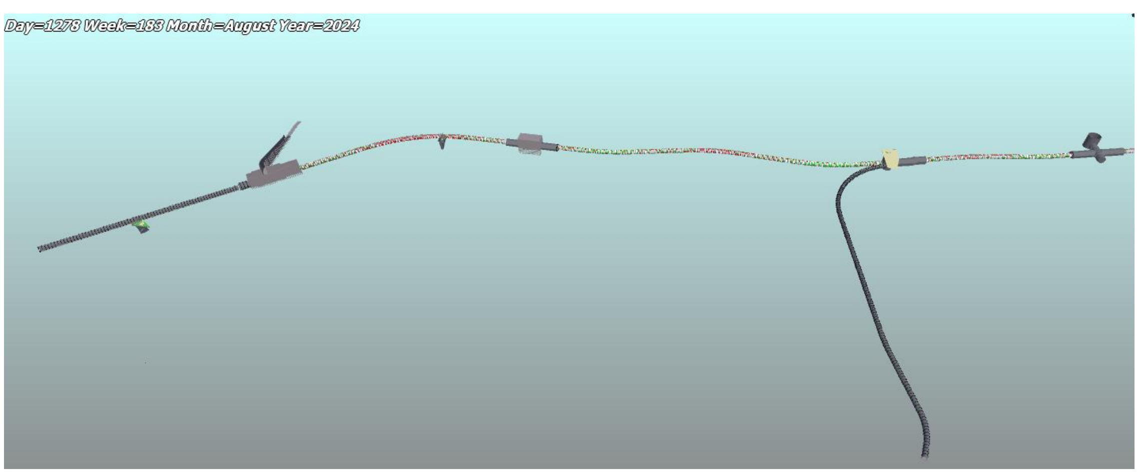


Figure 41 Entire project end at the end of the simulation-part 1

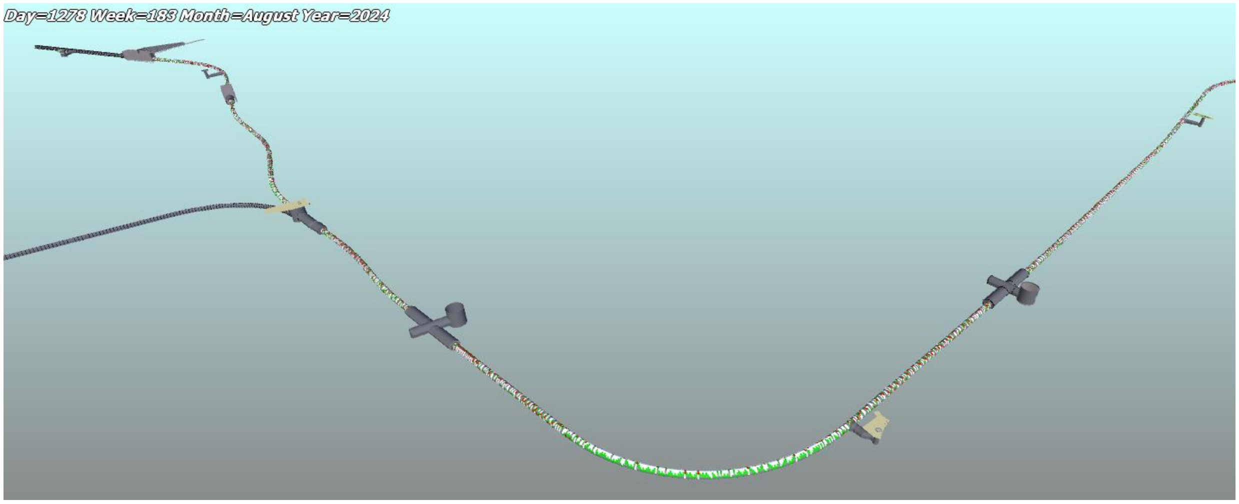


Figure 42 Entire project end at the end of the simulation-part 2

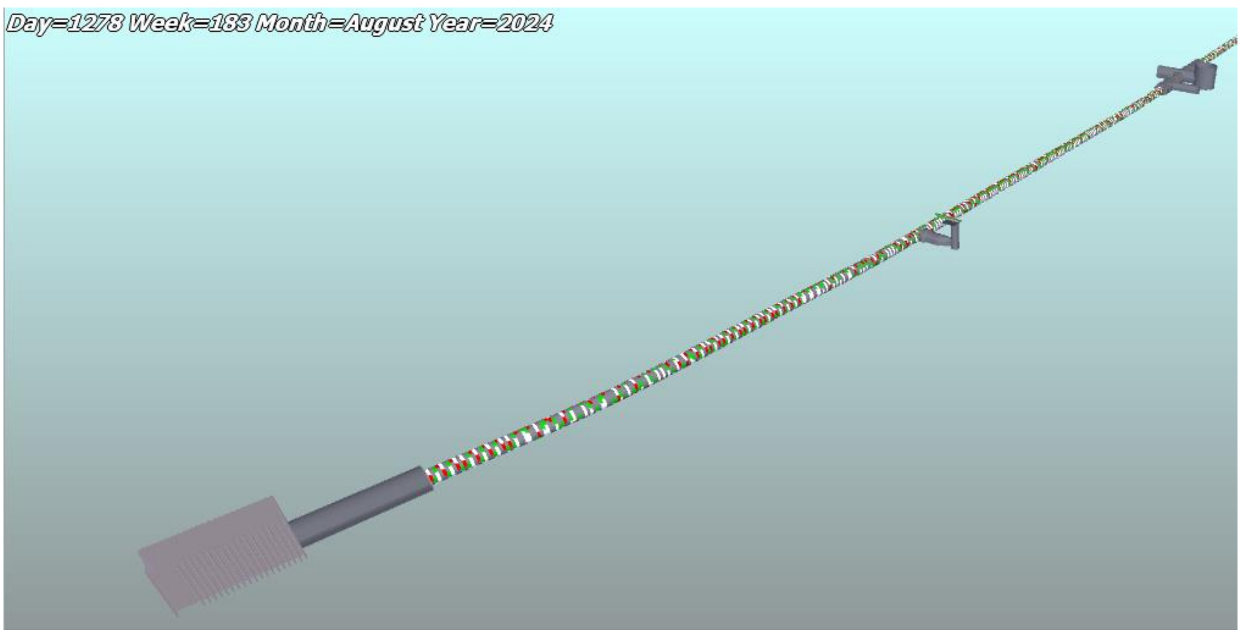


Figure 43 Entire project end at the end of the simulation-part 3

All the model’s Navisworks files with the 4D simulations will be reported in Appendix C of this Thesis.

7. 5D Cost

7.1 Cost Estimation

7.1.1 Importance

Cost estimation is a process to accurately predict the cost of delivering the project. Cost is one of the primary measures of a project's success. Generally, a project is considered successful if it is completed within the estimated cost. "Project Management Body of Knowledge guide (PMBOK) defines cost estimates as a developed approximation of the monetary resources needed to complete project activities. Estimating is the primary function of the construction industry; the accuracy of cost estimates starting from early phase of a project through the tender estimate can affect the success or failure of a construction project." (Choge & Muturi, 2014).

7.1.2 Application in Case Study

In this report the cost estimation of the tunnel excavation will be elaborated. The method of excavation is full-section mechanized tunneling, and to be more specific the machine used will be earth pressure balance-tunnel boring machine "EPB-TBM". The Earth Pressure Balance (EPB) is used for soft cohesive soils to avoid ground settlements in these formations. "The basic excavation principle of the EPB is to allow the pressure in the cutter head and face cavity to build up naturally by the pressure of the ground itself and the accompanying ground water. Thus, excavated material can be used for supporting the excavation." (Tatiya 2013) In the tail shield of the EPB machine the segmental lining is installed. The segmental lining is a set of prefabricated concrete segments that form 1 ring. It has two important roles: to support the ground and to function as a support for the jacks that push the EPB machine forward.

7.1.2.1 TBM advance Rate

Usually, the first 5 months of a tunneling project are called the launching phase, during this phase the equipment gets its final embracing to the project conditions and the staff are being trained on the working process and are gaining the required skills. Therefore, in this phase of the project the prediction of the TBM advance rate is a very ambiguous task and different approaches have been found to estimate it, thus creating the TBM learning curve.

The estimation of the advance rate of the TBM is an important task, especially during tendering, because it helps achieve an accurate time schedule and cost estimate for the entire project. Two different approaches to estimate the TBM advance rate were suggested in the article "Predicting the Learning Curve in TBM Tunneling". These approaches are useful in the tendering phase because they are simple and can be rapidly applied.

The first approach is by Gehring, which is based on experience and knowledge from different past projects worldwide. The exponential formula of this approach is as follow: (Wais, A., Wachter, R)

$$f_{famil.} \approx 1 - e^{-d*0,65}$$

with: f_{famil} = Percentage of the maximum rate of advance
d = Duration of advance in months

Where the maximum rate of advance provided by Geodata, based on their previous work experience, is approximately 590m/month.

The following graph represent the output of Gehring approach.

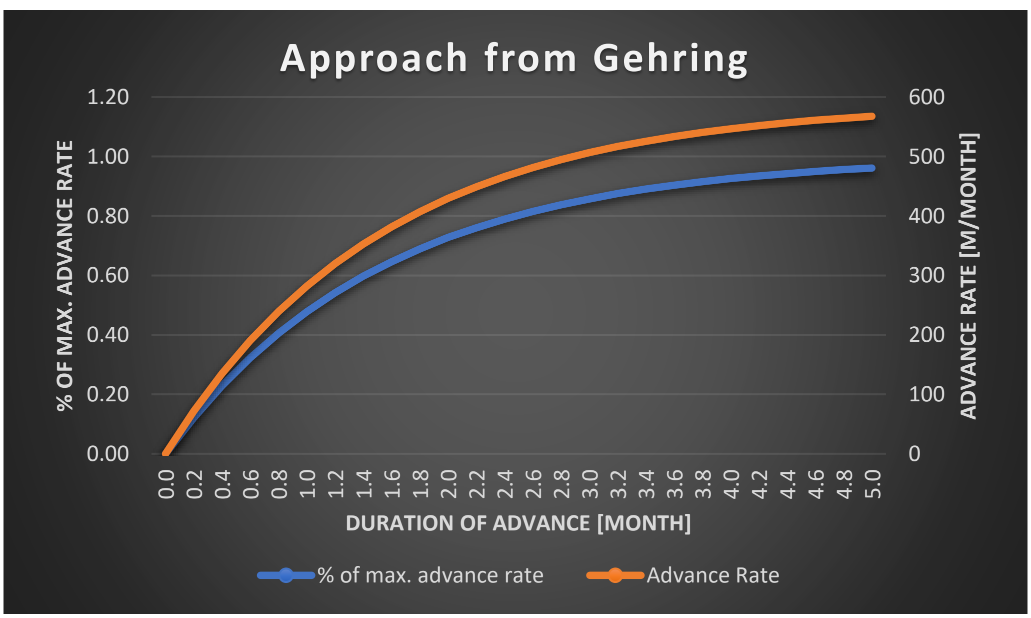


Figure 44 Gehring Approach Tunnel Learning Curve

The second approach is a Simple approach for single shielded TBM suggested from Wais. This approach was based on data from nine different previous projects so it may not be valid for all projects. The exponential formula of this approach is as follow: (Wais, A., Wachter, R)

$$f_{famil} \approx 1 - e^{-d*0.1}$$

with: d : Duration of advance in weeks

f_{famil} : Percentage of the maximum rate of advance

Where the maximum weekly advance is 590m/month ÷ 4 weeks/month = 148 m/week

The following graph represent the output of Wais simple approach:

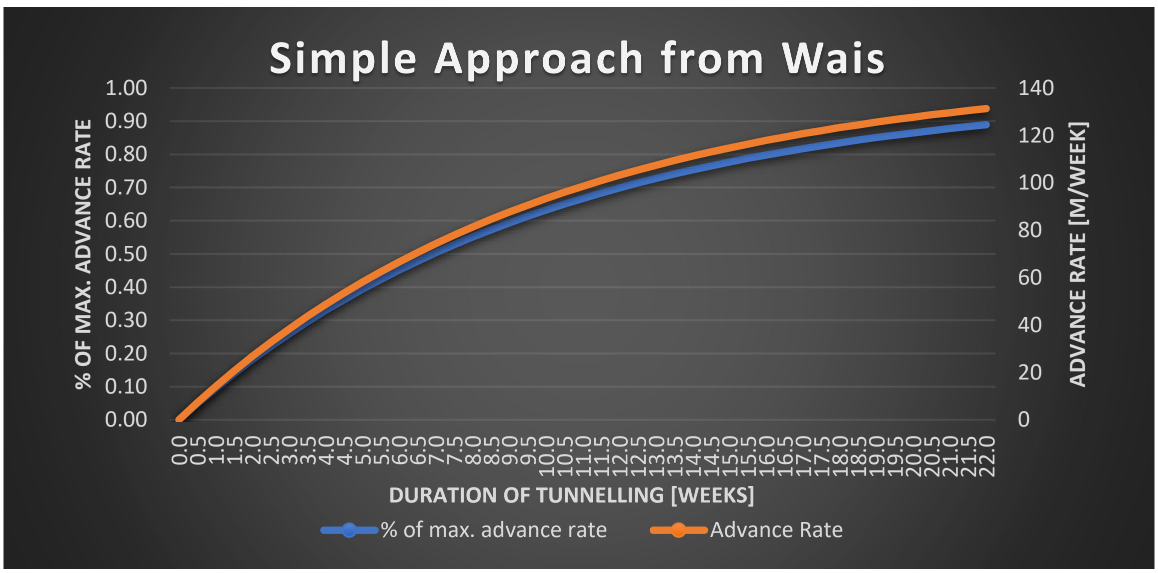


Figure 45 Wais Simple Approach Tunnel Learning Curve

Analyzing the curves of the two approaches it is evident that the advance rate of the TBM will increase as time passes during the first 5months of the project construction till it reaches the maximum. This improvement in the advance rate is what is known as the TBM learning curve. The main reason behind this learning curve is because of training and familiarization. There are several factors that influence the pace of training such as the type of staff being trained labor, foreman, mechanics and others, the machine and lining support used, the geology and other general conditions.

