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Decision Support System for optimal tunnelling Preliminary design

Development of an interactive model automatically responsive to environmental constraints for the feasible technical configuration evaluation in tunnelling projects

Authors:

TABARRINI Alessandro
970773

TRIONI Francesco
970873

Supervisor:

MIRARCHI Claudio

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0 ABSTRACT (Italiano)

L' automatizzazione dei processi è uno dei principali protagonisti dello sviluppo tecnologico come l'utilizzo delle metodologie BIM lo è nel settore dell'edilizia. La tesi si pone come ambizioso traguardo di creare una sinergia tra questi due potenti strumenti creando un decision support system (DSS) atto ad automatizzare il processo di progettazione, modellazione e gestione cosciente delle risorse nell'early design stage.

Affinché sia garantito il funzionamento di tale dispositivo si è reso necessario acquisire conoscenze specifiche relative al mondo delle scienze minerarie, della progettazione parametrica e della metodologia BIM nelle infrastrutture civili. Il funzionamento del DSS concretizza con la lettura delle informazioni imput e nella restituzione di un modello tridimensionale della galleria oggetto di studio, completo di tutte le componenti tecniche a loro volta allegate delle informazioni relative alle risorse, ai tempi delle lavorazioni e ai costi.

Per poter fornire il risultato descritto è necessario dotare il DSS dell'allineamento del tunnel, la direttrice come pura linea curva tridimensionale, e del set di parametri geologici che definiscono il tratto di curva interessato.

La potenzialità dello strumento risiede nell'automatizzazione del processo, infatti questo consentirà all'utilizzatore, di fronte all'incertezza tipica dei parametri geologici nelle zone più difficilmente raggiungibili, di poter mettere a confronto tutti i possibili scenari o di poter considerare come e quanto un imprevisto potrebbe condizionare. Il modello ottenuto, oltre che per la lettura delle informazioni da parte del software, potrà inoltre essere di supporto per le fasi successive alla progettazione come costruzione e manutenzione.

Nonostante si sia presa coscienza della complicatezza che avrà la raffinazione dei meccanismi di selezione tra le alternative nel DSS per renderlo applicabile, attraverso questo studio il settore compie un consistente avanzamento nell'approccio mettendo in un campo restio all'innovazione come quello della costruzione delle infrastrutture civili due aspetti ormai fondanti del futuro delle costruzioni: BIM e automazione.

0 ABSTRACT (Inglese)

Process automation is one of the main protagonists of technological development as the use of BIM methodologies is in the construction sector. The thesis sets itself the ambitious goal of creating a synergy between these two powerful tools by creating a decision support system (DSS) capable of automating the process of design, modeling, and conscious management of resources in the early design stage.

In order to guarantee the functioning of this device, it was necessary to acquire specific knowledge relating to the world of mining sciences, parametric design and BIM methodology in civil infrastructures. The functioning of the DSS materializes with the reading of the input information and the return of a three-dimensional model of the tunnel under study, complete with all the technical components in turn attached with information relating to resources, processing times and costs.

In the aim of providing the described result, it is necessary to equip the DSS with the alignment of the tunnel, the director as a pure three-dimensional curved line, and the set of geological parameters that define the section of the curve involved.

The potential of the instrument lies in the automation of the process, in fact this will allow the user, faced with the typical uncertainty of the geological parameters in the most difficult to reach areas, to be able to compare all the possible scenarios or to be able to consider how and how much a unexpected event could affect. The model obtained, as well as for reading the information by the software, can also be a support for the subsequent phases of the design such as construction and maintenance.

Although we have become aware of the complexity that will be involved in refining the selection mechanisms among the alternatives in the DSS to make it applicable, through this study the sector makes significant progress in the approach by entering a field that is reluctant to innovation such as that of infrastructure construction civilians two aspects that are now fundamental to the future of construction: BIM and automation.

1 INTRODUCTION

1.1 - Pre-phase

The construction industry has always been characterized by the value and importance placed on the experience and preservation of practices and techniques perpetrated over time. Methodologies more aligned with contemporary technologies have always emerged with difficulty and slowness compared to other professional spheres such as mechanical and marine engineering. The rationale for this is the immense value placed on experience as initially the only tool in the hands of designers and engineers to foreshadow the long path and contingencies that lead to the success of a project. The result of this reluctant mindset to change becomes more evident the faster the development of technology, of the use of new cutting-edge materials, and of the information technology approach grows.

This thesis aims to explore how the construction industry can evolve toward a new way of designing and building by implementing modern information technology techniques while enhancing past knowledge and achievements. This presents a challenge in an industry that has often been characterized by a slow and resistant mindset to change based on experience.

However, the starting point for this change will be precisely the valorization of the past and the knowledge acquired over the years as it is only through them that we have been able to acquire the needed competence. This knowledge can be an extra support and tool available to the designers of the present to meet modern engineering challenges and develop new solutions aided by the value of experience.

Therefore, the goal will be to create a bridge between the past and the present, preserving traditional knowledge, experimentally obtained results, and the successes and failures found and documented in the history of construction by implementing them with modern information technology. In this way, the benefits of new technology and traditional knowledge will be obtained, creating an integrated and innovative approach to construction.

Ultimately, the thesis will show how the road to a new way of building does not have to be at odds with the past and traditions but can be seen as an opportunity to combine knowledge gained over the years and new technologies, to meet the challenges of the future.

1.2 - Progress of the world of Construction

In modern construction project management, the idea of collecting and managing data via the use of information technology is gaining popularity. These new developed informatics infrastructures allow handling of big data which can have diverse applications and be interpreted for multiple purposes. The tools which have the capability to store, manage, classify, and interface with potential users (clients, architects, engineers, contractors, suppliers, manufacturers, builder, etc.) are emerging with these advancements. BIM originally surfaced as an integration tool and was used for modelling applications, however recently it has been an interface of information for different users and applications through assortment of different input sources; Furthermore, compilation of raw data from design, detailed specification, schedule cost, sustainability and project lifecycle issues has become possible.

In addition, since the information technology revolution in the 60s and 70s an ongoing tendency existed towards the application of computerized decision support technology to process large number of complex models in a timely manner. The technology has made huge improvements to the quality of decision-making processes by sharing, accumulating, and updating information accurately, making processing much easier and faster with less human error. With further advancement in computer programming and graphic capabilities the demand for decision making tools has increased and their application has amplified exponentially in all disciplines.

The construction industry is also trying to apply more of the technological advancements; for instance, being able to estimate operation costs during the development of the worksite has always been desired and now is much more effectively achievable with the emergence of schematic design technologies and BIM in construction. The concept of life cycle costs and project whole life value has been rejuvenated through the application of BIM and is increasingly factored in decision making process.

The ability to make timely decisions is always vital in construction projects, and this approach certainly entails data management linked tightly to geometries definition. However, this have always been a great challenge due to huge uncertainty of data or unavailability of structured processes and evaluation techniques. On the other hand, failing to make appropriate decisions at critical stages like the pre-design stage can be detrimental to the outcome of construction projects. It can rapidly lend to huge costs and time overrun leading to project failure. This issue of decision making is extremely complex for construction projects because these are temporary and inherently complex, multifaceted with large number of tasks, multiple stakeholders, constraints, and criteria.

Accordingly, there may be no absolute right or wrong decision, but the question is what could be the best decision with the optimal outcome which can contribute to project success. Supplier and timing selection normally involves a range of quantitative and qualitative factors. Therefore, it is critical to make the best procurement decision at the right time and potentially the earliest possible to increase chances of project success. Often due to large number of factors, data and information processing is required and for such, decisions information technology applications are used. However, integrating these applications with other modern tools and platforms used for design and project management will lead to enhanced control capacity.
It is also necessary to mention the general direction of the construction sector and specifically the infrastructure sector where digitization and BIM are becoming part of the discipline of Public Contracts. The direction is now firmly outlined and is also confirmed in the New Public Contracts Code, currently under parliamentary consideration.

Technically, this will be a legislative decree, implementing Law No. 78 of June 21, 2022, by which the government has been delegated to adopt one or more legislative decrees to regulate Public Contracts. The results the new standard aims to achieve are:

- Adapt the regulation of these Contracts to European law and the principles expressed in the case law of the Constitutional Court and higher courts, domestic and supranational.
- Rationalize, reorganize, and simplify the existing regulations in this area.
- To avoid the initiation of infringement procedures by the European Commission and to achieve the resolution of the initiated.

The draft legislative decree was approved by the Council of Ministers on December 16, 2022, and was sent to Parliament for the opinion of the relevant committees on January 5, 2023.

Although the measure may at first glance suggest a fractured identity with the CAD (computer aided design) design and construction methods that have accompanied professionals in this field for the past two decades it may in fact constitute the start of a practice sensitive to the influence of the past. A tool, as specified above, capable of sensing the effect of time and effectively suggesting strategy toward a more conscious, responsible, and flexible way of building.

1.3 - DSS and Design Optioneering: application fields, Results

The Decision Support Systems (DSS) are software tools that aid in decision-making by providing information, data analysis, and decision models. DSS has been widely used in various fields such as business, healthcare, and government to improve decision-making and increase efficiency. Over the years, there has been significant progress in the use of DSS, and this has led to numerous successful applications.

The utilization of Decision Support Systems (DSS) has been spreading rapidly across different industries and organizations. This is due to several factors, including advancements in technology, the availability of vast amounts of data, and the need for organizations to make informed decisions quickly and accurately.

One of the main drivers of the spread of DSS is the increased availability of data. With the rise of the internet and digital technologies, vast amounts of data are being generated and collected by organizations. DSS can help to analyze this data and provide insights that can inform decision-making and lead people to better understand the value of stocking experience.

Another factor driving the spread of DSS is the need for organizations to make informed decisions as soon as possible. In today's fast-paced business environment, organizations need to be able to respond to changes in the market and make decisions in real-time. DSS can help to provide timely and accurate information that can inform these decisions with its capacity to revise and learn from its database to prevent mistake made in past.

Advancements in technology have also contributed to the spread of DSS. With the development of cloud computing, machine learning, and artificial intelligence, DSS can now be more powerful and sophisticated than ever before. This has made DSS more accessible to organizations of all sizes and has allowed them to harness the power of these technologies to make better decisions.

Overall, the utilization of DSS is spreading rapidly across different industries and organizations. With the increasing availability of data, the need for quick and informed decision-making, and advancements in technology, DSS is becoming an essential tool for organizations that want to stay competitive in today's fast-paced business environment.

One of the significant areas where DSS has been successfully applied is in the healthcare industry. DSS has been used to aid in diagnosis, treatment planning, and patient management. For example, the Mayo Clinic has developed a DSS called Clinical Decision Support (CDS) that helps physicians make informed decisions about patient care. CDS uses algorithms that consider a patient's medical history, test results, and other relevant data to provide personalized treatment recommendations.

Another area where DSS has been successful is in the field of finance. Financial institutions use DSS to aid in decision-making about investments, risk management, and fraud detection. For example, JPMorgan Chase uses a DSS called COiN that helps detect and prevent fraud in its payment systems. COiN analyzes vast amounts of data to identify suspicious transactions and alert investigators. In addition to healthcare and finance, DSS has also been used in agriculture, transportation, and logistics. For example, the U.S. Department of Agriculture uses DSS to help farmers make decisions about crop management and disease control. In the transportation industry, DSS is used to optimize routes, reduce fuel consumption, and improve delivery times. Overall, the progress in the use of DSS has led to numerous successful applications across different fields. With the continued development of technology and the availability of big data, DSS is poised to become even more effective in aiding decision-making in the future.

2 SCOPE OF THE WORK

2.1 - Reason of the study

In the context of large civil infrastructure, the sources of complexity with which the project interfaces are many, and most of these are capable of generating high-magnitude effects on the timing and cost trends of the construction phase. A civil work such as the construction of a rail tunnel amplifies and enriches the context with additional complications set by the contest generating need of in-depth studies of the project development area aimed at obtaining a comprehensive portfolio of the complications to be addressed. Just think of the problematic issues generated by the geological context alone, studied by means of probabilistic models, which in the event it does not turn out to be aligned with forecasts would go on to necessitate a massive mobilization of resources [1].

According to a simple principle that is as general as it is valid, it is easy to understand how much the mere physical dimension, the "scale," the so broad scope of the projects analyzed is interconnected to eventualities of the same intensity. Indeed, the most recent references on which it has been possible to base statistical analyses show ranges of variation on the order of their size if not even more.

The Brenner Base Tunnel has seen costs per kilometer rise by 411 M/km from a base of 237 M, but even in the COCIV-Terzo Valico project the "extra expenses" compared to the initial forecast of 4.5 billion are already 1.8 billion (for a total of 6.3) and further surcharges and surcharges are expected. Continuing then with the analysis of the dynamics of expenditure forecasts for the Lyon-Turin link, with an initial estimate in the order of 5.2 billion in the pre-project phase that now sees its costs rising to a record 9.6 billion. The question arises as to the nature and motivation of this. Hence, according to a simplistic approach, one is driven to consider possible errors in estimates, schedule changes and any kind of deviation from forecasts as the result of serious shortcomings on the part of the professionals involved in the project, but this is not the case [2].

Infrastruttura-faro nel settore dei trasporti	Stima originaria (milioni di euro)	Stima più recente (milioni di euro)	Incremento (milioni di euro)	Incremento percentuale
Rail Baltica	4 648	7 000*	2 352	51 %
Lione-Torino	5 203	9 630	4 427	85 %
Galleria di base del Brennero	5 972	8 492	2 520	42 %
Collegamento fisso Fehmarn Belt	5 016	7 711	2 695	54 %
Basque Y e suo collegamento alla Francia	4 675	6 500	1 825	39 %
Collegamento Senna-Schelda**	1 662	4 969	3 307	199 %
Autostrada A1	7 244	7 324	80	1 %
Linea ferroviaria E59	2 113	2 160	48	2 %

Figure 1 - Cost overruns in tunnelling projects

As anticipated in the chapter intro, the cause of such problematic and wide variations is not to be found in the incompetence of the figures involved but more likely in the low ability to represent sources of uncertainty from such a linear process.

The origin of the decoupling is also to be found in the organizational scheme that manages project development. This, in fact, tends to divide into separate contexts those who are in charge of the technical feasibility studies and design of the tunnel itself and those who are in charge of calculating the expense associated with the construction generating some problems. In order to carry out the economic evaluation for the construction of the tunnel, in fact, the project is necessarily "frozen" and forced to take the form that it is most likely to have, but without having the certainty with a consequent great loss of information in the form of "technical solutions" that are necessary in contexts with a non-zero chance of materializing.

After delving into the reasons that lead to the steady increase in the use of BIM technologies in the construction world, it is important to emphasize how in the world of infrastructure this tool can coincide with the problematic issues identified in this chapter. In particular, virtual support will allow us to connect fundamental aspects such as construction technologies and their life cycle allowing us to obtain cite- specific answers from models.

2.2 - Aim of the research

Since around the 2000s, there has been a growing awareness that some of the process's peculiar to the world of mechanics could be translated and applied to other specific worlds of manufacturing such as construction. The research proposed in this thesis focuses on the progressive integration of data into the design journey in the construction industry. The goal is to fit within the trend of integrating data into the design process using the Building Information Modeling (BIM) approach.

The BIM approach is seen as a tool that enables the creation of a virtual environment in which different parties involved in the realization of the project can interact. This virtual environment considers not only three-dimensional geometry, but also other information dimensions relevant to the project.

The benefits of this integration of data into the design path are many. The use of the BIM model encourages collaboration among different professionals, facilitating communication and sharing of information in real time. This can help reduce errors and inefficiencies, improving planning and cost control.

In addition, the integration of data into the design path enables project success goals, such as meeting deadlines, budget control, durability, and safety of the work. The BIM model supports the evaluation and management of these key variables, enabling better planning and more accurate decision making.

Numerous success stories have already been found where the BIM approach has been successfully implemented in projects in the construction and civil engineering sectors. The use of the BIM model has led to significant improvements in efficiency, quality, and collaboration.

Guidelines are recommended to further promote the integration of data into the design journey in the construction industry. Strategies to foster collaboration among different professionals and promote widespread adoption of the BIM approach should be considered. In addition, challenges, and possible solutions for the effective implementation of the BIM model in the construction context should be discussed.

In conclusion, the proposed research focuses on the progressive integration of data into the design path in the construction industry using the BIM approach. This integration improves project collaboration, planning, and control, contributing to the achievement of successful project goals.

Thus, the research proposed in this thesis aims to fit within the progressive integration of data into the design path.

2.3 - DSS and Goals of the model

In the context of this thesis, the goal is to develop an interactive decision support tool that will enable professionals to select from a wide range of available technological solutions for tunnel construction enriching their knowledge in multiple ways making their decision more and more informed through the experience-based database. This tool is designed to be applied to the context of a specific project and will result in a detailed three-dimensional model of the underground infrastructure.

Within each component of the three-dimensional model will be included packages of associated information of different natures. This data will include economic information, such as the costs associated with different technological solutions; project timing data, such as construction phases and expected completion times; logistical information, such as material procurement and transportation activities; and information on the socio-environmental impact of the materials used, enabling an assessment of energy efficiency, carbon emissions, and other factors relevant to the sustainability of the project.

The inclusion of this detailed information greatly amplifies the range of considerations and tools available to a project manager, enabling him or her to make more informed and informed decisions in the decision-making process. This approach maximizes the likelihood of project success, regardless of KPIs (key performance indicators) and project-specific drivers.

In conclusion, the proposed interactive decision support tool is an important resource for project managers in the tunnel industry. The system offers a holistic approach and detailed information to make data-driven decisions and improve the planning and execution of underground infrastructure projects. The three-dimensional model will be created by assembling the structural and technological elements that define the typological matrix of the infrastructure. The main macro categories can be identified as: consolidation system, support system, reinforcement structure, internal structure, and waterproofing system. Each category will include different technological solutions that perform the same function, but each will be suitable for specific contexts with scope parameters that vary over a range of possibilities.

The goal of the model is to gather prior experience to link technology solutions to the application context, minimizing the possibility of errors and unforeseen events. Its practical application is to design an underground infrastructure by combining the technological solutions selected as the most suitable for the context and applying them to the excavation line. Through this operation, a variety of different results can be achieved. The three-dimensional model, called DSS (Digital Twin for Future Infrastructure Management), serves as a managerial tool for quickly generating estimates, evaluating different situations and determining whether or not a risk deserves to be addressed. It also enables the storage of expert experience in the field, improving equations linking context inputs to design responses in relation to critical aspects of the project.

The goal of this thesis is precisely to implement a Decision Support System (DSS), which is a bridge between knowledge gained in the past and modern technologies to deeply understand the dynamics related the estimation during the early design phases. Such a system enables current and future challenges in the construction industry by facilitating the management of estimates, situation analysis, and the use of accumulated experience to address critical project aspects effectively and efficiently.

3 FRAMEWORK

The path that guided the study up to the creation of the Decision Support System was for practical purposes described through the division into successive steps although, for the state of the art and the production of the model the development was in parallel, further considerations will be made in the dedicated chapters. The thesis was therefore structured according to the pattern of its three basic parts: the state of the art, the creation of the device, and lastly its example application.

3.1 - Bibliographic studies

It has been crucial to conduct a thorough study of the literature and of the past projects to ensure the possibility of obtaining results that are applicable in real contexts, especially when the objective is to tackle a complex project. In this case, the issue is branched out into several thematic areas:

The bibliographic studies constituted the substantial part in the information retrieval phase, but they are not the only one. Several themes found space within it, some of them more linked to Tunneling a mineral sciences and other much more related to the BIM methodologies in civil infrastructure project construction and management.

- Building Information Modelling (BIM) and digital restitution techniques of projects related to civil engineering, as well as techniques, technologies, and resources are necessary for designing subsurface infrastructure. By focusing on these main spheres, the thesis can approach its objective and achieve its applicability to real-world scenarios. The in-depth study of the specifics dedicated to civil engineering in relation to BIM use in construction is particularly relevant as it provides insights into how BIM can be leveraged to optimize the construction process and ensure efficient project delivery. Similarly, exploring the techniques, technologies, and resources required for designing subsurface infrastructure is crucial to address the challenges associated with this complex task and context. By combining these two spheres, the thesis can provide a comprehensive overview of how BIM can be applied to underground infrastructure design and construction, ultimately leading to improved project outcomes and applicability in real-world contexts.

- However, the acquisition of data and information did not stop at the bibliographic study but also went through a phase of comparison with two recently completed projects: the railway connection between Turin and Lyon and the one between Ancona and Perugia. The interface with concrete projects is a fundamental part of the creation of a DSS since this, similarly to many other digital support devices, has its roots in the analysis of data and experience. The richer the database of analyzed solutions is, the more the DSS will be able to get closer to a realistic forecast and be able to use the analysis of the resources necessary to complete these two projects, both developed in recent times.

