Study of BIM applied to Geotechnical Project

A 5D/BIM Approach

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Abstract

The construction industry is traditionally a labor-intensive activity with a productivity ratio below other sectors. Today, in the digital age, new Information Technology solutions are being applied to different activity sectors and turning processes more efficient. In the Architecture Engineering and Construction segment, also new methodologies are being implemented. It’s the case of Building Information Modeling (BIM), a methodology that can bring advantages as a support for project’s development, based on the creation of a parametric model as a repository for the project information. This information will help in the project’s documentation, in construction planning support, in quantities measurement or in cost control activities.

Although, companies are struggling to take full advantage of BIM potential, mostly using it as a tri-dimensional representation tool. Also, some specific engineering sectors as the geotechnical engineering are lagging behind in BIM implementation. The geotechnical engineering is known by its risk and uncertainty and can take benefits from this approach.

The purpose of this research is to investigate the use of less implemented BIM capabilities for the specific case study of a geotechnical project. This document will approach BIM use for a geotechnical project development, from the conception to the pre-execution. For this, a 3D/BIM model will be created and then, used for scheduling, quantities measurement, and costs control activities, generating the 4D and 5D models. Several software tools will be used, testing the interoperability among different platforms.

Keywords: BIM, Geotechnical Engineering, Construction Management, 4D/BIM, 5D/BIM.
Resumo

A indústria da construção é caracterizada por mão-de-obra intensiva e índices de produtividade relativamente baixos. Atualmente, num contexto digital, novas soluções de tecnologia de informação têm sido aplicadas a diversas áreas de atividade, tornando os processos mais eficientes. Também no sector da Arquitetura, Engenharia e Construção novas metodologias têm vindo a ser aplicadas, como é o caso de Building Information Modeling (BIM), uma metodologia que introduz vantagens no desenvolvimento de projetos, tendo por base a criação de um modelo paramétrico digital que funciona como arquivo de informação. Esta informação contribui posteriormente para a produção de documentação, planeamento de obras, medição de quantidades, ou controlo de custos.

No entanto, as empresas têm demonstrado dificuldade em retirar todo o proveito da implementação BIM, utilizando-a majoritariamente como ferramenta de representação tridimensional. Também alguns sectores da construção, como a engenharia geotécnica, têm indicado algum atraso na sua implementação. A geotecnia é caracterizada pelo seu grau de risco e incerteza e pode retirar vantagens desta metodologia.

O objetivo desta dissertação é abordar o uso de ferramentas de base BIM aplicadas a um caso de estudo de um projeto geotécnico, desde a sua concepção até à pré-execução. Nesse sentido, é inicialmente criado um modelo 3D/BIM, o qual é utilizado como suporte ao planeamento da construção, à medição de quantidades e ao controlo de custos, criando-se assim os modelos 4D e 5D do projeto. Neste estudo, são utilizados diferentes softwares, sendo analisado o nível de interoperabilidade entre plataformas de trabalho.

Palavras-chave: BIM, Engenharia Geotécnica, Gestão da Construção, 4D/BIM, 5D/BIM.
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1 INTRODUCTION

The digitalization process of the industry is a nowadays reality. Concepts like cloud computing, big data, and the internet of things are creating a new industrial revolution. The once standardized industry is now giving place to a more efficient customized production. This digitalization process has the potential to be especially positive for the Architecture, Engineering, and Construction (AEC) sector, where the production process is traditionally a project type characterized by (Russell & Taylor, 2011):

- unique types of products;
- an unstable demand;
- a specialized type of work;
- a labor-intensive work, done by craft persons.

1.1 Background

This paradigm shift is also affecting the AEC sector. There is a concept emerging called Building Information Modeling (BIM) that is changing the workflow of the project development. The BIM concept is a methodology and a framework that is based on the use of parametric elements that include, not only a tri-dimensional geometry but also other useful information for the whole building’s lifecycle, from the conception to the exploitation, and its deconstruction.

This methodology promotes an early stage design team-up with an improved collaboration among the different project’s stakeholders. The collaboration is guaranteed by a high degree of interoperability – the capacity of seamlessly exchange information between different platforms. One key benefit is the time saved in the production of project’s documentation that can be used to improve the engineering solutions.

Regardless its potential, the implementation of BIM has been uneven across different regions. Some countries already acknowledge its potential and created norms and regulations to promote its implementation. In Portugal, only the first steps in BIM implementation are being given. Some national companies have been already investing in BIM implementation. But there are some branches of engineering where its use was yet barely explored, as the case of the geotechnical projects.

Many projects have a geotechnical component that require solutions for excavation containment and the use of different types of retaining structures. This kind of projects are based on data obtained by geotechnical prospection and the degree of uncertainty is high. Another characteristic of this sector is the risk associated for both the construction staff and for the structural integrity in case of failure or collapse of this kind of geotechnical structures. This makes the underground construction both a physical and a financial risk (Sterling, 2017).
Besides this, the geotechnical projects need an early constant coordination with the structure and architecture disciplines. This process of interdisciplinary collaboration must be fluent in order to increase the project’s delivery time. The development of collaborative projects, involving different disciplines, is one of the most recognized positive aspects of BIM implementation.

Research suggests that companies are having trouble to take benefits from BIM capabilities as a tool for project management and to use its scheduling and budget management potential. This research will then focus on how the BIM methodology can be applied to a geotechnical project, from the design stage till the pre-construction stage. The advantages and shortcomings of BIM methodology as a base for the project design and the construction management will be investigated, in the specific case of the geotechnical project. This research will be based on a real study case of a project for the execution of an underground parking lot in Lisbon city.

1.2 Objectives

There are not many studies available regarding the use of BIM on its scheduling and budget management dimensions (4D and 5D). The time variable applied to the tri-dimensional (3D) parametric elements can be a tool to help prepare the construction stage. The BIM potential to relate the cost information with the parametric elements seems yet to fully explore. Adding the budget information to the time variable, with facilitated bidding and tendering capabilities, can potentially help construction managers to attain a leaner construction process.

There is also lack of research regarding BIM applied to the geotechnical projects. Considering the characteristics of uncertainty and the need for early and constant interdisciplinary coordination with other project specialties, it can be important to study if BIM can bring advantages to this particular sector.

This study will first focus on the tri-dimensional parametric modeling of a retaining structure for an underground parking lot. Then, with the geometry defined, the interoperability will be tested with the connection to a structural analysis software. With the completion of the 3D model, the study of BIM will be approached to the pre-execution stage, regarding the planning and budget analysis. The execution will be planned and the outcoming schedule will be linked to the geometric elements. This will allow the generation of an construction process simulation. Finally, the construction cost will be associated to the geometric objects, using a construction management software compatible with BIM. This will allow the integration of the project design, the construction planning and the construction budget in the same platform, and some available construction management analysis tools will be tested. During the process, the interoperability will be tested among different platforms and file formats.

This work is expected to be a prove of concept of BIM as a supporting tool for planning and budget management, demonstrating its applicability to geotechnical projects. Across this document it is demonstrated the capacity of this methodology to be a promoter of efficiency and productivity in the different stages of project development. It is intended to be a contribute to the industry in direction towards achieving a more competitive and digitalized production in the AEC sector.
1.3 Document’s Structure

This document will be divided into five chapters, being the first chapter regarding the introduction and background of the research.

The second chapter describes the state of the art concerning the BIM methodology. It starts describing some of the current issues of the construction industry - mainly addressing its lack of productivity and digitalization - and how can BIM help to tackle some of them. In the same chapter, the BIM methodology is defined referring different authors and some of its characteristics are exposed, namely the "nD" models, the collaboration and the interoperability capacity. References to BIM methodology implementation and its maturity at the current stage, are made. To finalize the chapter, some of the capabilities for the construction and management are mentioned.

The third chapter introduces the case study that will be the target of BIM methodology application across the following chapters. The geotechnical solutions for the future infrastructure are made here including the materials, constructive methods, and other project related issues. Then, the generation of the 3D/BIM model for the geotechnical solution for the study case is described. The text exposes the main steps to build the geometric model, using a specific BIM based software. In this model, the topographic surface is modeled along with the representation of the underground geotechnical zones and the structural elements of both the retaining structure and the parking structure. Due to the specificity of geotechnical projects, the editing of some parametric elements was needed and one of them was described in this section. The creation of annotations and creation of sheets is required for all projects delivery and it is shortly addressed here. In the end of the chapter, the 3D model is linked with a structural analysis software and the interoperability was tested between the two platforms.

The forth chapter approaches BIM from the construction management perspective, taking part of the potential to be supporting tool for scheduling and budget management activities. For that, the execution stage is planned, and the established schedule is associated to the geometric 3D elements, in order to create a 4D/BIM model. After that, the cost variable is also added to the elements, and a 5D/BIM model is generated. This model is used for cost control across time and some tools are tested, namely for automated quantity take-off, bidding and tendering, and cost analysis with changes in design.

In the final chapter, a general analysis of results will be made along with the main conclusions of the research and the objectives attained. Suggestions regarding some topics for further development in future research are mentioned here.
2 STATE OF THE ART

Since the industrial revolution, the industry sector developed and innovated. New technologies and management philosophies were implemented to promote increases in the productivity, reducing the production costs through the standardization of processes and mass production, creating economies of scale.

In the construction sector, unlike other manufacturing industries, each project is unique and represents a different final product. The projects are usually complex to manage, with the need of several multidisciplinary technicians to take part. An extensive list of materials and equipment are needed. The production flows are not as clear when compared with other industries.

These obstacles are some of the factors that contributed to the stagnation of the productivity growth in the recent years (Farmer, 2016). There is a clear need for the architecture, engineering, and construction (AEC) sector to catch the pace to the rest of the industry, investing in the digitalization of their production, increasing productivity and reducing the production of waste.

There are signs that the AEC sector is now in a shifting process. Raising trends as the increase in prefabrication adoption, use of methodologies as Building Information Modeling (BIM) and Lean Construction philosophies are consistently being applied to tackle some of the management risks in this industry. In this chapter, the concept of BIM will be defined according to some authorities on the topic, and some of its characteristics and capabilities will be addressed.

2.1 Construction Industry Challenges

Performance issues in construction are not a debate of just nowadays, it has been discussed throughout the 20th century and they are still real nowadays (Koskela, 2000). In 1983, a study was done to find out the reason behind the lack of productivity of the construction sector. It referred that more than the half of the time wasted in construction activities was due to the lack of effective management practices and that it was needed “a more timely and accurate control over design, planning and scheduling, budgeting, procurement, material logistics, and quality assurance” (The Construction Industry Cost Effectiveness Project, 1983).

Another analysis reported the lack of understanding of the client’s needs and the lack of understanding from the client of the possibilities and limitations. This would lead to reduced efficiency at all subsequent stages of the project (Higgin & Jessop, 1965).

Koskela (2000) characterized the features of the mainstream construction as a mixture of the influence of the “T” concept principles and the legacy of the craft period and defined it in three points:

- Separation of the design and construction;
- Procurement through bidding;
- Institutionalized roles and division of work.

Even considering the increasing proportions of preassembled or offsite built components, the construction sector is still labor-intensive (sometimes untrained and unskilled). It is characterized by a low productivity, high uncertainty and a high level of resources wasted.

In the design process, the broadly used CAD 2D systems are error-prone, sometimes due to the difficulty in visualizing 3D elements and detecting clashes. The clashes analyses are very useful in the development of a project, particularly when combining different specialties like Mechanical, Electric, and Plumbing (MEP) with architecture or structure. Besides this, the reliance on 2D models creates the need for at least two drawings of the same piece of the element to represent and interpret it in a tridimensional way (Eastman et al., 1974). The extensive time invested in drawing detailing could be applied for design improvements or for optimization of the construction solutions. These factors contribute to a poor performance in the construction sector as budget and schedule overruns, and reduplication of tasks occur in many projects causing low efficiency.

![Diagram](image)

*Figure 2-1 – Symptoms of failure and poor performance in the construction industry (Farmer, 2016)*

There is a need for the AEC sector to find solutions for these challenges. How to better control of the project and the costs; how to facilitate the production process from the design to the production and the lifecycle; how to increase the collaboration and interoperability among the different disciplines of a project, how to reduce the overlapping and reduplication of work. These are some of the questions the industry is looking for answers.
Regarding the Portuguese case, the recent years showed a productivity stagnation in the construction sector, in comparison with the remaining industries. In 2015 the apparent labor productivity – a measure that relates the added value at factor costs over by the number of persons employed – was about 13.000€ below the total industry average (Figure 2-2).

![Figure 2-2 – Portugal apparent labor productivity in the construction vs total industry (PORDATA, 2016)](image)

In the case of geotechnical engineering, these factors are much related to the lack of timely and accurate data regarding the geological and geotechnical conditions that create difficulties in the project conception stage. Along with these, there are also the factors related to the restraints coming upstream from the other project’s stakeholders. According to the National Economic Development Office (UK), 37% of the schedule overruns had ground problems as a major cause (Grice & Development, 2015).

The Building Information Modeling (BIM) is gaining popularity and increasingly being applied to the AEC sector (Cachadinha & Taborda, 2012). It is seen as a contribution to overcome some of the industry challenges being faced. This chapter will focus on BIM methodology by describing the concept, making a historical background and stating some of its potential and limitations.
2.2 The BIM Concept

In 1974, Eastman identified some of the weaknesses of the architectural drawings at the time. He considered them to have "many inherent weaknesses" and to be "highly redundant". He envisioned what he called at the time a “Building Description System” (BDS):

“Our premise was that a computer database could be developed that would allow the geometric, spatial, and property description of a very large number of physical elements arranged in space and ‘connected’ as in an actual building. (…) The elemental parts of a building would be drawn in by the user or stored in one or more libraries of components. (…) With such a database, qualitative analyses would be similarly facilitated. (…) Visual inspection should be greatly enhanced, due to the infinite range of views available. (…) building code checks on this database have the potential of being automated and violations could be checked for during design regularly. (…) Quantity take-offs and parts lists of mechanical and other fabricated parts could be done automatically.” (Eastman et al., 1974)

More recently, in 2011, Eastman defined the building information model (BIM) as parametric Information Technology (IT)-enabled model supported by a computer that contains the data and geometry required to develop the design, fabrication and procurement activities needed to execute the building (Eastman, 2011).