Those two approaches are very useful for the metro project at the current tendering stage. The tunnel learning curves are handy for the construction of the time schedule and the cost estimates "Cash flow curves" especially that the TBM tunneling activity is usually a critical activity on the Gantt chart.

7.1.2.2 Cost estimation of the tunnel built with EPB

Following the above literature review regarding mechanized tunneling advancement rate, it was possible to go in depth in the cost estimation process of tunneling using EPB machine.

In the BOQ document the tunnel excavation was subdivide into different elements as follows:

- TBM assembly
- Tunnel Excavation between different stations
- Tunnel segmental lining between different stations
- TBM advance through stations
- TBM disassembly

Part of the BOQ document of the section being excavated between the first station "B.1" and the second station "B.2" will be reported below:

Table 7 BOQ of the Section with TBM. Source: Geodata

B.16	**SECTION WITH TBM**			
B.16.1	**B.1 Station Initial Section**			
B.16.1.1	**ASSEMBLY AND INTRODUCTION OF THE TBM, INCLUDING THE BACKUP AND OTHER COMPLEMENTARY FACILITIES, AS WELL AS THE REACTION STRUCTURE NECESSARY FOR PUSHING AT THE START OF EXCAVATIONS**	**5.3.1**	un	1.00
B.16.2	**B.1 Station Interstation Section – B.2 Station (476 m)**			
B.16.2.1	**Tunnel Excavation with EPB TBM**	**5.3.2**	m	476.00
B.16.2.2	**Manufacture, supply, and assembly of tunnel lining based on precast reinforced concrete segments**	**5.3.3**	m	476.00
B.16.3	**Advance TBM B.2 Station (120.3 m)**			
B.16.3.1	**Advance of TBM by B.2, includes Proportional Part of Supplies, Assembly and Disassembly of the Reaction Metallic Structure for the Start of Drilling, Segments, and all the Materials and Operations Necessary for the Complete Execution**	**5.3.4**	m	120.30

This section excavated with the TBM had to be priced. The elements and quantities found in this section are part of the Recap sheet that was created by Geodata. A Recap sheet is a cost summary sheet that typically shows the same items as those found in specification sections. In Addition, a recap sheet is used to summarize the entire project on one sheet and to find total cost through a simple addition of the component costs. The steps to reach a Recap cheat, with trustworthy costs, will be discussed in the coming paragraph.

For each element in the Recap sheet a summary sheet was created. In the summary sheet the element cost was subdivided between:

- Labor cost
- Equipment cost
- Materials cost
- Subcontractors cost

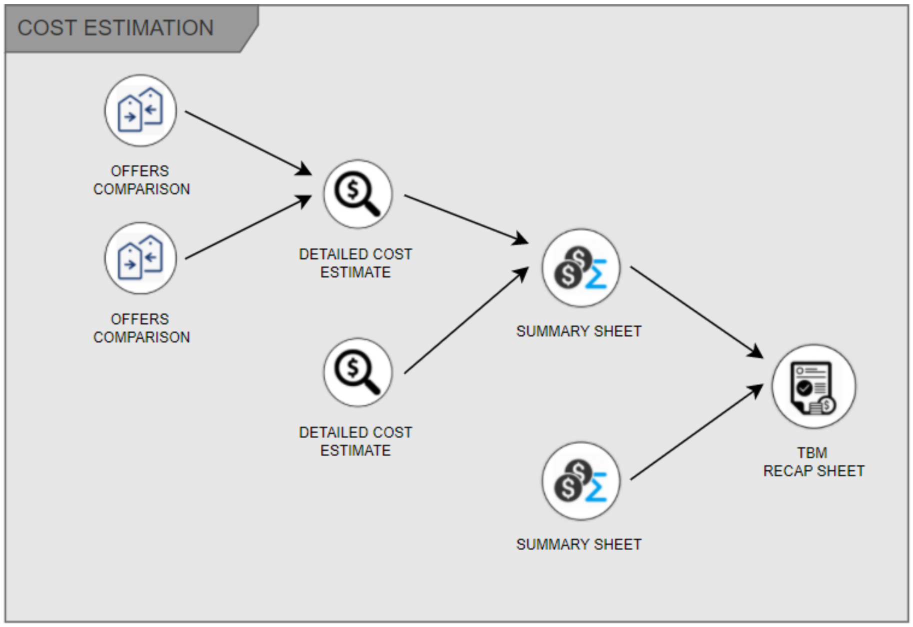
Then under each cost division "labor, equipment, material and subcontractors" the cost of different work items was specified. Items are separated if they have different unit costs due to different crews, materials, methods, productivity, and units of measurement.

For each work item in the summary sheet there will be a detailed cost estimate. A detailed cost estimate is prepared as follows:

1. Quantities Take Off "number of units."
2. Find and calculate unit costs for material, equipment, and labor "cost/unit".
3. Extend the unit prices by the quantity to estimate the total cost of each item "(cost/unit) x (number of units) = Cost

Therefore, labor, equipment and material costs found from the detailed cost estimates in addition to the subcontractor's costs are reported into the Summary sheet. Then using all Summary sheets costs are collected to create the Recap sheet. Later indirect costs, markup, and profit are added to get the final bid price.

The flow chart below summarizes the steps followed to prepare the TBM Recap sheet.



To elaborate more on how the prices in the recap sheet are built an example will be used. Let us consider the element/Task in the BOQ with a name "Manufacture, supply, and assembly of tunnel lining based on precast reinforced concrete segments" and with a mark "B.16.2.2". In the summary sheet of this element the costs to perform the work were partitioned between labor, equipment, materials, and subcontractors as shown below.

The data in element B.16.2.2 are left empty due to the fact that it is highly confidential data for the bidding process.

Table 8 Element B.16.2.2 Summary Sheet. Source: Geodata

ITEM				0.0
Code	Description	Quantity	Unit	cost
B.16.2.2	Fabricación de dovelas túnel - B.1I Station Interstation Section - B.2 Station			
B.16.2				

APU constants			
K1	Advance TBM	m / month	
K2	Amortization of voussoirs plant during excavatic	%	
K3	Total inter-station tunnel length	m	
K4	Production months Segment plant	month	
K5	Effective electricity consumption Plant and syst	MWh	
K6	Backfilling mortar consumption	m3 / m	
K7	Segment volume (+ 2% waste)	m3 / m	

DIRECT COST APU, PROVISORY VALUES IN USD

CONCEPTS					INCIDENCE		COST
Code	Act.	Description	Unit	Cost / Unit	Formula	Adjustment	USD / Unit
WORKFORCE							0.00
X2D21	X	Segment plant staff	month				
EQUIPMENT							
XD16	X	Amortization of the Segment Plant, gantries and	GI / 100				
X2D31	X	Auxiliary equipment Segment plant	month				
X3D32	X	Disassembly and removal of segments Plant an	GI / 100				
MATERIALS							
X2012	X	Tunnel segment backfilling mortar	m3				
X2D12	X	Reinforced concrete 40 Mpa voussoirs	m3				
X2D11	X	Segment ring accessories - tunnel mounting	GI / 100				
SUBCONTRACTS							
P-22016	S	Electric power	MWh				
P-22016	S	Natural gas	m3				
TOTAL UNIT COST							

The labor costs related to this element consisted of only one work item "Segment plant staff". A detailed cost estimate for the segment plant staff was performed. The Staff consisted of managers, electricians, mechanics, operators, technicians, and others. The cost per unit for each member of the staff was found and then all the staff's unit costs were summed up and entered in the summary sheet.

The equipment cost for the tunnel lining was divided into three different work items:

- Amortization of the Segment Plant, gantries, and molds
- Auxiliary equipment Segment plant
- Disassembly and removal of segments Plant and others

A detailed cost estimate for each of the work items above was performed. For simplicity only the detailed cost estimate of the auxiliary equipment will be discussed in this report. The auxiliary equipment consisted of forklift, truck crane, front loaders, and shallow truck. The cost per unit for each equipment was found and then all equipment's unit costs were summed up and entered in the summary sheet.

Moreover, the material cost was also divided into three different work items:

- Tunnel segment backfilling mortar
- Reinforced concrete 40 Mpa voussoirs
- Segment ring accessories - tunnel mounting

A detailed cost estimate for each of the material work items above was performed. For simplicity only the detailed cost estimate of the segment ring accessories will be discussed in this report. The segmental lining accessories consisted of bolts, packers, guiding bars, and gaskets. The cost per unit for each accessory was found and then all accessories' unit costs were summed up and entered in the summary sheet.

Finally, the subcontractors needed for the tunnel lining were two: electric power and natural gas. Therefore, their unit costs were part of the summary sheet also.

To wrap it up, the discussion above showed how the unit cost of one element in the recap sheet/BOQ was found, hence the same procedure was repeated to all the remaining elements until a complete recap sheet for the TBM excavation was attained.

However, during the above discussion the unit costs were stated to be found but the procedure on how to find a unit cost for a specific equipment, material or labor was not elaborated yet. In order to find the best unit cost to be used as part of the contractor's bidding price, the contractor usually requests written quotations and apply an offer comparison to choose the best offer that can be used. The contractor normally requests quotations in case the equipment, material or labor are not already available in house.

The written quotation can be provided by a company, manufacturer, vendor, supplier, or others. The quotation includes prices, taxes, shipping charges, handling charges, delivery schedules, warranties, etc. An offer comparison is done between the different offers to choose the lowest responsive and responsible offer, which means that the chosen offer should not only has the lowest price, but at the same time the quality provided should meet the required specifications.

In this report the offer comparison done to reach a unit cost for certain materials will be examined.

The material work items, considered in the offer comparison, are the following:

- Gaskets
- Connectors “Dowels"
- Bolts
- Guiding Rods
- Pads
- Foam
- Grease
- Concrete Additives
- Grout

Eleven different manufacturers submitted offers to supply the project with the material stated above, but not every offer covered all the material. A comprehensive offer comparison between all manufacturers had to be utilized in order to choose the supplier of every material.

Geodata asked the manufacturers to submit offers including two options: A and B.

In option A the segmental ring design is the one included in the Bidding documents. Its configuration is a universal typology with straight trapezoidal geometry. It has 6 + 1 segments, with the key being half the size of the other segments.

While in option B the segmental ring design is the one recommended by Geodata which is a universal typology ring configuration with trapezoidal geometry. The recommended geometric configuration is a ring with 7 + 0 segments, with the key having the same size as the other segments. The main benefits behind this design are to improve structural behavior, minimize assembly times, and reduce the total number of rings needed. Moreover, there will be a significant decrease in quantities (and costs) for gaskets, guiding rods and bolts, while for connectors, packers, and steel bars there is a slight decrease due to the additional connector required for each ring.

Throughout the offer comparison process the first challenge encountered was regarding material shipment. The material unit cost provided by some manufacturers included the shipment cost to the project location while other manufacturers did not include shipment cost, in their unit cost, but provided a shipment cost per container to the project location. Consequently, for all offers to be comparable the shipment cost had to be included in all the unit costs available.