- As the last category of technical knowledge obtaining, necessary to tackle the project, it was decided to seek experience and practice through the consultation of professional figures available to share their knowledge belonging to the world of the thematic spheres affected by the project. In the context of the development of the thesis, an opportunity was found to share the objectives with WeBuild, a reality of international fame and scale in the world of construction and infrastructure, in two moments of exchange in which through their feedback it was possible to direct the research and its objectives, aligning them with the concrete needs that will be faced one day. Secondly (as will be explained in more detail in the following chapters) through a six-month collaboration at IDeCOM have been possible to learn the design, modeling and data management techniques of BIM proposed by the Dassault Sistèmes's software. It has been of crucial importance in the possibility to lead the informatic support in the right way.

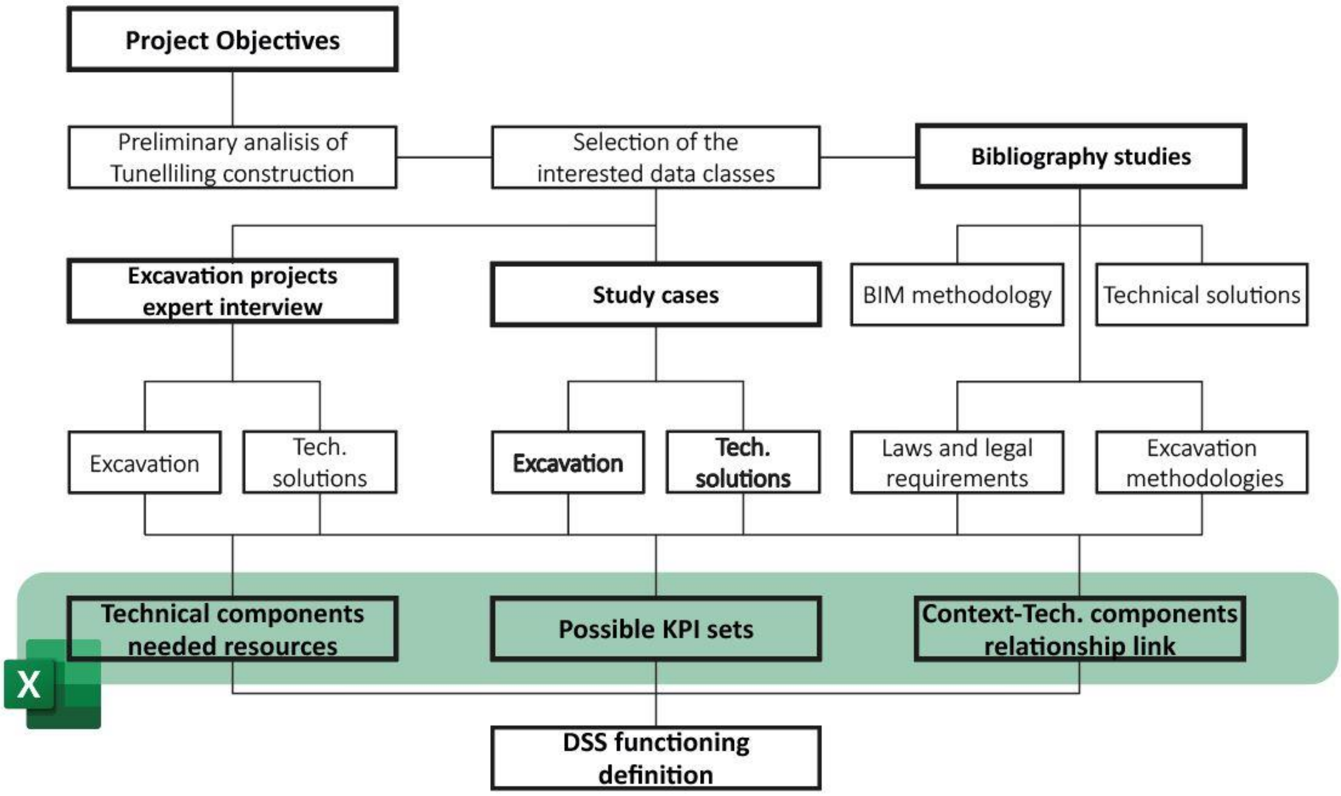
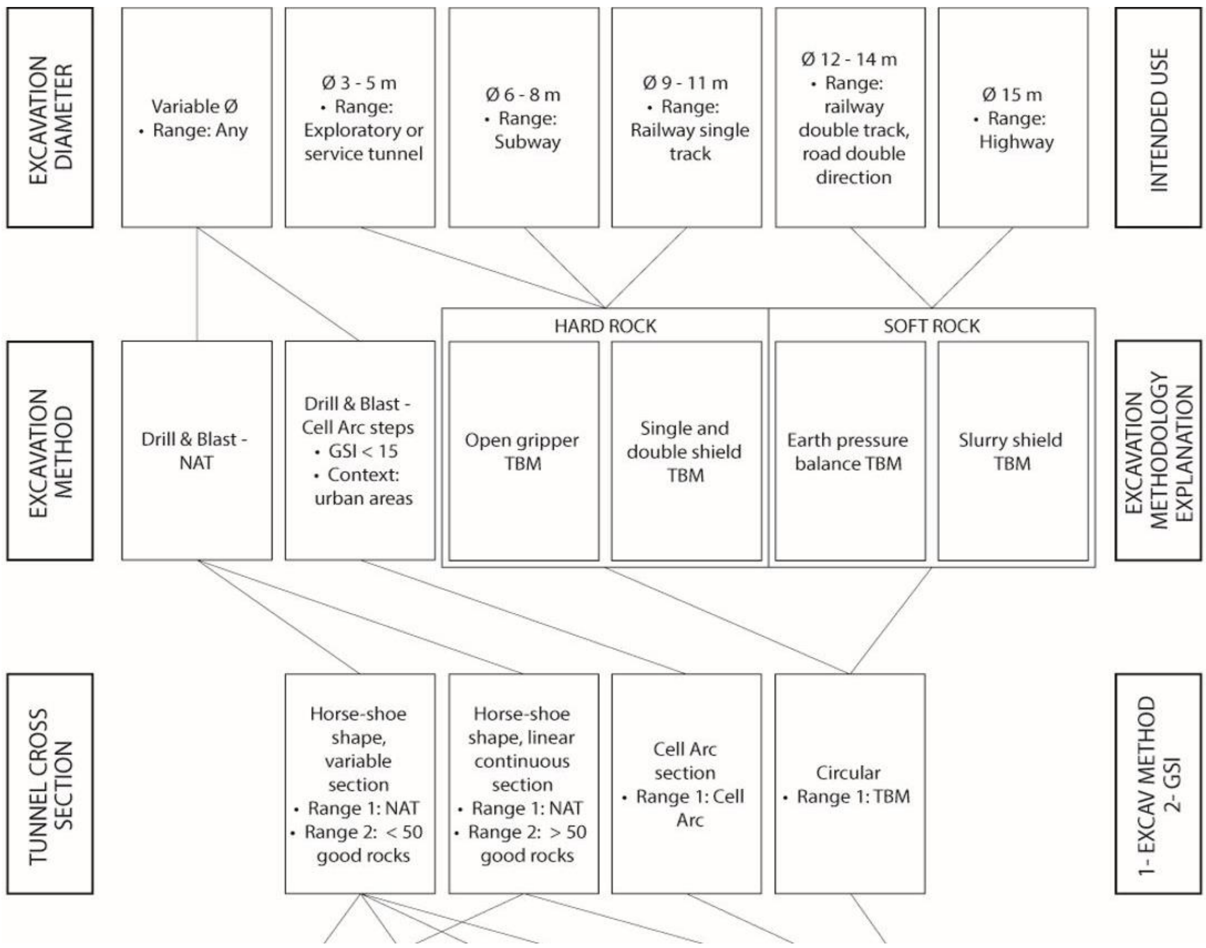
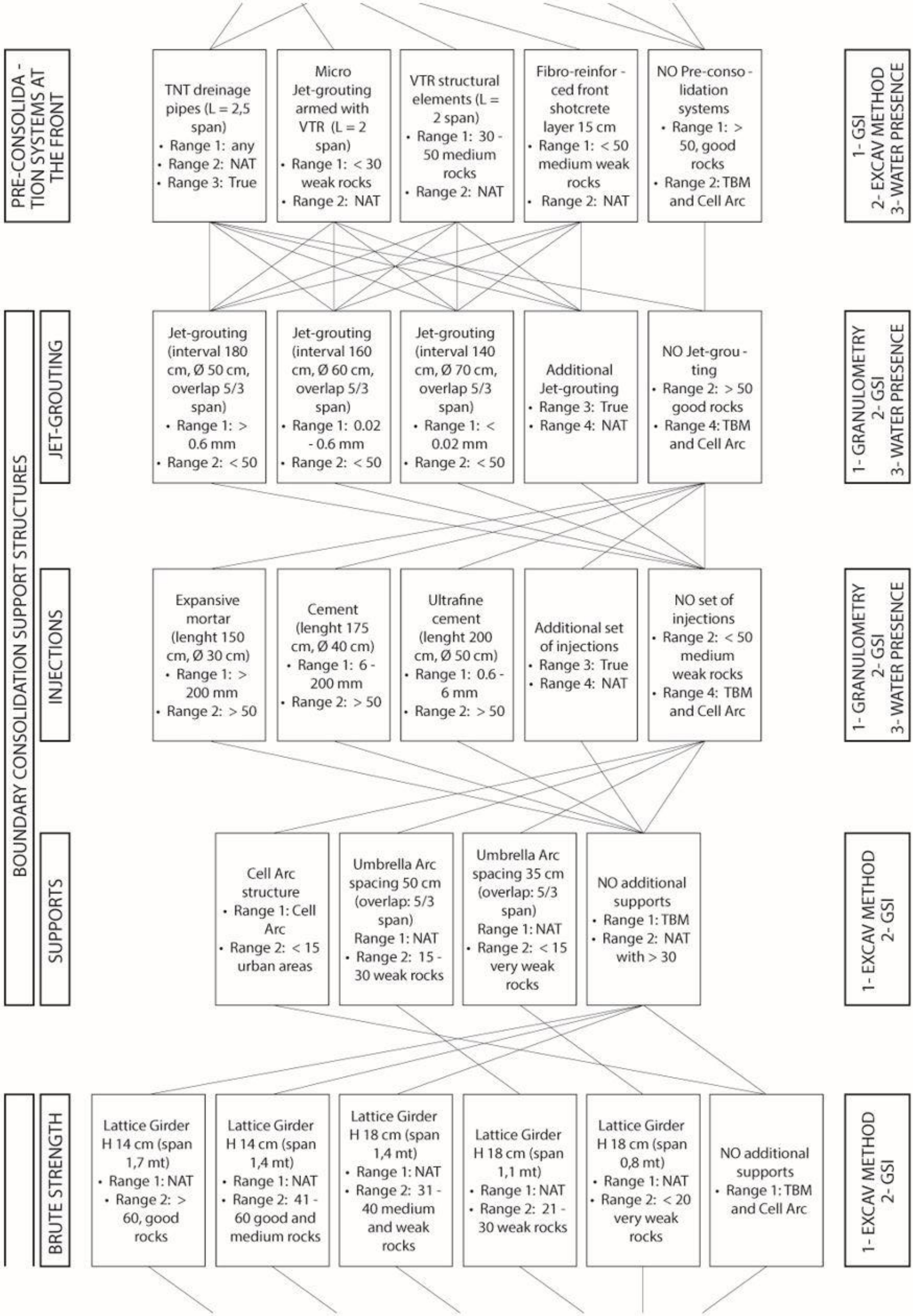


Figure 2 - Graphic concept of the Sources of information

3.2 - Development of Decision Support System

Having collected all the information on which to base subsequent assumptions, the research passes through a data readjustment phase. In this phase, the documentation and information collected are used to first define relationship links between an excavation method and its optimal context of use, secondly the dependency link between excavation methods and technological solutions and finally how to implement a selection process of the most suitable construction technology taking into consideration the constraints imposed by the excavation technique and the context, with all the possible variations that affect it. In this phase, the subsequent connection operation between the technological solutions of each class and the respective resources necessary to implement the technology is also addressed. The result of the sum of the two operations relevant to this phase of the study consists in the creation of a database containing all the possible design combinations defined by a technological solution for each typological class. The resources necessary for its construction are in turn connected to each possible design combination. With these operations, the phase of preparing the information for the final reading and interpretation of the DSS is carried out which, depending on the selected KPI set, may suggest for one or another combination of technologies according to the priorities defined in the project.




PRE-CONSOLIDA - TION SYSTEMS AT THE FRONT
TNT dreinage pipes (L = 2,5 span) • Range 1: any • Range 2: NAT • Range 3: True
Micro Jet-grouting armed with VTR (L = 2 span) • Range 1: < 30 weak rocks • Range 2: NAT
VTR structural elements (L = 2 span) • Range 1: 30 - 50 medium rocks • Range 2: NAT
Fibro-reinfor - ced front shotcrete layer 15 cm • Range 1: < 50 medium weak rocks • Range 2: NAT
NO Pre-conso - lidation systems • Range 1: > 50, good rocks • Range 2: TBM and Cell Arc
1- GSI 2- EXCAV METHOD 3- WATER PRESENCE
BOUNDARY CONSOLIDATION SUPPORT STRUCTURES
JET-GROUTING
Jet-grouting (interval 180 cm, Ø 50 cm, overlap 5/3 span) • Range 1: > 0.6 mm • Range 2: < 50
Jet-grouting (interval 160 cm, Ø 60 cm, overlap 5/3 span) • Range 1: 0.02 - 0.6 mm • Range 2: < 50
Jet-grouting (interval 140 cm, Ø 70 cm, overlap 5/3 span) • Range 1: < 0.02 mm • Range 2: < 50
Additional Jet-grouting • Range 3: True • Range 4: NAT
NO Jet-grou - ting • Range 2: > 50 good rocks • Range 4: TBM and Cell Arc
1- GRANULOMETRY 2- GSI 3- WATER PRESENCE
INJECTIONS
Expansive mortar (lenght 150 cm, Ø 30 cm) • Range 1: > 200 mm • Range 2: > 50
Cement (lenght 175 cm, Ø 40 cm) • Range 1: 6 - 200 mm • Range 2: > 50
Ultrafine cement (lenght 200 cm, Ø 50 cm) • Range 1: 0.6 - 6 mm • Range 2: > 50
Additional set of injections • Range 3: True • Range 4: NAT
NO set of injections • Range 2: < 50 medium weak rocks • Range 4: TBM and Cell Arc
1- GRANULOMETRY 2- GSI 3- WATER PRESENCE
SUPPORTS
Cell Arc structure • Range 1: Cell Arc • Range 2: < 15 urban areas
Umbrella Arc spacing 50 cm (overlap: 5/3 span) Range 1: NAT • Range 2: 15 - 30 weak rocks
Umbrella Arc spacing 35 cm (overlap: 5/3 span) Range 1: NAT • Range 2: < 15 very weak rocks
NO additional supports • Range 1: TBM • Range 2: NAT with > 30
1- EXCAV METHOD 2- GSI
BRUTE STRENGTH
Lattice Girder H 14 cm (span 1,7 mt) • Range 1: NAT • Range 2: > 60, good rocks
Lattice Girder H 14 cm (span 1,4 mt) • Range 1: NAT • Range 2: 41 - 60 good and medium rocks
Lattice Girder H 18 cm (span 1,4 mt) • Range 1: NAT • Range 2: 31 - 40 medium and weak rocks
Lattice Girder H 18 cm (span 1,1 mt) • Range 1: NAT • Range 2: 21 - 30 weak rocks
Lattice Girder H 18 cm (span 0,8 mt) • Range 1: NAT • Range 2: < 20 very weak rocks
NO additional supports • Range 1: TBM and Cell Arc
1- EXCAV METHOD 2- GSI

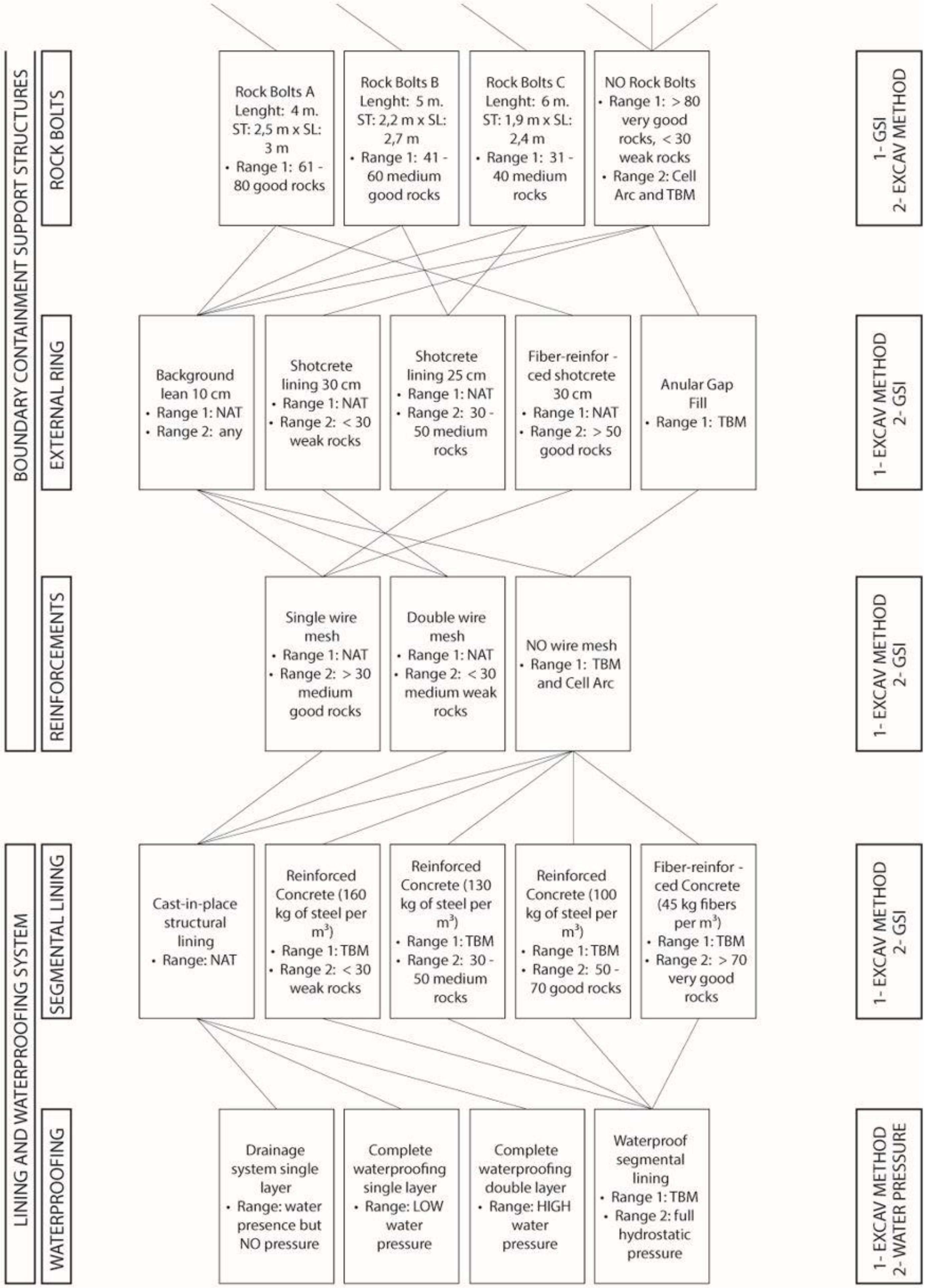


Figure 3 - Graphic rapresentation of solutions combinantion amtrix

3.3 - Suitable application study case

Once the two phases described above have been completed, it is necessary to relate the descriptions of the performances and the heads of applications of the technologies with their three-dimensional model. To carry out this operation, a platform that supports BIM files is required in which the link between the two aspects, geometry, and behavior, can be consolidated. To do this we made use of 3D Experience as in addition to allowing us what has been described it further allows the use of parametric design, thanks to which the model can be adaptive to the alignment of the excavation.