One of the differences between a CAD 2D model and a BIM model is that editing one of the 2D models implies a change and update in the other views of the model, making it an error-prone process (Azhar, Hein, & Sketo, 2007). In BIM, the models are constructed by assembling parametric objects as walls, beams, and columns while in 2D CAD is constructed by lines, circles or arcs (Mitchell & Schevers, 2005).

Azhar (2011) referred to BIM as an innovative way of virtually design and manage projects is such a way that the predictability of building performance and operation is greatly improved in a computer-generated n-dimensional (n-D) models (Azhar, 2011). And Succar (2009), defined the term BIM associated with multiple connotations and capabilities (Figure 2-3).

Figure 2-3 – Connotations of BIM multiple terms. Source: Succar (2009)
2.2.1 nD/BIM Models

In a first stage of the project, a tri-dimensional parametric model is created. This model is a visual representation of the project, very close to the real one yet to be built. It characterizes spatial relationships, geometry, and geographic information. A BIM based software is used to make the integration among disciplines of the project and to navigate inside the model. This stage is designated by 3D/BIM.

After the 3D/BIM model is generated, it is possible to add a time variable to the tri-dimensional elements, creating a 4D/BIM model. This time information makes possible the visualization of the construction processes through the project schedule, allowing a simulation of the project and a better control of allocated resources and the necessities at different stages of the execution.

When adding the budget information to the 4D/BIM model, a 5D/BIM model is obtained. With the information regarding the cost associated with the parametric objects, it is possible to simulate the cost of different constructive solutions or materials and to have a tighter control over the budget along the execution plan.

The dimension 6D/BIM concerns the energetic and sustainability performance and the 7D/BIM is usually related to facilities management capability (Bazjanac, 2004). The figure 2-4 shows some of the nD/BIM capabilities.

![Figure 2-4 – A proposed description of the BIM “nD”. Source: (Bazjanac, 2004)](image)

According to Construction Research Congress (CRC) for Construction Innovation, BIM methodology has the following key attributes (CRC for Construction Innovation, 2007):

- Objects described with an accurate and robust geometry;
- Comprehensive object properties that can include product manufacturer code, cost, date of maintenance, etc.;
The relationship among objects that can be accessed or analyzed in the simulation;

The model holds all information integrated into a single repository ensuring consistency and accessibility;

Support for facility management providing lifecycle support data from conception to demolition.

2.2.2 Level of Development (LoD)

The Level of Development (LoD) is an important definition of the BIM models. It is related to the level of detail used when building the model. This level of detail is not only graphical but also characterized by the information associated with it such as physical and mechanical material properties, cost or supplier details, among others.

In order to improve the coordination and communication, the American Association of Architects (AIA) developed a classification of the different Levels of Development (LoD) of a model. Table 2-1 lists the considered LoD's:

<table>
<thead>
<tr>
<th>LOD</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>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.</td>
</tr>
<tr>
<td>200</td>
<td>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.</td>
</tr>
<tr>
<td>300</td>
<td>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.</td>
</tr>
<tr>
<td>350</td>
<td>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.</td>
</tr>
<tr>
<td>400</td>
<td>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.</td>
</tr>
<tr>
<td>500</td>
<td>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.</td>
</tr>
</tbody>
</table>

Higher levels of development involve more data input. At the beginning of the project, the LoD required should be defined for each kind of activity (e.g. cost estimation, structural analysis). LoD defines the evolution of the model that, when used correctly, becomes more smart and useful. The LoD play an important role in the scheduling and cost, when the level increases, the estimations become more accurate (Hardin & Mccool, 2015).

Figure 2-5 – Levels of Development (LoD). Source: BIM Modeling (2017)
2.2.3 Collaboration

In the traditional design-bid-build process of construction, the building design development is done by the architect that handles it to the design engineers and all the construction documentation is completed before handing out the documentation to the contractor. With BIM, the project’s stakeholders must team-up together much earlier the same way as a design-build process. The process is no longer linear but collaborative. Any modification imposed by a team member affects the whole model, creating the need for constant communication (Carmona & Irwin, 2007).

In figure 2-6, multiple disciplines and stakeholders that incorporate BIM methodology are described. The diversified information coming from different sources is aggregated in a single BIM model, making it updated and available (Hardin & Mccool, 2015).

![Figure 2-6 – BIM multiple stakeholders. Source: Hardin and Mccool 2015](image)

All the processes, disciplines and parties in a determined project can be incorporated within a single virtual BIM model, allowing owners, engineers, architects, suppliers, contractors, and subcontractors to collaborate with more accuracy and efficiency, compared with the traditional methods. In a company or project, collaboration among different disciplinary teams should increase along with the acceleration of BIM implementation. This will lead to reduced costs, better time management, improved profitability and customer-client relationships (Azhar, 2011).
2.2.4 Interoperability and Standardization

To make an effective collaboration possible, it is required to assemble numerous different blocks of data coming from different disciplines and from a diverse number of platforms. This information should be capable to be integrated into the same environment in such a way that it can be easily accessed and exchanged in an interoperable way.

Interoperability means that different data can be combined and shared in one platform and information can be seamlessly exchanged. This information should be able to come from different parties in the same project, making the cooperation among specialties more integrated across the whole building’s lifecycle. Interoperability means not only an integration of systems but also a collaborative way of working, making it more efficient, predictable and successful (Aranda, Tasbihi, & Turner, 2015).

But interoperability is not only an IT issue, is also a peoples’ issue (Aranda et al., 2015). The technical bonds need to be established alongside with the employees’ culture and values of trust and mutual expectations, improving the way enterprises operate with other enterprises or business units inside the same enterprise. Figure 2-7 represents this interaction (Grilo & Jardim-Goncalves, 2010).

![Figure 2-7 – Interoperability needed at the enterprise level. Source: Grilo and Jardim-Goncalves 2010](image)

This information sometimes comes from different software environments. Building information models should be able to store and transmit data from dissimilar systems and make it work well together (Eastman, 2011). The variety of expertise needed for the current building projects is related to the variety of different systems needed to be integrated. Construction Management Association of America (2015), after interviewing several players in the industry as owners, construction managers, architects, engineers, IT managers and experts in water and transportation, came up with a list of systems used. These are the following (Aranda et al., 2015):

- PMIS – Project Management Information Systems (owner vs. GC centric);
- BIM – Building Information Management software;
- GIS – Geospatial Information Software;
- Asset management software;
• Reporting and dashboarding software;
• Financial software;
• Scheduling software;
• Space planning.

Despite the importance of combining these different systems in a seamless way, full interoperability is still yet to be attained. The National Institute of Standards and Technology prepared a study where it concluded that inadequate interoperability causes inefficiencies that include manual reentry of data, reliance on paper-based information and duplication of functions. These inefficiencies had a cost of almost $16 billion per year (Gallaher, O’Conor, Dettbarn, & Gilday, 2004).

Considering that one of the factors for software purchase is the capacity to communicate with other BIM tools, is predictable to have a consolidation of capacity to exchange different types of data in the future (Hardin & Mccool, 2015).

The CRC for Construction Innovation (2007) launched a report where it was described the application of BIM as a solution for the Sidney Opera House facility management. One of the main issues was to collect diverse types of information from different systems and combine it on a centralized platform. This integration of information included maintenance, budgeting, building condition, technical document data, among others. The integration of information in the same environment had benefits at business and maintenance levels and the combination of this data made possible to obtain improved performance and benchmarking values and offer different services to the end-user (CRC for Construction Innovation, 2007).

Organizations like the BuildingSMART International, the Open BIM Network and the National Building Specification (NBS) are working with software companies and pushing forward towards attaining better interoperable systems. With these efforts was possible to create the Industry Foundation Classes (IFC), a software standard in which several software producers agreed to comply with. The figure 2-8 represents the interoperability standards for BIM.

![Figure 2-8 – Interoperability supported by 3 standards. Source: BuildingSMART (2014)](image)

The interoperability is supported by three different international standards:
• **Industry Foundation Classes (IFC):** The IFC was developed by the BuildingSMART organization and is an open and independent data storage standard. It was first launched in 1997 and since then have been constantly improving and launching new versions, being the most recent the IFC4 certification (BuildingSMART, 2017a). With the use of IFC, electronic building elements can be shared between different software systems and across different segments of the AEC and facilities management. It provides an environment of interoperability among software applications in compliance with IFC, allowing building simulation software to acquire building geometry and other data, and facilitating the direct exchange of input and output with other simulation software. Its open philosophy makes possible to help develop the database over the value chain;

• **Industry Framework Dictionaries (IFD):** While the IFC describes the objects, how they are interconnected and how the information should be exchanged and stored, the IFD describes only the objects themselves with its components, properties, units, and values. The IFD is a reference that collects the terms, vocabulary, and attributes for objects with the purpose of avoiding ambiguities and incompatibilities (BuildingSMART, 2017b).

• **Information Delivery Manual (IDM):** The IDM is the processes component of the interoperability system developed by the BuildingSMART. It captures and progressively integrates the business processes. At the same time, it provides detailed specifications of the information about what a particular user would need at a particular part of the project (Grilo & Jardim-Goncalves, 2010).

### 2.3 BIM Implementation and Maturity

#### 2.3.1 Level of Maturity/Integration

Succar (2009) proposed a linear framework for BIM stages of maturity development. He defined a pre-BIM level stage, three levels of integration, and the goal to attain the Integrated Project Delivery (IPD).

![Figure 2-9 – BIM maturity stages framework. Source: Succar (2009)](image)

He refers to Pre-BIM as the industry stage before the arrival of BIM. The construction industry is characterized by the reliance on 2D documentation to define a 3D reality. In this stage, the workflow is usually linear, and the collaboration is not prioritized. The industry is defined adversarial relationships with contracts promoting risk avoiding and shedding.
The Stage 1 refers to an object-based modeling. In this level, BIM methodology is initiated by the development of a 3D parametric model based on a software tool. Users can generate single-disciplinary models that later are combined and generate documentation from a unique 3D model. The collaborative practices are similar to the Pre-BIM stage.

In Stage 2, a Model-based collaboration is attained. The interoperability concept plays a very important role in this step. Stakeholders from different disciplines can cooperate and different software systems can be used and associated with the same model. Scheduling (4D) and cost estimating (5D) software tools can seamlessly exchange data with the 3D model.

Stage 3 is defined by a Network-Based integration. Here, the models become interdisciplinary “nD” models based on network systems and technologies as cloud computing and big data are used, allowing complex analysis in the first stages of design. It includes lean construction principles, green policies, and a whole life cycle analysis (Succar, 2009).

After the 3rd stage is reached, the conditions for an Integrated Project Delivery (IPD) are created. The IPD is a concept introduced by the American Institute of Architects. This approach is defined by an early
and highly effective collaboration among different players. It “integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction” (American Institute of Architects California Council, 2007).

2.3.2 International BIM Implementation

The international BIM implementation is running at a different pace across different regions. Some countries were able to make a faster integration of BIM, much due to the application of government policies. There are also several institutions that have been supporting the BIM technology development and international implementation, among them are, for example:

- BuildingSMART;
- The American Institute of Architects (AIA);
- The National Building Specification (NBS);
- Building Information Modelling (BIM) Task Group.

North America and the Scandinavian regions are generally regarded as the construction industry leaders in BIM development and implementation (Wong, Wong, & Nadeem, 2011). McGraw Hill Construction found that BIM adoption by project team professionals in the North American industry had grown from 17% in 2007 to 71% in 2012 (McGraw Hill Construction, 2012).

The Scandinavian region has a strong BIM implementation record and development. Public projects have a mandatory use of BIM in countries like Norway, Denmark, and Finland. This provided a further encouragement to BIM transition. The Norwegian government is a strong supporter of BIM and invests heavily in research and development and requires the use of BIM on all the public projects (Smith, 2014b). In Denmark, every project over 5.5 million Euros are required to use BIM, and the information to be exchanged according to the IFC format (Smith, 2014a).

<table>
<thead>
<tr>
<th>Ref</th>
<th>Theme</th>
<th>Objective</th>
<th>Specific actions and timescales</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BIM</td>
<td>5.1 BIM Level 2 mandate</td>
<td>Develop mechanism to evaluate impact of BIM Level 2,</td>
<td>BIM Level 2 mandated on all appropriate centrally funded government construction projects. (2016)</td>
</tr>
<tr>
<td></td>
<td>BIM</td>
<td>5.2 BIM Level 2 communications and best practice guidance</td>
<td>Identify projects for BIM Level 2 best practice case studies.</td>
<td>Disseminate best practice and case studies of BIM Level 2 and extract lessons learnt to drive continuous improvement.</td>
</tr>
<tr>
<td></td>
<td>BIM</td>
<td>5.3 Maturity of BIM Level 2 implementation</td>
<td>Develop a set of BIM Level 2 maturity measures.</td>
<td>Increase maturity of BIM Level 2 implementation across government to a point that supports development of BIM Level 3 with a view to government adoption at a later date.</td>
</tr>
<tr>
<td></td>
<td>BIM</td>
<td></td>
<td></td>
<td>Agreed BIM Level 2 maturity measures. Demonstrable departmental attainment against the maturity measures.</td>
</tr>
</tbody>
</table>
In the United Kingdom, the objective is to make the country the most advanced globally in a relatively short time, to become a BIM global leader (Withers, 2012). To attain this, UK is implementing a program for BIM implementation considered to be the most advanced and ambitious in the world (HM Government, 2012). The table 2-2 describes the current action plan for BIM Level 2 implementation in the UK.