Most offers included an estimate of the total number of containers needed to ship all the material "gaskets, dowels, bolts, rods and pads" together without specifying each material will require how many containers. To resolve this challenge a research regarding the storage capacity of a forty-foot container had to be performed in order to predict how the total number of containers will be subdivided between different materials.

- Dimensions of a 40ft container : 2.38m x 2.35m x 12m
- Fresh air in a 40ft container : 67cbm

Figure 46 Forty Foot Container Filling Capacity. Source: Shippo

To find the required number of containers needed to chip each type of material, first the volume per piece of each material had to be calculated then multiplied by the total quantity needed and by an expansion factor. Finally, the volume needed is divided by the forty-foot container filling capacity to find the number of containers loaded. A summary of the results for all different material is reported in the table below:

Table 9 Lining Accessories Distribution in Containers

Material	dimensions	Unit Volume m3		Quantity	Volume m3	Containers #
Dowel Pin Male	284x70	0.0013916	option A	51129	71.1511164	3.9
			option B	50610	70.428876	3.9
Dowel Socket Female	140*70	0.000686	option A	102258	70.148988	
			option B	101220	69.43692	
Connection Bolt	25x410	0.00079376	option A	11032	8.75676032	0.6
			option B	10290	8.1677904	0.5
Connection Bolt Washer	70x27x5	1.92423E-05	option A	11032	0.212280557	
			option B	10290	0.198002804	
Connection Bolt Socket	25x140	0.000224	option A	55062	12.333888	
			option B	50610	11.33664	
Guiding Rods	50x660	0.001295907	option A	27531	35.67761478	1.0
			option B	25305	32.79292587	0.9
Anchoring Clip			option A	55062		
			option B	50610		
Packers	690x190mm	0.0002622	option A	102258	26.8120476	0.7
			option B	101220	26.539884	0.7

Another method to distribute the material into containers was based on the information given in one of the offers. The offer stated the number of pieces that can be placed in one pallet and some research was done to find how many pallets can fit in one 40 ft container.

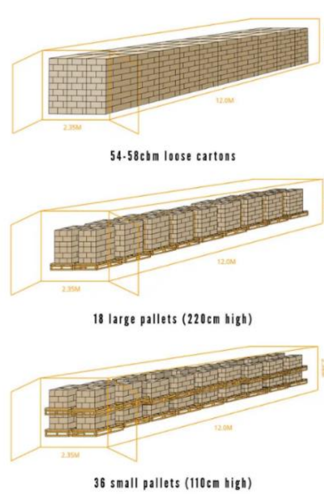


Figure 47 Pallets in a 40 ft Container. Source: Shippo

Hence to find the number of containers needed for each material, the total number of pieces of the material was divided by number of pieces that can fit in one pallet. Then the number of pallets needed was divided by the number of pallets that can be placed in one 40 ft container. The results of containers needed per material are reported in the table below:

Table 10 Lining Accessories Packaging in Pallets Then into Containers

Material		Quantity	Pc/pallet	pallet dim [m]	pallets #	container #	total container #
Packers	option A	102258	3000	1.3*1.1*1.5	34.09	0.95	0.95
	option B	101220	3000	1.3*1.1*1.6	33.74	0.94	0.94
Dowel Pin Male	option A	51129	1000	1.2*0.8*1.5	51.13	1.42	1.88
	option B	50610	1000	1.2*0.8*1.6	50.61	1.41	1.86
Dowel Socket Female	option A	51129	4400	1.2*1.0*1.35	11.62	0.32	
	option B	50610	4400	1.2*1.0*1.36	11.50	0.32	
Dowel Socket Female	option A	51129	10500	1.2*1.0*1.95	4.87	0.14	
	option B	50610	10500	1.2*1.0*1.96	4.82	0.13	
Connection Bolt	option A	11032	1000	1.1*0.8*1.1	11.032	0.31	0.49
	option B	10290	1000	1.1*0.8*1.2	10.29	0.29	0.45
Connection Bolt Socket	option A	55062	8400	1.2*1.0*1.95	6.555	0.18	
	option B	50610	8400	1.2*1.0*1.96	6.025	0.17	
Guiding Rods	option A	27531	300	1.35*1.0*0.85	91.77	2.55	2.5
	option B	25305	300	1.35*1.0*0.86	84.35	2.34	2.5

Finally, the material that will be provided by any supplier was divided into containers as shown in the table below. The names of the suppliers were replaced by numbers for confidentiality.

Table 11 Material subdivision into containers for the offers provided

Offer		Gasket	Connectors	Bolts	Guiding Rods	Packers	Others	Total Containers
Supplier 1	Option A	14	4	0.5	1	1	0.5	21
	Option B	14	4	0.5	1	1	0.5	21
Supplier 6	Option A	-	2.2	0.7	2.7	1.2	1.2	8
	Option B	-	2	0.5	2.5	1	1	7
Supplier 7	Option A	-	2	0.5	1.5	1	1	6
	Option B	-	2	0.5	1.5	1	1	6
Supplier 3	Option A	16	-	-	-	-	-	16
	Option B	15	-	-	-	-	-	15
Supplier 4	Option A	12	-	-	-	-	-	12
	Option B	11	-	-	-	-	-	11

Consequently, knowing the number of containers needed to ship every type of material and the container shipment cost provided differently in each offer, the material unit cost including shipment was achieved so offers can be compared.

In order to compare offers a comparison excel sheet for each material was created. In each excel sheet all the different offers were stated including:

- Suppliers contact details.
- Product technical name
- Offer date.
- Unit price for both options
- Total price for both options
- Product technical specifications
- Offer includes.
- Offer does not include.
- Notes

Due to the fact that mutual NDA was signed between Geodata and the suppliers, the content of the offer comparisons including the costs and the suppliers name should stay confidential. “A non-disclosure agreement “NDA” is a legally binding contract that establishes a confidential relationship. The party or parties signing the agreement agree that sensitive information they may obtain will not be made available to any others. Such agreements are common for businesses entering into negotiations with other businesses. They allow the parties to share sensitive information without fear that it will end up in the hands of competitors. In this case, it may be called a mutual non-disclosure agreement." Twin, (2021, January 3)

Therefore, to respect the agreement, in this report the names of the suppliers will be replaced by numbers and the cost of the material will be stated in terms of a percentage of the highest offer received for each material separately. The output of the offer comparison excel sheets were summarized in tables containing the total cost percentage and technical specifications of each offer.

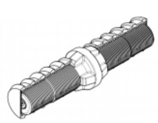
For instance, starting with the offer comparison of the gaskets. Gaskets are one of the segmental lining accessories that are used to guarantee water tightness. The water tightness is created through compression of gaskets during the assembly process of segments. As shown in the table below five different suppliers submitted offers on gaskets. All offer's technical specifications meet the contract requirements even if they are expected to be higher than the real project water loads. Consequently, after all offers passed the technical specifications inspection, they now can be compared in terms of cost. As noticed in the table below supplier 2 offered a bid with the lowest price which is approximately 27% lower than the highest bidder supplier 3.

Table 12 Sealing Gaskets Summarized Offer Comparison

Sealing Gasket	Supplier									
	1		2		3		4		5	
	Total price €		Total price €		Total price €		Total price €		Total price €	
OPTION A	87.04%		73.32%		100.00%		89.22%		78.00%	
OPTION B	87.30%		73.81%		100.00%		89.14%		78.38%	
	**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**	
	Maximum pressure:	9 Bar (from graph)	Maximum pressure:	10 Bar	Maximum pressure:	10 Bar	Maximum pressure:	14 Bar (from graph)	Maximum pressure:	17 Bar (from graph)
	Gap at maximum pressure:	6 mm	Gap at maximum pressure:	6 mm	Gap at maximum pressure:	6 mm	Gap at maximum pressure:	6 mm	Gap at maximum pressure:	6 mm
	Offset at maximum pressure	10mm	Offset at maximum pressure	10mm	Offset at maximum pressure	10mm	Offset at maximum pressure	10mm	Offset at maximum pressure	10mm

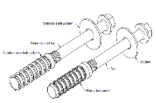
Moving to another segmental lining accessory that was part of the offer comparison "Dowels". The dowels are used to connect different rings in the tunnel. As shown in the table below 5 suppliers submitted offers on dowels. The first offer submitted by supplier 8 did not meet the design specifications since the dowels' ultimate pull-out resistance was 80 kN which is lower than the specifications 100kN. Hence, supplier 8 had to update the submitted offer to pass technical specification before comparing the costs. In terms of cost supplier 2 submitted the lowest bid which is approximately 38% lower than the highest bidder supplier 8.

Table 13 Connectors "Dowels" Summarized Offer Comparison

Connectors "Dowels"	Supplier											
	1		2		6		7		8		8	
	Total price €		Total price €		Total price €		Total price €		Total price €		Total price €	
OPTION A	79.07%		61.85%		63.02%		66.77%				100.00%	
OPTION B	79.13%		61.85%		62.87%		66.79%				100.00%	
	Technical Specifications		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**	
	Shear Test	160 kN	Shear Test	≥ 145 kN	Shear Test	176 kN Ultimate	Shear Test	160 kN	Shear Test	Ultimate 145kN	Shear Test	Ultimate 130 kN
	Pull Out Test	100 kN	Pull Out Test	≥ 100 kN	Pull Out Test	100 kN Ultimate	Pull Out Test	100 kN	Pull Out Test	Yield 60kN (Ultimate 80kN) does not meet min. requirements	Pull Out Test	Yield 80 kN (Ultimate 110 kN)

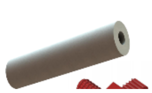
Bolts are also one of the segmental lining accessories considered in the offer comparison. Bolts are used as connections between different segments, the segment is first placed in position and then the bolts are inserted and tightened. In the table below the offer comparison for the bolts is reported. As seen the bolts offered by supplier 1 did not meet the design specifications with a pull-out resistance 175 kN lower than the minimum 220 kN so it was excluded from the cost comparison although in all cases it was not the lowest bidder. In addition, supplier 8 offered two different types of bolts with the same technical specifications but different steel material. Finally, the lowest bidder for bolts was supplier 6 with a difference of approximately 17% from the highest bidder 8.

Table 14 Bolts Summarized Offer Comparison

Bolts	Supplier											
	1		2		6		7		8		8	
	Total price €		Total price €		Total price €		Total price €		Total price €		Total price €	
OPTION A	97.66%		90.75%		83.38%		93.64%		91.59%		100.00%	
OPTION B	98.10%		90.87%		83.02%		93.88%		91.53%		100.00%	
	**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**	
	Elastic limit		Elastic limit		Elastic limit	640 Mpa	Elastic limit		Elastic limit		Elastic limit	
	Pull-out Test	175kN does not meet requirements	Pull-out Test		Pull-out Test		Pull-out Test	> 220 kN	Pull-out Test	220 kN	Pull-out Test	220 kN

Guiding Rods were also part of the offer comparison. “A guidance rod is used between segments of the same ring; it allows the segment to be guided into its position during the assembly stage and it functions as a shear pin.” (Peila, 2019) Two types off guiding rods were submitted in the offers either anchored or glued guiding rods. As shown in table below bidder 8 submitted an offer for both types of rods however the remaining suppliers submitted an offer for one of the two types. In order for the offers to be comparable each type of rods was considered separately. The lowest bidder for anchored rods was supplier 1 approximately 20% lower than the highest supplier 8. Moreover, the lowest bidder for glued rods was supplier 2 approximately 15% lower than the highest supplier 8.

Table 15 Guiding Rods Summarized Offer Comparison

Guiding Rods	Supplier											
	1		6		7		8		8		2	
	Total price €		Total price €		Total price €		Total price €		Total price €		Total price €	
OPTION A	80.05%		88.60%		80.38%		100.00%		100.00%		84.89%	
OPTION B	80.56%		88.68%		80.91%		100.00%		100.00%		78.04%	
	**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**		**Technical Specifications**	
	Shear Stress	15,9 Mpa	Shear Stress	44kN	Shear Stress		Shear Stress	158kN	Shear Stress	158kN	Shear Stress	
	Type	Anchored	Type	Anchored	Type	Anchored	Type	Anchored	Type	Glued	Type	Glued

One more material considered in the offer comparison is the pads. The pads are placed on the segments sides where the jacking force is applied. They allow good load sharing and enhance the resistance to the mechanical stresses. As shown in the table below as a result of the offer comparison supplier 6 is the lowest bidder with an approximately 62% lower price than the highest bid supplier 8.

Table 16 Pads Summarized Offer Comparison

Pads	Supplier				
	1	2	6	7	8
	Total price €	Total price €	Total price €	Total price €	Total price €
OPTION A	63.46%	52.82%	37.75%	83.41%	100.00%
OPTION B	63.48%	52.82%	37.52%	83.42%	100.00%
	**Technical Specifications**	**Technical Specifications**	**Technical Specifications**	**Technical Specifications**	**Technical Specifications**

More offer comparisons for different material were performed and will be reported in appendix D of the report.