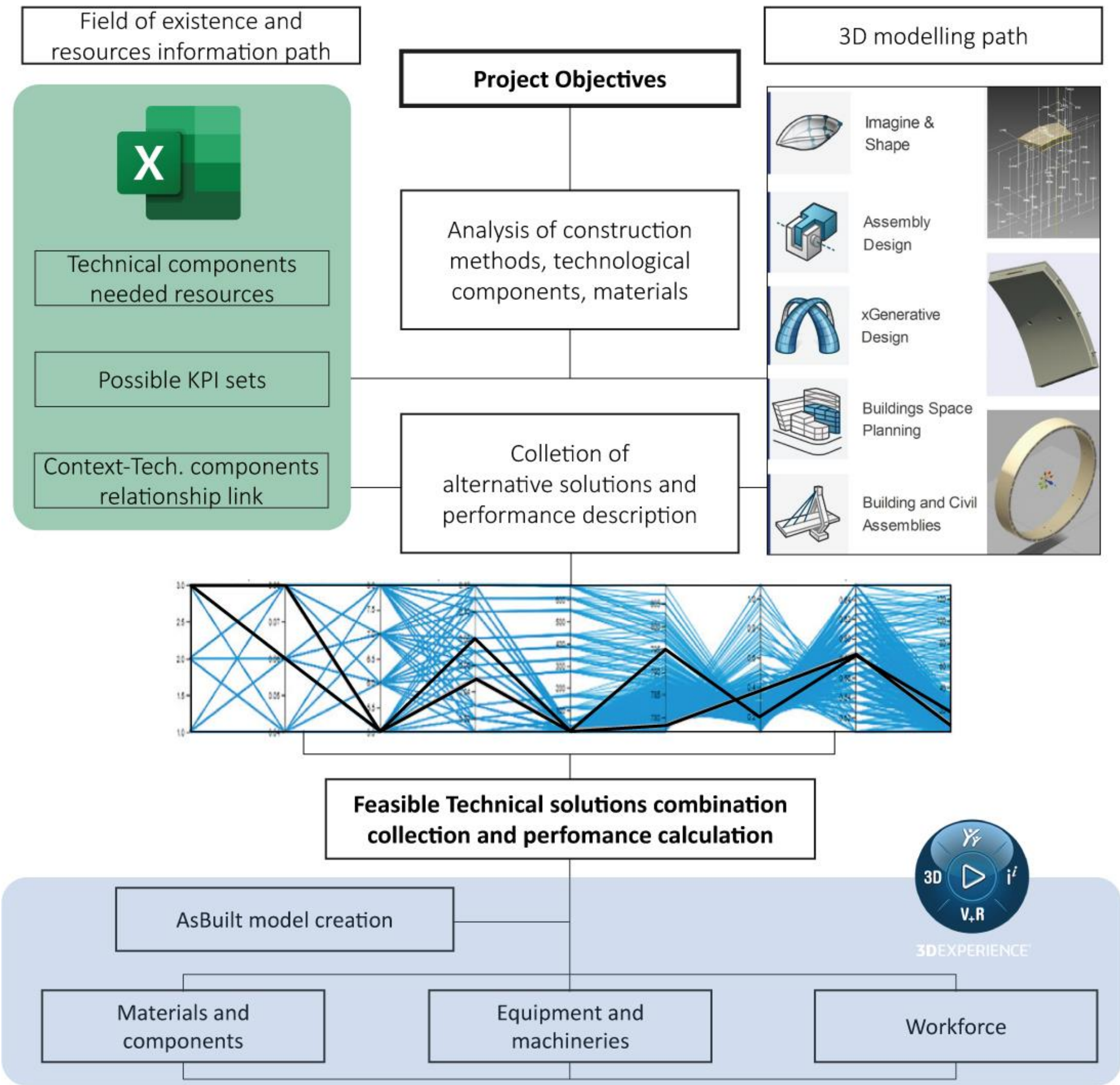


Figure 4 - Graphic representation of the DSS creation workflow

4 STATE OF THE ART

4.1 - BIM methodologies and BIM Management System

4.1.1 - Building Information Modelling and Management system

BIM, or Building Information Modeling, is a process that involves the creation and management of digital representations of physical and functional characteristics of a building. BIM is an intelligent 3D model-based process that provides architecture, engineering, and construction professionals with the tools to plan, design, construct, and manage buildings and infrastructure more efficiently.

One of the primary benefits of BIM is that it allows all stakeholders in a construction project to collaborate more effectively. This means that architects, engineers, contractors, and owners can work together in a virtual environment to share information, identify and resolve issues early in the design process, and improve the overall quality of the construction project. BIM also helps to reduce costs and waste by enabling designers and contractors to identify and resolve issues before construction begins. It also allows for greater accuracy and precision in construction by providing detailed information about materials, components, and systems.

Overall, BIM is a powerful tool that has the potential to transform the construction industry by improving collaboration, reducing costs, increasing accuracy, and enhancing sustainability. As technology continues to advance, it is likely that BIM will become an even more important part of the construction process in the years to come.

Management systems refer to the set of policies, procedures, and practices that are put in place to manage an organization's operations effectively. These systems provide a framework for decision-making, resource allocation, and risk management. There are different types of management systems, and each one is designed to address specific organizational needs. Regardless of the type of management system implemented, the goal is always to improve organizational efficiency, effectiveness, and overall performance. By providing a structured approach to managing operations, management systems can help organizations achieve their goals and objectives while minimizing risk and maximizing value.

BIM and management systems can be connected in several ways. One way is by integrating BIM data with project management software. This allows access to real-time data about the project's progress, including schedule, cost, and resource allocation. Collecting the entire set of information in one place can lead to better management of decision and consequently to produce better solutions for the project.

BIM can also be used to support facilities management. After the construction of a building is complete, BIM data can be used to create a digital twin of the building. This digital twin can be used to manage the building's operations, including maintenance schedules, equipment management, and energy usage. By having access to this information, facilities managers can optimize the building's performance and reduce operational costs. In addition, BIM can be integrated with asset management systems. This allows us to track the lifecycle of building assets, from design to decommissioning. By having access to this information, the stakeholders involved in the project can make more informed decisions about asset maintenance, replacement, and upgrade.

At the end, these methods can help construction sector operators to streamline the construction process, reduce costs, and improve project outcomes. By providing accurate and detailed information, BIM can help construction managers to make informed decisions and optimize project performance.

4.1.2 - BIM Infrastructure methodologies

The infrastructure sector poses unique challenges for the implementation of Building Information Modeling (BIM) due to its distinct characteristics and complexities. These projects are typically larger and more intricate than building projects. They encompass extensive networks, vast geographical areas, and intricate systems. Managing and integrating the large volume of data and information associated with infrastructure projects wouldn't be easy. These also require collaboration among various disciplines such as civil engineering, structural engineering, transportation, utilities, and environmental engineering. Each discipline employs its own specialized software, data formats, and workflows, making it difficult to integrate and synchronize information across disciplines. Many infrastructure projects involve upgrades, renovations, or expansions to existing infrastructure and the integration from legacy systems, as-built information, or outdated drawings into a BIM model can be complex and time consuming. It's often important to guarantee accurate geospatial information that can include topography, land boundaries, and geographic features, integrating geospatial data into the BIM model. Another issue can be that the infrastructure sector comprises a diverse ecosystem of software tools and platforms used by different stakeholders, and achieving seamless interoperability and data exchange between these tools can be difficult. Standardization efforts are ongoing, also promoted by laws and regulations, but they are still far from an effective result. Infrastructure projects are also subject to numerous regulations, standards, and legal requirements and incorporating these requirements into a BIM model and ensuring compliance can be complex, particularly when regulations and standards vary across regions or countries. At the same time another complex issue can be infrastructure lifecycles, that span decades or even centuries. BIM implementation must consider the entire lifecycle of the infrastructure, including design, construction, operation, maintenance, and eventual decommissioning.

4.1.3 - Tunnelling solution collection & Technical components

As previously anticipated, BIM methodologies are the most powerful instruments that can lead the evolution of design and management in the construction world. Linking to the choice of case study, underground tunneling is a great field of application for BIM related to project management, because it is a complex and challenging sector that requires a thorough understanding of many different technical components and solutions. Starting from the criticality relating to the level of previous knowledge, focused on the building and construction world, and not vertical and specific on tunnels and infrastructures, it was necessary to undertake an important phase of bibliographic study, all in order to obtain a coherent and high-level result.

Principally, tunneling involves a range of geotechnical, structural, and environmental considerations that need to be addressed during the planning, design, and construction phases of a project. These considerations can include soil and rock mechanics, ground improvement techniques, waterproofing, safety systems, and emergency response planning, both during construction and utilization phase.

Tunneling projects are usually highly specialized and require interdisciplinary collaboration between civil engineers, geologists, architects, and other professionals. This means that this type of project involves the participation of different teams of experts and considerably increases the complexity of project management. At the same time, the probability that problems of different nature arise during excavation and construction, generates the risk of time dilation and increasing in expense. From these features emerges the importance of adopting a BIM environment that can improve project management and lead to better decisions, avoiding the issues previously mentioned.

Another element connected with complexity and multidisciplinarity in underground tunneling is represented by technological design. Technical variables and the difficult predictability of the geological context can lead to choices with significant impact on the success of the project. By choosing the most appropriate and efficient tools and techniques, the tunnels can be excavated and stabilized safely, quickly, and cost-effectively. For this type of infrastructures there are a lot of technical components because it is a complex and challenging process that requires the use of a wide range of items, materials, and technological solutions to achieve the final results, following logistic requirements and geological context.

The progress of the underground works, inside environments that are often unstable, hazardous, and difficult to access, involves a safely and efficiently variety of technical components to address all different aspects of the project, that are usually very subject to change along the way. Consequently, monitoring and control systems are fundamental to track ground movement, groundwater levels, and other key parameters during the tunneling process, to outline step by step the best technological answers and ensure the safety and stability of the tunnel. Furthermore, the choice of technical components depends on the specific ground conditions, geological features, and project requirements and different solutions are used for tunnels, adapting step by step to the excavation context.

The use of a large number of technical components is therefore necessary in tunneling due to the complexity and variety of tasks involved in the excavation, stabilization, and support. Only using the most appropriate and efficient technical components combination, these infrastructures could be completed respecting the requirements of safety, efficiency, and affordability.

4.2 - Excavation methodologies

Tunnels are undoubtedly a key element that defines the mechanism of connection and accessibility between distant or remote places. Although there are many factors associated with the economic resonance of a geographic area, the density of the network and the spatial connections are an effective indicator for assessing the degree to which an area is moving forward. In this context, tunnels have historically been one of the preferred solutions to greatest engineering challenges, despite the real risks and significant investment of resources required.

In the context of human expansion and the need to create efficient connections, mining technologies have always played a major role. The progress and development of methodologies in this area are indicators of the level of efficiency and optimization in space management. Therefore, the study of new techniques in mining sciences takes on concreteness and justification as a means of understanding the reasons behind this process and future goals.

Deepening geological knowledge, considered through this perspective, allows for a more precise assessment of the efficiency of space utilization strategies and the identification of possible improvements. This study aims to contribute to technological advancement in the field, enabling optimization of resource acquisition and minimization of environmental impacts. At the same time, it pursues the goal of advancing the development of safer and more efficient engineering solutions for the construction of tunnels and underground infrastructure.

Ultimately, the study of mining science as it relates to the construction of tunnels and underground infrastructure is a crucial aspect of understanding and improving our ability to manage space efficiently. It’s the reason as it is also the application filed to technological advancement and resource optimization, asking for the engineering challenges to be addressed effectively and sustainably.

The rock mass excavation project has been an ambitious field of application, which has found justification in the great economic repercussion involved and the engineering challenge it represents. Facing those aims has driven the adoption of cutting-edge technologies, turning experimental solutions into practical realities.

As scientific discoveries have progressed, multiple different techniques and approaches to excavation have followed. The evolution of technologies and machinery has allowed the transition from manual excavation methods to increasingly sophisticated mechanized and automated systems. The ambition to overcome geological challenges and optimize the tunneling process has driven imagination and research.

The optimization of excavation techniques has been one of the reasons for the applications of technological advances, such as geology and geotechnics, which allow for accurate assessment of soil characteristics and design of solutions suited to specific geological conditions.

Technological advances have also enabled the development of more sustainable and less invasive approaches, reducing environmental impacts and risks to workers, the use of nondestructive excavation techniques, and the adoption of practices to mitigate environmental effects.

As can be seen from the objectives chapter, the aspiration of the study is to determine the methods, technologies, and materials to be used in the construction of a tunnel, based on the specific priorities and needs of the project.

The first step involves the selection of alternatives among different excavation methods. This choice will have a largely significant impact not only on the cost and schedule of the project, but also on the overall effectiveness and efficiency of the activities and their safety. Moreover, the choice of excavation method will have cascading repercussions on all other decisions regarding the technologies and materials to be used.

Adopting, for example, a faster excavation method could result in increased initial costs or risks but reduce overall construction time by allowing tight deadlines to be met, while a less invasive excavation method could have a positive impact on the surrounding environment but require more time and resources. These choices will directly influence the selection of materials and components in tunnel construction by having purposes of weighing geological characteristics of the soil, safety, and reliability of the structures.

It is important to carefully consider the different options available and assess how each will affect the other alternative selection within the project. This complex decision-making process requires detailed analysis based on accurate data and specialized technical expertise in order to align project course and objectives.

4.2.1 - Drill & Blast

In the world of underground construction, there are two main methods of excavating tunnels in rock: conventional excavation methods and mechanized excavation methods. The former includes the Drill & Blast technique, while the latter is best known for excavations performed with huge machines called Tunnel Boring Machines (TBMs).

It must be said, however, that for the past decade or so the Drill&Blast excavation method has come to be regarded as unconventional, taking the place previously held by mechanized excavation by TBM. Nowadays, in fact, tunneling by mechanical means is very common, especially in urban areas, reserving for the Drill&Blast method special occasions when tunneling cannot be done in a "conventional" manner.

Drill blasting has accompanied underground infrastructure design from the discovery of explosives to modern times; it has been refined over the years in methodology but only partially in concept. As technology has progressed and machinery has been applied, it has undergone substantial modifications but remains defined by the cyclic repetition of the sequence of excavation with reduced cross-section and varying length at the face, filling the generated cavities with explosives.

Through detonation of charges, the rock portion of the affected segment is crushed, after which, after ensuring the static tightness of the portion, the next cycle is continued. As has been extensively mentioned numerous other excavation methods have been consolidated over the years, but despite its rudimentary operation it remains a cost-effective method and extremely flexible to the context, reasons why it remains widely used to this day.

Drill & Blast Working phases

This is mostly used method for the excavation throughout the world. The method is suitable in all types of rocks and the initial cost is lower than the mechanized method like TBM. Compared with bored tunnelling by Tunnel Boring Machine, blasting generally results in higher duration of vibration levels. The excavation rate is also less than TBM (usually 3 to 5m a day).

1 - Drilling

A jumbo is used to drill holes in the rock face. This one has three drilling arms and an operator tower. It is run by electric cable; a hose brings water to the drills. The drills are pneumatic. That means that the drill bits both hammer and rotate. Broken bits of rock are flushed out by water. These drill holes are 2.4-3.6 metres long. The first sets are straight holes (parallel cut) located around the edge of the face and in the middle. A second set (V-cut) is angled toward the centre. These allow the rock to be blown away from the face into the drift (tunnel).

2 - Loading and Blasting

The drill holes are now filled with explosives, detonators are attached to the explosive devices and the individual explosive devices are connected to one another. The holes are blasted in a proper sequence, from the centre outward, one after the other. Although more than 100 explosions may be set off, one after the other, the blast sequence is completed in several seconds. The devices should not explode at the same time, but rather one after the other at specified intervals. Only when the blast master has ensured that nobody is left in the danger zone can the explosion be triggered by the blasting machine.

3 - Ventilating

The blast causes lots of rock to be flung through the tunnel, dispersing clouds of dust that then mix with the combustion gases of the explosion. So that the miners can resume work in the tunnel, the bad air must be removed from the tunnel. This is done by using so-called air-ducting systems, long steel or plastic pipes, which are attached to the roof of the tunnel and blow fresh air onto the working face. This gives rise to localized excess pressure and the bad air is pushed towards the tunnel exit.

4 - Dislodging and Removing rubble

Dislodging refers to the stripping away and removal of loose pieces of rock, which were not completely released from the rock during the blasting procedure. This working step is completed by a robust tunnel excavator. After the loose pieces of rock have been dislodged from the working face, the blasted material – the rubble or spoil – is carried out of the tunnel. The material is either loaded onto dump trucks with wheel loaders and taken from the tunnel to an outside landfill or it is transported from the site of excavation to the landfill on conveyer belts. During the construction of the Brenner Base Tunnel, the transportation of the excavated material mainly takes place automatically using conveyor belts.

5 - Securing

The quickly drying shotcrete used for this purpose enables a cavity-free connection of the securing mechanism to the rock. Depending on the type of rock, a variety of securing measures can be implemented: wire mesh, tunnel arches, stakes, or so-called bolts, which can be driven into the rock. The final method for stabilizing rock faces is most commonly rock bolting. A jumbo is used here to first drill holes into the rock. The holes vary from 2.4-6 metres long. Under the poorest ground conditions, it may be necessary to put steel arches in place to hold up the walls and roof of a tunnel. In other situations, a steel mesh may be secured to the walls and roof to prevent other loose materials from falling on workers below.

7 - Geological mapping

The working face is now freely accessible, and the geologist has a few minutes to map it. In the process, he determines what type of rock is present and how the rocks lie. At the same time, the strength of the rock, the reaction of the rock mass to the excavation process and any mountain water infiltration are also documented. The mapping report created from this – with sketches and photos – serves as the basis for the selection of appropriate supporting measures.

Drilling Pattern Design:

Many mines and excavation sites still plan their drilling patterns manually, but advanced computer programs are available and widely used. Computer programs make it easier to modify the patterns and accurately predict the effects of changes in drilling, charging, loading and production. Computer programs are based on the same design information used in preparing patterns manually. [3]

Advantages:

- Potential environmental impacts in terms of noise, dust and visual on sensitive receives are significantly reduced and are restricted to those located near the tunnel portal.
- Compared with the cut-and-cover approach, quantity of C&D materials generated would be much reduced.
- Compared with the cut-and-cover approach, disturbance to local traffic and associated environmental impacts would be much reduced.
- More flexible regarding geometry, radius, and slope. The geometry can fit every project type.
- Less extensive pre-investigation required.

Disadvantages:

- Potential hazard associated with establishment of a temporary magazine site for overnight storage of explosives shall be addressed through avoiding populated areas in the site selection process.
- By providing for the use of explosives to open the cable, the Drill & Blast involves an important limitation to its application which is the vibration levels generated.

4.2.2 - Tunnel boring Machines (TBM)

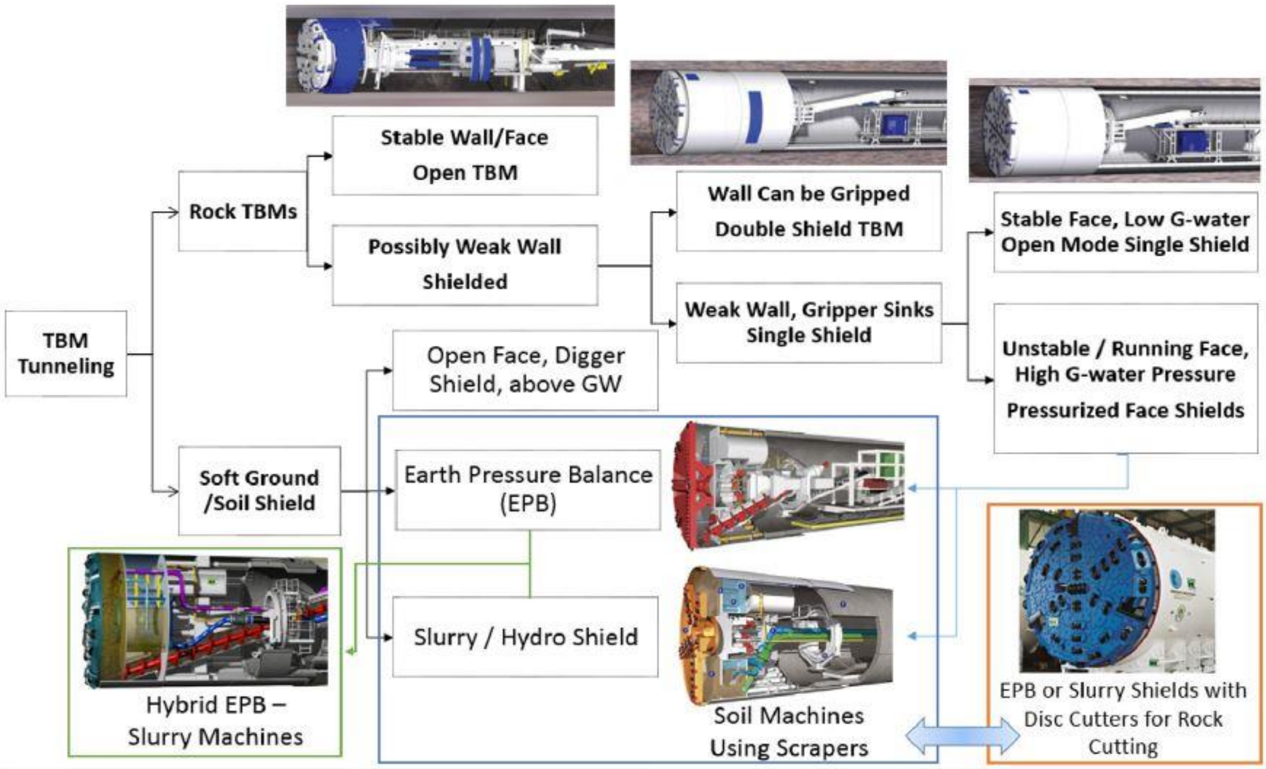


Figure 5 - General classification of TBMs for various ground conditions (pictures from Robbins, Herrenknecht, Tunneltalk).