In 2011 the UK government introduced the BIM implementation strategy that required that by 2016, all BIM projects to be modeled on BIM. The objective was to attain a 20% cost cut in the procurement activities (The Infrastructure and Projects Authority, 2016). This strategy introduced a dramatic dynamic in the industry that struggled to find the required technical capabilities to meet those requirements (Smith, 2014a). The figure 2-13 shows the adoption of BIM in recent years.

![Figure 2-13 – BIM adoption over time in the UK. Source: (Waterhouse & Philp, 2017)](image)

2.3.3 BIM Implementation in Portugal

These countries all have in common the investment devoted to research and development activities, and a comparatively high productivity ratio. In Portugal, the lack of competitiveness is much related to budget and schedules overruns that damage the image of both the sector and its professionals (Santo, 2006). The implementation of BIM platforms for public tendering in Portugal would tackle some of the issues faced by the construction industry (Cachadinha & Taborda, 2012).

The first steps to promote BIM implementation in Portugal were given by the Portuguese Technological Platform for Construction (PTPC) that created a workgroup dedicated to the topic, the GT BIM. Also, a multidisciplinary group of designers, academic institutions construction companies and software makers created the BIM Forum Portugal, to help promote and develop the BIM methodology in Portugal and increase the competitiveness of Portuguese AEC enterprises. These two workgroups developed some activities, which, among them, the 1st National BIM Workshop that happened in late 2012 (PTBIM, 2018).
Besides these organizations, there is the “CT197 - BIM”, a qualified organization responsible for developing a strategy for BIM implementation along with its policies and standards. In its recently issued document, “Vision Construction 2020” (Costa, 2018), it was defined some targets for the digitalization of construction sector in Portugal:

- 10% increase in contracts with execution according to the budget and deadline;
- 20% increase in productivity;
- 20% reduction in errors and omissions;
- 20% carbon reduction;
- 10% reduction in operation and maintenance costs.

The “CT197 – BIM” developed some activities as the implementation of the BIM excellence prize, that awards the best BIM practices in Portugal. It also organized the 1st Portuguese Congress on BIM in 2016 and it is currently organizing the 2nd edition of the Portuguese Congress on BIM for the 2018 year.

Despite these efforts, the implementation in Portugal is still far from other countries. The Portuguese market needs to be aligned with this reality, not only the companies, but also public and academic entities.

2.4 The BIM concept applied to the Construction Management

A research from Dodge Data & Analytics revealed that 93% of building owners report projects running over time and 85% say that projects exceeded the agreed budget (Jones & Laquidara-Carr, 2017). According to Carmona and Irwin (2007), a BIM model itself is capable of, not only communicate the design concepts to the owner but can also run the material take-offs for cost-estimation and perform clash detections. This allows a shift in the job site modifications to just model-based corrections, which can dramatically reduce the budget and schedule overruns (Carmona & Irwin, 2007).

Azhar (2011) considered that BIM has the potential to achieve a reduced project cost and delivery time, increasing the quality and productivity. On his research, he concluded that average BIM return-of-investment (ROI) for projects under study was about 634% (Azhar, 2011).

Another change that BIM made possible was the time spent in the various stages of design. With the 3D based parametric modeling, the time required to produce drawing sketches and other construction documentation was reduced. The time spent in the documentation repetitive work was shifted to the full development and improvement of the design solutions (Carmona & Irwin, 2007). This shift allowed more time invested in the designing stage and an early collaboration among parties - and especially the owner – as shown of a crucial importance for the project’s success. In figure 2-14 is represented a graphic describing the influence of overall project cost over the project lifecycle.
In 2016, a study done by Dodge Data & Analytics, in collaboration with Lean Construction Institute (figure 2-15), has examined the project’s performance from the building owners’ perspective. The findings demonstrated a clear difference in the projects’ performance the related to premature project team integration. Over 76% of the best projects that finished ahead of both the schedule and budget were correlated with an early team project integration. They have engaged key stakeholders (owner, architect, general contractor, structural, mechanical, electrical and plumbing contractors) before or during the conceptualization, in the initial stages of the design. Also, collaborative delivery methods like construction manager at risk and integrated project delivery shown correlation with an improved project performance (Jones & Laquidara-Carr, 2017).

A research done on 23 construction projects in 2013 suggested that the return of investment on BIM adoption would be substantial in the long-term. In the same research, the use of BIM presented the following success criteria ranking (Bryde, Broquetas, & Volm, 2013):
For an effective construction management is required an ideal use of the funds available, control the project schedule effectively by controlling the scope of the work and resources, enhancing the project design and construction quality and finding flexibility in contracting and procurement activities (Arditi & Ongkasuwan, 2009)

2.4.1 Prefabrication

The prefabrication applied to the construction has some benefits in terms of productivity and quality of construction. Some of these are, for example:

- produce elements that were fabricated in a controlled environment improving the dimensional and structural integrity;
- increase the efficiency of equipment, material, labor and time savings by assembling the parts on site;
- reduce the onsite resources required, decrease the uncertainty and increase the site safety;
- reduce the waste produced;
- improved seismic structural performance.

A research done on prefabrication demonstrated that it can lead to significant reductions in the schedule and budget (McGraw Hill Construction, 2011). In the same report, 50% of the firms using BIM referred to have a decrease in the schedule of about four weeks or more due to their use of prefabrication (figure 2-16).

![Figure 2-16 – Use of Model-Driven (BIM) Prefabrication. Source: McGraw Hill Construction 2011](image)
With a BIM-based tool, the prefabrication becomes facilitated with the improved visualization and collaboration of the design teams that decide where to “slice” the building into preassembling parts. The process is described in the following steps (Hardin & Mccool, 2015):

1. The building design is done and sent to the fabricator;
2. The building is “sliced” into buildable and transportable parts;
3. Components are sent to engineering for equipment procurement and material ordering;
4. The pieces are laid onto assembly lines;
5. After produced, the components are numbered and shipped according to project schedule;
6. “Slices” are installed on site.

A survey to 582 construction industry players in North America done by McGraw Hill Construction (2012) reported that 81% of the contractors considered that the return-of-investment (ROI) from the use of BIM would be improved by the increase in prefabrication facilitated by the use of BIM tools (McGraw Hill Construction, 2012).

2.4.2 The 4D and 5D capabilities of BIM

As mentioned, BIM is not just a 3D digital representation but it is also a comprehensive database that includes information regarding basic construction management practices such as cost estimating, scheduling control, and procurement orders (Yalcinkaya & Arditi, 2013). BIM is capable to connect structural design, time, and cost-effectively (Gabbar, Aoyama, & Naka, 2004). “The use of BIM allows the efficient development of extremely complex projects in ways that might otherwise not be possible given constraints of site, time or finances” (American Institute of Architects California Council, 2007).

Project managers will play a central role in the usage of BIM on built environment sector projects (Sawhney, Khanzode, & Tiwari, 2017). Not taking advantage of the benefits provided by 4D and 5D BIM models reduces management efficiency and it is detrimental to the overall performance of the project (Yalcinkaya & Arditi, 2013). In table 2-4 is described some of the BIM manager roles.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Project Manager’s BIM Role</th>
<th>BIM applications</th>
</tr>
</thead>
</table>
| Briefing, Inception and Pre-construction | Feasibility analysis (technical and financial) | • BIM adoption question  
• Challenges to BIM adoption  
• Concept-stage BIM  |
|                           | Value engineering                          | Options selection using BIM, Conceptual Estimating Modelling, Energy Analysis, Design Analysis |
|                           | Design management                          | BIM information exchange, 3D (rapid cost feedback to design changes), BIM Coordination |
|                           | Risk analysis and safety                   | Simulation, Virtual Reality (VR) and Augmented Reality (AR)                      |
|                           | Scheduling                                 | 4D Modelling                                                                     |
|                           | Constructability analysis                  | 4D Modelling, virtual mock-ups, VR and AR                                       |
|                           | Procurement [design and construction]     | BIM skills and capability mapping, BIM enabled Supply Chain Management, Constraint Analysis |
| Construction              | Phasing and prototyping                    | 4D                                                                              |
|                           | RFIs and issue resolution                  | BIM information exchange, BIM coordination                                      |
|                           | Change management                          | BIM information exchange                                                        |
|                           | Monitoring and control                     | 4D and 5D, Constraint Analysis, Progress Tracking and Production Planning       |
| Project closure           | Contract and financial closure             | Record model                                                                    |
|                           | Project closure                            | Record model, Asset Information Model                                           |
|                           | Handover                                   | Record model, BIM for FM, Asset Information Management                          |
Due to the foreseeable BIM take-over in construction and design activities, all parts should have a common understanding of the new responsibilities of the construction managers (CM) over all stages of construction. The CM can serve the industry better if they were trained to be effective in BIM environment.

In a study applied to the construction management of a waste-to-energy plant, some advantages were defined as the onsite clash detection and interactivity between elements and subcontractors. Also, the quantity take-off was more accurate and facilitated the management (Silva, 2015).

According to Jrade and Lessard (2015), BIM is an enabler of constructability by improving "technical work at the design stage by creating 3D models that integrate all building’s features and better represents the infrastructure’s requirements. Those models can also be enhanced if linked with the schedule (4D) and costs (5D); the construction can thus be better planned almost entirely at the design phase" (Jrade & Lessard, 2015).

Despite its value, the BIM approach is still barely used as a support platform for the execution stage and the BIM dimensions 4D and 5D are not yet being broadly used in as a current practice. In a research done regarding the supervision of the construction of a water treatment plant, this methodology demonstrated to be useful in the cost control (Barbosa, 2014).

The integration of geometry with schedule and cost in a 5D/BIM model have the potential to be a fundamental value proposition in the future for the construction sector. Although, research suggests that the 5D seamless incorporation is, at this point, still viewed as difficult. Figure 2-17 shows a 5D/BIM model framework.

![Figure 2-17 – BIM 5D data flow. Source: Vico Software](image)

In a survey research done to more than 500 stakeholders from different fields in the AEC sector (2012), the results suggested that constructability analysis and job site planning/logistics are the contractor's top uses when applying BIM methodologies. Although, many users of BIM tools where struggling with the application of 4D and 5D capabilities of BIM. Only 8% of the BIM users replied that the 5D model was easy or very easy to implement. Also, the 4D models have shown some difficulty ratio at this stage, as show in figure 2-18 (McGraw Hill Construction, 2012).
The use of 4D and especially the 5D models could be of a great use for the Quantity Surveyors (QS). Actual methods still rely on 2D CAD drawings to make the quantities take-off, turning it into a particularly error-prone activity in the construction. The incorporation of BIM with a 5D-enabled tool would allow a more efficient and reliable surveying. Despite this fact, there are few levels of engagement of QS with these tools, according to a Royal Institute of Chartered Surveyors (RICS) study (2011). Only 14% of the QS interviewed referred that BIM was the most frequent tool for construction scheduling. The biggest barriers to adopting BIM were cited as the lack of client demand, lack of training, and lack of application interfaces and adequate software (BCIS, 2011).

2.4.3 Synergies between BIM and Lean Construction

Due to the characteristics of the construction industry, the production flow is harder to visualize and consequently increases the uncertainty of the scheduling. With the help of BIM improved models, the Lean Construction implementation can be facilitated, in comparison with the 2D CAD systems.

The Lean Thinking concept aroused in the middle of the XX century and it was first applied to the Toyota Production Systems (Cusumano & Nobeoka, 1998). The idea was to reduce the waste and resources needed in the flow process of production and, at the same time, increase the value for the final consumer.

This philosophy has been consistently studied and applied to the AEC sector in the recent years as a way to increase the productivity and improve the quality of the final product of construction. The Lean Construction concept has characteristics much similar to the ones promoted by BIM methodology and are described as following (Ballard, 1999):

- A clear understanding of the customer needs and of the objectives established of the final product;
- An interdisciplinary developing team;
- Change in the supply chain optimizing quantities and volumes of work;
- Structuring the activities in global processes increasing value and reducing waste.

In 2010, Sacks conducted a research in which was tested a BIM-enabled system based on Lean Construction philosophy called KanBIM. It allowed a clear visualization of the production flow process and a more detailed planning coordination (Sacks, Radosavljevic, & Barak, 2010).
In a study regarding Lean Construction to increase the safety and production for geotechnical works, Flor (2012) mention that the geotechnical works were an important field of study and application of BIM-Lean concepts due to its technical and economic characteristics (Flor, Cachadinha, & Flor, 2012).

Eastman mentioned that BIM facilitates leaner construction in four points (Eastman, 2011):

- A greater degree of prefabrication and preassembly;
- Improvement of workflow stability with the use of 4D and 5D techniques;
- Enhanced teamwork;
3 3D/BIM Model

The creation of a 3D/BIM model is based on a set of parametric elements with a defined position, geometry and with other types of variables associated that can be edited or created. Some examples of commonly used parameters are the cost, the manufacturer, the concrete type, the thermal or acoustic properties, among others.

To build the 3D model it was used the project from a retaining structure case study, mentioned in this chapter. The modeling is based on the available project documentation, including 2D CAD drawings, descriptive memory, and design calculations.