7.2 5D Simulation

At this stage, all models have already been moved from 3D to 4D and the recap sheet for the EPB tunneling was prepared. Therefore, it was possible to add the cost into both, the TBM and entire project models. Hence, the goal was to move the project model from 4D BIM model to 5D BIM model.

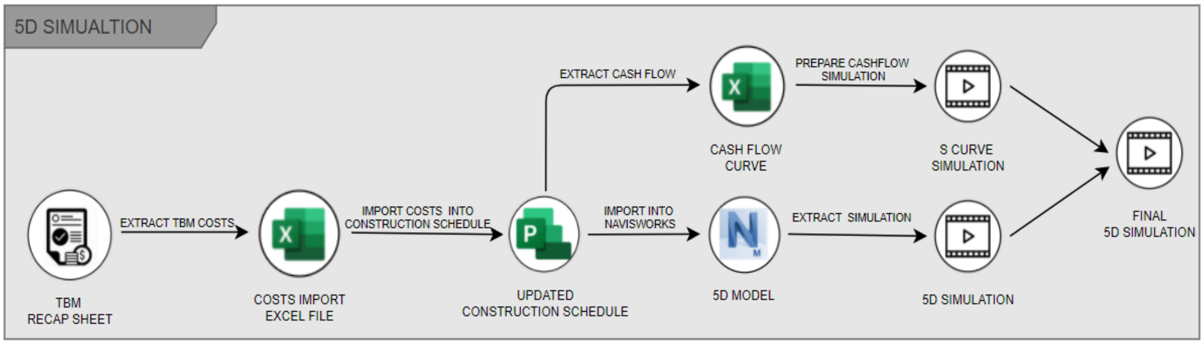
7.2.1 Importance

BIM 5D enables the instant generation of cost budgets and genetic financial representations of the model against time. "The development of 5D (Cost) capabilities is gaining momentum and leading project cost management firms are starting to realize the competitive advantages by embracing this 'new-age' approach to cost management." (Smith, 2015). Thanks to 5D models it is possible to simulate and explore various design and construction scenarios for the project since cost data and quantities are integrally linked in the BIM model.

7.2.2 Application in Case Study

To integrate the activities' labor, equipment, material, and subcontractors cost into the 4D model the same Autodesk software was used "Naviswork 2020". This process was applied to the TBM 4D model first and later these costs were appended into the entire project model.

As a first step the cost estimates found in the recap sheet were moved into an excel file in order to be prepared in the correct file format and then be imported into the Microsoft project construction schedule. Then after the Microsoft project construction schedule is updated to contain the total labor, equipment, material, and subcontractors' costs for every activity, it was possible to reimport this file into Naviswork. Finally, in Naviswork since the activities are already linked to the elements, costs will automatically be considered and thus be part of the model simulation. To clearly show the cash flow throughout the 5D simulation, the S curve is extracted from Microsoft project and converted into a simulation curve. Below is the flow chart of the work done to move the model from 4D into 5D.



To explain more the technique used to prepare the 5D simulation. First a section of the recap sheet will be reported. Data inside the recap sheet will be hidden for confidentiality.

Table 17 Section of the TBM Recap sheet. Source: Geodata

B.16	SECTION WITH TBM	Labor Cost	Equipment cost	Material Cost	Subcontractor Cost	Total Cost
		[USD]	[USD]	[USD]	[USD]	[USD]
B.16.1	Brazil Station Initial Section					
B.16.1.1	ASSEMBLY AND INTRODUCTION OF THE TBM, INCLUDING THE BACKUP AND OTHER COMPLEMENTARY FACILITIES, AS WELL AS THE REACTION STRUCTURE NECESSARY FOR PUSHING AT THE START OF EXCAVATIONS					
B.16.2	Brazil Station Interstation Section - José Miguel Infante Station (476 m)					
B.16.2.1	Tunnel Excavation with EPB TBM					
B.16.2.2	Manufacture, supply and assembly of tunnel lining based on precast reinforced concrete segments					
B.16.3	Advance TBM José Miguel Infante Station (120.3 m)					
B.16.3.1	Advance of TBM by Est. J. M. Infante, includes Proportional Part of Supplies, Assembly and Disassembly of the Reaction Metallic Structure for the Start of Drilling, Segments, and all the Materials and Operations Necessary for the Complete Execution					

As shown above, each activity in the recap sheet has its total cost distributed between labor, equipment, material, and subcontractor. Using these costs, an excel sheet was prepared and imported into Microsoft project. Below is the updated construction schedule in Microsoft project after costs have been added. Data in cells containing costs will be removed for confidentiality.

Table 18 Section of the TBM Construction Schedule with Costs

A.16.1	Tramo Inicial Estación B.1			102 day	April 24, 2022	August 5, 202	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.1.1	Montaje y Pruebas Equipo TBM	un	1	102 day	April 24, 2022	August 5, 2022	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.2	Tramo Interestación Estación Brasil-Estación J.M.Infante			74 days	July 4, 2022	September 1	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.2.1	Montaje Estructura de Reacción Estación Brasil	gl	1,0	21 days	July 4, 2022	July 25, 2022	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.2.2	Desmontaje Estructura de Reacción Estación Brasil	gl	1,0	7 days	August 12, 202	August 19, 202	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.2.3	Excavación de Túnel con Tuneladora EPB	m	476,0	42 days	August 5, 2022	September 16	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.2.4	Montaje de Dovelas	m	476,0	42 days	August 5, 2022	September 16	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
A.16.3	Avance Tuneladora Estación José Miguel Infante (120,3 m)	m	120,3	11 days	September 16	September 29	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00

Later the updated construction schedule was imported into the TBM Navisworks model, hence costs became part of the simulation.

7.2.2.1 5D Model Output

Screenshots at different stages during the simulation will be reported below. At the upper left corner of the simulation the anticipated costs of labor, material, equipment, and subcontractor are reported as time passes. Costs are hidden since it is confidential data.

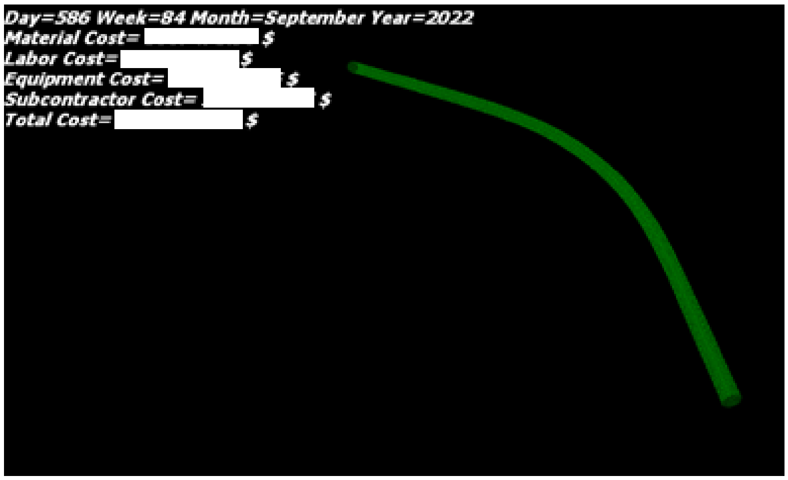


Figure 48 TBM Tunnel 5D Simulation at Week 84 (Sep. 2022)

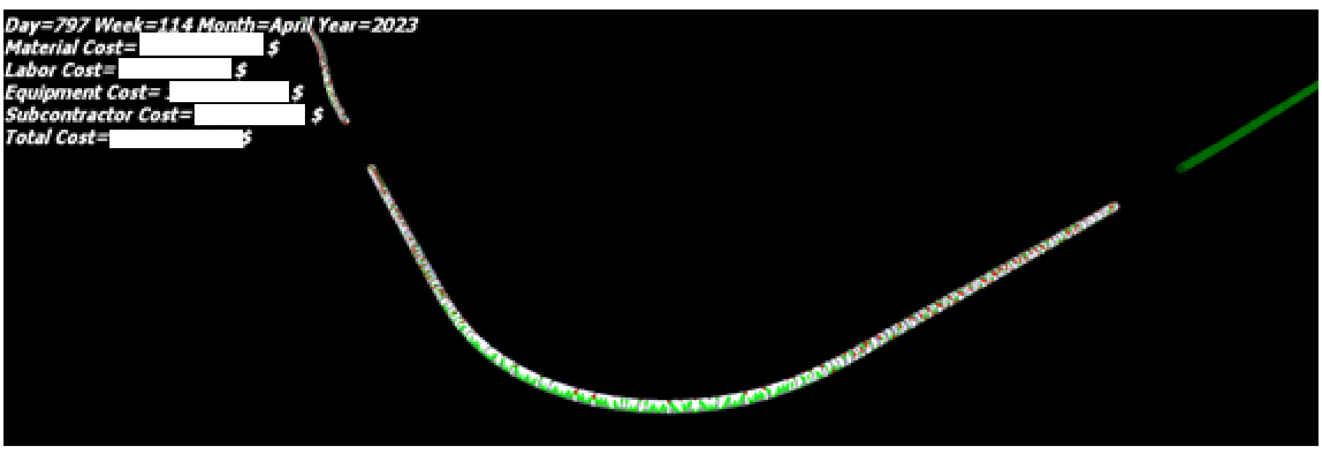


Figure 49 TBM Tunnel 5D Simulation at Week 114 (Apr. 2023)

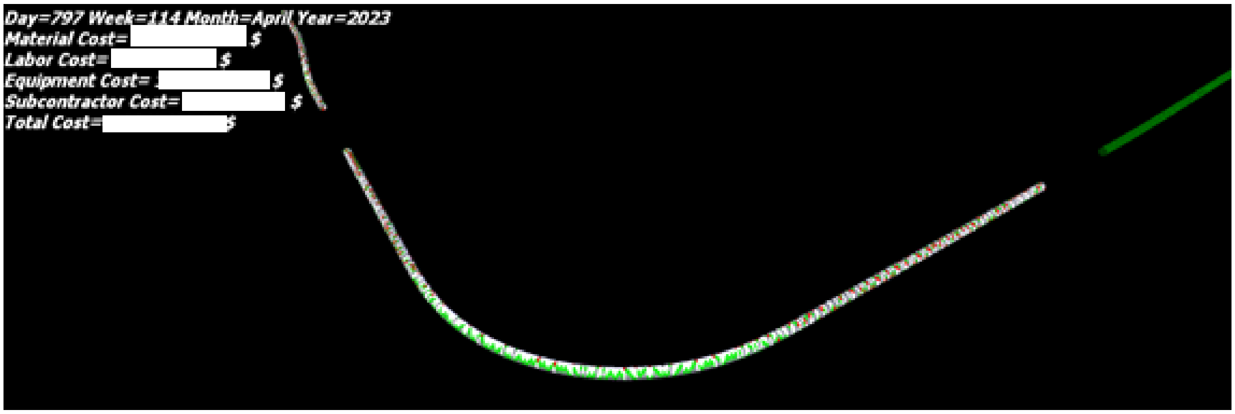


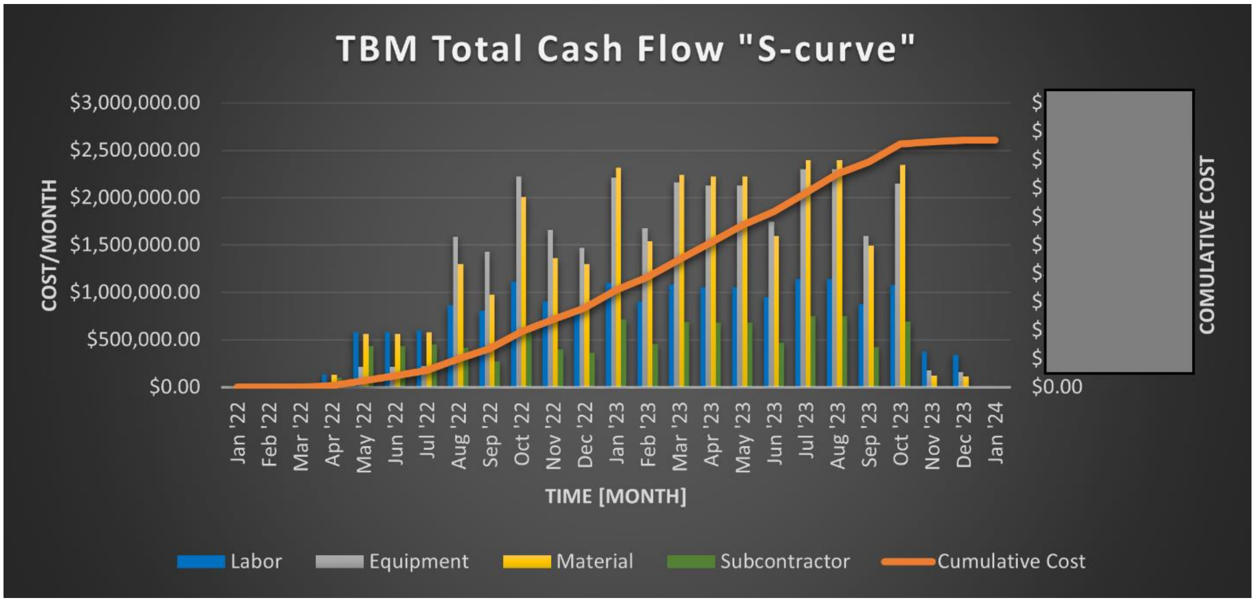
Figure 50 TBM Tunnel 5D Simulation at Week 152 (Dec. 2023)

Now that the TBM model was moved from 4D into 5D it was appended into the entire project model prepared before.