Interestingly, innovation in mining technology led to a gradual replacement of traditional means and tools. The old methods of excavation and mining were becoming increasingly inefficient and expensive, prompting the industry to seek more advanced and automated solutions. The tools now mentioned, commonly called "moles," represent a significant step forward in the automation and efficiency of excavation and extraction operations, they've deeply changed the approach to the issue of excavation, they are less risky, and they've progressively shown a growing excavation rate not achievable whit other means. A TBM is a machine used to excavate tunnels with a circular cross section through a variety of soil and rock strata. They can bore through hard rock, sand, and almost anything in between. Tunnel diameters can range from a meter (done with micro-TBMs) to almost 16 meters to date. Tunnels of less than a meter or so in diameter are typically done using trenchless construction methods or horizontal directional drilling rather than TBMs.

TBMs have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of lining the tunnel and makes them suitable to use in heavily urbanized areas. The major disadvantage is the upfront cost. TBMs are expensive to construct and can be difficult to transport. However, as modern tunnels become longer, the cost of tunnel boring machines versus drill and blast is less. This is because tunnelling with TBMs is much more efficient and results in a shorter project.

These industrial excavators are composed of three key components:

1. **Rotary Head**: The rotary head is the element that penetrates the ground and drills it. This head can be equipped with cutting tools, such as bits or blades, designed to break up the soil and facilitate excavation. The rotation of the head makes it possible to create a continuous excavation face without having to manually remove material.
2. **Conveyor Belt**: After the rotating head has created the excavation face, the spoil material is transported away via a conveyor belt. This belt allows the waste material to be removed efficiently, preventing accumulation, and slowing down the excavation process.
3. **Handling System**: Moles are equipped with a handling system that allows them to move forward in the soil while maintaining constant pressure on the digging face. This system may include motors and mechanisms that push the mole forward while the rotating head and conveyor belt continue to work.

The adoption of these moles in the mining industry offers several advantages. First, it increases the overall efficiency of the excavation operation, minimizing downtime and improving productivity. Second, it helps ensure worker safety as many of the risky tasks are automated. Finally, mole technology can reduce the environmental impact of excavation operations, as it can limit the extent of disturbed areas.

However, it is also important to consider the challenges associated with these advanced technologies, such as the need for regular maintenance and the adaptation of existing infrastructure and operational processes to integrate moles into the workflow.

Hard rock TBMs

In hard rock, either shielded or open-type TBMs can be used. All types of hard rock TBMs excavate rock using disc cutters mounted in the cutter head. The disc cutters create compressive stress fractures in the rock, causing it to chip away from the rock in front of the machine, called the tunnel face. The excavated rock, known as muck, is transferred through openings in the cutter head to a conveyor belt, where it runs through the machine to a system of conveyors or muck cars for removal from the tunnel. [4]

Gripper Tunnel Boring Machine (GRT)

Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	–	o	+	+	+	+
Bohrkern – Gebirgsqualität [RQD] Core sample – rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	–		o	+	+	+
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	–		o	+	+	+
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	+		+	+	o	–
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5		sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+		+	+	o	o
Quellpotential Swelling potential	kein none		gering poor	mittel fair	hoch high	
	+		+	o	o	
Stützdruck [bar] Confinement pressure [bar]	0		1 – 4		4 – 7	7 – 15
	+		–		–	–

Figure 6 - Gripper tunnel Boring Machine Field of Existence (DAUB 2023)

Gripper tunnel boring machines are utilized in rock with a medium to long stand-up time. There is no active support of the tunnel face and excavation profile. The usual practice for systematically reinforcing the tunnel profile involves placing support structures either behind the cutterhead shield or in protection of the finger shield. In cases where fault zones comprise less stable rock, especially when there's a potential for rockfall, additional measures such as the installation of steel arches, shotcrete, spiles, or anchors should be feasible, and they should be positioned as closely as possible behind the cutterhead. A systematic shotcrete lining should only be installed in the trailing gantry area, to reduce, as much as possible, contamination of the drive and steering units in the front part of the machine. In sections of unstable or heterogeneous rock conditions (high degree of fracturing, fault zones), it is recommended that the tunnel boring machine is equipped with devices to enable forward probe drilling and perhaps also rock improvement, ahead of the machine.

Methods of dust suppression can be:

a) Water spraying at the cutterhead,

b) Dust shield behind the cutterhead,

c) Dust extraction in the excavation chamber with dedusting on the backup.

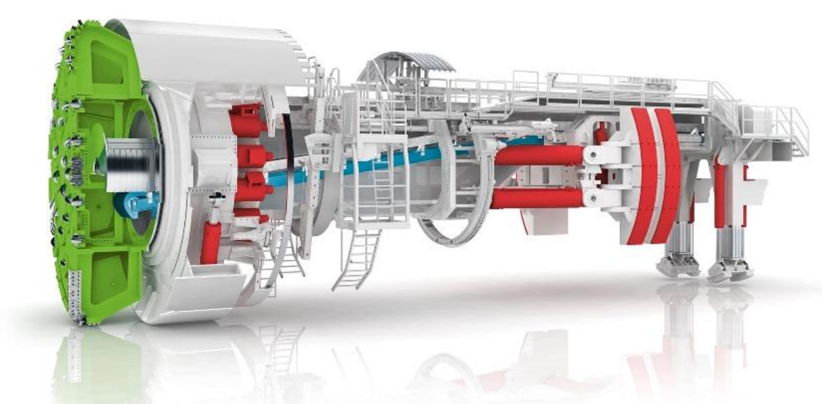


Figure 7 - Gripper Tunnel Boring Machine (Herrenknetcht, 2023)

Single shield, Open shield machine (OPS)

Its main field of application is stable tunnel faces, an example of those could be clays with a firm consistency and sufficient cohesion or in rock, single shields can be employed. The tunnel lining is constructed within the shield in the form of a segmental ring. The thrust forces and the cutterhead torque are transmitted via the thrust cylinders to the last constructed segmental lining ring. In segments characterized by unstable or diverse rock conditions, such as a high degree of fissuring or the presence of fault zones, it is advisable to outfit the tunnel boring machine with mechanisms that facilitate forward probe drilling and rock improvement in advance of the machine.

Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o	o	+	+	+	+
Bohrkern – Gebirgsqualität [RQD] Core sample – rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	o		+	+	+	+
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	o		+	+	+	+
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	+		+	+	o	–
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5		sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+		+	+	o	o
Quellpotential Swelling potential	kein none		gering poor	mittel fair	hoch high	
	+		+	o	o	
Stützdruck [bar] Confinement pressure [bar]	0		1 – 4		4 – 7	7 – 15
	+		–		–	–

Figure 8 - Single Shield, Open shield Machine field of Existence (DAUB 2023)

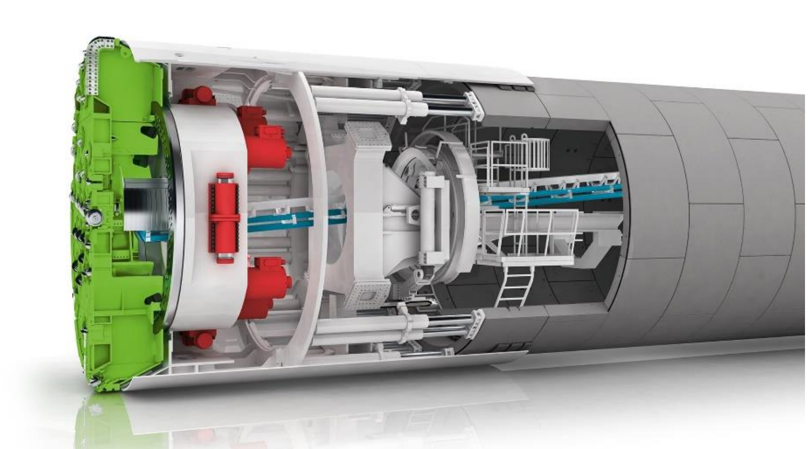


Figure 9 - Single Shield Tunnel Boring Machine (Herrenknetcht, 2023)

Double shield machine (DOS)

Double shield machines consist of two telescopic machine parts. These machines are employed in solid rock or soils with a stable tunnel face. The foremost section is referred to as the front shield, housing the cutterhead with its disc

Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o	o	+	+	+	+
Bohrkern – Gebirgsqualität [RQD] Core sample – rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	o		+	+	+	+
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	o		+	+	+	+
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	+		+	+	o	–
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5		sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+		+	+	o	o
Quellpotential Swelling potential	kein none		gering poor	mittel fair	hoch high	
	+		+	o	o	
Stützdruck [bar] Confinement pressure [bar]	0		1 – 4		4 – 7	7 – 15
	+		–		–	–

Figure 10 - Double shield Boring Machine field of Existence (DAUB 2023)

cutters, the cutterhead drive, and the main thrust cylinders. The posterior segment of the machine is identified as the gripper shield, which accommodates the gripper plates and the auxiliary thrust cylinders. In this configuration, there is typically no provision for active support of the tunnel face. It's worth noting that in double-shield mode, where two shields are employed, the intrados of the excavation is left unprotected by a shield, necessitating careful consideration of the stability of the tunnel face under these conditions. This design choice emphasizes the importance of stability assessments, particularly in situations where active support mechanisms are not readily available for the tunnel face during excavation. Therefore, the rock shall exhibit a sufficient stand-up time in order for the intended support to be installed. In the single-shield mode, areas of rock with a shorter stand-up time can also be excavated.

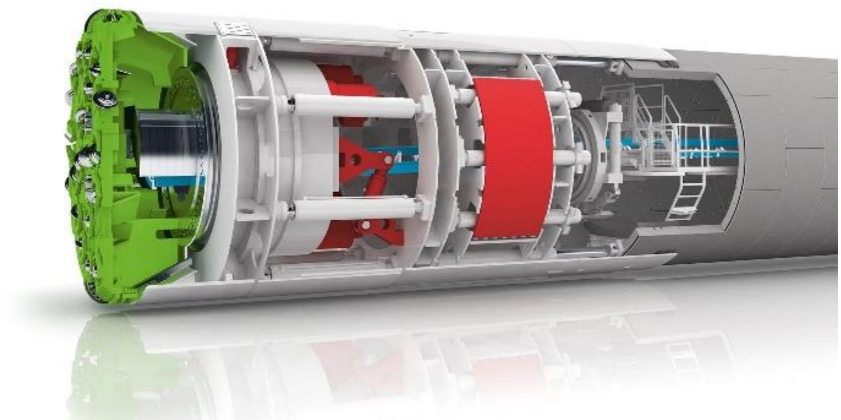


Figure 11 - Double shield Tunnel Boring Machine (Herrenknetcht, 2023)

Soil TBMs

Slurry shield machine (SLS)

In tunnel boring machines with fluid support the tunnel face is actively supported by a pressurized medium (slurry). The excavation chamber is sealed off from the tunnel by a pressure wall. Slurry shields are usually used under conditions in which the tunnel face must be actively supported, and the inside of the machine protected against soil and water penetration. The tunnel lining is built within the protection of the shield casing through erection of segmental rings. The properties of the support medium shall be determined in accordance with the permeability of the existing subsoil. It shall be possible to vary the density and viscosity of the slurry. Prior to the start of tunnelling, the required and maximum support pressures shall be calculated over the entire length to be tunneled (support pressure calculation). Removal of the soil takes place through full-face excavation by a cutting wheel equipped with tools. The soil is then removed via the suspension. Subsequent separation of the removed suspension is essential. The support slurry can be completely (empty) or only partially (lowering) removed and replaced by compressed air. In stable ground, the slurry shield can also be operated without pressurization, with the excavation chamber partially filled with water, which is then used as the conveying medium.

Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o	o	o	o	o	o
Bohrkern – Gebirgsqualität [RQD] Core sample – rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	o		o	o	o	o
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	o		o	o	o	o
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	o		o	o	o	o
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5		sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+		+	o	o	o
Quellpotential Swelling potential	kein none		gering poor	mittel fair	hoch high	
	+		+	o	–	
Stützdruck [bar] Confinement pressure [bar]	0		1 – 4		4 – 7	7 – 15
	o		+		+	+

Figure 12 - Slurry shield boring machine field of Existence (DAUB 2023)

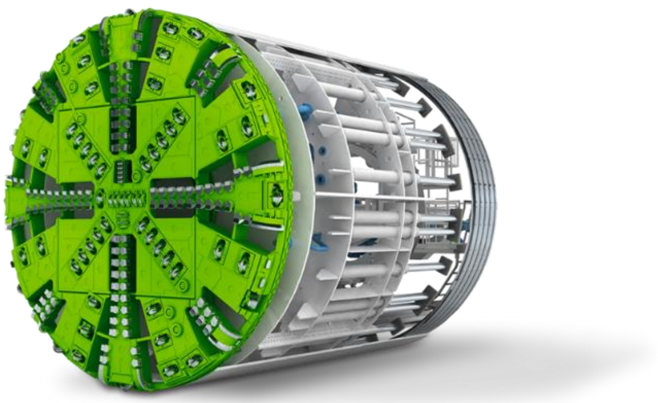


Figure - Slurry shield Tunnel Boring Machine (Herrenknetcht, 2023)

Earth Pressure Balance Machine (EPB)

The operational state in which the excavation chamber is filled with soil paste is termed the closed mode. In this mode, a cutting wheel with a relatively low opening ratio is employed, and the support pressure is monitored using earth pressure cells strategically positioned on the front of the pressure bulkhead. Support pressure is finely tuned by adjusting the screw conveyor speed, TBM advance rate, and the controlled injection of conditioning agents. The reduction in pressure between the excavation chamber and the tunnel is accomplished through friction within the screw conveyor. This multi-faceted approach ensures precise control and optimization, demonstrating the synergy between mechanical and chemical elements for a stable and efficient tunneling process.

Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o	o	o	–	–	–
Bohrkern – Gebirgsqualität [RQD] Core sample – rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	+		o	o	–	–
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	+		o	o	–	–
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	o		o	o	o	o
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5		sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+		+	o	o	–
Quellpotential Swelling potential	kein none		gering poor	mittel fair	hoch high	
	+		+	o	–	
Stützdruck [bar] Confinement pressure [bar]	0		1 – 4		4 – 7	7 – 15
	o		+		o	–

Figure 13 - Earth Pressure Balance machine field of Existence (DAUB 2023)

In stable ground, the earth pressure balance machine can also be operated without pressurization with a partially filled excavation chamber. It is called open mode. In stable ground with water ingress, operation is also possible with partially filled excavation chamber and compressed air (transition mode). In the event of high groundwater pressure and if the ground tends to liquefy, the – in this case critical – material transfer from the screw to the conveyor belt can be replaced by a closed system (pump feed).

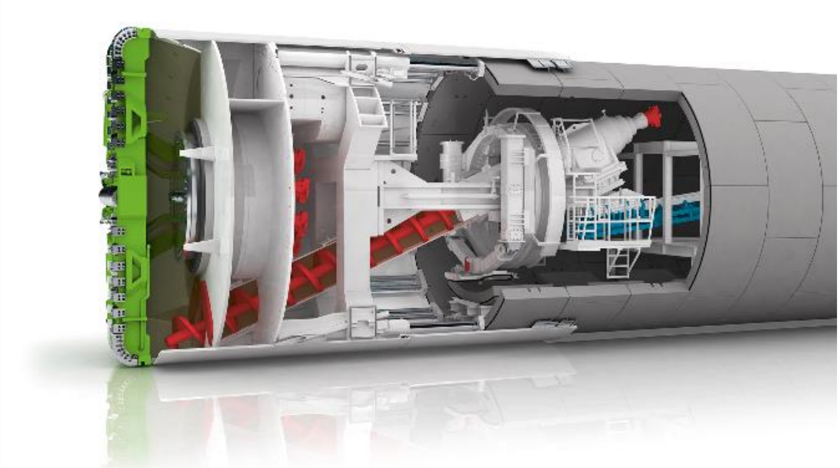


Figure 14 - Earth Pressure Balance Boring Machine (Herrenknetcht, 2023).

4.2.3 - TBMs Performance prediction models

The development of underground infrastructure has increased significantly during recent decades and the great demand of infrastructure projects is expected to continue to increase in the future. The need to excavate deeper and longer, especially in urban areas, is continuously growing, and building tunnels using tunnel boring machines (TBM) is currently the most used method in tunneling industry. Using TBMs as excavation technique leads to high investments and geological risks. Therefore, accurate performance predictions are of major importance to control risk and avoid delays. Several performance prediction models are made to calculate penetration rates as well as cutter consumptions and many other critical factors connected to the usage of these grate machineries. The various models require different input parameters, including both geological and machine related parameters and as output they foresee the net penetration rate (NPR). Some of these prediction models are based on empirical data while others are numerical or analytical models. A broad variation of models has been investigated and several different input parameters have been tried. Some of the models have been modified, and both original and updated versions were taken into consideration in this study.

Performance prediction of TBMs is an essential part of project scheduling and cost estimation. This process involves a good understanding of the complexities in the site geology, machine specification, and site management. Ever since Tunnel Boring Machines (TBM) were introduced in 1950s, design engineers and contractors have been preoccupied with the question of accurately estimating machine performance for a given project setting as it the key for the optimization.

In general, the performance estimation for a TBM refers to two main parameters which are:

- Rate of penetration **(ROP)**

  which is referred to as penetration rate (PR) and often expressed in m/h and refers to the linear footage of excavation per unit time when machine engages the ground and is in production.

  (Advance rate) AR = ROP * U * Ns (shift number) * Sh (shift duration)

  Another parameter that is often cited as part of performance prediction is cutter life. This parameter is typically expressed in terms of average cutter life in hours, meter travelled on the face, cutters per meters of tunnel, or cutters per cubic meter of excavated rock. While cutter life is a cost issue and is not directly related to the parameters listed above, TBM experts are expected to offer an estimate for this item. Obviously, increased cutter consumption will impact maintenance time and its costs consequently.

- Utilization rate **(U)**

  expressed in percent (%) and representing the ratio of boring time to the total time. Total time could refer to the number of hours worked per workdays, boring days, or calendar days.

Before starting to carry out results, a literature study was performed. The aim of analysis was to obtain detailed knowledge about all the models, as well as information about tunnel boring in general as it was the only way to reach the goals set. [5]

Looking at the estimation of the first of the parameters there are two camps among researchers when it comes to performance prediction models of TBMs. One is the force-balance or theoretical approach, and the other is the empirical approach. The first group of models are based on estimation of cutting forces acting on disc cutters and balance of forces between the head and the face. These models are based on the laboratory testing of disc cutters in various rock types and allow for estimation of normal and rolling forces acting on disc cutters while cutting rock of certain strength. The estimated forces are then used to estimate cutterhead torque and thrust and to estimate maximum ROP for a TBM with given specification. The most frequently used model in this group is the Colorado School of Mines (CSM) model. The Colorado School of Mines (CSM) model was first published in 1977 by Ozdemir et.al. The model was designed to be an analytical penetration prediction model based on performing laboratory tests at the Earth Mechanics Institute in Golden, Colorado. Results from these tests have been compared with TBM field data to include practical findings. In 1997, Rostami updated the original model and created the most established version of the model. He revised several formulas and gathered new data with

Performance prediction model	Geological input parameters	Reference
NTNU model Modified NTNU model	DRI, porosity, rock mass fracturing,	Bruland (2000) Macias (2016)
CSM model MCSM model	UCS, BTS, rock mass fracturing, brittleness, density	Rostami (1997) Yagiz (2002)
Gehring model Alpine model	UCS, rock mass fracturing, BTS, abrasivity/breakability	Gehring (1995) Wilfing (2016)
Q_{tbm} model	Q-value, UCS, PLT, density, porosity, induced biaxial stress	Barton (2000)
Model by Yagiz	UCS, brittleness, rock fracturing	Yagiz (2008)
Model by Hassanpour et al.	UCS, RQD	Hassanpour et al. (2011)
Model by Farrokh et al.	UCS, RQD	Farrokh et al. (2012)

Figure 15 - Performance prediction Models, respective geological input parameters and Authors Rozmani

constant cross-section cutters (Wilfing et al.). The philosophy behind this model is to first start from the individual cutter forces acting on the rock mass, then determine the overall cutterhead thrust- and power requirements to obtain the maximum rate of penetration (Rostami & Ozdemir, 1993). By comparing these estimated values with the installed machine parameters, the maximum obtainable rate of penetration will be achieved [7].

The empirical models allow for estimating the ROP of a TBM of certain size in a rock mass with given characteristics. These models are based on the field observations and analysis of machine performance in past projects. In this category, the most used models are the Norwegian model (NTNU) or Field Penetration Index (FPI) models. [8]

Empirical models typically include field operation issues and have naturally accounted for conditions. However, they cannot predict machine behavior and speed of cutting when deviating too much from a normal operating condition. Theoretical models can offer better prediction if the operating levels of the machine are known or can be prescribed. [9]

The scheme is a summary of advantages and disadvantages of these modelling concepts.