The software used to produce the 3D model was the Autodesk Revit 2018. This software is broadly used in the AEC sector (Waterhouse & Philp, 2012) and it guarantees IFC interoperability with other applications. This software comes with a library of parametric elements and allows the modeling of new ones. Besides, it also provides a free student license for the use of the academic community.

3.1 Case Study

With the urbanization rate and the evolution of the real estate prices in the main Portuguese cities, the underground structures are gaining preponderance. Also, the surface space is consistently being devoted to leisure and public spaces. The number of surface parking lots is, therefore, being gradually replaced by underground ones.

3.1.1 Background and Construction Restrains

This research is based a public underground parking lot project for the Lisbon city. This project includes the excavation and construction of four underground floors and the corresponding exit ramp. In the figure 3-1 is possible to see the project’s deployment area alongside with some of the main construction restraints.

![Figure 3-1 – Case Study site and surroundings. Source: Adapted from Google Maps](image-url)
Some of the restraints to the execution of the excavation and retaining structure are the surrounding streets and infrastructures, especially the future Learning Center of Lisbon University and the Lisbon’s subway line. Due to its proximity, the increase in displacements from the excavation works must be controlled and monitored throughout the execution stage. This is done by the application of an instrumentation plan. The underground services should also be target of surveying, in order to define its precise location and guarantee that they won’t be affected during the execution stage.

The geological and geotechnical conditions were assessed by four Standard Penetration Tests (SPT) and a piezometer, to determine the groundwater level position. After the SPT was done, the underground soil of the site deployment area was divided into four geotechnical zones, according to the geotechnical characteristics of the soil. These zones are shown in table 3-1.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Geotechnical Zone</th>
<th>N_{spt}</th>
<th>Weight (kN/m³)</th>
<th>Angle of Friction (º)</th>
<th>Cohesion (kPa)</th>
<th>Young Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>ZG3</td>
<td>0 – 7</td>
<td>18</td>
<td>24</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Miocene</td>
<td>ZG2A</td>
<td>6 – 26</td>
<td>19</td>
<td>32</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>ZG2B</td>
<td>30 - 45</td>
<td>20</td>
<td>34</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>ZG1</td>
<td>60</td>
<td>20</td>
<td>36</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

### 3.1.2 Construction Technology and Construction Process

The conceived solutions to tackle the above mentioned restraints were a peripheral retaining structure, with the execution of contiguous flight auger piles (CFA) and, in some places, by the execution of king-post walls.

The CFA system adopted included piles with 600mm diameter with a displacement of 1.20m. These piles will have a length of approximately 16.0m to cover the depth of the excavation and an embedment length of 4.0m. The soil between the piles will be covered, after the excavation, by a 4+4cm layer of shotcrete, for stabilization and protection of this soil. Geodrains will be installed with an average displacement of 3.60m at all floor levels to ensure drained conditions and consequently the reduction of the soil pressure on the retaining structure.
The CFA will be held by two levels of temporary ground anchors and steel props, at the corners. At each level, the CFA will be braced by distribution beams and, at the top, by a capping beam.

For the exit ramp of the parking lot and the side adjacent to the future Learning Center, the solution will be the execution of king-post walls. These walls are made by primary and secondary panels which are executed alternately. The primary panels are held vertically by micropiles which are embedded in the bored piles previously executed. Anchors will hold them horizontally.

Regarding the general execution process, it can be shortly described as follows:

a) Survey the neighbor buildings, infrastructures, and diversion of the underground services affected;
b) Preparation of the site and diversion of the traffic from the affected streets;
c) Set up the monitoring devices in the neighboring structures and infrastructures;
d) Drilling and casting of the peripheral CFA piles and underpinning of the “Gare do Arco do Cego” columns;
e) Cleaning of the piles top and execution of the capping beam;
f) Execution of the temporary ground anchors and the corner props;
g) Set up the load cells and execution of tests in the monitored piles;
h) Excavation till the level of the first distribution beam;
i) Installation of geodrains and application of the two layers of shotcrete (4+4cm);
j) Execution of the distribution beam;
k) Execution of the temporary ground anchors and corner props;
l) Set up of the instrumentation devices;
m) Repetition of step i) to l) till reaching the bottom of the excavation level;
n) Execution of the structure, from down to up;
o) Unload the anchors and deactivate the steel props.
3.2 Preparing the Model

The preparation of the model is important and it can avoid time losses and increase the modeling efficiency in the long-run (Thakur & Rao, 2014). The more time is addressed adjusting the template in the beginning, the better the model will respond in the future.

For this project, the units, project phases, and survey points where early defined. There are other settings that can be important to define, according to each project's features. Some settings usually defined are the project location, the characteristic of the different materials, the way how the elements or the annotations will be graphically represented, the files to be linked to the model, among others. These settings can be saved and transferred from other models already produced, this promotes a policy of standardization among the company and can save modeling time.

3.2.1 Units

Since BIM methodology promotes an early stage collaboration among the project participants, it is important to define the units in use for the project and ensure that they will be consistent with the information coming from other sources. In the “Manage” ribbon, the command “Project Units” allows changes in the way values are represented in the project and which units are used. The Revit software comes with millimeter by standard and, in this case, the length units was changed to meters.

3.2.2 Phases

The definition of phases gives the model a time variable for the project. This is done by addressing the information of which construction phase belongs a determined element in the model, and which phase it will be demolished if the case. Having this information associated with the parametric elements will allow a quantity take-off associated with each phase and ease the graphic representation of the model for each defined construction stage. This can be particularly useful for rehabilitation projects, where it is important to represent graphically the existing elements, the ones to maintain, the ones to demolish and the new ones to build.

As the modeling process is based on parametric objects, this kind of information can be added to each modeled element. Revit comes with an “Existing” phase and a “New Construction” phase already created by default. For the case of this project, it will be important to schedule the earthworks for each step of the excavation. The phases can be managed in the command “Phases” in the “Manage” ribbon. It can be added any number of phases and they should be ordered by their correct timeline.

3.2.3 Levels, Project Point and Survey Point

When modeling in Revit, the levels represent reference planes and the parametric elements can be constrained to these levels. These constraints are particularly useful, for example, when changing the elevation of a floor. The elements constrained to that level will adjust accordingly, saving time and
helping to avoid drawing mistakes. These levels can be optionally associated with a plan view that will be available in the “Project Browser”. For this project, the levels corresponding to the various floors reference were created. Figure 3-4 illustrates the aspect after this step.

Figure 3-4 – Levels created for the model

Another feature that the levels provide is the possibility to define its level height according to predefined project points. Revit models come with two points by definition: the “Survey Point” and the “Project Base Point”. They are used to reference the model and cannot be deleted.

The “Project Base Point” defines the origin of the project coordinate system and the “Survey Point” is used to represent a known point in the physical world, for example, a geo-referenced point. They can be used, for example, to set the model to display the elevations according to the sea level or according to a relative elevation.

To align the model in the plan view to the true north or project north and it is particularly important to have the model referenced when importing data from other sources. For coordinated projects, the “Project Base Point” should be set the same for different model files. When combining them, the geometric elements and geographical position will be correctly displayed.

3.3 Topography Surface

Concerning the geotechnical kind of project, it is advisable to start the modeling with the creation of the existing site surface. The topography surface is important to help interpret the construction site. It can facilitate the designer and the project owner to understand the project’s constraints and the contractor to better manage the site space and adequate it with the construction schedule and the resources needed. Besides it, the site surface will be important for the further development of the 4D and 5D models.
With the existing and new topography modeled, it can be associated with specific phases. This makes possible for the software to create an estimation of the cut and fill earthwork quantities. The quantities take-off for the earthworks will be more accurate the more accurate the topographic surface is defined. This will involve the insertion of more level points to increase the detailing of the surface.

It should be mentioned that Revit is not a civil engineering application, so the values obtained for the earthworks are an only estimation and should be considered to have a level of accuracy of +/-2% (Autodesk, 2017).

In this software, there are three different ways to create a topographic surface that can be used, according to the existing project data available. It can be created placing individual points with specific elevations, by importing a file with point coordinates or, by linking a CAD file with points or lines with a given elevation (Duell, Hathorn, & Hathorn, 2016). In this case, a 2D CAD file was available with the drawing of the construction site surroundings and some level points were available. This file is available for consultation in Annex A.

The modeling of the topographic surface started with the import of the 2D CAD file using the command “Import CAD” following the selection of the CAD file in the dialog box. This dialog box offers some options to define the position where to place the CAD drawing, which level to place it, and how to convert their length units. It is also possible to specify which layers to import from the file and how their color will be displayed. In the next figure is shown the command and the respective dialog box.

For this case, was imported a CAD file with the information of the level points along with the location of some structural elements of the retaining structure. It was placed in the project elevation zero, at the level -4 and the positioning were set to “Auto – Origin to Origin”.

The Revit software offers a tool to create surfaces using the command “Toposurface” available in “Massing & Site” ribbon tab. After importing the 2D CAD file, the level points were available in the work pane and was used this tool to generate the surface by placing the points assigned to a determined elevation. This process can be time-consuming, especially if a high detail of the terrain is required. To facilitate the procedure, having a CAD file with marked contour lines or a linked 3D CAD file with the surface model will facilitate this step.

![Figure 3-5 – CAD file Import](image)
Some specific areas of the existing terrain can be important to detail. This happened in the area between the “Gare floor” and the Avenue Defensores de Chaves, where a wall was dividing two areas with an elevation difference of more than 3.0m that was below the deployment area of the retaining structure. The obtained terrain is illustrated in the figure 3-6.

![Figure 3-6 – Existing site surface](image)

Along with the existing surface, also the Gare and some surrounding streets were drawn to simplify the interpretation of the site. For this was used the “Subregion” and the “In-Place Mass” commands.

### 3.4 Retaining Structure

The model for the retaining structure was created based on the project documentation available in 2D CAD drawing files and descriptive memory for the project. The modeling started with the import of a CAD drawing to the design pane. Then, the flight auger piles were modeled, following the distribution and capping beams along with the slabs. The entrance and the top level of the structure were left for the last step. The reinforcement was also modeled along with the reinforced concrete elements.

#### 3.4.1 Driven Piles

To bring the flight auger piles into the project, a parametric element was chosen among the ones already available in Revit library. The element chosen was a structural round concrete column and the diameter was then assigned according to the project information (600mm).

With the 2D CAD file imported and a plan view selected, the element was placed in its exact location. It is important to define well the constraints of the element. In this case, the element base level will be at
Level -4 with a base offset of 4.0m to define the piles’ embedment length. The top level was set at Level 0. The elements automatically adjust their length according to the defined constraint’s position.

After defining correctly the position and the geometry of the first pile, the reinforcement bars were added to the element. The software automatically assumes that concrete elements can host rebars so, when selecting one of these elements, the command “Rebar” is available. To place the reinforcement bars correctly in the concrete elements and facilitate the detailing, is advisable to combine the visibility to plan views and section views, sectioning the element orthogonally.

![3D model with the auger flight piles](image)

Figure 3-7 – 3D model with the auger flight piles

After the stirrups and the longitudinal rebars were placed in the piles, a group was created with these elements using the “Group” command. Because these elements are repeated in the project, a group can facilitate some other operations like copying the element to other different locations, creating sheets, and for the scheduling. After creating this group, the element was placed according to the project using the “Copy” and the “Array” commands. The model obtained at this stage is illustrated in the figure 3-7.

Revit allows enabling and disabling the view of specific elements in the model. The rebars elements were disabled in this view to avoid an overloading the image and they will be shown following in this chapter, in figure 3-9.

3.4.2 Concrete Beams

The future parking infrastructure will be built with the slabs following the surface slopped terrain, that have an inclination of about 1º. The slabs are supported on the distribution beams of the auger piles’ curtain wall, therefore, their position will have to be taken into account with this slope.
In Revit, the position of the element can be constrained to a reference. In case this reference changes, the position of the elements will adjust accordingly. In the case of the distribution and capping beams, it will be useful to constrain them to the position of the sloped slab so that, in case design changes happen, the beams will follow their relative position regarding the slab.

To constrain these objects, the “Reference Plane” tool should be used. This tool allows choosing the reference where the element will be placed, and it will be constrained to that position afterward.

There are three different kinds of framing elements in this project: the reinforced concrete framing for the distribution and capping beams, the steel profiles for the props, and the temporary ground anchors connected to the concrete framings in level -3 and level -1.

Starting from the concrete framings, the procedure was similar to the one used to draw the driven piles. It was chosen an element from the families available and then it was adjusted to fit the project requirements. The element family chosen was a rectangular shape concrete beam and then its type was adapted to a 400x600mm sized cross-section.

Using the imported 2D CAD drawing as guiding lines, the slabs were placed and then, the respective slope was given. Then, the bottom of the slab was selected as a reference plane and the beams were placed by picking the edge of the slab. With this process, any changes in the slab position or geometry will be reflected in the beams. This was particularly useful later when the project was changed, and the thickness of the slab and its slope were altered.

In the “Properties” panel, some important options are available as, for example, the rebar cover, and the structural material for the element. The rebar cover can be previously set in the “Structure” ribbon, “Reinforcement” tab, and selecting “Rebar Cover Settings” as illustrated in the figure 3-8.
The reinforcement bars were placed according to project details for the level -3. Confirming that the configuration of the beam plus reinforcement was the same for the level -1, these were copied across levels and hosted correctly. For the beam in the level -2, it was required a change in the rebar position to make it compatible with the ground anchors. The figure 3-9 shows a cross-section cut through beam -3 and beam -2.

In figure 3-9 (right), the rebars are displayed with different colors. This is due to an option to change the graphic representation of each type of reinforcement. This option facilitates the conformity check of the reinforcement detailing. It can be enabled in the “Visibility/Graphics” command and in the “Object Styles”, defining subcategories for the different kinds of rebar. Then, the graphics display can be edited in the respective rebar parametric element to adjust to the subcategory previously created.