7.2.2.2 Simulation with Cash Flow Curve

However, to visualize the cash flow throughout the project a cash flow simulation curve "S curve" had to be prepared. In project management terms, an s-curve is a mathematical graph that shows relevant cumulative data for a project, such as cost, plotted against time. The s-curve often forms the shape of an "S" because the growth of the project in the beginning stages is usually slow. In our case, the TBM learning curve that has been discussed in the previous chapter will mainly cause the "S" shape of the curve. When the launching phase of the TBM is over, production rate increase so the growth accelerates rapidly creating that upward slope that forms the middle part of the "s." During this period, project team members are working heavily on the project, and many of the major costs of the project are incurred.

The cashflow data were extracted from the Microsoft project file in order to prepare the S curve reported below. The cumulative cost of the project that constitute the y-axis of the curve will be hidden, because it shows confidential data which are part of Geodata's bidding price.



As shown in the cash flow curve the cumulative cost is reported against time and the histograms represent the monthly cost distribution between labor, equipment, material, and subcontractor.

The cash flow was then converted into a simulation to show the monthly cash variation throughout the project and combined with the entire project 5D simulation. Screenshots at different stages during the project simulation will be reported below. Similarly, in the coming screenshot the cost related data was concealed.

Figure 51 Entire Project 5D Simulation at Week 70 (Jun. 2022)

Figure 52 Entire Project 5D Simulation at Week 118 (May. 2023)

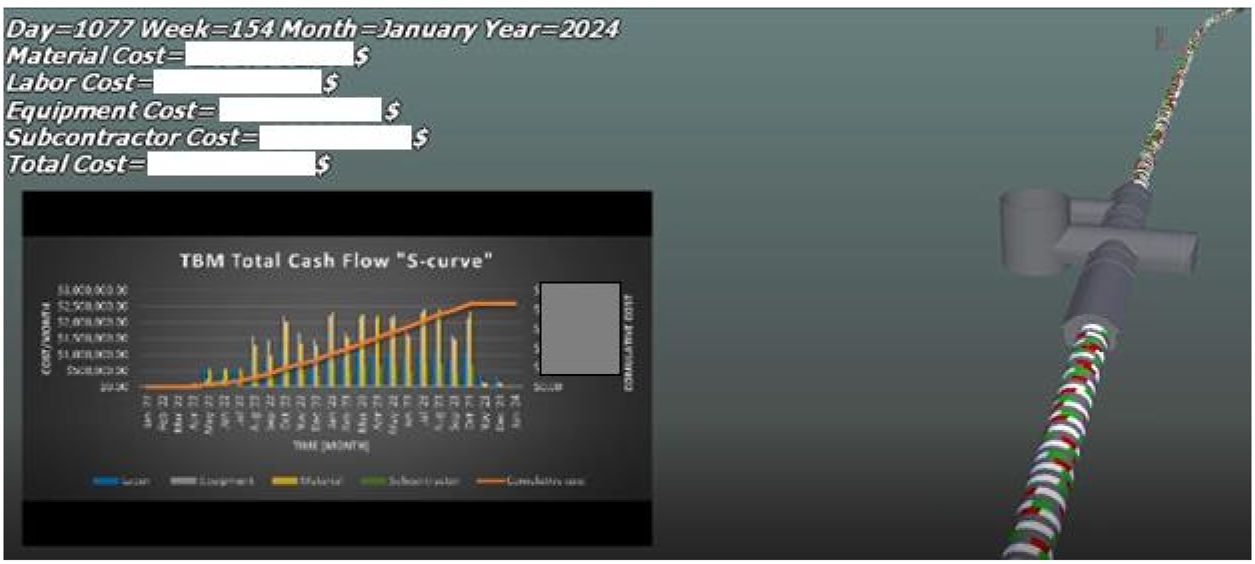


Figure 53 Entire Project 5D Simulation at Week 154 (Jan. 2024)

To wrap it up, the model was successfully moved from 4D to 5D, so it contains both time and cost. 5D BIM implementation can bring unprecedented efficiencies to the project lifecycle and solve costing and budgeting-related issues at a later stage.

The TBM and entire project model's Navisworks files with the 5D simulations will be reported in Appendix E of this Thesis.

8. Results Interpretation

8.1 4D Time

As an interpretation for the 4D results a comparison between the time schedule baseline that was part of the bidding documents and the construction schedule prepared at Geodata will be done. Therefore, challenges encounter by geodata while trying to respect the client's milestones will also be specified.

The milestones provided in the bidding documents specified major dates that had to be respected by the contractor during the construction process without going into more details regarding the construction timeline. Hence it was the responsibility of the contractor to create a construction timeline while keeping in mind the major milestones that had to be attained.

Thus, for Geodata to create the construction timeline the first milestones considered where the TBM test start, TBM excavation start, tunnel excavation end, and tunnel invert end. The main milestones are summarized in the chart below.

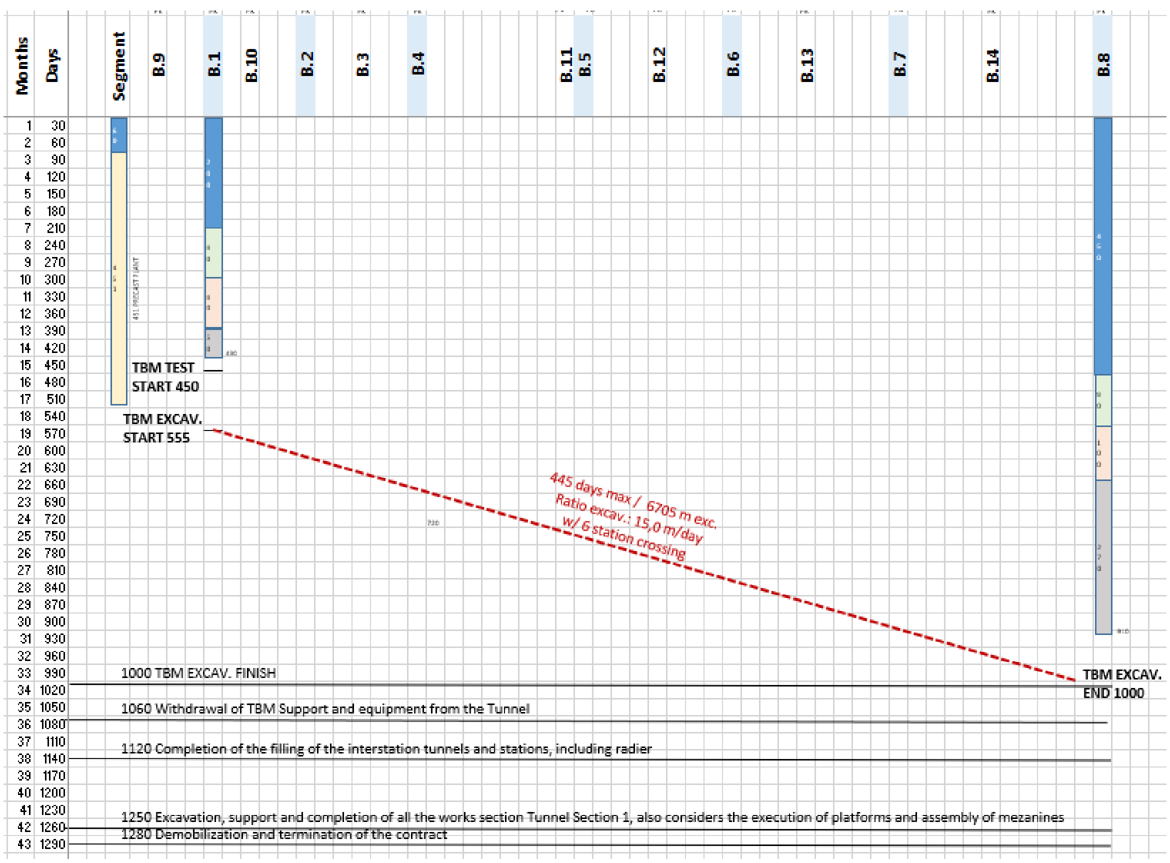
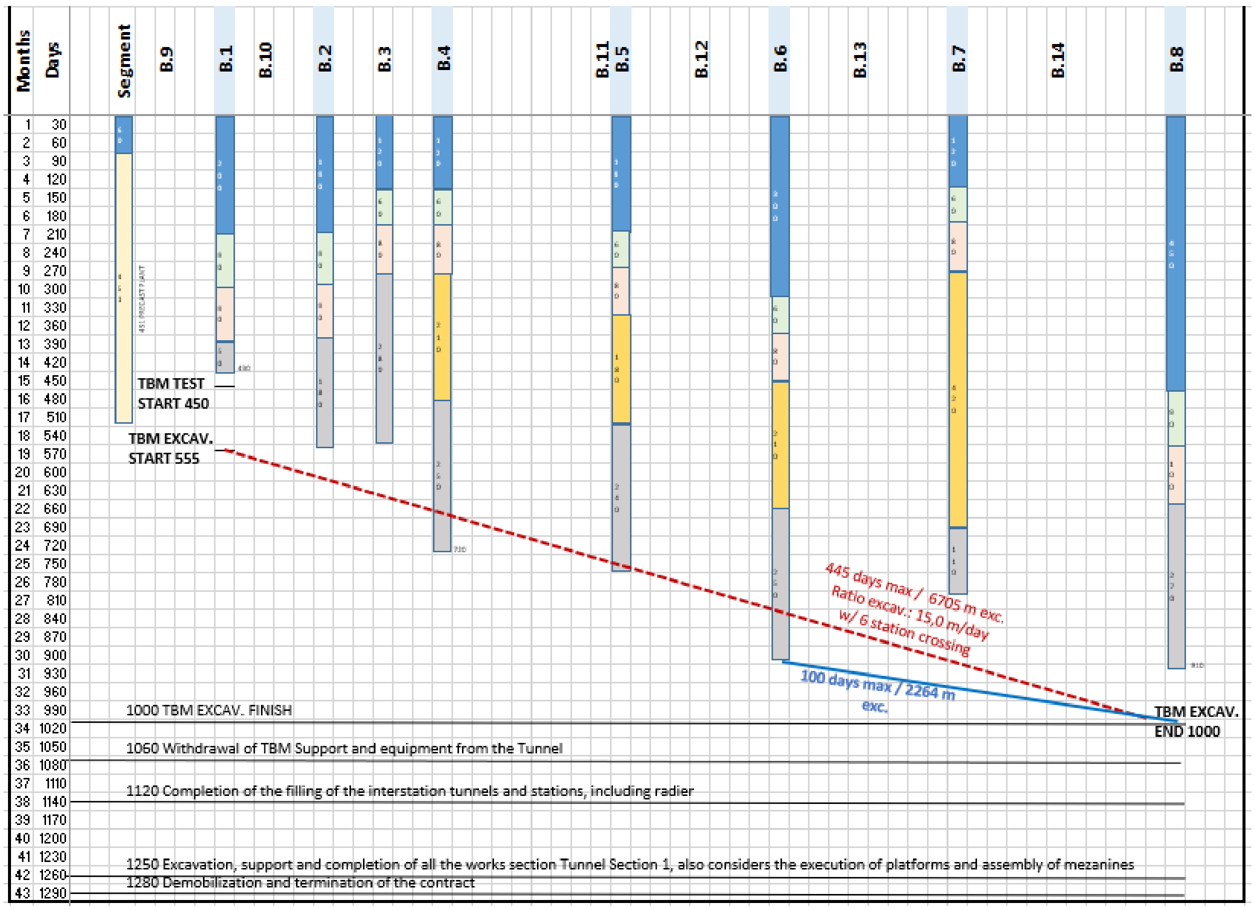


Figure 54 Preliminary Construction Schedule. Source: Geodata

Using the chart above a TBM advance rate ratio of 15m/day was needed to finish the total tunnel excavation respecting the milestones in a duration of 445 days knowing that the excavation length is 6705 meters. During the excavation process the TBM should encounter a total of 6 stations crossings, so the milestones related to each station had to be added into the chart and the output is reported below:



Legend	
Deliver of the lands from Metro	
Shaft start	
Shaft fihish	
Cradle finish, considers the completion of the civil works associated with the cradle, to allow the displacement of the TBM	
Main tunnel finish	

Figure 55 Construction Schedule including Stations Milestones. Source: Geodata

As shown in the legend the milestones of each station included the land delivery, construction, and the cradle completion for the TBM crossing.