Model Type	Advantages	Disadvantages
Theoretical	• Flexible with cutter geometry and machine specifications • Can be used in trade off between thrust and torque and optimization • Can be used for cutter-head design and improvements • Can explain the actual working condition of the discs and related forces	• Unable to easily account for rock mass parameters • Lack of accounting for joints • Can be off by a good margin in jointed rock • Inability to account for required field adjustments
Empirical	• Proven based on observed field performance of the TBMs in the field • Accounts for TBM as the whole system • Many of field adjustments (i.e. average cutter conditions) are implied. • Ability to account for rock joints and rock mass properties	• Lower accuracy when used in cases when input parameters are beyond what was in the original field performance database • Unable to account for variations in cutter and cutter-head geometry, i.e. cutter tip width, diameter, spacing, gage arrangement • Extremely sensitive to rock joint properties

Figure 16 - Advantages and Disadvantages of performance prediction model types

In each category of modes there are some published works that are somewhat universal, whereas some that are site/rock/cutter machine specific. The users should be very careful with this issue since the site-specific models are often more accurate within the dataset used for their development but very inaccurate with used under different set of parameters. The experience shows that in most projects, TBM ROP can be estimated with reasonable degree of accuracy using these models. Obviously, the accuracy of the models is somewhat limited by the accuracy of the input parameters, mainly the variability of the ground relative to index parameters used in the models to calculate ROP. The accuracy of the models is fairly good in grounds where the rock is uniform nevertheless usually site-specific models are developed by contractors and construction management teams for adjustment of original schedule for their tunnelling operations.

Several types of TBMs are available in the industry and different systems are used to classify them. Clear cut classifications cannot be done because of the complexity of geologies. This is the basis for development of concepts for hybrid machines, which could be between rock and soil machines, as well as shield and gripper TBMs. Complex geological settings and mixed ground conditions require a delicate study of machine selection and related performance issues to balance the cost and risks of operating selected machines in given ground. (Bruland 2014)

Machine utilization rate is an integral part of TBM performance prediction which reflects the amount of time that the TBM excavates rock. The typical utilization rates range from 5% for very difficult and complex geologies with poor site management to around 55% in perfect working conditions the most common range of TBM utilization is in 20–30% range.
This indicates that machine only work a few hours a day and most of the work time is spent on machine maintenance, repairs, ground support issues, surveying, personnel change over, resolving back up issues, muck transportation delays, etc. These so-called downtimes often account for 70–80% of the total time and are usually recorded and analyzed in tunnelling projects to evaluate the time distribution for various activities and related delays. Decreasing downtime will have a direct impact on the machine utilization and hence the advance rate and is the objective of many studies and on-site continuous improvements. Another source for lack of success in predicting TBM utilization is the impact of human/site related factors. This refers to contractor/ crew experience, Management style, labor issues, site arrangement, and logistical issues with supplies, repair, and spare parts, electricity and power supply, transportation and site access issues that could limited muck haulage due to special city/site ordinances, availability of local workforce, and so on. however, this is a very difficult parameter to evaluate, but overall, the lack of experience can

reduce the overall utilization by about 10%. Mixed face conditions can reduce utilization by 5–10%. One must keep in mind that the ranges offered in this table should not be applied to the entire tunnel, rather the alignment should be broken into certain reaches and for each section of the alignment, a value for U is assigned and the overall utilization rate of the tunnel will then be based on the geometry, curvature, slope, etc. and length of each section, that determines the project-based machine utilization. The reductions can be compounded (multiple reductions if the said conditions exist on a given section of the tunnel). The selection of the machine type can also be done based on the utilization rates [5].

Another approach for estimation of machine utilization is to evaluate delay times based on downtimes assigned to various categories of activities. This concept has been used in both CSM and NTNU models where the total time is broken to sub-activities such as boring, regripping, cutter inspection/change, haulage delays, surveying, machine repair, and back up repairs…

$$U = \frac{T_b}{T_b + T_{tbm} + T_{bu} + T_c + T_y + T_{sp} + T_w + T_g + T_{tr} + T_r + \ldots}$$

Decreasing downtime will have a direct impact on the machine utilization and hence the advance rate and is the objective of many studies and on-site continuous improvements.

Adjustments for the suggested rates can be made for surveying by reduction in offered values in the table by 3–5% for wide and tight radius curves, respectively. If the tunnel is in slopes higher than normal <1%, a 2% reduction for every 1% of slope may be considered. This reflects the slowdown in the process due to transportation and water/drainage issues (i.e., a 3% slope causes a 6% reduction in U). the lack of experience can reduce the overall utilization by about 10%.

Machine type	Ground conditions	Muck haulage	Suggested utilization rates (%)
Open	Simple/consistent	Train	35–40
	or uniform	Contentious/conveyor	40–45
	Complex/faults	Train	15–20
		Contentious/conveyor	20–25
Single Shield	Simple/consistent	Train	20–25
	or uniform	Contentious/conveyor	25–30
	Complex/faults	Train	15–20
		Contentious/conveyor	20–25
Double Shield	Simple/consistent	Train	25–30
	or uniform	Contentious/conveyor	30–35
	Complex/faults	Train	20–25
		Contentious/conveyor	25–30

Figure 17 - Suggested Utilization percentage (Rotsmani J.)

No	Category name	Definition	Suggested formulas
1	TBM, T_{tbm}	TBM breakdowns times	See Fig. 2
2	BU, T_{bu}	Back-Up breakdowns times	See Fig. 2
3	Cutter, T_c	Cutter check/change time	See Fig. 2
4	Support, T_{sp}	Support installation time (planned)	See Fig. 3
5	Regrip, T_r	Resetting times of TBM after each excavation stroke	$T_r = \frac{1000 \times t_r}{60 \times L_s} + \frac{409,000}{R^2}$ L_s is stroke length (m), t_r is regripping time (min) per stroke (2–6 min), and R is radius of curves (m)
6	Transport, T_{tr}	Times related to muck transportation and unloading	Condition / T_{tr} (h/km) / Comment Very good / <50 / Tunnel conveyor belt prone to no or very low breakdowns Good / 50 / Belt or Train, low breakdowns Normal / 150 / Belt or Train, normal breakdowns Poor / 350 / High breakdowns (especially in long tunnels) Very poor / >500 / Trains, very high breakdowns (e.g. simultaneous breakdowns for locos, wagons, and switches)
7	Maintenance, T_m	Routine maintenance of cutter head, TBM, and Back-Up	Based on ground conditions, • Good, Massive soft to medium rock: 50–100 h/km • Normal, Massive hard rock:100–200 h/km • Poor: TBM prone to high clogging and high water inflow in poor cementations, presence of expansive clay, very high rock strength for TBM: 300 h/km
8	Ground, T_g, T_w	Downtimes related to unfavorable ground conditions, which needs additional or support or dewatering	See Fig. 3
9	Probe, T_p	Probing times for ground exploration	Should be estimated based on field conditions
10	Utility, T_u	Line extension times	$T_u = 1.3 \times \theta$ (h/km) where θ tunnel slope in degree
11	Survey, T_y	Times for changing surveying stations and checking tunnel direction	$T_y = 192,000/R^2$ (h/km) R = tunnel turning radius (m)
12	Other, T_o	Unclassified times	Up to 200 h/km for crew with low experience

Figure 18 - TBM workflow possible downtimes components (Farrock et al.)

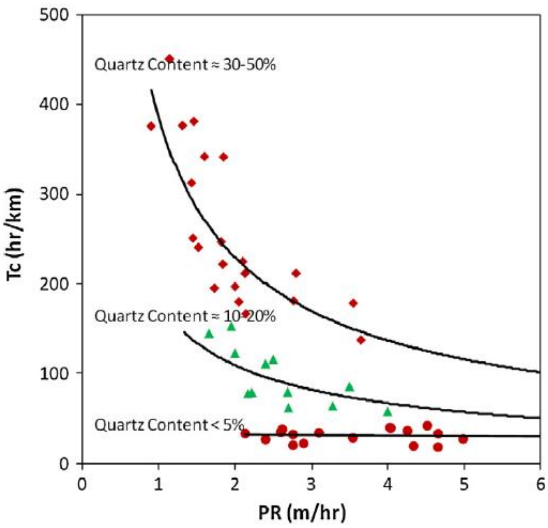


Figure 20 - Penetration Rate deviation by quartz content (Farrock et al.)

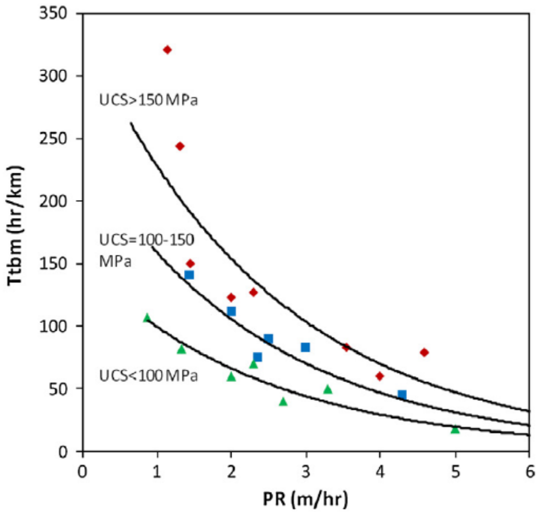


Figure 19 - Penetration rate deviation by UCS (Farrock et al.)

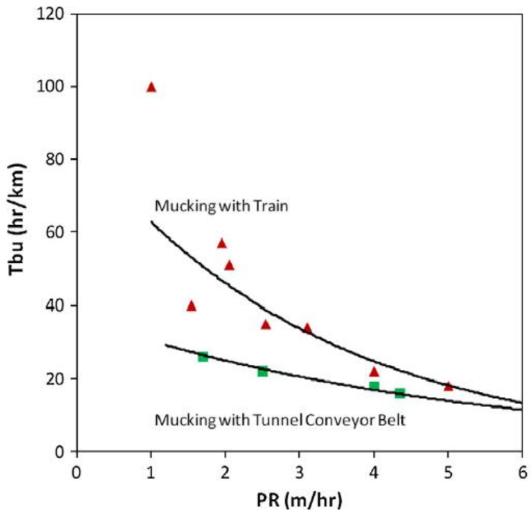


Figure 21 - Penetration rate deviation caused by Backup Time (Farrock et al.)

4.3 - Solutions collection & Tunnel technical components

Technical knowledge is essential for tunneling construction due to the complexity and unique challenges involved. It enables engineers to design tunnels with structural integrity, stability, and functionality, considering factors such as intended use of the tunnel, dimension of the excavation, ground condition, granulometry, water presence and pressure. Technical knowledge also ensures the implementation of proper construction techniques, safety measures, and quality control processes. It's a fundamental part of the process because equips the project teams with problem-solving skills and the ability to adapt to unforeseen circumstances. For the same reasons, it's also important to stay updated with advancements in the field, that allow professionals to leverage innovative technologies and materials for improved efficiency and sustainability. Overall, technical knowledge serves as the foundation for successful tunneling construction projects [11].

Consequently, the list of technical components is essential in tunneling construction for several reasons. It helps with project planning by providing a detailed inventory of materials, equipment, and systems required. It assists in estimating costs, timelines, and resources analysis accurately. The list also aids in procurement by guiding the acquisition of specific items, quantities, and reaching quality standards. During construction, it serves as a checklist to ensure all necessary components are on-site, minimizing delays and guaranteeing the efficient response to unpredictable events during the works. It includes specifications for materials, promoting quality control and enhancing the durability and safety of the tunnel, helping to identify critical safety equipment and supports compliance with regulations. Additionally, the list facilitates future maintenance and operations by providing a reference for replacement parts and maintenance schedules. Overall, the technical knowledge serves as the foundation for successful tunneling construction projects, leading the list of technical components for effective planning, procurement, construction, quality control, safety management, and long-term maintenance [12].

The subdivision of the works for the construction of a tunnel into its main phases and technological classes will therefore be proposed in the next chapters. The purpose of this section of the thesis was to recreate, through an analysis that goes from large to small scale, the anatomy of the underground infrastructures, considering all the possible typological and technological configurations that can be implemented to cope with the typical needs and requirements of this kind of works [13].

The analysis activity was then added to that of research, in order to effectively break down all the variable components in a hierarchical manner and according to reference technological classes. The final product in this phase is thus constituted by a general framework which follows the logic from large to small scale, or more generally the dynamics of the execution of the works. Starting from the use required for the tunnel, the following technological classes are part of this general breakdown structure: the excavation method and the consequent typological section, the pre-consolidation systems at the front, the surrounding consolidation structures, the containment and boundary support, the external consolidation ring, the waterproofing systems, and finally the internal structural ring. These elements, united and combined, contribute to the creation of consolidation systems and fundamental structures, both elements common to all typologies of tunnels, and variable based on requirements of projects, characteristics of geological context, and frequent unpredictable conditions along the excavation phases.

4.3.1 - Excavation diameter and intended use

To introduce the technical solutions collection, it's fundamental to start with the necessary excavation diameter, connected with the intended use of the tunnel, usually required by the commissioning of the project. The relationship between excavation diameter and intended use in tunnel construction is an important consideration that depends on several factors. The excavation diameter, also known as the tunnel size or cross-sectional area, has a significant impact on the functionality, safety, and cost of the tunnel, and must necessarily align with the requirements for the intended use of the infrastructure.

The intended use of the tunnel plays a crucial role in determining the required diameter. Different types of tunnels serve various purposes, such as railway or road transportation, water conveyance, mining, or utility installation. The functionality of the tunnel directly influences the excavation diameter.

Another feature that can influence the cross-sectional area is related to geological and geotechnical characteristics of the tunneling site. The type of soil or rock, stability, groundwater conditions, and potential geological hazards all impact the feasibility of excavation and the required tunnel support systems. For these reasons, the geotechnical conditions can sometimes dictate a specific diameter to ensure the stability and durability of the tunnel.

In turn the diameter of the excavation has several influences on different aspects of the construction. It affects tunnel safety, particularly in terms of ventilation, emergency evacuation, and structural stability. It also has a direct influence on the cost of tunnel construction, because generally larger diameters require more excavation material, support structures, and construction materials, resulting in higher costs. The intended use of the tunnel must be balanced with the economic considerations to determine an optimal diameter that meets the functional requirements while minimizing costs. Particular attention should also be paid to potential future needs and expansion of the tunnel system. If there is a possibility of increased traffic, additional utilities, or changes in the intended use, designing a larger excavation diameter from the outset can save future costs and disruptions associated with retrofitting or expanding the tunnel [14].

It's important to note that specific projects may have their own guidelines and regulations regarding excavation diameter based on local codes, standards, and engineering practices. Consequently, the relationship between excavation diameter and intended use in tunnels should be assessed on a case-by-case basis, considering all the factors mentioned above. Despite this, recurring fields of application can certainly be identified, starting from five types of intended use: exploratory or service tunnel, subway, railway single track, railway double track or road with double direction, and highway [15].

Finally, the optimal diameter for a tunnel is determined by a careful evaluation of all the factors analyzed, primarily considering the specific requirements of each intended use. Traffic studies, engineering analysis, and consultations with commissioning are conducted during the planning and design phases to ensure the chosen diameter aligns with the functionality needs of the tunnel.

The diameter of the excavation section is therefore closely related to the dynamics described above, generating dimensional ranges of use that will be outlined in a more precise and analytical way in the next chapter. The latter, being linked to the project requirements and the intended use of the infrastructure, are common, with small differences, to both the main excavation methodologies. The management of these dimensional parameters therefore varies little between common traditional excavations and those mechanized using TBMs, having relatively similar thicknesses and dimensions in terms of structural layers. The difference mainly concerns a greater capacity to accommodate vehicular traffic for traditional excavations, which commonly have a more elongated and flexible section. A geometric characteristic which can therefore vary both according to the intended use and according to the type of excavation chosen, is certainly the shape of the cross section. The main types used in the context of large transport infrastructures are: circular section, cellular arc section, and horseshoe-shaped section, which in turn can be continuous or variable based on the characteristics of the geological context.

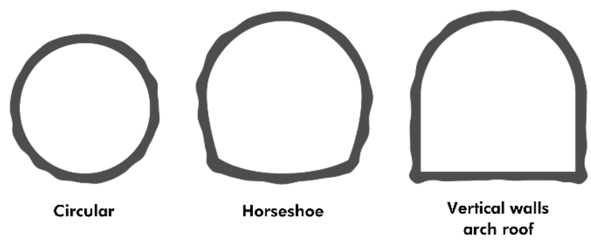


Figure 22 - Different Tunnel cross-section typology

In conclusion, the choices of the excavation diameter and the cross section are strictly interrelated and depend on factors such as the purpose of the tunnel, available space, and both construction and excavation techniques. Each cross section has its advantages and limitations, and the teams involved in the design have the primary objective of selecting the most appropriate design to ensure safety, efficiency, and functionality of the tunnel.

4.3.2 - Pre-consolidation systems at the front

Once the technical direction of the traditional excavation has been taken and the necessary diameter of the same has been identified, as described in the previous chapter, a series of interventions take place which aim to support and secure the tunnel structure and the geological context in which it is moves. three families of interventions belong to this category: pre-consolidation of the excavation face, pre-consolidation, and contour support, and finally containment and support, always on the contour.

In this chapter the attention is placed on the technological class of the interventions necessary to pre-consolidate the surface that will be subject to excavation, for a length useful to guarantee its effectiveness. Pre-consolidation systems in tunneling play a crucial role in ensuring the stability and safety of tunnel excavation. In many cases, the ground conditions encountered during tunneling can be challenging, with soft soils, water presence in pressure, or loose rock formation. Pre-consolidation systems are employed at the front of the tunnel to address these challenges and enhance the overall stability of the excavation process. The primary objective of pre-consolidation systems is to control and manage ground movements before the tunnel face is excavated. By doing so, these systems help mitigate potential ground settlements, subsidence, or other adverse effects that could compromise the integrity of the tunnel.

For all these reasons, the stability of the excavation face plays a decisive role in the static mechanism of a tunnel under construction. Therefore, when in the diagnosis phase it is possible to foresee that the deformations can be triggered during the advancement span, consequently through soil already predisposed to failure or already affected by deformation phenomena, it is necessary to intervene upstream of the face with interventions capable of anticipating these phenomena and to avoid uncontrollable convergences on the excavation profile. The path that can be usually followed in these cases, to avoid advancing in an already collapsed context, is: raise forward speeds as much as possible, compatibly with logistic problems, keep the digging rate constant, suitably shape the front wall giving it a concave shape, and intervene with the tools necessary to preserve the integrity of the nucleus at the front.

The interventions and tools usually put into operation, according to the context conditions and characteristics, are the following: drainage pipes, micro jet-grouting armed with fiberglass structural elements, fiberglass structural elements fixed with mortars, and the fibro-reinforced concave shotcrete layer at the front.

Figure 23 - VTR temporary structural elements disposal

These tools, which act inside the mass upstream of the excavation face, therefore have the function of preventing the minor principal stress from decaying until it vanishes when the deformation phenomena are still controllable.

4.3.3 - Boundary pre-consolidation support structures

Boundary pre-consolidation support structures in tunneling are an important aspect of underground construction and, as happens for the pre-consolidation interventions at the front previously mentioned, have the scope to provide stability and safety during excavation. Unlike the previous ones, these structures are designed to control ground movements and prevent excessive deformation of the surrounding soil and rock mass. Boundary pre-consolidation is implemented to mitigate effects like stresses and displacements, which can lead to ground movements and potential instability [16].

Since there are several possible interventions that are very different from each other, it was decided to divide this technological class into two macro areas, respectively related to injections and support structures.

Injections

Injections cover significant role in tunneling projects, particularly in the case of boundary pre-consolidation support structures. These are used to improve the ground conditions, enhance stability, and control groundwater during the excavation. They can involve the injection of various materials into the ground, according to geological context and conditions, to achieve specific objectives and enhance ground strength, control water flow, fill voids, or stabilize the surrounding soil or rock mass.

The basic type of injection consists of the use of cement mortars, in different quantities according to the needs dictated by the context. Another type of injection is the one with expansive mortars, indicated for filling voids in the rock and areas of subsidence. Finally, jet-grouting can be considered the most used and important method of injection, that consists in the jab of a high-pressure cement mixture into the ground through small nozzles in order to consolidate the soils or to create diaphragm walls. Also for jet-grouting, like happens for the other mortar injection types, quantity, frequency and depth are strictly connected to geological context, especially to water presence and pressure.