Regarding the creation and placement of the reinforcement, it is relevant to refer that each rebar corresponds to a parametric element and that will demand more computation. Has the model becomes heavier, the modeling is not so fluid and reduces the workability, always depending on the users’ computation capacity. For this case study, the reinforcement bars were removed in order of the model to be imported for another software, as described in the chapter 4.

If there is no need to obtain reinforcement quantities from the model, one alternative is to represent the rebars only on single objects, instead of the whole model. Another alternative for sheets creation purposes would be the use of detailing objects to represent the rebar characteristic and constructive dispositions.

3.4.3 Steel Framing

There are 3 types of steel framing used for props in the interior side of the structure, HEB120, HEB200 and HEB 260. The steel framing was modeled in a much similar way as the concrete beams. It was selected a parametric element from the ones already available in the software’s library and its cross-section adjusted to the project requirements. Along with the steel framing, was also imported the elements that make the structural connection to the reinforced concrete beams. The steel props and the corresponding connections are represented in the figure 3-10.
3.4.4  Modeling Challenges Faced

As mentioned, Revit uses references to geometrically position the objects and make them adapt if changes in the restrained position happen. Elements such as floors or beams are, by standard, restrained to the levels previously defined by the user. These levels must be horizontal, what creates an additional modelling method in the case there is the need to define slopped elements. This situation happened when defining the beams, so the solution was to manually define the work plane and then create the element that will be associated with it. In figure 3-11 is visible the slopped floors and beams.

Still regarding the beams, another challenged was faced when was required to model the slopped beams that were supporting the ramps. These ramps were defined by a spiral shape geometry with varying grading slopes. Besides, the ramp should land with an inclination, to be compatible with the slope of the parking lot floors. The level in the border of the ramp should be determined so the position of the beams could be defined accordingly. The tools available in Revit were not enough do define this geometric problem. The solution was to use AutoCAD in the 3D mode and define a 3D spline passing across the middle line of the ramp then, a loft was made across this spline with a corresponding section. The element built was then imported to Revit. The result is shown in figure 3-12.

For geotechnical projects, it is important to represent the excavated slopes accurately with a specific inclination. To make this kind of modeling can be time consuming as it would require a manual editing.
of single points elevation to define the surface. In this case, the slope should meet with the level of the capping beam base, in order to clean the CFA piles and execute this element. To do so in a more fluent and accurate way, was created a line following the bottom edge, using the “Model In-place” command. Then this line was exported and re-imported in DWG file type. When importing origin-to-origin, the element is positioned on the desired location and a surface modeling option is now available. Using the “Create from import” option in “Toposurface”, the points corresponding to the line position are created and some additional adjustments to the surface might be needed. The result is shown in figure 3-13.

![Figure 3-13 – Excavation slopes representation (green)](image)

### 3.5 Editing a Parametric Element – Ground Anchor

The anchors are an important element to guarantee the structural integrity of the retaining structure. Therefore, the model should describe clearly and accurately its geographic position and characteristics.

In Revit software, it was not possible to find any suitable parametric element available in the database. In this situation, the modeler usually has two options, either create a new family element with the required parameters associated or, alternatively, search on the web for a similar element already sketched by another user or organization. In this case, an element was found in a BIM related forum with some of the required parameters and geometric features. This element is shown in the figure 3-14.

![Figure 3-14 – Anchor Element](image)
This element was already prepared to be hosted by concrete frames or walls and allows the adjustment of the plate dimensions, the angles, and the length. Although, some parameters were missing. For example, the grout bulb was not represented - an important feature to define in this kind of projects. The grout bulb should be anchored to competent soils and the information of its length and placement should be clear for the contractor. This element was then edited to create the required features of a grout bulb.

To make the desired changes, the anchor file was opened in Revit. When opening a family type file, Revit has a proper user interface, showing the options and commands necessary to edit this kind of elements. The first step to do was to create the new parameter values. They were the bulb length, bulb diameter, and total anchor length, defined by the free length plus the bulb length.

The configuration of these parameters was done by accessing the “Modify” ribbon tab, “Properties” and “Family Types”, as shown in figure 3-15. In the “Family Types” dialog box, the parametric values for this element are shown. Here is possible to edit, create new, or delete parametric values. A new parameter was then created using the “New Parameter” button.

In the “Parameter Properties” dialog box, the new parameters can be set. The option “Parameter type” regards the option to make it a “Family parameter” or a “Shared parameter”. The “Family parameter” refers to a kind of parameter that is only used by elements of the same family. The “Shared parameter” type is the one that is common to other family types and other projects. For example, the parameter “Length” is a shared parameter and is recognized as the same type of parameter across different families of elements type or different projects. This is useful to consider when, for instance, doing quantity measurements. The parameters to measure should be shared across the elements to guarantee that the measurements are summed up accordingly.

![Figure 3-15 – Creating a new parameter value](image-url)
Another option available is to choose between a “Type” parameter or an “Instance” parameter. “Type” parameters mean that, to change this parameter, another object must be created, under the same family type. This happens, for instance, when defining the framing section, the height and width are “Type” parameters. On the other hand, “Instance” parameters can be changed in each instance of the same object type. For example, to define the height of a column is used an “Instance” parameter.

The parameters generated were defined as “Type parameter” and as “Instance parameters”. The remaining options refer to the parameter name and how to classify it. The parameter values can be defined by formula expressions, and it was done for the case of the “Total anchor length” parameter. This parameter included a simple expression summing up two other parameter values, the anchor length, and the bulb length.

After defining the parameters, the element was modeled to include the geometric representation of the grout bulb. When editing or creating a new family, the reference planes, the reference lines and the dimensions created are very important. They will then relate to the parameters values and make the geometric element editable when modeling.

The bulb was represented using the “Extrusion” tool and creating and extruding a circle on the bottom end of the anchor. To make possible the changes in the bulb length, a reference line was placed in the bulb axis. To guarantee that the bulb is kept concentric with the anchor when varying the anchor angle, the top of the bulb was aligned with the bottom of the anchor and then locked, using the locker icon. Then, two dimensions were placed, one regarding the bulb diameter and other the bulb length. These dimensions were associated with the previously created parametric variables.

It was also required to define the material of the grout bulb created. This is done by selecting the bulb and, in the “Properties” menu, defining the material in “Materials and Finishes”.

After editing the anchor family element, it was placed according to the 2D CAD file imported into the model. After placing them and adjusting the angles. The results obtained are shown in the figures 3-17.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulb diameter (default)</td>
<td>750.0</td>
</tr>
<tr>
<td>Length (default)</td>
<td>5000.0</td>
</tr>
<tr>
<td>PLATE W</td>
<td>200.0</td>
</tr>
<tr>
<td>PLATE T</td>
<td>12.0</td>
</tr>
<tr>
<td>PLATE L</td>
<td>200.0</td>
</tr>
<tr>
<td>NUT T</td>
<td>53.0</td>
</tr>
<tr>
<td>LENGTH (default)</td>
<td>5000.0</td>
</tr>
<tr>
<td>DRILLED DIA</td>
<td>25.0</td>
</tr>
<tr>
<td>BAR R</td>
<td>140.0</td>
</tr>
<tr>
<td>ANGLE OVERAGE (default)</td>
<td>25.0°</td>
</tr>
<tr>
<td>ANGLE (default)</td>
<td>115.0°</td>
</tr>
<tr>
<td>ANCHOR LENGTH (default)</td>
<td>5000.0</td>
</tr>
<tr>
<td>Bulb length (default)</td>
<td>8000.0</td>
</tr>
<tr>
<td>Total Anchor Length</td>
<td>13000.0</td>
</tr>
</tbody>
</table>

![Figure 3-16 – Defining parameter values with a formula](image-url)
With a BIM approach, any kind of geometric element can be defined and associated with parameter values to meet the user’s requirements. These parameters can then be used for quantities take-off, construction planning or facilities management. This flexibility allows several kinds of project stakeholders to take part in BIM methodology and be a support for the study of design changes and for the decision-making process.

### 3.6 Representation of the Geotechnical Zones

The information regarding the properties of the underground soils is an important component to define in geotechnical engineering. A geological survey is usually done in the intervention areas when dealing with excavation works. This survey helps to characterize the subsoil in different geological and geotechnical zones. In this project, the survey was based on four boreholes.

These zones represent the areas of the soil sharing similar geotechnical properties. For this case study, the information of each geotechnical zone is important to define, for example, to define the position of the grout bulb. The grout bulb should be placed in soils with enough capacity to hold the prestress tension of the anchor.

The representation of these zones is usually part of the geotechnical projects’ documentation and the section views in the projects’ drawings should represent the limits of these areas. Can though be an
advantage to have geotechnical surfaces represented in tri-dimensions to verify the conformity of the anchor's position. It can also make the representation of these zones more accurate for documentation purposes.

To define these surfaces directly in Revit could be required to create four different layers, one for each geotechnical zone. Considering the kind of data available in the Geological and Geotechnical Report, a more specialized software was used to create these surfaces and the interoperability with Revit was tested.

The software used was Autodesk AutoCAD Civil 3D. This software is used for civil engineering projects usually dealing with terrains and 3D analysis. It has useful tools for geotechnical kind of projects, especially because of its capacity to model soils and measure earthwork quantities with a satisfying accuracy.

This software comes with an add-in called “Geotechnical Module” that is usually installed separately. This add-in is a tool to help manage geological and geotechnical data, allowing the tri-dimensional representation of the subsoil stratification and a dynamic analysis of the fence diagram across alignments defined by the user.

![Creating a new geotechnical module in AutoCAD Civil 3D](image)

To create the soil surfaces with this tool, it is needed to first create a new project and importing the data regarding the geological and geotechnical survey. This survey includes the boreholes geographic position, the depth of each geotechnical zone and the designation of each zone. The data input is done by a comma-separated value (CSV) file, that can be edited in a common spreadsheet program. To do this, it was used two template files in which the values were changed to match the ones relative to this project. One file was relative the geographic position and the other the designations and depth of each geotechnical zone. The spreadsheets have the appearance of the following figure.
After the data input, the files can be imported to AutoCAD Civil 3D. This is done using the “Import” button. In the dialog box, the files can be added, and the information imported can be confirmed in the following dialog boxes. This is shown in figure 3-19.

After processing the data, the software converts the information into tri-dimensional surface layers. Some useful functions are available, for example, to create a longitudinal profile of the soils intersected by an alignment, defined by the user. The diagram created is dynamic, what means that if the user changes the position of the alignment, the diagram showing the intersected soils will adjust accordingly. The result obtained in AutoCAD Civil 3D is represented in figure 3-21.

These surfaces were then imported from Revit, using the tools mentioned before to create a topographic surface. In the image, is possible to see the command to use for the import, and the surfaces already imported into the model.
After the import, the geotechnical surfaces represent parametric elements like any other in the model. The conformity with the anchor’s placement was then checked using some cut sections like represented in the figure 3-23.

As shown in figure 3-22, the surfaces don’t cover the whole deployment area of the retaining structure. This is because the geological and geotechnical surveying was done to cover both of the parking lot area and the future learning center of Lisbon University, adjacent to the parking lot. This kind of surveying is expensive and usually, just some few boreholes are done, being the remaining area target of the designer interpretation.
With the surfaces added to the model, was possible to confirm that the length and the vertical angles of the anchors are compatible with the soil characteristics, and some optimizations were possible.

### 3.7 Annotations and Creation of Sheets

When creating a 3/D BIM model, the Level of Development (LoD) should be defined. The LoD is important to consider taking into account the purposes of the model. If the purpose is to extract detailed quantities, the LoD should increase accordingly.

But not all the information needs to be represented as parametric objects. The option can be to represent come some if the information as a symbolic annotation in sections or elevation views. This can avoid an overload of objects in the model that could make the file excessively heavy and make the computation slower.

Regarding this case study, some objects were represented as annotations. It was the case of the instrumentation (load cells, targets, and inclinometers) and the geodrains. Due to its specificity, these elements were not present in the annotation symbols library and had to be created.

The creation of these elements was done by creating new families of symbols. This procedure to handle with families was shown in the previous section regarding the ground anchor and the process is similar. The difference is that in this case, the family created have only a 2D representation and has fewer parameters associated.

After defining the required annotation symbols, they were compiled into a legend. In Revit, when creating a legend, there is the option to insert a legend component from the families in use in the model. When placing this legend element, it adjusts the size to the scale defined by the user and it adapts dynamically when changed. Different legends can be created and placed in the drawings by drag-and-drop. When one legend is changed, the changes are done across all the drawings where this legend is. In figure 3-24 is represented one of the legends with some of the annotation symbols created.
With the annotation symbols created, the section, elevation and plan views can be composed for the creation of sheets. In Revit, the sheets are also parametric objects and can be edited as much as any other families of objects. The block tiles in these sheets can be composed by text labels that read the project information. Some useful parameters are the project name, the stage of the project, the discipline of the project, the designer, the name of the sheet and the number of the sheet. All these parameters can be set so that the information is always updated across all drawings when changes happen.

After the block tiles are defined, the composition of sheets is done by dragging the desired views into the sheet with a specific scale. These views can be previously prepared to adjust the graphical elements.
appearance and using section crops to select the area of the view that the user wants to display. This view options can be saved into templates and used afterwards.

In the figure 3-25 is represented one of the sheets created for this project. It is important to refer that, any change done in the model will be reflected in all drawings done, because the information is centralized in the parametric objects. This is particularly useful when design changes happen in cross-sections, for example. In this case, if the annotation is done using the “Tag by category” families, these annotations tags will change automatically, saving time and avoiding mistakes.