Hence, based on the chart results in some stations the cradle formulation was not ready at the time the TBM was supposed to be crossing. So, in order to solve this challenge, the TBM advance rate had to be modified in a way that the TBM arrive to the station at the allocated time but still respecting the TBM excavation end milestone. The TBM advance rate had to be reduced to 9.36 m/day before B.4 station, increased to 16.09 m/day between B.4 and B.6 stations, and increased to 22.64 m/day from B.6 till B.8 station. The chart below summarizes the project milestones and the TBM advance rates needed to respect those milestones.

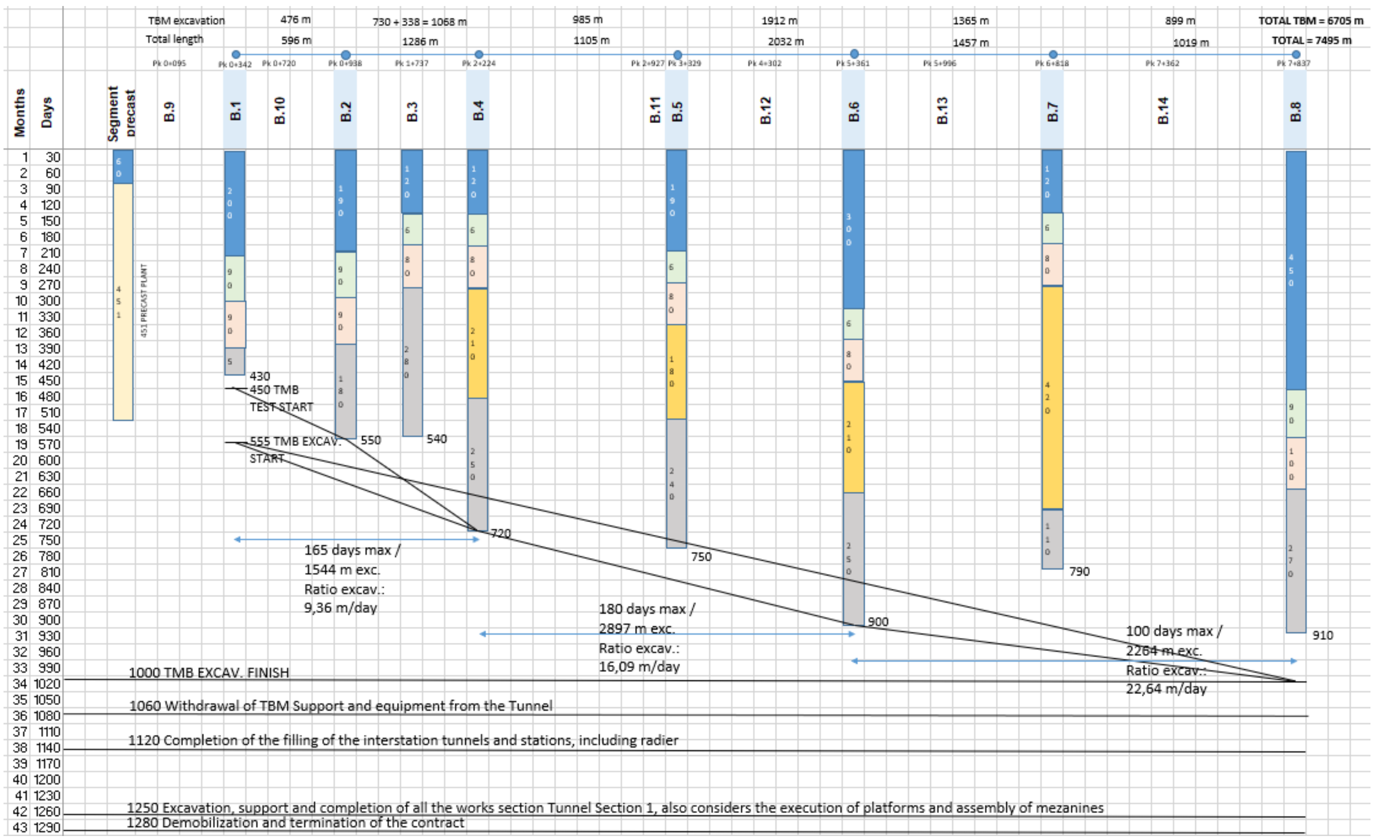


Figure 56 Construction Schedule Respecting Project Scheduled Milestones Source: Geodata

However, a TBM advance rate of 22.64 m/day was considered unfeasible by Geodata, so consequently the project construction timeline was further updated in a way to respect the project milestones following the most economic strategy. The modifications performed to the construction timeline included crashing the schedule of all of the metro stations hence assuring that the station cradle will be ready for the TBM crossing at a date earlier than what was assigned by the client in the contract milestones document. Moreover, the TBM advance rate between different stations was tailored to respect the date in which the cradle in each is station is ready.

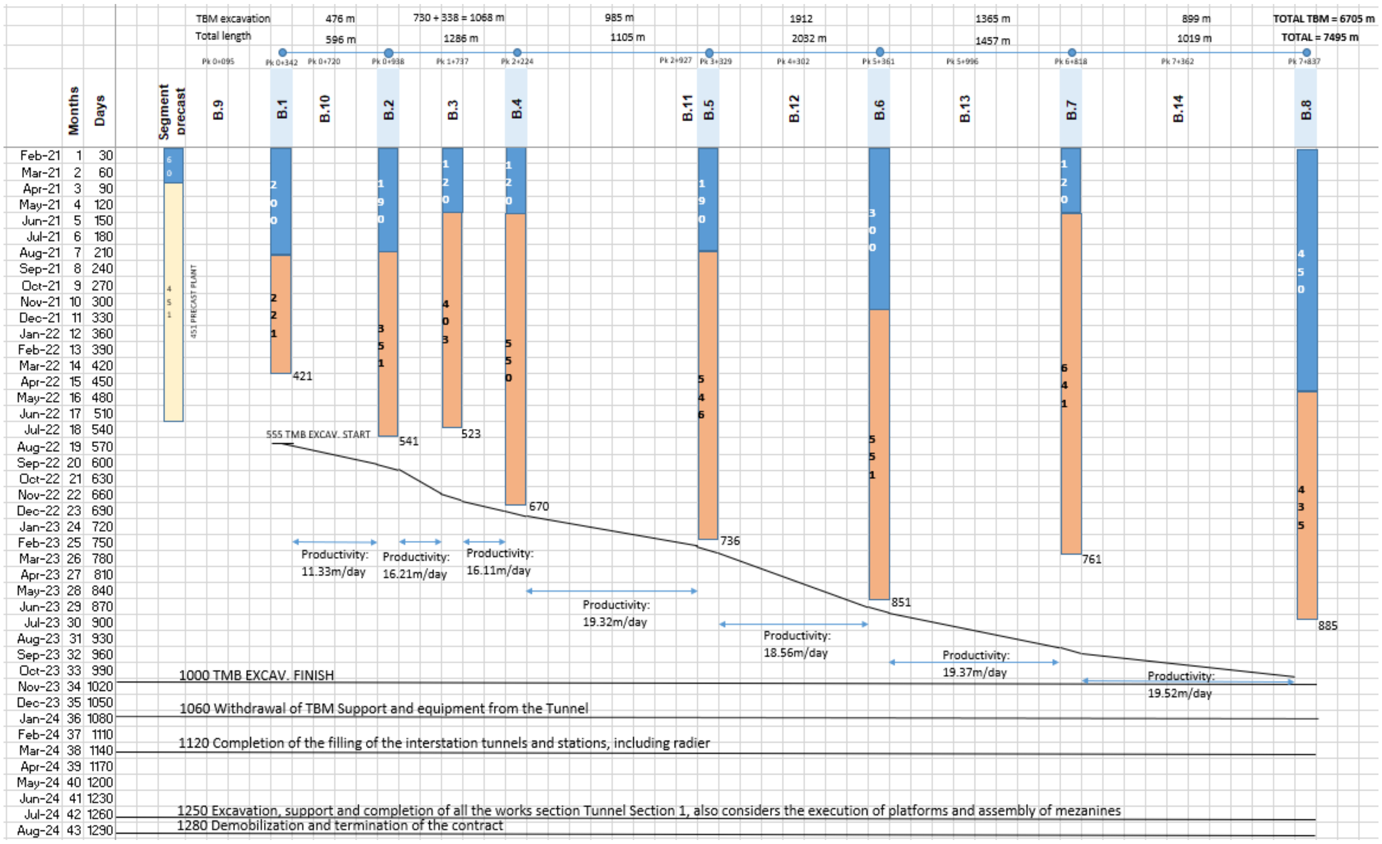
A summary of the final modifications done to the construction timeline will be reported in the tables and the time space diagram below:

Table 19 Stations' Schedule Crashing

Station	Land available	Excavation starts	Cradle ready for TBM Crossing	Calendar days	Land available	Total [days]
B.1	Sunday, August 22, 2021	Sunday, August 22, 2021	Thursday, March 31, 2022	221	200	421
B.2	Thursday, August 12, 2021	Thursday, August 12, 2021	Friday, July 29, 2022	351	190	541
B.3	Thursday, June 3, 2021	Monday, August 2, 2021	Monday, July 11, 2022	403	120	523
B.4	Thursday, June 3, 2021	Monday, August 2, 2021	Monday, December 5, 2022	550	120	670
B.5	Thursday, August 12, 2021	Tuesday, September 28, 2021	Thursday, February 9, 2023	546	190	736
B.6	Tuesday, November 30, 2021	Saturday, January 29, 2022	Sunday, June 4, 2023	551	300	851
B.7	Thursday, June 3, 2021	Sunday, July 18, 2021	Monday, March 6, 2023	641	120	761
B.8	Friday, April 29, 2022	Thursday, June 2, 2022	Saturday, July 8, 2023	435	450	885

Table 20 Interstation TBM Tunnel

From	To	Distance [m]	Duration [days]	Productivity [m/day]	Start	End
B.1	B.2	476	42	11.33	Friday, August 5, 2022	Friday, September 16, 2022
B.2	B.3	729.3	45	16.21	Thursday, September 29, 2022	Sunday, November 13, 2022
B.3	B.4	338.3	21	16.11	Thursday, November 24, 2022	Thursday, December 15, 2022
B.4	B.5	985.51	51	19.32	Wednesday, December 28, 2022	Sunday, February 19, 2023
B.5	B.6	1911.9	103	18.56	Thursday, March 2, 2023	Wednesday, June 14, 2023
B.6	B.7	1336.5	69	19.37	Sunday, June 25, 2023	Saturday, September 2, 2023
B.7	B.8	898.1	46	19.52	Wednesday, September 13, 2023	Tuesday, October 31, 2023



Legend	
Deliver of the lands from Metro	
Duration from land deleviry till the time the cradle is ready for the TBM crossing	

Figure 57 Updated Time Space Diagram

In addition to the stations milestones the construction schedule was also linked to the segments' production schedule and MSV fleet capacity. To respect the milestones and the increased advance rate beyond B.6 station the segments' production rate had to also be increased into two shifts instead of one and the MSV fleet had to be increased into two MSVs instead of only one.

In conclusion, the 4D simulation was prepared based on the client's contract documents, thus all decisions taken in the formulation of the construction timeline were tailored to meet the project requirements.

8.2 5D Cost

To interpret the output of the 5D simulation an article was used to get familiar with the tunneling costs that can be compared with geodata's cost estimations. The article name is "Advantages and limitations of mechanized excavation: when with a machine and when without."

Several charts were reported in this article that served as indication for the TBM costs. For instance, the chart below plots the TBM diameter versus the value of investment in millions of euros for a 6 km tunnel. In our case the TBM's diameter is 9.8 meter so the value of the TBM investment is supposed to be approximately 21.6 million euro. (GRANDORI, 2017)

In our case the tunnel length is 6.77 km so if we consider a linear increase in the investment cost as tunnel length increase the expected investment should be 25 million euro. However, the estimated investment cost by geodata for the TBM is approximately double due to many factors such as the type of the TBM used, the treatment and transport systems of excavated materials, and the location of the construction site.