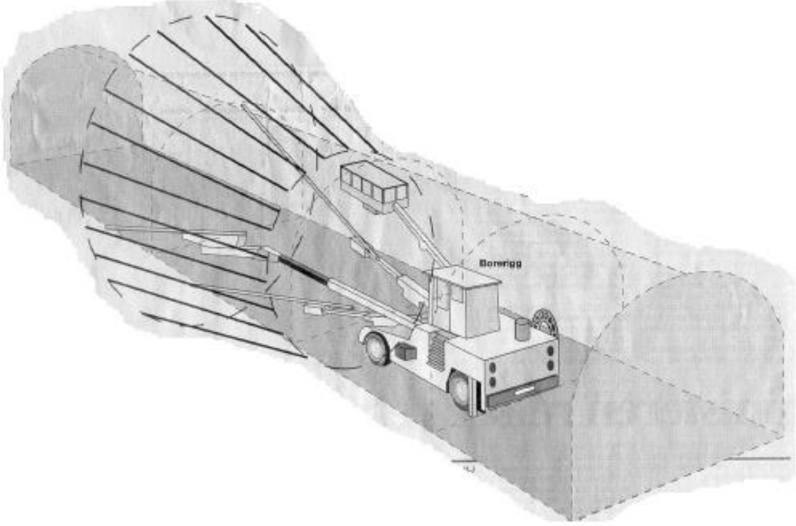


Figure 24 - Radial Injections execution mechanism

Support structures

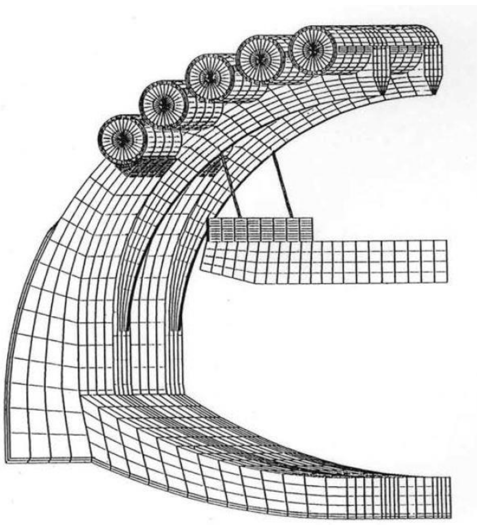


Figure 25 - Cellular Arch Structure

For the other main area, composed by support structures also applied to the boundary of the excavation, the scope is similar to that of the injections, but characterized by a greater structural value. This type of structures, installed on the tunnel periphery, is intended to form a safety and stable boundary between the excavated tunnel face and the undisturbed ground.

The main interventions in this area consist of two principal techniques: the cellular arch and the umbrella arch. The cellular arch is a construction technique that aims to fully consolidate the excavation environment even before starting to dig, with the help of service tunnels and a structure made up of large reinforced concrete pipes arranged above the cap. The umbrella arch is instead a support system with the aim to form a structural umbrella with the insertion of an assortment of longitudinal valved poles above and around the crown of the tunnel face, followed by the consolidation through injection of mortars in the poles.

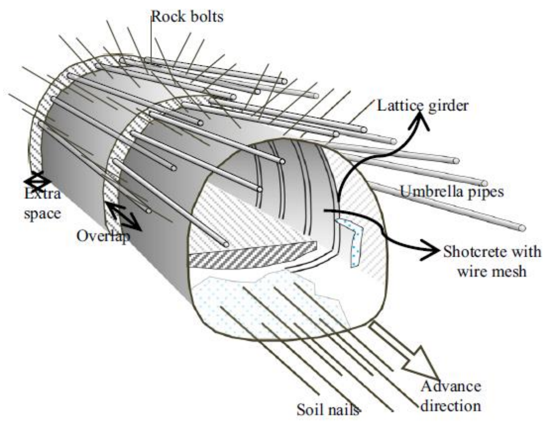


Figure 26 - Umbrella Arch Method

The primary objective of boundary pre-consolidation support structures is to redistribute the stresses induced by tunnel excavation to prevent excessive deformations and maintain the stability of the surrounding ground. These structures are typically installed on the tunnel periphery, forming a boundary between the excavated tunnel face and the undisturbed ground.

4.3.4 - Boundary containment support structures

Like pre-consolidation interventions, containment interventions also play a fundamental role in guaranteeing structural stability and making the infrastructure safe. Unlike pre-consolidation, which as previously discussed can be applied to the face or to the excavation boundary, the containment works instead act downstream of the excavation face and perform a function of regulating the deformation phenomena at the boundary. This containment action takes place through a series of interventions which on the surface are mainly aimed at preventing the decay of the excavation walls and while in depth they allow to increase the shear resistance of the soil. The main tools capable of performing this function are lattice girders, rock bolts and reinforced shotcrete.

Lattice girders

Lattice girders cover an important role in this field of application, being used in almost all the tunneling projects made with traditional method. The aim is to provide containment and support to ensure the stability and safety of the tunnel during and after construction. Lattice girders are structural elements composed by steel bars arranged in a grid-like pattern, forming a rigid framework that can bear loads and forces which are e propagated during tunneling operations. These are commonly installed on the perimeter of the excavation, following its shape and

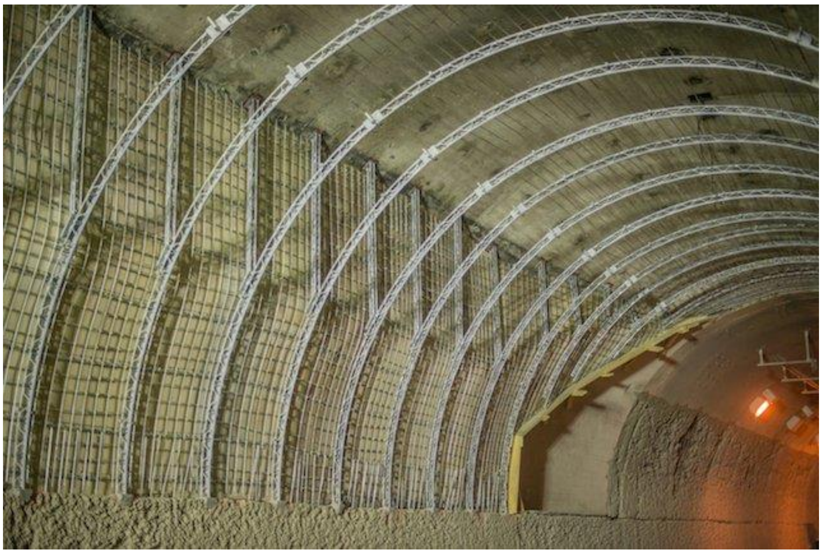


Figure 27 - Lattice Girders

guaranteeing maximum flexibility as needed. This is guaranteed by the possibility of variation of all their dimensions like thickness, width, height, and type of section, and the same goes for the frequency of installation along the tunnel advance span.

Rock bolts [17]

Lattice girders are normally used in combination with other construction elements with a structural and stabilizing function, such as rock bolts and reinforced shotcrete. A rock bolt is a long anchor bolt used to stabilize the rock mass around the excavated volume, with the capacity to transfer loads from the unstable exterior to the confined, and much stronger, interior of the tunnel. The main purpose of rock bolts is to counteract the stress and precarious conditions of geology, as well as the force of gravity, all elements that can constitute dangers and instability both during and after construction. As in the case of steel ribs, they are an extremely flexible and adaptable tool according to the conditions of the rocky context in which it is built, being able to vary the thickness, length, and the pattern with which they are applied on the excavated surface, considering both longitudinal distances on excavation line and radials around the tunnel section. More generally, the purpose of rock bolts during the execution phase is to

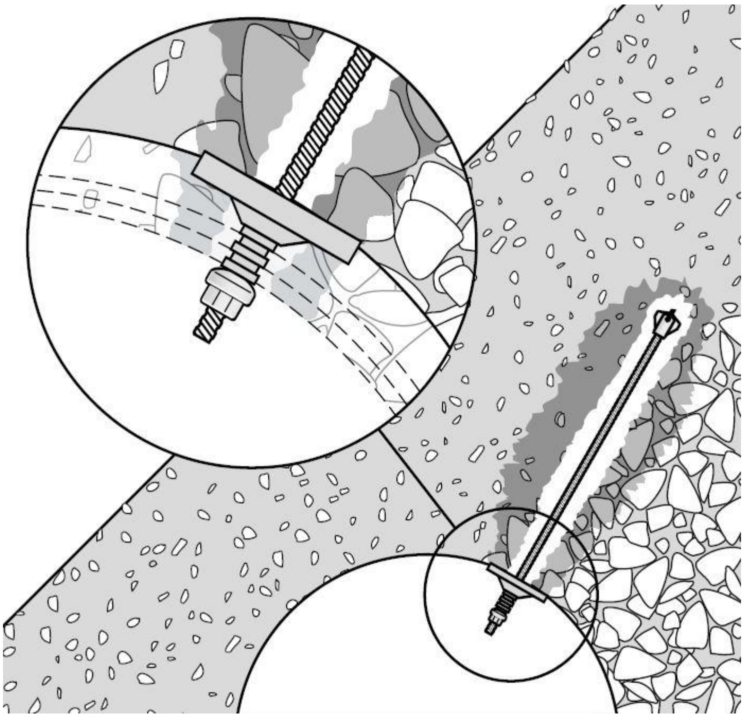


Figure 28 - Rock Bolts

reach the stable rock mass at the right depth and ensure that the bolt is completely fixed and adheres well to the surface with which it is in contact. In this regard there are different types that differ precisely in the way in which the bolts are driven into the rock and blocked inside it. Among these there are completely grouted and filled bolts, hollow bolts that allow injections from the inside, point anchored, split set bolts, swellex bolts and self-drilling bolts. Each of these is clearly indicated for a certain type of rock and situation, with the aim of responding best to the conditions of the geological context.

Reinforced shotcrete

The last intervention applied as a containment for the excavation boundary is the reinforced shotcrete. It involves the application of a mixture of cement, aggregates, and water, pneumatically projected at high velocity over the excavated surface, incorporating a wire mesh previously settled, guaranteeing support and stabilization to the tunnels, reinforcing the surrounding rock and soil. it is a fundamental element in underground constructions, as it guarantees stability, partial waterproofing, and a more homogeneous and well-distributed final surface, suitable for the subsequent laying of the actual tunnel structure. It also has, unlike traditional methods of casting concrete, several advantages including flexibility in adapting to the excavated surface, rapid application, ease in controlling the thickness applied, greater safety of the work environment during construction, and durability in time under stress.

Figure 29 - Shotcrete layer disposal

Within this technological class, a particular case is the annular gap fill. This element consists in the casting of cement mixtures or other filling materials inside the void space which usually remains between the excavated surface and the segmented structural lining typical of mechanized excavations carried out using TBMs. In these situations, it carries out an important and diversified action with multiple objectives including providing an initial waterproofing, guaranteeing structural stability and cohesion with the excavated surface, ensuring a better redistribution of loads from the geological context to the primary lining.

4.3.5 - Waterproofing system

Waterproofing plays a fundamental role in an underground environment to ensure that all the elements and technological solutions implemented can actively collaborate in meeting the safety, functionality and above all durability requirements of the infrastructure. As tunnels are typically located below the water table or surrounded by water-bearing formations, preventing water ingress is essential to maintain structural integrity and prevent potential hazards. The primary goal of a waterproofing system in tunneling is to create a barrier that effectively seals the tunnel from water intrusion.

Waterproofing therefore has a central importance, which otherwise risks preventing the success of the entire project over time, and for this reason they must meet high demands. In fact, it protects the load-bearing construction, guaranteeing its operation and durability, as well as the flawless functioning of the plant systems and technical installations within the building work. It is also important that these systems resist the various chemical and mechanical stresses, not only during the subsequent use of the structure, but also during the construction phase.

The construction of a tunnel is subject to various stresses which can have serious consequences. Waterproofing systems protect the infrastructure, preventing several hazardous consequences. Among these, penetration of water, that can cause damage to construction, cables and electrical installations, and corrosion of the armature. The infiltration of aggressive chemical agents, that can increase damage to the concrete, like for the action of sulphates, and corrosion of reinforcement, like happens for the action of chlorides. Static and dynamic loss of load bearing capacity, due to cracks in the primary-lining construction. And finally, temperature fluctuations, causing condensation, forcing, flaking or cracks in the concrete.

All these reasons point out the importance of this technological class for the underground infrastructure, directly posing attention to the geological and hydrological conditions of the site, that need to be crucially analyzed for effective waterproofing. Assessing the water table, permeability of surrounding soils, and potential water sources helps in designing appropriate waterproofing systems.

For the same reasons regular quality control inspections and monitoring are essential throughout the whole tunneling process, from the excavation activities to the subsequent use of the tunnel. These measures ensure that the waterproofing systems are installed correctly and remain in good condition over time. Monitoring can include water pressure measurements, crack monitoring, and visual inspections to detect any signs of water infiltration or potential issues.

The technological solutions commonly used for this purpose can be traced back to two main types. Depending on the characteristics and needs, the two main concepts with which the waterproofing systems are designed can be related to the open structure in drainage, and to the closed one on the entire extrados of the tunnel section. Important determining factors are the use of the facility, the hydrogeological, ecological and climatic conditions, as well as the water pressure. The execution of the works and the construction system also determine the choice of waterproofing techniques.

In the case of drainage systems, groundwaters are constantly diverted from the waterproof layer, protecting the concrete, towards the pipes and drainage elements. The groundwater level is kept below the tunnel foundation, and the concrete construction is thus not subjected to water pressure.

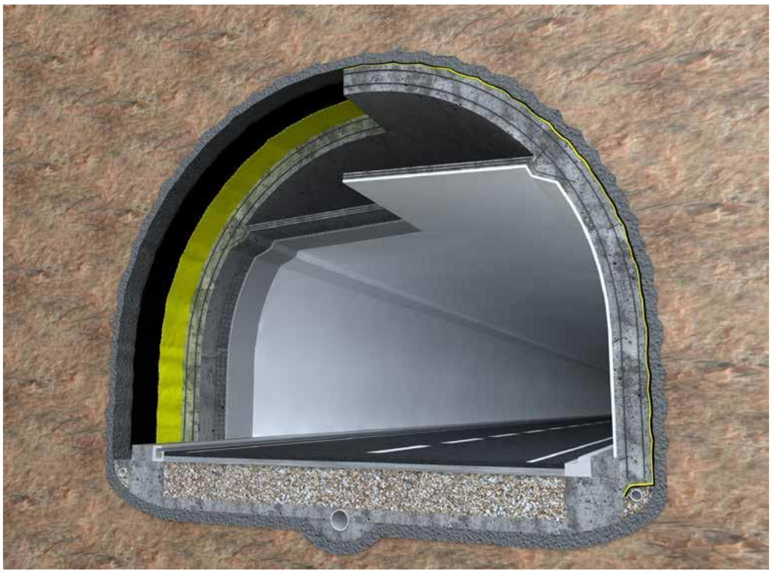


Figure 30 - Waterproofing Drainage system

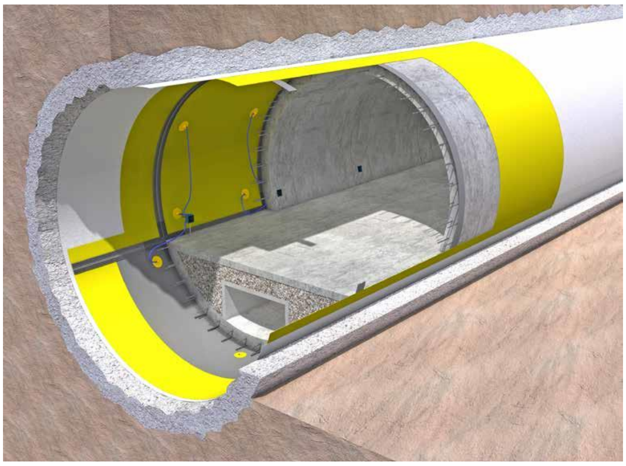


Figure 31 - Integral Waterproofing system

Conversely, for complete waterproofing systems, groundwaters are not diverted. The construction is constantly exposed to water pressure, which must be considered at the design stage. In these cases, the system must fully protect the concrete construction against water infiltration and chemical agents and must be able to permanently withstand the pressure.

In addition to those reported, which are the most common waterproofing methods, there are many technological solutions, also treated in other chapters, which actively help the underground construction to be watertight, safe, and reliable over time. Among these, a great contribution certainly comes from the consolidation injections, analyzed in the chapter concerning the pre-consolidation systems around the excavation section, which in addition to guaranteeing greater cohesion in the adjacent rock mass, also prevents the infiltration of water into the closer areas and in contact with construction.

Finally, it is also useful to mention the case of mechanized construction using TBMs, in which the use of waterproofing systems is less common, since the prefabricated ashlars are commonly already prepared, thanks to waterproofing sheaths and profiles, to meet safety, waterproofing and durability requirements of the infrastructure.

4.3.6 - Structural lining

Once the necessary operations to make the tunnel safe have been completed, and therefore those of pre-consolidation at the excavation face and at the boundary, and those of consolidation and support on the excavated surface, the next phase consists in the construction of the primary lining. This is the main structural ring of an underground infrastructure which, thanks to the cooperation with all the consolidation interventions, makes it possible to achieve full satisfaction of the various requirements of this type of civil works.

This technological element is essential to guarantee stability, safety, and counter the forces that the geological context imposes on the structure, collaborating with the other consolidation systems. The factors that determine its characteristics, including technology, materials, and thicknesses, are once again attributable primarily to the geotechnical characteristics of the context, and subsequently to the excavation methodology and its diameter.

Unlike other technological classes mentioned above, that usually are more functionally specialized, it performs multiple tasks. It has a primary importance in managing the loads and deformations to which the structure is subjected, contributing with its bearing capacity to the long-term stability of the tunnel. Together with the waterproofing layers, it forms the rigid physical barrier thanks to which the construction can keep water infiltrations away, especially when they exert pressure on the waterproofing systems. It also guarantees the complete safety of the environment inside the tunnel, essential for its subsequent use, maintaining homogeneous and uniform surfaces along the entire section [18].

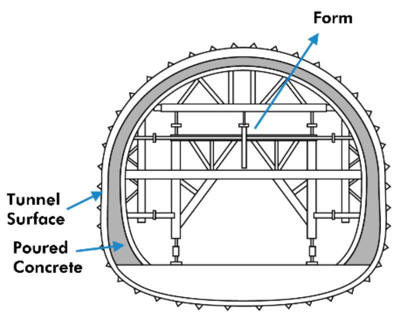


Figure 32 - Cast-in-situ structural lining

As regards the possible technological solutions, this class is initially divided into two macro areas according to the excavation technique. In the case of traditional excavations, the cast-in-situ reinforced concrete technique is commonly used. While for mechanized excavations with TBMs it's about a prefabricated segmented ring, subdivided into pre-designed ashlars and designed from the first stage of production to meet the needs of the project. A further variable component concerns, in the case of ashlars for the TBM, the materials involved, which can vary between classic reinforced concrete and fiber-reinforced concrete.


Figure 33 - Segmental TBM structural lining

Finally, considering the importance of this element and the various technological solutions presents, analysis and research activities aimed at identifying the best answers in terms of dimensions, technologies and materials become indispensable. Among these, tasks such as structural analysis, geotechnical investigations, and numerical modeling are crucial and usually employed to ensure that the primary lining meets the specific project needs and standards.

5 METHODOLOGY

5.1 - Performance data collection

5.1.1 - Reliable sources of Information

In the context outlined in the chapter on project objectives, it emerges that the goal of this thesis is to create an automated tool capable of assembling a complete three-dimensional model of the fundamental parts of a railway tunnel, along with the definition of the vast set of resources information critical to the management optimization of the subsequent stages of project development. The realization of this ambitious goal requires the collection of a vast amount as well of relevant information from all stakeholders involved in the project.

To conceive of the total cost of a project, viewing it as the sum of each of its parts, it is essential to know how each resource interacts in the implementation of technical solutions and how variations in context affect these interactions. Just as with economic performance, so too with all alternative fields of analysis which could be as critical or even more.

Consequently, after identifying the different case histories that require the adoption of one solution over the others, the research needs to take a deeper level and focus on finding the additional class of data related to the different needs emerged by choosing one or another processing. To this aim, documentation achievable through reliable sources reporting the consideration of resources put in place was crucial. Through consultation of the price list "GALLERIE A FORO CIECO DI NUOVA COSTRUZIONE" provided by the Italian State Railways Group, edition 2021 in which some technical solutions are listed, it was possible to access a narrow range of unit prices of technologies. [19]

Figure 34 - Logo Rete Ferroviaria Italiana

The methods and equipment for performing the work, on the other hand, are found in the fee schedule and are listed in the General Technical Specifications for Civil Works Contracting - Part II Section 11 "Tunnels." In that specification, for each activity, there is a summary description regarding the work to be performed, the reference standards and recommendations, a description of the equipment to be used, and the operating methods.

However, the price schedule in question does not provide complete information with respect to two fields of analysis of fundamental importance in the proposed study; it does not provide access to the detail of the components of the proposed unit price, it is not made explicit how it is generated and what the fluctuations in the performance of the factors are, the next and necessary step of information without which it is impossible to proceed in the definition of the management plan and optimization of the terms participating in it.