Another two examples of sheets are available in Annex B.

3.8 Connection with a Structural Design Software

After the retaining structure was modeled, the project of the parking lot structure itself was also done using a BIM approach. The modeling of this structure won’t be described here because the 3D modeling was already exemplified for the retaining structure, and this kind of projects uses types of elements that Revit already provides by default.

It is although interesting to explore the potential of BIM to facilitate the design of structures. Since the modeling in BIM is done using parameters that represent geometry and material properties attributed to elements, is natural that this information could be used for the structural design. This can avoid the reduplication of work when modeling the structure in the respective analysis software.

The Revit program comes with a shortcut command for Robot Structural Analysis. This is a structural design software provided by the same software house as Revit. Due to this fact, it is expected to have
an improved interoperability between the two programs. In figure 3-26 is represented the parking lot structure and the shortcut command for Robot.

Before exporting the model for this kind of analysis software, it should be prepared beforehand. Revit comes with tools to manage the model’s analytical properties in order to prepare it for a structural analysis. Also, supports and boundary conditions can be defined in Revit, along with the loads, load cases and load combinations. It is although advisable to do so in the software dedicated to this kind of analysis.

The preparation for the export can be done by turning on the analytical model view in the “Visibility/Graphics Overrides” command. When this view is turned on, the structural elements are represented by nodes and lines and the way they are connected define their analytical behavior.

Is though important to ensure the elements are properly linked and that there are no unconnected nodes. To do so, a filter option can be defined in the “Visibility/Graphics Overrides” command and set to show only the nodes that are unconnected. After this, the unconnected nodes can be adjusted to its correct analytical position, using both the move commands or changing the settings of the nodes in the respective properties panel.

![Figure 3-27 – Representation of the analytical model](image)

The figure 3-27 represents the kind of graphical view that is obtained when turning on just the analytical model. Is also possible to see the properties associated with the analytical elements that can be manually set to correspond to the desired analytical behavior.

When the adjustments are done, the model can be exported to the Robot Structural Analysis software. This application should be previously opened and then, the model can be exported using the command available in the Revit ribbon tab. There are two options to export the Revit model to Robot, it can either...
be using a direct integration or using an intermediate file. The intermediate file can be useful to, for example, send the model for another user to perform the analysis.

The connection between the two programs is not perfect, being additional adjustments needed in the model after the export. Is although an advantage to have the information regarding the sections, the grids and the materials of the elements automatically ready after the export. Setting the names of the materials in Revit according to the ones used in the Eurocodes provided by Robot will save time adjusting the section properties in this software. Therefore, the concrete sections material in Revit was set to “C30/37” to match the same naming as the defined in the Eurocode provided by Robot.

After optimizing the solution in Robot, the changes in the dimensions of the sections are assumed by Revit, because the models are linked. So, when the cross-section of an element is changed due to optimizations or to ensure design code’s requirements, the changes can be updated in Revit using the command mentioned before and choosing the “Update model” option. When updating back to Revit, some corrections might be needed.

Figure 3-28 shows the image of a structural slab and the distribution of moments in the X-axis, after applying one of the load cases.

Although useful, this interoperability is not completely seamless. It is required to pay attention to the creation of the analytical model of the structure when modeling. The analytical model in Revit is the bridging connection to structural design software. The compatibility between the analytical model and the geometric one is though important to ensure a more fluid interoperability and to avoid being constantly making adjustments when exchanging the model.
4 Construction Management Based on BIM

After the 3D model was completed, it was required to create the construction program for the execution stage. Since the project was in the design stage at the time of this research, no construction scheduling data was available from the contractor. A sample of the schedule was thus made, trying to use a realistic approach to the project implementation. The common process of a construction planning is as following (Levy, 2007):

1. Splitting the project into smaller interrelated activities;
2. Identification of the dependency relationships among activities;
3. Estimation of each activities’ duration;
4. Scheduling of the activities and identification of the required resources to complete them;
5. Risk analysis and evaluation.

After these steps, the construction program should be balanced conveniently, considering these three main variables:

- The quality;
- The time;
- The resources.

To make the construction planning for this project was used the Critical Path Method (CPM). This method’s main purpose is to reduce the completion time of the project by focusing mainly on the time variable of the activities. In this method, the relationships between activities are represented in a network diagram as represented in figure 4-1. In the CPM method, the critical path is determined. The critical path is the tree of activities that are important to control because a change in their duration will affect the duration of the entire project.

![Figure 4-1 – Example of CPM diagram with the critical path – red (Source: Designing Building Wiki)](image)

The lines represent the activities and the dependencies, and the knots represent the completion of the activities. Inside each knot is represented the earliest completion time and latest completion time. The knots with no lag represent the critical path of the dependent activities.
To create the schedule was used MS Project 2018 software. The purpose of this software is to help create and manage schedules for projects and the different resources needed to complete them. The MS Project is a broadly used software, although with some shortcoming as for example the difficulty of keeping track of the project by performing the data maintenance, and lack of risk management capabilities (Corker, 2013). The decision to use MS Project for this research is also related to the free software license provided for students.

To create the schedule is important to break the tasks into smaller activities, creating a Work Breakdown Structure (WBS). This structure can be the much detailed as wanted for a determined project. In the case of this research, it is important to consider the cost associated with each activity and break the tasks according to it. These tasks will later be associated with each parametric BIM elements to simulate the construction process across time and the resources associated with it.

The workflow of activities within the WBS has dependence relationships. These relationships can be defined in the Project software with four different types:

- Start to start: the activity must start when the other activity starts;
- Start to end: the activity starts after the other has finished;
- End to end: the activity must end for the other to end;
- End to start: the activity must end for the other to start.

### 4.1 Construction Planning

Among the elements available for this project was a summarized description of the construction processes and some requirements needed. The schedule was made based on these project elements and it was completed with some other tasks, after breaking down the process into smaller activities. The main activities were then assigned to the estimated production rates and the respective duration was determined. The critical path determined was the following:

1 – Preparation of the construction site including inspection to the surrounding buildings, diversion of roads and underground laying services, setting up of the office, work platform, accessibilities, and displaying the instrumentation devices;

2 – Execution of the soldier piles including excavation and laying of the reinforcement;

3 – Excavation, transportation, and deposit of the materials;

4 – Execution of the capping beam and the distribution beams with the anchors at the different levels.

The excavation must be coordinated with the execution of the piles, beams and corresponding anchors to avoid an excessive reduction of the soil's passive impulse and the risk of collapse of the retaining structure. The excavation should then be made just until the bottom level of the last beam executed.
The excavation activity was broken-down in levels from 0 to -4. It was considered that the excavation could be done in a sloped shape in the direction of the center of the site. The first level of excavation and the execution of piles’ activity had an end-to-end relationship. This means that, for the excavation to be done till the level -1, was necessary the execution of piles to be also completed. Besides, a lag was added to some activities to guarantee, for example, the hardening of the piles’ concrete. The program allows the use of lags to adjust the relationships among activities.

To calculate the amount of time required to complete the activities was considered the values of productivity available for the machinery. These values are merely indicative, with the purpose of making a 4D/BIM model and could be changed considering other variables as the experience of the driver or motivation of construction workers, for example. For the productivities was considered that:

- The execution of the soldier piles could be done at a rate of 4 piles/day/machine;

- The general excavation to be done at a rate of 2 trucks of 12m$^3$/hour, what represents a rate of 115m$^3$/day counting with the earth-shattering effect;

- The execution of anchors at a rate of 4 anchors/machine day with 3 machines.
The timeline chart for the project obtained is shown in the figure 4-3 and a more detailed Gantt chart is available in Annex C.

4.2 4D/BIM Model

After planning the execution of the construction works, the BIM 3D model and the schedule data were exported to a different software to create the 4D/BIM and 5D/BIM models. There are some commercial programs available that can handle the BIM methodology applied to scheduling and budgeting. The figure 4-4 shows some of the software available and its positioning regarding 4D and 5D capabilities.

![Figure 4-4 – Market positioning of some BIM 5D software. Source: adapted from CSI Portugal](image)

The purpose of this research is to study how BIM methodology could help in efficiency gains both on design and execution stage. The execution and the scheduling and budgeting of the project represents important and complex management issues. Some of the important functionalities of this software should facilitate the bidding, tendering and be a resource management tool that guarantees the following:

- Interoperability with other software files including BIM standard format (IFC) and scheduling file types;
- Quantities and dimensions take-off from BIM models;
- Effective cost control by keeping track of the project temporal economic data;
- Management of different price lists and price comparison;
- Preparation of bill of quantities and cost analysis;
- Graphical representation of the project’s execution across time.

The software chosen was the **STR Vision CPM** from **TeamSystem** company. It does guarantee interoperability with several programs used by AEC sector including IFC and scheduling files types. This software allows the budget management of several projects simultaneously and promises a facilitated bidding and tendering with the connection to 3D/BIM models and subsequent quantities take-off.
4.2.1 Working with the STR Vision CPM Software

The STR Vision CPM software does offer several functionalities designed to help the construction managers and the company’s daily operations. This software is therefore tailored for the management of budget, resources, and schedule. Some graphics and geometric tools like clash detection or renderings creation are not available, although possible to use the construction planning information to make a construction process simulation video.

Perhaps the key capability of this software is the combination of construction project management tools with the BIM methodology. Tri-dimensional parametric models can be uploaded to the software and quantities can be measured by drag-and-drop or almost automatically, if measuring rules are previously set. These quantities are then associated with formerly created pricelists and bid offers can be exported in an almost automatized way. With the construction planning associated with it, the project’s cash-flow can be controlled. When the prices are offered following the tendering, it is possible to import and compare them in a dashboard, helping to analyze and choose the best proposal.

The option for this software had also the purpose to test the compatibility between different software makers. Some software companies create several software tools made to be fully compatible and seamlessly integrated with each other. Since the 3D model was created using the Autodesk Revit, the option was towards using a different software maker. It will then be needed to use the standard IFC file format to guarantee the interoperability between the two platforms. The use of the STR Vision CMP software was possible due to the use of a full student software license.

The user’s interface is represented in figure 4-5. In the left pane, a menu is available with different tabs, allowing to configure and manage one or more projects. In this menu, the user can navigate across the projects’ information, and use some of the following toolsets:

- Configure the system settings: users’ permissions and roles; units to be used in the project; nominatives (entities); currencies; different payment condition; BIM processing rules (quantities take-off); among others;

- Price lists: Enter and manage price lists data;

- Input of specific projects related data: Companies involved (suppliers, clients, etc.); company resources involved (employees and equipment); accounting documents, WBS for each project, IFC models associated, among others;

- Estimating: Associate the schedule to the parametric elements in the IFC BIM model; quantities take-off from the elements in the IFC model; export supplier bids; among others;
- **Operating budget**: import supplier bids, compare and analyze the prices;

- **Accounting**: Produce documentation to control the resources and budget from the execution of works

- **Subcontracts**: Similar to “Accountings” but referring to the subcontracts and subcontractors;

- **Site documents and project controls**: Make purchase requests, keep a record of the labor and equipment used on site;

- **Maintenance plans**: Create manage and keep track of the items in the project needing a scheduled maintenance;

- **Building a site journal**: Keep a daily diary of the weather conditions and the record of the staff on the site;

- **Safety Plans**: Functionalities to help manage site safety related issues.

### 4.2.2 Preparing the Model

The creation of the model started by introducing some initial information like the company’s name and description, internal and external entities such as workers or suppliers, introducing unit prices lists, currencies, and conversion rate, calendars, among others.

To create a 4D/BIM model was necessary to set a new project in STR Vision software. This was done in the “Projects and contracts” tab and selecting again “Projects and contracts”. In this window, the existing projects are listed, and new ones can be configured. This window is also used to choose the current working project, in case that several different projects are being managed. By clicking “Add” in
the “Projects and contracts” ribbon, it will insert a new row for the project. A dialog box appears, and
some information input is requested regarding the project. When finished setting the options presented,
a new row concerning the project is created in the “Projects and contracts” window (figure 4-6).

![Figure 4-6 – Creation of a new project in STR Vision CPM](image)

In the same window, on the bottom, some other information regarding the project can be set. Here,
details about the project’s designer, costumer, or responsible entity, for example, can be filled in the
respective fields.

The user interface is shown in figure 4-6. On the left side, is available a navigation pane. On the top of
the window, there are ribbon tabs with modifying options. In the middle of the window, are listed the
items related to each selected option in the navigation pane. In the bottom of the window, options
regarding a selected specific item are available. Finally, a “Tree” menu next to the navigation pane will
facilitate the user to find a specific item. This is particularly useful in big and complex projects.

4.2.3 Connecting the 3D Model through an IFC File

After the project is created, the BIM IFC model can be associated with it. In the same ribbon or in the
drop-down menu the IFC Models button allows the import of the project file. By pushing “Add”, a new
entry row shows up with some empty fields where the model code, description, and discipline should be
filled. Here also the models can be set to an active or inactive status. Then, by clicking “Import Ifc File”
in the “Project: IFC Models” ribbon, the IFC file can be uploaded into the software.

To import the BIM IFC file, it is first necessary to create and export the model in the IFC file extension,
in the Revit platform. This can be done by using the “Export” – “IFC” command. A dialog box pops-up
with the destination path and the IFC file setup. In this drop-down, several types of IFC files are
presented. This file types should be carefully chosen due to compatibility reasons. The algorithm of the
files types has been updated and improved to follow the BIM developments. The most common IFC file types used nowadays are the IFC2x3 and the IFC4:

- **IFC2x3 Coordination View 2.0:** In use since 2008, the Ifc2x3 was improved until this last version and it adds to the previous facility management and structural analysis capabilities, the possibility of quantities take-off for all building and structural members and 2D annotations add-on view (BuildingSMART-Tech.org, 2017).