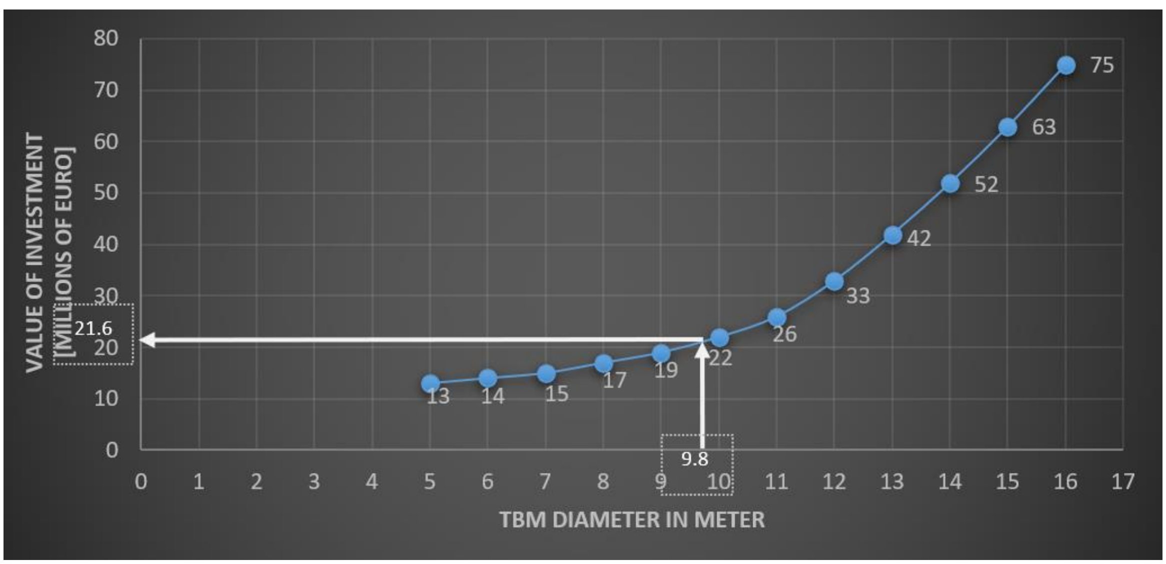


Figure 58 Value of the investment in equipment in relation to the TBM diameter

Another important chart gives an indication on the cost per linear meter of excavation and prefabricated lining based on the tunnel diameter and length. In our case the tunnel excavated using TBM length is 6.77 km with a diameter 9.8m hence the cost per linear meter of excavation and prefabricated lining is expected to be 14,000 euro/meter. (GRANDORI, 2017) Hence, comparing the expected cost with that estimated by Geodata it is a higher by a range 20-30%.

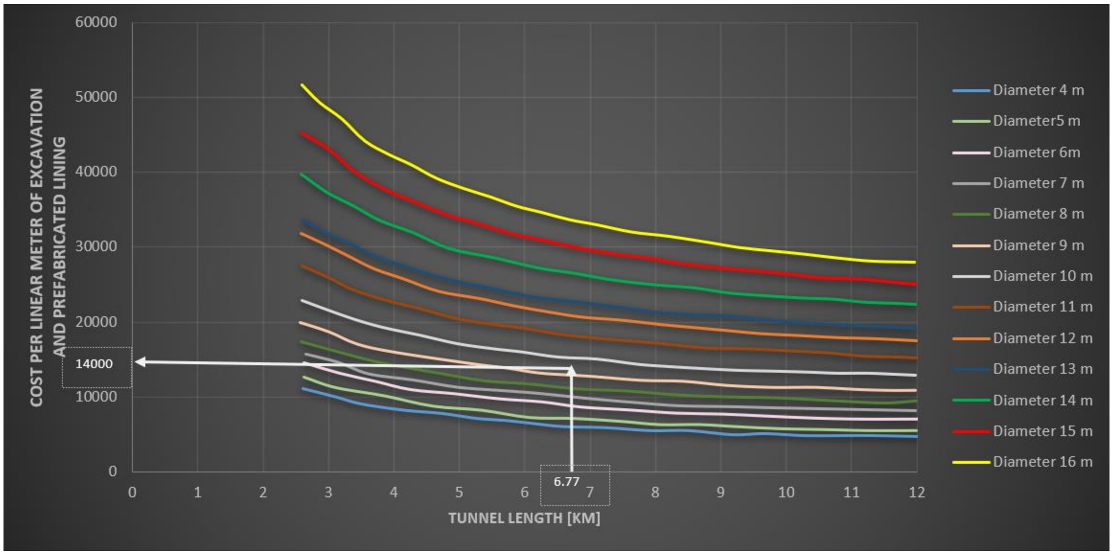


Figure 59 Mechanized excavation - Construction cost variation with the length of the tunnel.

Moreover, a chart showing the tunnel cost per linear meter based on the average daily production rate and TBM diameter was used. Based on Geodata's advance rate estimates, the daily production rate would vary between 11.3 and 19.5 m/day. Therefore, the expected tunnel cost per linear meter is between 15000 and 16000 euro/meter. (GRANDORI, 2017) The expected linear cost is higher than that estimated at Geodata.

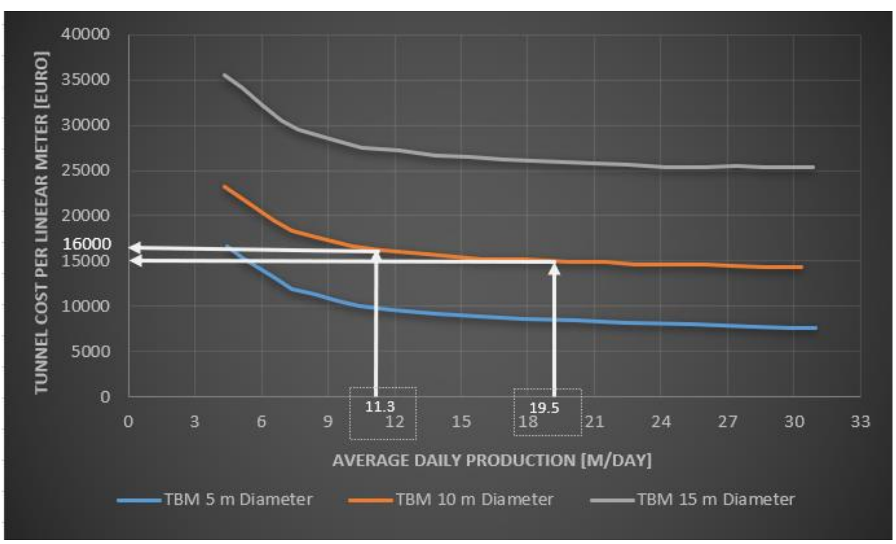


Figure 60 Mechanized Excavation - Construction cost variation with average production

Finally, a histogram showing the distribution of the costs between fixed and variable costs based on the production rate was reported. (GRANDORI, 2017)

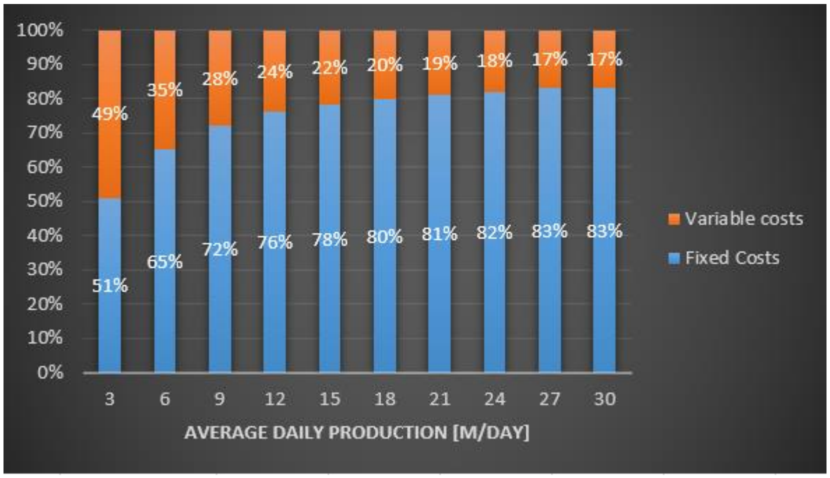


Figure 61 Mechanized excavation - Incidence of fixed costs and variable costs as the average daily production varies per tunnel with a diameter of 10 m.

Since the estimated production rate by Geodata is between 11.3 and 19.5m/day. Thus, using the histogram, the TBM variable costs will vary between 25% and 20%. Therefore, the TBM will be operating within the optimal production since the fixed costs are highly predominant.

At the end of the cost estimation some charts were created in order interpret the TBM costs. For example, a pie chart was created to show how the total TBM cost was distributed and that the highest percentage goes for excavation as shown below.

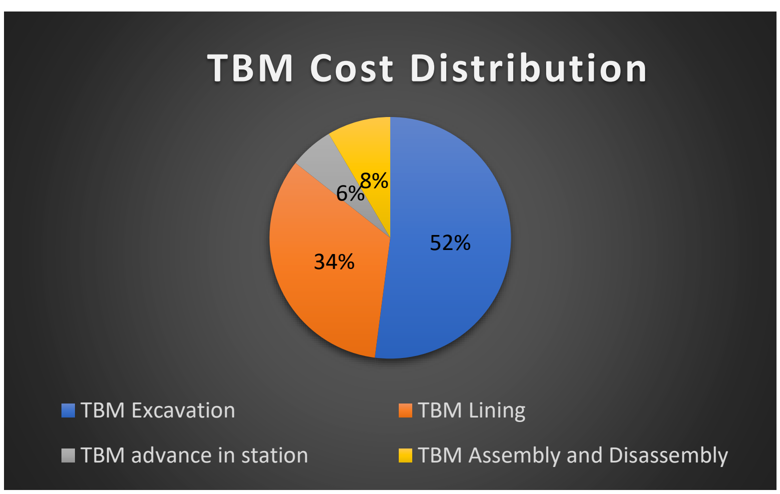


Figure 62 TBM Cost Distribution

Another significant graphs that were created were labor, equipment, material, and subcontractor excavation unit costs as a function of the tunnel length. Those graphs are reported below. They show that the TBM excavation labor and equipment costs will decrease along the tunnel length, due to the effect of the TBM learning curve that was discussed earlier. However, the material and subcontractor unit costs are not linked to the TBM learning curve.

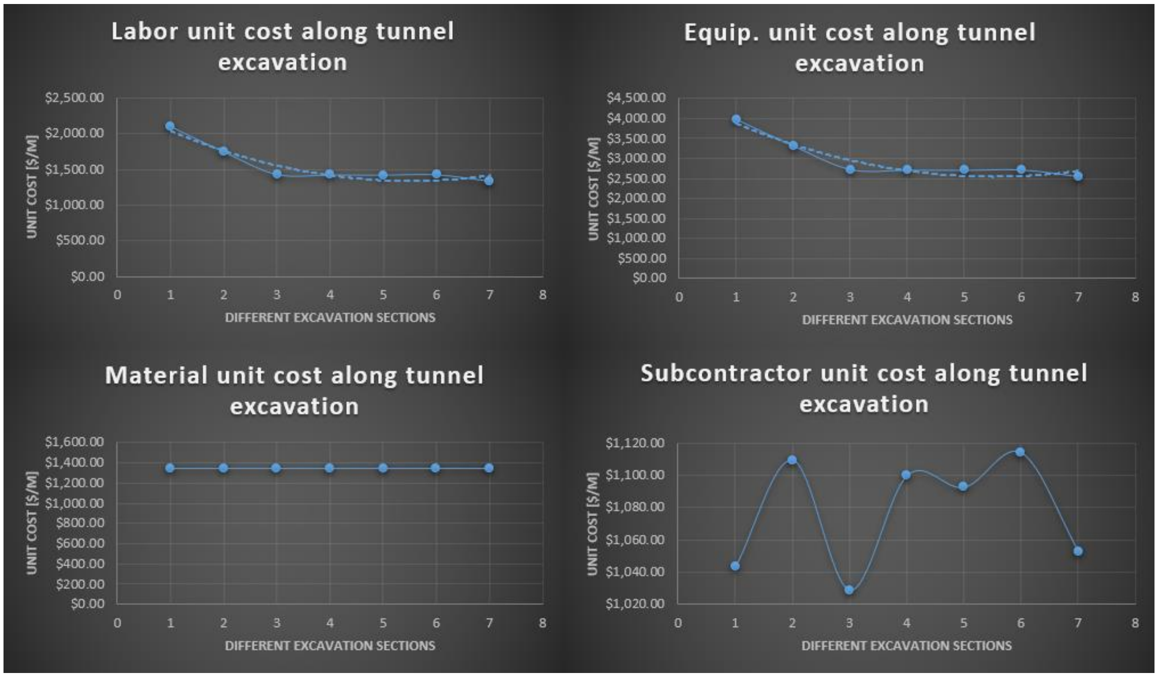


Figure 63 Tunnel Excavation Unit Costs Variations Along Different Sections

Furthermore, other pie charts were prepared to represent the cost subdivision between workforce, equipment, materials, and subcontractors for different TBM activities.