Secondly, the RFI's proposed Tariff Schedule designates for the same technical solution different frequencies or concentrations of application without tracing them back to the subsequent relationship with the variation of the input parameter but simply increasing the unit price which is one of the main fields of study of the thesis.

Regarding the excavation method, which can be traditional or mechanized, another relevant challenge emerges. The lack of an approach that accounts for alterations in resource use according to contexts and input parameters complicates performance assessment. Moreover, the complexity of the system, in which multiple factors interact to determine performance, requires a more sophisticated approach that considers the various possible interpretations.

In summary, the current pricing schedule and the RFI's proposed tariff schedule have significant issues in providing key information for our study. Further insights and detailed analysis are needed to effectively address the challenges related to resource management and optimization of technical solutions in the context of the projects under consideration.

The in-depth research needs led to the identification of two actual projects of considerable importance, the Umbria-Marche Road axis project to connect Perugia and Ancona and the Torino-Lyon link project, for which it was possible to come into possession of the documentation on the part of responsibility shared between Italy and France. These case studies played a key role in the project, as they are tunnels that were built. In the mountainous section to be drilled, it was necessary to conduct an in-depth geomechanical analysis, and the resulting technical documentation was supplemented with an analysis of the resources used for the project.

Figure 36 - Logo Asse Viario Marche - Umbria

Figure 35 - Logo Collegamento Torino - Lione

Through this comparison, it was possible to establish precise and defined links between the technological solutions adopted, both for excavation and construction, and the specific context in which they were applied. This made it possible to clearly contextualize how and why the same technological solutions undergo variations in the resources required for their implementation. In addition, it is important to note that this analysis was conducted in a rigorous and methodical manner, ensuring a comprehensive and detailed view of the dynamics involved in the projects. This contributed significantly to our understanding of the complex interactions between technical solutions and available resources, thus providing a solid basis for future design decisions. [20]

5.1.2 - Resource Analysis

Given the analysis of the available data, the present study builds on foundations that support the hypotheses developed in the following steps, thus contributing to its increased reliability. In line with other studies with similar aims, the objective is to estimate and forecast the resources needed in relation to a specific context, and to achieve this it is necessary to learn from past experience. The robustness of this approach is based on the concreteness of the starting predictions, which is a significant value in allowing us to learn from the obstacles previously faced. Evaluating results through a specific perspective allows us to gain awareness and provide useful information to those in similar contexts. Given the above considerations, it is in the interest of thinning the margin of error to delve as deeply as possible into the fields of inquiry. By increasing knowledge of cause-and-effect interactions, scenarios and perspectives can be developed with greater precision.

Since the amount of information collected is nonetheless capable of detailing a large group of technical solutions DSS processing goes through a phase of reworking the data by constructing a spreadsheet that would collect what was acquired.

Each technical solution was then associated with an identification code through a working breakdown structure (WBS) that groups the solutions into technology classes, categories, and individual items. Each of the technical solutions is then identified by three digits, one for each level, and associated with them are the cost of materials, processing time, and the cost of labor and equipment rentals. In a spreadsheet composed through the solution list operation, it has the function of interacting through the WBS code with the three-dimensional model, thus associating the parametric values obtained from the automatic analysis of volumes, surfaces and lengths to the resources expressed in a unitary way.

In order to coordinate the two sources of information, a formatting alignment operation of the two files is necessary which will be described in the subsequent phases of the thesis. From the interaction of the values relating to the execution of the processes and the measurements of the model, the sum of all the categories of information used as input is obtained.

To effectively coordinate the two sources of information, it becomes imperative to perform an alignment operation of the formatting of the two files, an aspect that will be extensively discussed in the subsequent phases of this discussion. Through the interaction of the values relating to the execution of the processes and the measurements of the model, the sum of all the categories of information used as input is obtained.

In the analysis presented, the economic dimension of the project is taken into consideration as the only accessible category of data but through this approach increase the number of fields of investigation of the DSS by conceiving the use of additional dimensions connected to chronological and environmental aspects.

In the tunnel project that will be examined by the DSS, therefore, a variable number of processes and technologies for each class may be applied, some are alternatives, other elements whose application is envisaged individually or complementary to others.

The DSS decision support tool also goes from providing the possibility of having an interactive comparison with the variations in the use of resources related to design changes and in the selections between alternatives, being able to simultaneously compare their specifications across multiple areas.

CODICE AR	LAVORAZIONE	UdM	Qt.	COSTO UNITARIO (€/UdM)	COSTO PARZIALE (€)	COSTO TOTALE (€)
1.1.1						
						0,00
	RISORSE					
	Materiali					**Tot. Parz**
		€			0,00	
		€			0,00	
		€			0,00	0,00
	Macchinari e Noli					**Tot. Parz**
		h			0,00	
		h			0,00	
		h			0,00	
		h			0,00	0,00
	Mano d'opera					**Tot. Parz**
	Operaio 4° livello (in perforazione)	h		50,28	0,00	
	Operaio specializzato (in perforazione)	h		48,02	0,00	
	Operaio qualificato (in perforazione)	h		45,07	0,00	
	Operaio comune (in perforazione)	h		41,28	0,00	
	Operaio comune (all'aperto)	h		30,74	0,00	0,00
	Lavorazioni/Prestazioni erogate da terzi				0,0000	**Tot. Parz**

Table 1 - Resources information collection sheet model

Cod. AR	
1	**SCAVO**
1.1	**Tradizionale**
1.1.1	CLASSE I. SCAVO A FORO CIECO DI GALLERIE NATURALI IN METODO TRADIZIONALE PER TERRENI DI CLASSE I
1.1.2	CLASSE II. SCAVO A FORO CIECO DI GALLERIE NATURALI IN METODO TRADIZIONALE PER TERRENI DI CLASSE II
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Cod. AR	
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Table 2 - List of the Technical solutions

[21]

5.2 - Excavation Method Definition:

In tunnel projects, the first steps to take to address any of the economic, structural, or environmental feasibility studies are certainly those aimed at defining the correct method of excavating the rock mass. Regarding this issue, we have already distinguished two main methods for carrying out excavation activities, such as D&B (Traditional) and TBM (mechanized), from the beginning of the thesis.

The evaluation of alternatives constitutes a critical phase of the project as it defines not only the excavation method, and consequently the resources used, but has a "cascade" effect on the technologies and technical solutions that will make up the rest of the tunnel.

Furthermore, the excavation phase represents a stage of the project with a long duration and a strong financial commitment and in case of errors with potential drastic economic consequences, time slippage and delays and serious safety risks, it can alone determine the failure of the entire work.

Faced with this scenario, it was necessary to evaluate multiple aspects and acquire basic knowledge of all the techniques that have emerged as currently usable and present on the market, and with them their context of ideal use, and their field of existence.

In more recent times it has been demonstrated that the adoption of mechanized excavation methods is gaining ground, leaving less and less space for excavation with traditional techniques, despite the performance of the latter having been improved through the introduction of new tools and approaches.

Excavation with TBM machines is progressively becoming a protagonist due to multiple aspects, among which the speed of progress and safety appear authoritatively, for the operators and for the project itself. However, another big difference between these two excavation techniques must be taken into consideration: elasticity to conditions; given the variability of conditions in the environment and high compliance of the technological situation of ground with excavation machines and the prohibitive costs originated by the selection of wrong machines, the selection of an appropriate type of excavation machine has become an important issue in the mechanized tunneling projects. On the other hand, the initialization and disposal costs of the construction site for excavation with traditional techniques are faster and cheaper and the progress performance is less influenced by the variation of the ideal geology.

Given the peculiarities of this approach, the "problem" is therefore further articulated compared to the initial approach of selecting one of the alternatives, becoming a question defined by more than one step: first conceiving the selection of the TBM machinery most suitable for the geomechanical characteristics of the rock mass to be excavated and secondarily verify that the amount of use of the machinery justifies the important costs of installation.

It is in fact known that the fixed costs and timescales relating to the implementation of TBMs are so high that massive use of the machinery is required to make its use efficient.

LAVORAZIONE	UdM	Qt.	COSTO UNITARIO (€/UdM)	COSTO PARZIALE (€)	COSTO TOTALE (€)	TBM ATTRIBUTION		
COSTI FISSI TBM								
RISORSE					Tot. Parz	TBM interessata		
Macchina fresante scudata						Open	Shield	Slurry
Costo presunto della TBM, escluso il trasporto dallo stabilimento al cantier						25.850.000,00 €	32.591.258,88 €	33.041.258,88 €
Trasporto					**25.000.000,00 €**			
Costo per il trasporto dallo stabilimento	€			500000				
Costo per il trasporto dal cantiere al luogo di deposito dell'impresa	€			350000				
Ricambio scudo					**850.000,00 €**			
Ricambi scudo	€							
Attività scudo					**6.312.377,39 €**			
Totale Montaggio Scudo	€			643.322,24				
Totale Smontaggio Scudo	€			428.881,49				
Materiale Slurry mode					**428.881,49 €**			
Impianto trattamento fanghi	cad							
Tubazione	ml		150 €/ml					
					450.000,00 €			

Table 3 - TBM related Fixed costs.

This aspect, like others already mentioned, could be enriched in detail in a very profound way and generate the need for further in-depth theoretical studies, which is why in the context of the present study we refer to the value of experience.

By studying and analyzing the available projects already carried out with TBMs as well as the bibliographical references, it is in fact possible to determine a minimum volume of use of 1.5 km. For tunnels longer than 4.5 km, however, the use of the mechanized technique can be considered standard, within this range there is a gray area where the use of the TBM must be evaluated. These references are obviously subject to variations, but we can consider that in an "a priori" approach they can provide a valid indication. If the minimum length of homogeneous sections is not reached, then the most efficient solution would be to carry out the entire excavation with the traditional D&B technique. [22]

As described in the dedicated chapter, some TBMs are extremely rigid to the variation of the parameters of the rock mass, in the event that part of the section to be excavated is not sufficiently homogeneous, it will still be necessary to resort to interrupting the operation of the excavation machinery in favor of use of other techniques.

5.2.1 - Areas of application

The aim of the present chapter is to determine a process for the selection of Tunnel Boring Machine for use in a Project- specific environment and contest (made up by rock and/or soil), based on the results given by the geotechnical report and the geomechanical sections. Here il presented a reliable methodology emerged from the literature studies to carry on a selection procedure for the definition of the machinery aligned with project boundary specifications.

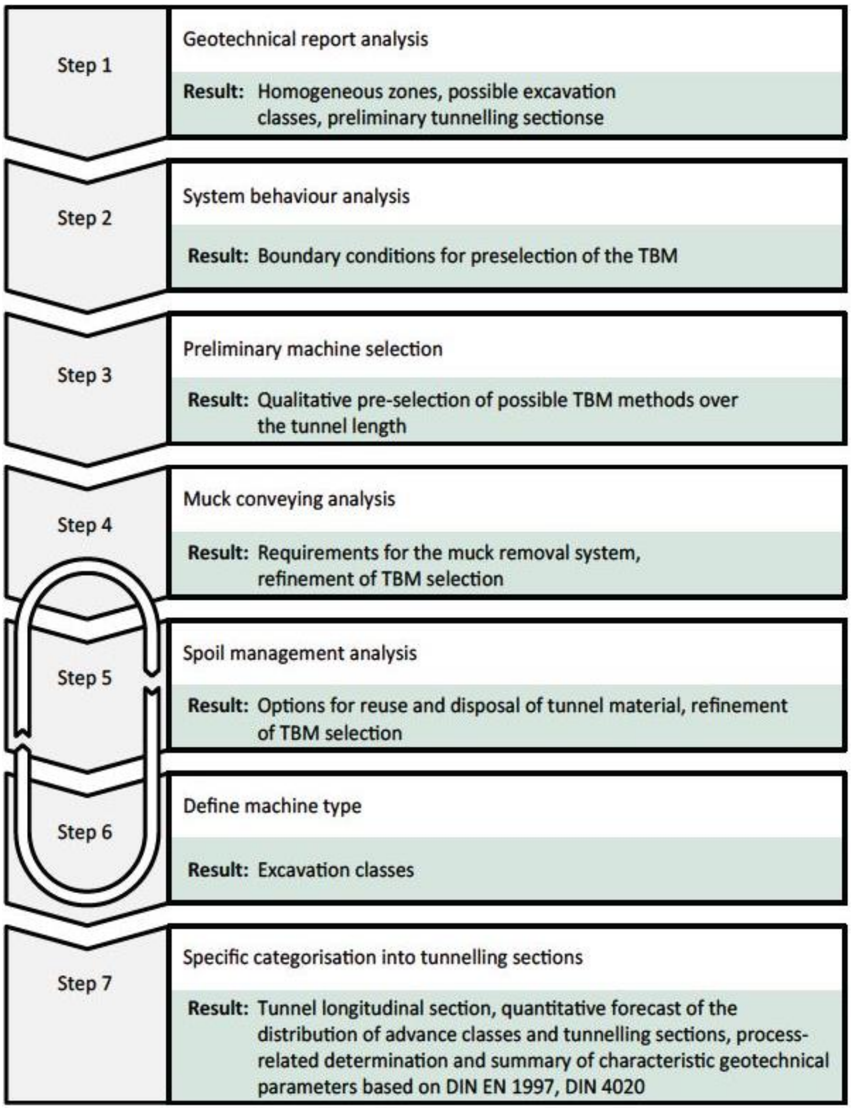

Table 4 - TBM selection seven step process (DAUB 2023)

The starting geotechnical analysis must be carried out in a way such that their criteria are satisfied, they can be performed with multiples tools and approaches and are carried out by the project's geology compartment. Existing relationships between local surroundings, environmental boundary conditions, process and machine technology must also be considered. The geotechnical report contains a proposal for the division of the alignment into zones with homogeneous geological properties and should include a representation of the homogeneous zones in the geotechnical longitudinal section. A homogeneous zone consists of one or more soil or rock layers which possess comparable properties for underground construction, referring to geological strength index (GSI), Rock quality designation (RQD) and fracture frequency and orientation. Potential excavation classes and/or preliminary tunnelling sections can be determined from the results of these analysis. Suitable machine types is assigned to individual homogeneous zones through the definition of the single zone's excavation class, so that a qualitative pre-selection of possible TBM types along the tunnel length is possible. For each tunnelling section, the machine type and the operation mode are to be determined. The more comprehensive and significant the initial investigations are, the more favorable the circumstances become for choosing the process technology and tunnel boring machine.

After a first preliminary selection many other factors must be considered, and other analysis must be performed. In a first step, it can be examined whether the ground is inherently stable or whether active support of the tunnel face is required. For a rough evaluation of stability, it is essential to consider criteria related to anticipated ground deformations and surface settlements, if required. Additionally, it's important to highlight that the support pressure may not necessarily align solely with the active water pressure. In any case, a support pressure calculation in accordance with the applicable standards and guidelines is required, in which the needed support pressure is determined from both the earth pressure and water pressure.

The Granulometry, the mean particle size distribution, of the soil directly and indirectly represents one of the primary evaluation criterion for the stability and permeability of the ground. Based on the shear strength parameters and the water pressure, and considering the particle size distribution, the stability of the rock shall first be evaluated, and the required support pressure shall be determined. In the closed mode, it is imperative to define the range of operating pressure. Based on the previously performed analyses of muck conveying and spoil management, follows a determination of the optimal excavated material disposal procedure under consideration of project-specific and economic factors or risks. This is often decisive for the choice of a tunnelling method, particularly in urban tunnelling and can narrow the range of possible choices.

It is also worth mentioning that there are restrictions in the selection of TBMs that are not dependent on the rock mass: Legal approval requirements, such as those set out in the planning approval decision, often restrict the choice of tunnel boring machines. For instance, temporary extraction of groundwater and the subsequent reduction in the groundwater level may face significant limitations or may even be prohibited. Below structures or infrastructure, the permissible ground deformations at the surface are generally limited. In addition to the absolute maximum values of the deformation, the extent and gradient of the settlement trough shall be considered as a criterion. Furthermore, for the evaluation of occupational safety, a risk analysis shall be prepared, considering the construction methodology and local boundary conditions. The result of the risk analysis highly influences the selection process of the tunnel boring machine.

If, for example, gases such as methane or argon are anticipated to be present within the rock, the construction ventilation system shall be designed accordingly or intrinsically safe equipment shall be incorporated on the tunnel boring machine. The presence of asbestos in rock also requires special attention. Closed machine types with active tunnel face support (SLS, EPB) offer further advantages because if the mucking system is closed as well emerges the possibility to lead the waste material away from the excavation site rapidly. [4]

The requirements for the segment gaskets shall also be defined. In the ultimate state, the examination of double-lining systems is warranted, if deemed necessary, particularly in situations requiring exceptional resistance to pressure thrust. In the context of the present study, interest is particularly focused on the pre-design stage where to make the DSS more functional, the possibility of comparing multiple scenarios in real time where eventualities triggered by a wide range of different possible contingencies can be contrasted in turn acquires relevance. Resolution of the issue of machinery selection for mechanized excavation is then integrated into the DSS through an exclusion approach. In the TBM presentation chapter, the field of existence of each type of machinery is made explicit, and together with the site-specific conditions that decree the exclusion of certain categories, the appropriate level of selection is created for this phase of the project.

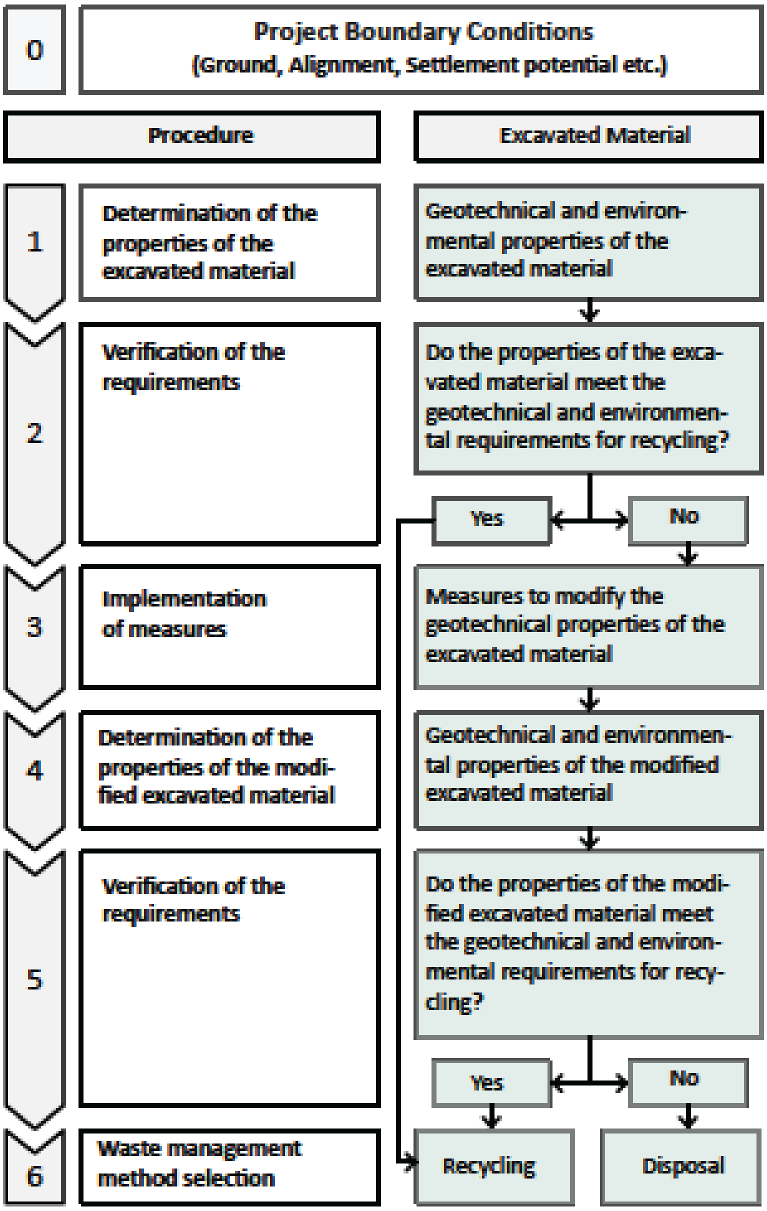

Table 5 - TBM selection Bounday requirement evaluation process (DAUB 2023)

5.2.2 - TBM Excavation performance.

Success in the construction of a civil work is also the result of the ability of the professionals associated with it to intervene promptly in its development, in the possibility of being able to correct some aspects, provided that this is done according to the appropriate timescales. The early availability of data on which to base design choices therefore acquires particular importance in this regard, but often the only way to obtain some of the critical information for far-sighted choices is to predict it. In this context, it is necessary to develop an effective method on the basis of the studies carried out previously, following the selection of the machinery and the excavation method most suitable for the context, to predict its performance, timing, logistical needs, and everything that can through conscious management be optimized.