- **IFC4:** Corrects technical problems found on previous IFC2x3 versions, have improved capabilities in the specification of parametric elements and enables a numerous of new BIM workflows including BIM 4D and 5D models, BIM to GIS interoperability and enhanced sustainability assessments (Liebich, 2013).
In this case, the file setup chosen was the IFC2x3 Coordination View, the one compatible with the STR Vision CPM software. The IFC type chosen was the one that ensured more data transfer from the original model. Some IFC versions didn't guarantee the transmission of all the parameter associated to the objects. Information regarding specific IFC format files to import was not found and the most compatible format was found by the trial-error method.

By pressing “Export” the model in the IFC file format is created in the chosen directory. After the export was complete, the IFC file could be imported into the STR Vision CPM. In the “Import Ifc File” command mentioned before.
The process of uploading the model will last some time, varying with the characteristics of both the model and computer’s capacity. The higher the level of detail of the model and its number of parametric elements, the longest will take for the computer to process the upload into the software. In this case, for being able to import the file was required to remove the reinforcement bar elements from the model before importing it.

When the import is completed, a dialog box shows up with some visibility settings (figure 4-9). Here the user can choose what kind of families of objects wants to be shown in the project viewer, and also the linear and angular deflection of geometric tolerances. This dialog box shows how the file format transforms the parametric element into standardized families like “IfcBeam”, “IfcWall” and “IfcSite”. To visualize the model, it is required to first activate the corresponding rows and then, open the tab on the right-hand side of the window referring to “BIMViewer”.

In this window, the BIM 3D model can be explored. Several models can be loaded simultaneously in the tab “Models”, this is particularly useful to combine files coming from different specialties like architecture, structure or MEP. On the “U.M.” tab, the measurements units can be adjusted by inputting the units’ conversion factors for different types of units. In the same window, some visibility options are available in the “Tree” tab where the elements to show and elements to hide can be chosen. There is also a “CutPlane” option (figure 4-11) that adjusts the visibility through a horizontal cut, at a selected level. Finally, the “Filter” tab helps in the selection of specific geometric elements according to their parameter values.

4.2.4 Importing and Linking the Construction Plan to the BIM Model

After the upload of the 3D/BIM model to the software is completed, now the schedule can be connected to it by linking the construction activities to the corresponding parametric elements in the model. To do so, the schedule previously created in Project 2018 was imported into the software.
In the “Estimating” tab, a new estimation should be opened. The procedure is much similar to the one previously used to create a new project. By opening “All estimates”, a window listing all the estimations done shows up, and a new estimate can be created. When the new estimation row is inserted, there are some settings possible to adjust, for example, the conditions of the bid, or other commercial conditions. The commercial conditions will be focused afterwards, on the “Procurement based on BIM” section.

![Figure 4-12 – Creation of the Job Planning](image)

Now, in the explorer tab in the left-hand pane, a new folder was created referring to the new estimation. In this folder, one of the available items is the “Job planning”. Here, schedules for the construction works can be set and configured. By adding a new row, a new scheduling type is created.

![Figure 4-13 – Setting up BIM model behavior](image)
Different calendar definitions can be attributed, along with the planning type (fixed resources, fixed work or fixed duration). Different scenarios can also be chosen (figure 4-13). These scenarios relate to the way BIM elements are represented in their different actions (install, maintain, demolish or temporary), and different phases (start, ongoing or end).

By choosing the “Gantt chart” command, in the top ribbon bar, the window with the list of activities is opened (figure 4-14). In this window, some options regarding the project schedule are available and new schedules can be created here from the scratch, although with some limitations compared with dedicated planning software programs.

Another option is to import a file with an already created schedule. This can be done using the “Import/Export” button and selecting the respective file path. The file type accepted by this program is the MS Project XML so, when saving the file in MS Project it should be done in the corresponding file type. After the import process, figure 4-14 shows the result obtained.

![Figure 4-14 – Gantt chart on STR Vision CPM](image)

After importing the construction program, the activities can be associated with each parametric element in the 3D model. To do this, the schedule can be broken down into smaller tasks and adapted according to the user’s requirements.

In the Gantt chart window, on the right side, there is a BIM viewer tab, with the imported BIM models. By opening it and selecting the elements, they can be associated with the activity in the schedule. To do this, the activity that the user wants to associate should be highlighted. Then, the element or elements in the BIM model should be selected and associated.

Instead of selecting the elements one-by-one, a filter tool can be used to select the complete number of elements sharing the same set of properties, for example, the same family and type or all elements restrained to the same floor. Then, by right-clicking on the selected elements and choosing the option
“Gantt” – “Associate to selected task”, the connection between the schedule and the elements is made. Figure 4-15 represents this action. Applying this procedure to all the geometric elements to associate with the schedule, the correspondent 4D/BIM model is generated.

![Figure 4-15 – Associating parametric BIM elements to the scheduled activities](image)

Regarding the excavation, was not possible with this software to have different individual surface terrain elements to work with, as it just recognizes an individual and complete topography surface. The option to go around this issue was the representation of another element, in this case, a slab, with the purpose to illustrate the different steps of the excavation.

This procedure could be done in a different manner, taking part of the capacity to create and manipulate parameters associated with objects. A parameter for the construction phasing could be added to the objects when creating the 3D model and attribute a value representing the execution stage of this element. This would facilitate the grouping and selection of elements.

### 4.2.5 Creating an Animated Representation of the Construction

With the association of the construction schedule to the geometry of the BIM 3D model, now new functionalities are possible. One of the interesting features is the possibility to generate a simulated animation of the construction process.

The process of planning a construction project is a complex task that includes several interrelated variables, sometimes difficult to predict. The site construction manager usually receives data from the different disciplines (geotechnical, structure, architecture, mechanical, electrical and plumbing, etc.) and must combine those by avoiding clashes and by promoting health, safety, and quality of the finished works. This should be guaranteed by using the minimum resources and time as possible.
Traditionally, the clash detection and the site planning process are done based on two-dimensional drawings, what makes it a difficult task. The scheduling needs to be interpreted by the project managers sometimes just based on abstraction. This process is more likely to be error-prone than in a three-dimensional approach. Suffolk’s BIM manager, that is responsible for the implementation of several BIM tools, including the construction planning, referred some of the advantages of the 4D-ready process (Daren, 2017):

- Increased value of the proposals;
- Better team collaboration;
- Improved control of logistics;
- Acknowledge manpower allocation;
- Sequencing of operations and facilitated re-scheduling.

A construction simulation is a tool that can help reduce the risks for the construction managers by supporting the visualization of the different project’s specialties combined in a time-lapse. It makes possible to analyze constraints that in the traditional 2D representation would be harder to detect. It is also useful for other stakeholders in the project, for example, to show the project owner different options in the construction processes that can be adjusted according to eventual set-backs found during the construction, usual to happen in geotechnical works.

To use the simulation tool of this software, there is the command “Simulation from/to” on the BIM ribbon bar of the “Job plan” window. Some options are available as the start and the end time, the duration and speed of the simulation, and the horizontal rotation, an option to visualize the animation while the camera spins around the 3D elements.

In Annex D, some screenshots are represented from the simulation of this project.
4.3 Budget Management and Procurement Based on BIM

One advantage of the BIM methodology is to have the information centralized and aggregated to the parametric elements of a digital geometric model. The budget control and the cost evaluation are one useful tool for contractors and designers. The quantities take-off tools can help avoid mistakes, common in the traditional CAD 2D approach. This section demonstrates how to build a 5D/BIM model and some of the advantages it can bring.

As mentioned, the STR Vision CMP software can help construction project managers to deal with budget control activities and do this based on a 3D/BIM model. The quantities will be measured and associated with a WBS code, corresponding to the project’s plan done in the previous section. With this association, it is possible to have the control over the global project’s budget and over the specified execution time.

4.3.1 Quantities Measurement Based on BIM

To do so, it is necessary to have an item list with the cost structure of each element. The resources that each parametric element needs to be executed must be first specified. Then, when this element is measured, all the materials, labor, equipment, time, and other relevant cost variables will be associated with it. In figure 4-17, is represented the data flow of a 5D BIM model.

To create this item list, it is possible to import it from a separate spreadsheet file or, alternatively, create it in the software itself. These items can be associated with a specific price category. The advantage of defining price categories is that it will allow, for example, a comparison between the prices offered by different suppliers, or to evaluate the impact of determined items’ price change in the global budget. To make a quantity take-off, the procedure is the following:

- Define the different price categories;
- Create or import the WBS;
- Create or import the items price lists;

![Figure 4-17 – 5D/BIM data flow. Source: Vicosoft](image)
- Analyze the items in terms of resources needed;
- Measure of quantities and creation of measuring rules.

Figure 4-18 – Defining the price categories

The price categories can be defined in the “Project and Contracts” menu, under the current project’s definitions (figure 4-18). In this window, different types of price categories with different configurations can be defined.

Besides the price categories, also the measuring units should be previously set. The measuring units defined will be used for the quantification of different types of objects. Some objects are more convenient to be measured in individual units, other in linear meters, areas, or volumes.

Figure 4-19 – Defining the measuring units for the project
The measuring units are defined under the current project’s definitions, in the “Measuring Units” window. These units are defined by a code and a description. For the case of this project, the units defined were the weight, linear meter, area, volume, and units (Figure 4-19).

Besides the price category and the measuring units, it is also important to define the work breakdown structure (WBS). This WBS will allow the elements association and corresponding cost to the schedule that was defined in the previous section. The WBS was created based on the construction planning previously done. These tasks were compiled in a spreadsheet file and imported into this program (figure 4-20).

Figure 4-20 – WBS import

Figure 4-21 – Imported WBS list
The WBS should be defined in the “Project and Contracts” menu and “WBS” window. When the WBS is imported, a dialog box appears with the option to insert missing WBS or update descriptions. After choosing the appropriate options, the WBS list is created (figure 4-21).

With the price category, the measuring units, and the WBS defined, a price list was then created. This price list contains all the items making part of the retaining structure. These items will then be analyzed in terms of resources needed for their execution.

To create the price list, the window “Price Lists” under the current project is opened, and here rows can be added to input the items cost information. Each element has several information and configurations that can be added. For this case, the information input will be the measuring units used for each item and the cost analysis.

![Figure 4-22 – Defining the items’ price list and the items’ price analysis](image)

The cost of each element can be defined in the “Analysis” tab, on the bottom of the same window. Here, the cost can be composed of the resources needed for each item. Figure 4-22 illustrates the example for one kind of a used concrete beam. This element is composed of the cost of the concrete, the steel rebars, and the formwork. On the quantity column, a function was placed to convert the units of these sub-elements’ units compatible with the one used by the element being analyzed. For example, to give the volume of concrete by a linear meter or the weight of steel by linear meter.

When this analysis is completed, the software calculates the total price per measure unit of this element. This analysis was repeated for each item contained in the retaining structure. These price lists can have many items, depending on the kind of projects. It is though important to have them correctly organized by item codes. Having these codes organized will make easier finding the items, using the “Tree” function. This “Tree” function organizes the items in a tree, corresponding to the code given to each element. This is visible in the figure above.
After these items are defined, the quantities take-off from the geometric model can be performed. The measure of quantities is done in the left menu, “Estimating” option, and then opening the window “Measurements”.

Assuming that the 3D model in the IFC format is already loaded into the project, the measurements can be started by creating a new measurement row, then opening the “BIM viewer” tab and selecting the elements wanted to be measured. The elements to be measured should be selected in this viewer. To select several elements is preferable to use the filter option available. With this option, specific parameters can be chosen to filter the desired elements sharing the same properties used in the filter. In figure 4-23, was filtered the distribution beam for the level -4 by defining the level and type of parametric element. The selected elements are highlighted by red color in the BIM visualizer. In the properties panel, is possible to confirm the number of elements, the type of the elements, among other parameter values.

![Figure 4-23 – Measuring from the geometric model](image)

To make the measurement, the “New estimate measurement” command is used, and a new window shows up. Here, will be defined the specific measurement rule by choosing which item from the price list to measure, which WBS to associate and then, in the “Formula” tab, the parameters to be measured from the objects. These parameters are usually length, area, volume, or count, but it can also be a formula defined by the user.

Each take-off rule can be saved for a future use. This can be particularly useful for an almost automatic quantities take-off. Also, if design changes happen – what is usually probable – the saved rules can be useful for a fast evaluation of the design changes in the global cost. This will be shown in the followings sections “Automatic Quantity Take-off” and “Cost Analysis with design Changes”.
After repeating this process for all the geometric elements in the model, a global cost estimation is ready. The cost can be analyzed in customizable dashboards, for example, to relate the cost of each WBS as represented in the following image of figure 4-25.

Although, was not possible to obtain the measurement of the earthworks using this method. When importing the model to this software, the surfaces defined in Revit were combined into a single surface element, making the measurements unviable. It is though possible to take-off the quantities in Revit software and then insert the data manually.
4.3.2  5D/BIM Model and Project’s Cash Flow

The measured items and the rules created includes a WBS information. It is, therefore, possible to associate the measured items with the construction planning done in the previous section. The WBS code associated to the construction elements should match the code from the activities in the planning done before.

To create the project’s cash flow, the procedure was similar to the one done in the previous section. When creating the new job planning, the option should be to add “New jobs plan from estimate”. Then, a new code and description should be attributed to the new job plan. To create the job plan based on the WBS should be chosen the specific option in the “Fields selection to build Activity” and selected the “WBS Code”. After confirming the options, the new job planning is created with the new Gantt chart is created with the WBS and associated with the items cost. Then, to complete the chart, the same construction program used before was imported. The result was a schedule with the cost field information available, as shown in figure 4-26.