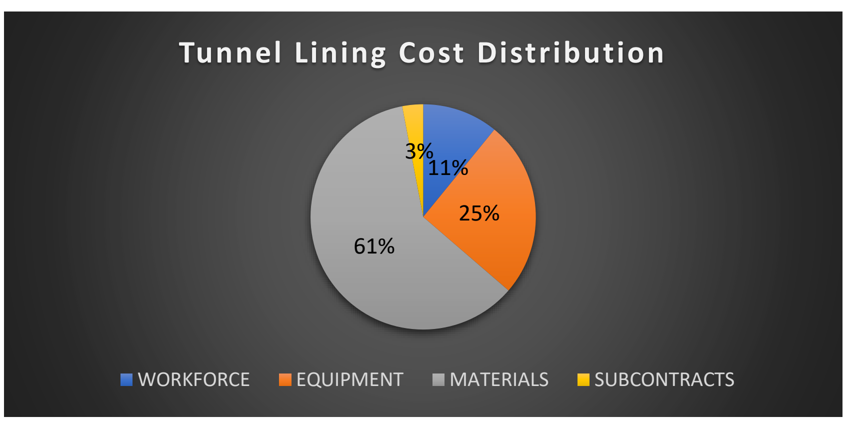


Figure 64 Tunnel Lining Cost Distribution

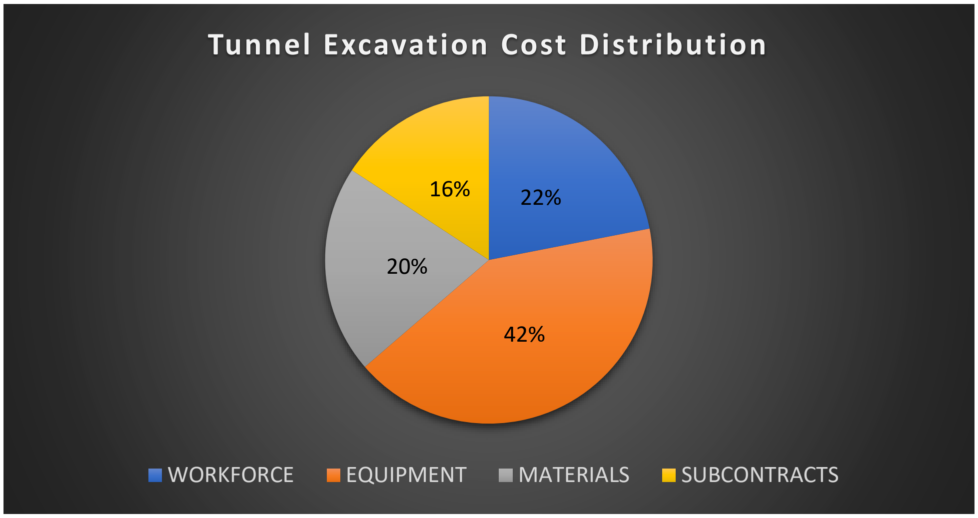


Figure 65 Tunnel Excavation Cost Distribution

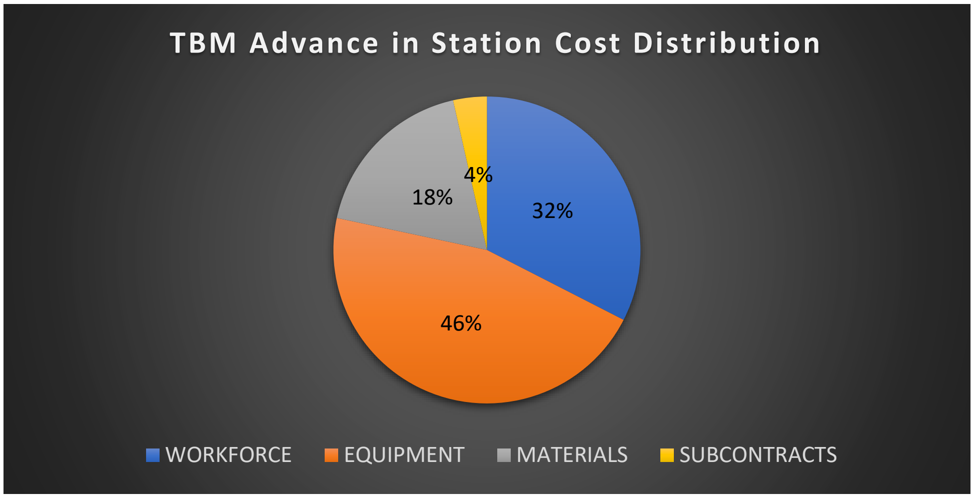


Figure 66 TBM Stations Crossing Cost Distribution

Analyzing the above pie charts, it is evident that for the TBM excavation and stations crossing the highest cost is that of the equipment which is mainly the EPB machine and the Cradle. However, for the tunnel segmental lining the highest cost is due to the material which is mainly prefabricated concrete segments and its accessories.

9. Conclusion

In this work construction scheduling, cost estimation and finally BIM modeling were performed at Geodata's offices for a metro project during its bidding phase.

The BIM literature review sets the necessary technical knowledge to understand the technologies under study and paved the way for the building of the case study.

This study aimed to test the application of BIM in real life underground construction projects. Based on the output of the BIM methodology in this real case study, it can be concluded that investing in BIM should be taken into consideration by every construction firm due to its numerous advantages in the construction process especially reflecting a better project quality at the lowest possible time and cost. The 4D/5D simulation results prove the importance of visualizing the data which improves the contractor's ability to interpret them more certainly, in addition to comparing several construction scenarios.

The methodology followed in this case study was based on the use of three different Autodesk software Revit, Naviswork and AutoCAD, in addition to Microsoft project and Microsoft excel. Hence the interoperability between different software was proven to be efficient and the output simulations at the end of the methodology resulted in reliable data that was of great benefit in the bidding process done by Geodata. Therefore, the methodology conducted in this report turned be a successful technique that can be used to transfer a 3D BIM model into a 4D/5D BIM model. Based on this conclusion, contractors may consider this methodology as a technique to integrate BIM into their work and benefit from its features. One suggestion for further studies is to consider different software available in the market while applying the methodology to test how effective interoperability can be if different software were used. An example of well know software that can be tested are Primavera for construction scheduling instead of Microsoft Project and Synchro for the preparation of the 4D and 5D simulations instead of Navisworks.

Furthermore, the visualization of the 4D/5D BIM model in this study was done in the form of a simulation, however one way to future develop this methodology is by introducing augmented reality. “Augmented Reality (AR) displays present computer-generated renderings within the context of the user’s real-world environment.” (Zollmann et al., 2012, p. 170) Thus, the future development is to visualize the project construction process versus time in an AR view. “By registering the 4D visualization with the real world, the user can inspect changes in relation to the real-world context.” (Zollmann et al., 2012, p. 170)

In conclusion, the implementation of BIM in all construction works will become compulsory in most of the countries worldwide very soon, therefore all construction firms should start investing in this application to guarantee their position in the future market. Moreover, BIM application have proven it significance in the construction field in many aspects associated to quality, cost, time, environment, and facility management.

References

- AHMED, S. M. A., EMAM, H. H. E., & FARRELL, P. F. (2014). The First International Conference of the CIB Middle East and North Africa Research Network (CIB-MENA 2014). BARRIERS TO BIM/4D IMPLEMENTATION IN QATAR, 551–554. (accessed 31 Dec 2020) https://www.researchgate.net/profile/Assem-Al-Hajj/publication/316091492_A_Measure_of_IAQ_Impact_on_Employees%27_Productivity_in_the_UAE_A_Case_Study/links/58efe5e6aca27289c20fd113/A-Measure-of-IAQ-Impact-on-Employees-Productivity-in-the-UAE-A-Case-Study.pdf#page=551

- Bergin, M. B. (2012). A Brief History of BIM. Arch Daily. (accessed 20 Jan 2021) https://www.archdaily.com/302490/a-brief-history-of-bim

- BIM Forum (2013), Level of Development Specification, www.bimforum.org/lod (accessed 20 Jan 2021)

- Choge, J. K. & Muturi, W. M. (2014). Factors affecting adherence to cost estimates: A survey of construction projects of Kenya National Highways Authority. International Journal of Social Sciences and Entrepreneurship, 1 (11), 689-705. (accessed 4 Jan 2021) http://ijsse.org/articles/ijsse_v1_i11_689_705.pdf

- Ciribini, A. C., Ventura, S. V., & Bolpagni, M. B. (n.d.). Informative content validation is the key to success in a BIM-based project. Agenzia Entrate. Retrieved December 27, 2020, https://www.agenziaentrate.gov.it/portale/documents/20143/325391/Informative+content+en_ENG+BIM-based.pdf/3e9e830f-4f53-5f20-7480-316ea99ae16a#:~:text=requiring%20BIM%20have%20been%20set%20up.&text=In%20order%20to%20guarantee%20reliable,Clash%20Detection%20and%20Code%20Checking.

- Erdoğan, C. E. (2016, June). Analysis of the EPB-TBM Excavation Parameters Used in a Tunnel Construction in Istanbul. Cemalettin Erdogan. (accessed 4 Jan 2021) https://www.researchgate.net/publication/308811702

- GRANDORI, R. G. (2017). Vantaggi e limiti dello scavo meccanizzato: quando con la macchina e quando senza. In GALLERIE E GRANDI OPERE SOTTERRANEE: Vol. n. 124 (pp. 39–44). REMO GRANDORI.

- Hall, J. H. (2018, July 27). Top 10 Benefits of BIM in Construction. AUTODESK BIM 360. (accessed 28 Jan 2021) https://bim360resources.autodesk.com/connect-construct/top-10-benefits-of-bim-in-construction

- Peila, D. P. (2019). Segment Lining. (accessed 9 Jan 2021) https://didattica.polito.it/pls/portal30/gap.pkg_guide.viewGap?p_cod_ins=01PPKMX&p_a_acc=2021&p_header=S&p_lang=IT

- R. T. Tatiya, Surface and Underground Excavations Methods, Techniques and Equipment. Netherlands: CRC Press/Balkema, 2013.

- Smith, P. S. (2015). Project cost management with 5D BIM (No. 29). (accessed 12 Jan 2021) https://opus.lib.uts.edu.au/bitstream/10453/41667/1/Smith-Procedia-BIM.pdf

- Tulenheimo, R. (2015). “Challenges of Implementing New Technologies in the World of BIM.” 8th Nordic Conference on Construction Economics and Organization. Procedia Economics and Finance, Volume 21, 2015, Pages 469–477.

- Turco, M. T. (2015). Representing and managing Real Estate: BIM for Facility Management. Representing and Managing Real Estate: BIM in Facility Management, 31–45. https://doi.org/10.14609/Ti_2_15_2e

- Twin, A. T. (2021, January 3). Non-Disclosure Agreement (NDA). Investopedia. (accessed 9 Jan 2021) https://www.investopedia.com/terms/n/nda.asp

- Wais, A. W., & Wachter, R. W. (2014). Predicting the Learning Curve in TBM Tunnelling, 143–154. (accessed 4 Jan 2021) https://silo.tips/download/15-predicting-the-learning-curve-in-tbm-tunnelling

- Zollmann, S. Z., Kalkofen, D. K., Hoppe, C. H., Kluckner, S. K., Bischof, H. B., & Reitmayr, G. R. (2012). Interactive 4D overview and detail visualization in augmented reality. International Symposium on Mixed and Augmented Reality (ISMAR), 167–176. https://doi.org/10.1109/ISMAR.2012.6402554

Appendices

- Appendix A: BIM models validation Excel files.
- Appendix B: Some models' Construction Schedule in Microsoft Project files.
- Appendix C: Models' 4D simulations videos.
- Appendix E: Models' 5D simulations videos.

Given that this is the public version of the thesis, appendix D will not be attached in this report due to the confidential cost data it includes. However, it is included in the thesis confidential version. Moreover, appendices A, B, C and E are modified to exclude all confidential data.