In figure 4-26, just the revenue is visible. This is because the data considered was just the price value. The cost information could be added, and the display would be as a cash flow chart.

With the increase in the schedule detailing, the cost information would also be more accurate. To increase the detailing, it is necessary to reduce the length of the timeframe considered and associate the parametric objects executed in this amount of time. The result would be a smoother chart, instead of a stepped one.
4.3.3 Automatic Quantity Take-off

When creating the measuring rules, the properties of the objects’ filter selection are defined based on the specified objects’ parametric values. These filter rules can be saved in different measuring rules’ folders and used afterwards for measuring of quantities for other projects of the same kind. The advantage is the reduced time required to process these measurements.

![Figure 4-27 – Generate parametric estimate](image1)

To do this, a new estimation should be created and then, the “BIM” ribbon tab is opened activating the BIM model wanted to be measured. The option “Generate Parametric estimate” will be available.

![Figure 4-28 – Parametric estimate rules](image2)
When using this tool, a dialog box appears (figure 4-28), and the take-off rule catalog can be chosen. From here, the measuring rules for the objects to measure are chosen. In the tab “IFC properties mapping” can be defined how the measurements will be organized, for example by floor or by a group previously defined. Then, by pressing the “Generate measurements”, the objects covered by the measuring rules selected are considered for the new measurement estimate. After this step, the measurements are generated.

The program comes with a way to graphically verify if the measurements are done consistently with the desired elements. This is done by selecting the measurement row and choosing the “Check estimated objects” available in the BIM ribbon tab. The objects associated with the measurement selected will then be highlighted in red color in the BIM viewer, as in figure 4-29.

![Image of BIM software interface](image)

*Figure 4-29 – Checking the measurements’ consistency*

### 4.3.4 Procurement Based on BIM

One available tool can facilitate the procurement and the evaluation of the supplier bids. The process is done by conducting a first estimation of the BIM geometric model, then filtering the items wanted to be sent to the supplier (figure 4-30).

![Image of procurement workflow](image)

*Figure 4-30 – Procurement workflow based on BIM. Source: Adapted from CSI Portugal*
Then, a spreadsheet file that can be exported to send to companies to request a price offer. The received bid offers can then be imported into a previously defined price category, as mentioned in the previous section. After, a comparative analysis can be performed to identify the best offer.

Figure 4-31 – Creating a supplier bid report

To do this, the estimate wanted to use for the bid offer is selected and then, the “Reporting” window is opened. Using the “Add report” a new report is added and then “Estimate measurements for bid”, creates the desired report. After selecting the corresponding row of the bid offer, the settings on the bottom of the window offer several options that can be configured (figure 4-31). Here, the layout style of the report can be defined choosing, headers, font colors, company logo, among others. On “Groups and filters” tab, the items wanted to be sent to the companies should be chosen by applying an appropriate filter. When finished configuring all desired setting, by pushing “Export Excel” the program will create a spreadsheet file with the items for bid (figure 4-32). The items can be grouped in activities, making request for bid based on this criteria instead.

Figure 4-32 – Exported supplier bid
The file can now be sent to the supplier companies that will fill in the spreadsheet file with the offered prices and send it back. This file is then imported with a specific price category associated.

Figure 4-33 – Creating price categories for the bid offers

To create new price categories, the menu “Projects and Contracts” is selected and after the “Price category” window is opened, under the current project. Here, a new price category for each supplier offer is created by adding a new row and entering a code and a description for each the price category. This is exemplified in figure 4-33.

Figure 4-34 – Importing supplier bids (left) and price update (right)

After creating the price categories, the bid offers can be imported into the “Items” window in the “Import offers”. In the dialog box, the import path to the spreadsheet file is selected. A bid code must be introduced along with the corresponding price category and the supplier code (figure 4-34 left). The supplier companies can be previously defined in the project settings. After filling in these fields, the
spreadsheet files received by the suppliers can be imported. Has we can see in figure 4-34 (right), if we select one item and open the price tab, we can check that the items’ price was updated with the information coming from the imported offers.

After updating the items list with the bid offers, the prices from the different suppliers can be analyzed with the help of the dynamic dashboard tool available. Here we can choose and add the desired parameters for rows and columns fields and create new parameters based on functions, by combining existing parameters.

![Figure 4-35 – Supplier bid offer dashboard price analysis](image)

After finding the best offer, the estimated measurements can be updated with the new prices, simply by changing the price category associated with the measured item.

### 4.3.5 Cost Analysis with Design Changes

Later on, some design modifications were made to the original project of the retaining structure by the contractor’s suggestion. The anchored king post walls were replaced by a sloped terrain excavation and the adjacent structure of the “Gare do Arco do Cego” was underpinned on its supports. Also, all the retaining structure was risen, reducing the length of the piles and the excavation quantity.

These design changes can be evaluated with the 5D/BIM tool by making the changes in the 3D/BIM model and then, importing it to the software using an IFC file, the same way as mentioned in the previous section. After that, under the estimating menu is possible to use the “Estimate update” tool, to make a comparison between a model already estimated and another model, for example, one including design changes.
As depicted in the figure 4-36, after selecting the IFC models and using the “Compare models” command, the software evaluates the changes that happened in the parametric model regarding the objects previously estimated. In this window, is possible to check the changes item-by-item. In the figure 4-38 is possible to verify the changes in the wall object were detected, by mention them as deleted objects and checking the elements highlighted in red color. Also, regarding the piles, is possible to check the length variation from the original model to the updated one (figure 4-37).
In the same window, a new estimation can be automatically obtained, by using the “Create updated estimate” tool (figure 4-38). Here should be filled the new estimate's code, description and a custom field can be chosen to, for example, estimate the updated design by level floors. This estimation is possible due to the previously defined measuring rules. After the new measurement is done, the cost variation can be evaluated in a dashboard, as shown in figure 4-39.

Due to the fact that this software is not a complete version, some of the items cost appears with the value “0”. Is, although possible to check the impact of the design changes in the pile's length that reduced from the previous design (blue column) to the updated one (orange column), in figure 4-38.
5 Final Statements

The purpose of this study was to demonstrate how BIM methodology can be used has an instrument to help promote a more efficient and productive AEC sector, following the digitalization path that other industries are chasing and taking positive results with. To do so, it was intended to approach BIM regarding less implemented tools for budget and planning purposes, in a less implemented engineering field – the geotechnical engineering. To do so, a tri-dimensional model of a retaining structure was created and then, it was used to generate the 4D/BIM and 5D/BIM models, exploring its capabilities to support construction management activities.

The procedure to build these models was described in this document, along with the advantages and challenges found in the process. It is expected that this document can contribute to a further digitalization of the AEC sector through BIM, by being a proof of concept as a valid tool to support different activities from the conception stage till the pre-execution stage. Considering this, the main objectives are considered to be reached.

Through the literature review done, was possible to conclude that, despite the potential of BIM, it is still far from being fully seized by the AEC industry. In the actual national and international paradigm, BIM is still mostly used for tri-dimensional representation, where the improved cooperation between project’s stakeholders is one of the advantage highlights. But the possibilities of BIM can reach further developments. With this methodology, the information regarding the whole life-cycle stages can be available for decision-making. This is possible because the information is linked, centralized and accessible.

In this research, a real case study was used to demonstrate how some of the BIM concepts could be applied. It intended to illustrate a BIM approach from both the designer and the contractor. In the first step, the geometric 3D model was created with some specific features of geotechnical projects. Then, this model was used for the planning and budgeting support, creating the 4D and 5D BIM models.

A retaining structure was modeled along with the existing topography. The geological and geotechnical survey was used to create parametric elements representing the geotechnical zones. Some specific parametric elements were not available in the library. It was the case of the anchors, an important feature of this kind of project. This family element was then edited to create a ground anchor with the desired parameters and geometry. When the 3D model was complete, the connection with a structural analysis software was tested to check if the design optimizations could be assimilated by the model.

The tri-dimensional model was then transferred to a construction management BIM based software, and the 4D and 5D capabilities were tested. The construction project was planned and then transferred to the construction management software. The geometric elements were associated with the project tasks and a construction process simulation could be performed.

To complete the 5D model, the cost variable was associated with the parametric elements. With an item list and the cost structure of each element was possible to obtain the construction budget. After this step,
automated quantity take-off was possible, along with a fast and detailed analysis of the global price with
design changes. Bidding and tendering activities based on BIM were also tested. Was possible to issue,
receive and compare bid offers from different suppliers or subcontractors. This allowed a consistent
support for decision-making when analyzing multiple construction processes, design options or when
evaluating the impact of price material changes.

The AEC industry can find in BIM methodology, a route for its so needed increases in productivity
because it is able to promote a leaner construction process, by reducing the reduplication of work and
some traditional error-prone activities. Although, shifting from the traditional methods to this new
paradigm is a shift that requires, information, training and adaptation time.

5.1 Analysis of Results

During this research, the interoperability was tested with interactions between different software
platforms. The software used was the following:

- Autodesk Revit 2018;
- AutoCAD Civil 3D 2018;
- Robot Structural Analysis 2018;
- Microsoft Excel 2016;
- Microsoft Project 2016;
- STR Vision CPM.

Not always the interaction between different software was done smoothly. The exchange between
Autodesk Revit model to the STR Vision CPM was done using the standard IFC file format. Some
versions of IFC file type were not fully compatible, neither was found information regarding this topic
from the software makers. Also, the connection between Revit and Robot needed some extra modeling
time spend to adjust the analytical connections between objects. The creation of the analytical model
by Revit seems to have a margin for improvement.

Regarding the creation of the geometric model, the learning process was facilitated. The extended
information available online made it easier to find solutions for modeling issues. There is an active online
BIM community that shares information and new methods to make faster and better models. The
cooperation making part of BIM philosophy was a reality in the online community.

Modeling needs some training experience in order to improve the models’ quality and reduce the time
required to complete the project’s documentation. The drawings production through BIM had benefits
when design changes were needed. Because the information is centralized, the changes in the 3D
model are transmitted across the different drawings pieces. This advantage has a positive implication
in the optimization of the engineering solutions, especially when project’s delivery deadlines are short.

Regarding the scheduling and budgeting based on BIM, the software used demonstrated to be a
platform with several useful tools for construction manager’s activities. Although, gaining practice in this
software was not an easy task. The lack of complete English tutorials and the lack of support from the software provider represented a challenge for the methodology implementation. This fact can potentially restrain companies to invest in a tool that, the research suggests being difficult for the companies to implement. It is necessary to facilitate the training and learning processes in order to remove obstacles for a deeper BIM implementation.

The quantities take-off through BIM helped to verify and improve measurements done in the traditional way. The centralized information gives a global overview for construction managers, that will reflect in a faster and more accurate decision-making.

Upstream changes in the project’s design or downstream changes coming from product price changes could be quickly evaluated. With the data centralized in the BIM parametric elements, the information could be switched and updated, giving the project’s manager an increased operational control. The companies with the capacity to early adopt these BIM tools will potentially gain competitive advantages over the remaining ones.

The development of this research was partially done in a geotechnical design office. This allowed observing some of the advantages of BIM methodology. Although difficult to analyze it in a numerical approach, was clear the advantage of visualizing the proposed solutions in a tri-dimensional way. It required less abstraction effort and allowed a faster analysis of the construction restraints. Also, with the 3D approach, some clashes were possible to detect in an early stage design. This is an advantage for the owners as better projects would save undesired expenses during the execution stage.

During this experience, there also found some external obstacles to BIM implementation. The fact that the municipal council is not ready to accept projects in a BIM platform, it was needed to convert the drawings and other documentation to the traditional 2D CAD files. This process meant a quality loss and reduced the efficiency of the process. It is therefore suggested that the national government, as one of the main AEC industry customer, look for good international practices, remove some of the existing obstacles, and create more incentives for BIM implementation.

5.2 Future Research

As the implementation of BIM deepens, early-stage design collaboration will be possible. Some BIM modeling software is prepared for the creation of centralized BIM models where different project teams can work simultaneously from different locations. It would be interesting to explore the application of these collaboration tools, in the project’s conception stage.

For design purposes, specific software tools are used to make different kinds of analysis, for instance, soil-structure interactions, structural design, or design code conformity checks. These software tools are usually based on finite elements methodology and analyze how a determined geometry with material properties responds to loads, stresses or displacements. Some of these software tools are compatible with BIM by using the standard IFC file type format, or other interoperable features. It is suggested to
further investigate if this interoperability can be done seamlessly enough to allow the BIM model to be transferred to the analysis software, make design optimizations, and then export it back again, without loss in the level of detail.

The software used in this research was prepared to help in the management of budget, schedule, human resources, and accounting activities during execution, with a BIM basis. Although, was not possible to follow up the execution of the construction works. It is therefore suggested the use of a real case study to follow up execution works with the budget control tool based on BIM, evaluating the advantages and shortcomings of the BIM methodology applied onsite.

Another suggestion would be to use different software platforms for the budget and cost control based on a BIM platform. Since research suggests that few companies are using the 4D and 5D approach, investigation on this topic approaching different software tools could be a proof of concept and an incentive for its implementation.

The fact that with BIM approach, the information is centralized, making it available to different stakeholders makes it a more transparent approach. Could though be interesting to study how BIM could be implemented and used as a platform for public procurement activities as a transparency-enabler in the sector.
Bibliography


Annex A – Topography and Deployment Area
Annex B – Project Sheets
Annex C – Construction Program Gantt Chart
Annex D – 4D Simulation Screenshots