A performance forecast aligned with realistic behavior would allow us to calculate not only the time needed for the machinery to dig the tunnel and the cost of its rental but also its operating cost (replacement of cutter-discs, maintenance, etc.).

With regard to mechanized excavation, three possible limiting factors for the advancement speed have been identified:

The digging speed of the cutterhead (defined by the relationship of several factors previously seen (such as rock quality designation (RQD), Rock mass Ratio (RMR) drillability index (DRI), Gross strength index (GSI)); the speed of arrival on the excavation face of segments and further structural reinforcement elements without which it is not possible to advance without risk, and the speed of removal of excavation residues by the conveyor system:

As regards the last two constraint factors on the speed of progress of the construction site, it is possible to consider them as outputs of the evaluation of a specific context, furthermore each machine specifies the capacity of its conveyor belt or in general the capacity of the means with which it intends to take out from the tunnel the excavated rock, however, for the ashlars the specific situation will dictate the procurement times in relation to the location of the excavation site and its morphology suitable or not for storage.

For the calculation of the drilling speed, however, the situation becomes considerably more complicated: a comparison was made with different performance prediction models (previously presented), each with specific input and output parameters often linked to specific conditions of the rock mass such as quantity, density and inclination of the faults, nature and components of the rock masses, rotation speed, coefficient of erosion of the cutters by the rock and much more…

predicting the performance of a TBM machine has been the subject of intense research in recent years, without any of the theories proposed by the most authoritative bodies on the subject being definitively recognized as conclusive (NTNU, CSM, etc.). As also emerged from the dedicated chapter, the topic is full of opinions and approaches which, starting from various basic information, estimate the drilling speed and consequently the duration of the overall excavation phase, its costs, etc... All models taken into consideration share the need for a wide range of initial information on which to base themselves (quantity, density and inclination of the faults, nature, and components of the rock masses), thanks to which complex algebraic operations are set in motion enriched with correction factors obtained experimentally to get to the result.

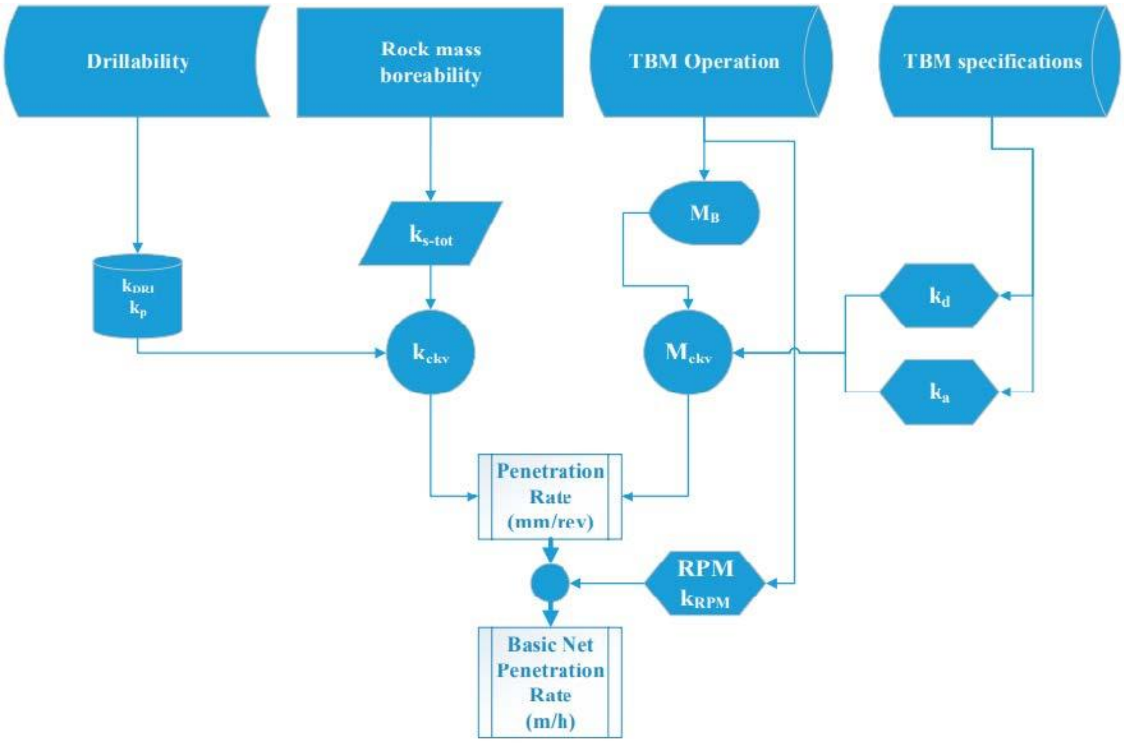

Figure 37 - TBM performance prediction parameters sources

This approach, although consistent with the circumstance described in the objectives of these studies, is not efficient for the purpose of the present analysis; this aims, in fact, to highlight the differences that emerge from the comparison of alternative excavation and construction methods. For this reason, it was decided (also to limit the consequences of possible errors in the management of a non-central theme in the thesis) to rely on the experimental and objective data collected in previous experiences and to concentrate the study on the effects of partial misalignments between the context defined as ideal for the use of a type of machinery and the actual context. (as can be seen from the figure, and as the theories of the calculation models say) in fact, given the results coming from the left part of the diagram, relating to the rock mass, as constant, it is evident that its intrinsic characteristics determine the performance of the machinery.

The TBM performance prediction is calculated by predicting the deviation of the machine from its standard behavior. This procedure therefore occurs using a multiplication factor that reflects the cohesion of the geological characteristics with those most suitable for the machinery. The result is the possibility of being able to compare how, in relation to the entirety of the excavation project, it could be more efficient to lean towards the adoption of a highly specialized machine in the drilling of some sections to the detriment of the inefficiency or impossibility of use in others rather than the selection of a machine that is less sensitive to changes in geological parameters but which, even if with a lower advancement speed, is capable of tackling the drilling of several different homogeneous sections. [4]

Hard rock TBMs suitable geology conditions application range

	ROCK TBM								
Machinery tipology	Open Gripper			Double shield			Open Schield		
Compressive strenght (Mpa)	0-5	5-25	25-250	0-5	5-25	25-250	0-5	5-25	25-250
Adaptability Level	0%	70%	100%	40%	70%	100%	70%	70%	100%
Rock Quality Designation (RQD)	0 -25	25-50	50-100	0 -25	25-50	50-100	0 -25	25-50	50-100
Adaptability Level	40%	70%	100%	70%	100%	100%	70%	100%	100%
Rock mass Ratio (RMR)	0-20	21-40	41-100	0-20	21-40	41-100	0-20	21-40	41-100
Adaptability Level	40%	70%	100%	70%	100%	100%	70%	100%	100%
Water InFlow (l/min x 10m di tunnel)	0-25	25-125	>125	0-25	25-125	>125	0-25	25-125	>125
Adaptability Level	100%	70%	40%	100%	70%	40%	100%	70%	40%
Abrasivity (CAI)	0-2	1-4	4-6	0-2	1-4	4-6	0-1	1-4	4-6
Adaptability Level	100%	70%		100%	70%		100%	70%	40%
Confinment Pressure (Bar)	0	1-6	6-15	0	1-6	6-15	0	1-6	6-15
Adaptability Level	100%	0%		100%	0%		100%	0%	0%

Table 6 - Hard Rock TBM performance deviation to the variation of the geological parameters

Soil TBMs suitable geology conditions application range

					SOIL TBM (SOFT ROCK)				
Machinery tipology	Open Schield			Slurry shield			Earth Pressure Balance		
Compressive strenght (Mpa)	0-5	5-25	25-250	0-5	5-25	25-250	0-5	5-25	50-250
Adaptability Level	70%	70%	100%	70%	70%	70%	70%	40%	0%
Rock Quality Designation (RQD)	0 -25	25-50	50-100	0 -25	25-50	50-100	0 -25	25-75	75-100
Adaptability Level	70%	100%	100%	70%	70%	70%	100%	70%	0%
Rock mass Ratio (RMR)	0-20	21-40	41-100	0-20	21-40	41-100	0-20	21-40	41-100
Adaptability Level	70%	100%	100%	70%	70%	70%	70%	70%	70%
Water InFlow (l/min x 10m di tunnel)	0-25	25-125	>125	0-25	25-125	>125	0-25	25-125	>125
Adaptability Level	100%	70%	40%	70%	70%	70%	70%	70%	70%
Abrasivity (CAI)	0-1	1-4	4-6	0-1	1-4	4-6	0-1	1-4	4-6
Adaptability Level	100%	70%	40%	100%	70%	40%	100%	70%	0%
Confinment Pressure (Bar)	0	1-6	6-15	0	1-6	6-15	0	1-6	6-15
Adaptability Level	100%	0%	0%	40%	70%	100%	70%	100%	0%

Table 7 - Soil TBM Performance deviation to the variation of the geological parameters

					SOIL TBM (SOFT ROCK)				
Machinery tipology	Open Schield			Slurry shield			Earth Pressure Balance		
Fines content (<0,06 mm)	< 5%	5% - 40%	>40%	< 5%	5% - 40%	>40%	< 5%	5% - 40%	>40%
Adaptability Level	0%	40%	70%	100%	70%	40%	0%	40%	100%
Permeability k (m/s)	> 10^{-2}	10^{-2}- 10^{-4}	> 10^{-6}	> 10^{-2}	10^{-2}- 10^{-4}	> 10^{-6}	> 10^{-2}	10^{-2}- 10^{-4}	> 10^{-6}
Adaptability Level	0%	40%	70%	0%	100%	70%	0%	70%	100%
Consistency (Lc)	0-0,5	0,5-1	>1	0-0,5	0,5-1	>1	0-0,5	0,5-1	>1
Adaptability Level	0%	40%	70%	40%	70%	70%	70%	100%	70%
Relative Density (Relative Density)	Dense	Med. Dense	Loose	Dense	Med. Dense	Loose	Dense	Med. Dense	Loose
Adaptability Level	100%	70%	40%	100%	70%	40%	100%	70%	70%
Confinement Pressure (Bar)	0	1-7	7-15	0	1-7	7-15	0	1-7	7-15
Adaptability Level	70%	40%	0%	40%	70%	100%	100%	70%	0%
Abrasivity (Equivalent Quartz Content)	0-15	15-50	50-100	0-15	15-50	50-100	0-15	15-50	50-100
Adaptability Level	100%	70%	40%	100%	70%	40%	100%	70%	0%

Table 8 - Soil TBM Performance deviation to the variation of the geological parameters

5.3 - Constraints, field of application and resources analysis

As explained in the previous chapters of the thesis, underground infrastructures involve an exceptional variety of technological solutions, having the aim to adapt the construction to different situations, often unpredictable at the design phase. It's fundamental a deep knowledge of all these variables to satisfy the requirements of the project and guarantee the tunnel to correctly perform under forced conditions.

An important part of this phase, after the pure analysis of technological classes and the factorization of tunnel anatomy, is the study of relations that bind technical solutions and materials to the underground conditions. These are fundamental and determinately contribute to the final composition of the infrastructure, influencing and forcing certain design and strategic choices. The main conditions that affect this design mechanism are strictly related to the characteristics of geological context. Among these, the thesis work is concentrated on the most impactful elements, such as Geological Strength Index (GSI), water presence, granulometry, and water pressure.

Besides these, other elements useful to determine the final technical configuration of a tunnel are less related to the geological conditions, and more dependent on general issues as in the case of intended use of the infrastructure, territorial context and logistic mechanisms. Moreover, another dynamic useful to mention is that, analysing the technical solutions from the large to the small scale, often the technological classes influence each other generating interdependent relationships between them. For example, is usual that the design solutions at each stage of the construction process can also be affected by the previous technological classes, and not only by the conditions of the context mentioned above. This happens mostly in the early phases of design solutions, where the choices at a macro level can influence a long series of successive technical components [23].

These elements are directly considered to correctly mapping all the relations and constraints existent between technical solutions at a lower level of the construction chain and technological classes at a higher level. At the same time tunnelling construction, due to its own challenging context and requirements, always as to do with other general constraints. Time and economic constraints constitute the most common guideline that leads the entire project. Tunnelling projects are particularly time-sensitive, due to the fact that contribute to the infrastructural well-being of the community, and often they are part of larger territorial development projects. For these reasons it's fundamental the correct and accurate assessment of logistic and construction timetable, while delays and incorrect predictions can be extremely costly and disrupt other construction activities. Indeed, the economic level is strictly related to the time constraints, constituting another important parameter essential for the correct evaluation and realization of the project.

The binding element between technological solutions design and the effective alignment to time and economic constraints is represented by the resources analysis. This instrument in tunnelling is essential to lead the assessment and management of the various resources required for the planning, design, construction, and operation of the infrastructures. Tunnelling projects always involve significant investments of time, money, labour, and materials, and an efficient resources management is fundamental to ensure the success and requirements of the project. Due to the complex nature of constructions for underground infrastructure resources analysis involve several key aspects. Among these the research of the work and the methodology definition focused primarily on economic and scheduling level, analysing material and machinery resources, construction timescales and human resources. Because of the vastness of the implication of resources management in tunnelling, other possible fields of research were therefore excluded. As for example in the case of risk management, quality control, environmental examination, operational and maintenance management.

All these elements can improve quality and completeness of the assessment, especially considering the preliminary design phase to which the thesis work is addressed, bringing the methodology to challenge other important issues and formulate new and different output. As anticipated, for both the main arguments treated in this chapters, the analysis considers only dynamics and data fully and certainly assimilated during the research phase, leaving out secondary and too thorough elements to which only long technical experience in the field can give the right importance and coherence.

Constraints and field of application from one side, and resources management from the other, were therefore analysed in a complete and in-depth way, although not extremely detailed, until they consolidated around a core of knowledge that made the methodology followed applicable and valuable.

5.3.1 - Excavation diameter and cross section

Excavation diameter and cross section are primary in the preliminary design phases of tunnels. They permit the infrastructure to meet principally the requirements of functionality, satisfying the main needs of the commissioning. The intended use of the tunnel is indeed the principal element that influences diameter and cross section type.

Traffic studies, strategical planning and territorial impact are at the base of preliminary analysis useful to generate the required use of the infrastructure. Usually, excluding extraordinary cases, tunnel roles can be resumed into five different functions, each of them characterized by different dimensions and configurations.

Excavation diameter

Tunnel characterized by small sectional size are usually used for exploratory or service functions. Exploratory tunnels have typically the purpose of investigating or exploring underground resources or geology. These infrastructures are not usually designed for long-term use, but rather for temporary activities like collecting data, conducting surveys, and evaluating the feasibility of future construction. Exploratory tunnels are common to lead assessment of mineral deposits for mining and site investigations for civil engineering. On the other side service tunnels are built primarily to provide access to utilities, maintenance, transportation, or other essential functions. They principally have the role of support for various infrastructure systems and facilities, carrying out functions such as light or safety transportation in emergency situations, utilities in the field of subservice networks, and maintenance access to large and widely construction without disrupting the routine usage of the principal infrastructures. This type of tunnels has excavation diameter which commonly vary from 3 to 5 meters, not needing space for huge means of transportation, and in some cases can even be less than three meters.

Moving up the dimensional scale, the second case is connected to subway infrastructure. They typically include a complex network of tunnels and associated facilities designed to support and operate a subway or metro system. These infrastructures serve as the underground skeleton of urban mass transit systems, providing a means of efficient, safe, and rapid transportation within highly and densely populated cities. Subways are usually characterized by two configurations, and in the case of single direction of travel, the excavation diameter swings between 6 and 8 meters. Instead, in the case of subway with double direction of travel the diameter grows up and vary from 9 to 11 meters. This dimensional field can also be suitable for tunnels addressed to railway use, but with single direction of travel, needing more internal space especially in height.

Lastly, tunnels for vehicular traffic are underground passages designed to facilitate the movement of cars, trucks, and other motorized vehicles usually over a larger territory. These tunnels are integral components of regional and national transportation infrastructure, fundamentals in urban areas densely built and regions with challenging topography. The use related to this function, commonly constituted by double track road, requires even more space due to sizes and safety requirements for a type of movement particularly subject to risks, bringing the diameter to a new range from 12 to 14 meters. This dimension can also be suitable for tunnels intended for railway double track. The limit case is related to the tunnel utilization as a highway road, that requires huge spaces and more than two lanes, exceeding the 15 meters for the diameter.

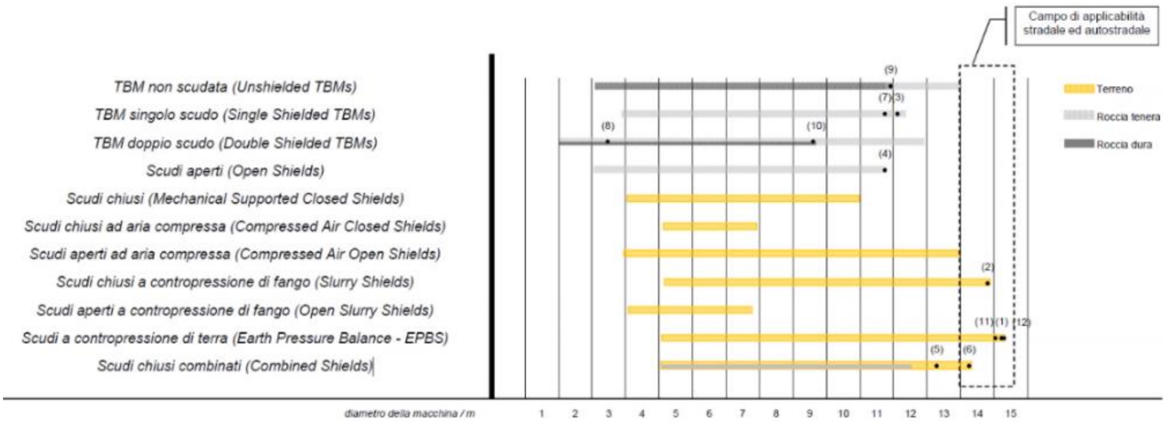

Figure 38 - Tunnel Intrados Diameters based on functionality.

Tunnel cross section

The excavation diameter ranges of application are quite similar between the excavation techniques commonly used for these infrastructures, attributable to mechanized and traditional. These main techniques introduce the next important element connected to the first phases of the tunnel design. Tunnel cross section is strictly related to the excavation method used, despite not receiving particular influence from the diameter of the excavation. The biggest difference regards the use of mechanized TBMs, that introduce the constraint of a circular shape for the cross section. As explained also in the previous chapter dealing with technological choices, excavation methods have transversal influences in almost every technological family, leading to completely different final configurations starting from that strategical choice. But at the same time the circular section used for TBMs isn't excessively affected from the dimensional point of view, maintaining the fields of application previously cited. The only thing to consider is that, differently from traditional cross sections, the circular shape has less internal space for the management of transport flows. Anyway from the structural point of view, total thicknesses of traditional and mechanized sections will be very similar, guaranteeing the same dimensional reasonings for both of them.

Tunnel cross section obtained from traditional excavation methodologies can lead to different shapes, having the freedom to configurate that based on different requirements. The geometry commonly used for transportation purposes, both for highway and railway tunnels, is the horse-shoe, that guarantees the best ratio between excavation diameter, internal width and structural integrity. For this reason, it is the only one considered within the thesis study for traditional excavation. Related to this type of cross section shape there can be two different configurations for the longitudinal development of the tunnel. The basic longitudinal shape is normally straight and continuous, but may vary following different inputs, making a variable conical shape necessary. The main input responsible for this technological choice is the Geological Strength Index (GSI), that's commonly used for estimating the strength of the rock mass. If the GSI, expressed in Kg/cm^2, is greater than 50 generally signifies that the condition of the rock mass are good and a continuous not variable cross section can be enough. While a GSI lower than 50 indicates that a variable cross section will be necessary. This type of longitudinal development, applied to each advancement field, is really useful in complex geological conditions, giving the opportunity to overlap field by field a good number of different consolidation systems, usually arranged in an umbrella shape.

Inside cross sections obtained with traditional excavation it's important to cite also the presence of Cellular Arc. This is a construction technique suitable for particularly incoherent geological context and terrains, and works with the help of service tunnels and a structure made up of large reinforced concrete pipes arranged above the cap. The shape is therefore similar to the horseshoe, typical for traditional excavation, but has several differences about the technological solutions. This construction techniques is addressed to really complex situations, with incoherent geology and low granulometry. For these reasons it's usually employed when GSI is lower than 15 and in urban areas where there is little soil cover. Cellular Arc has in fact the structural ability to entirely consolidate the site before the massive excavation of the tunnel, with the ring of reinforced concrete pipes over the cap, finding the fields of application mentioned above.

There can also be particular and exceptional cases in which both excavation diameter and cross section may vary from the fields of application previously described. This can become necessary when dealing with extreme situations, particularly frequently for the largest metropolises across the world. It will lead to an outstanding series of different and customized dimensions, technological choices and materials, generating solutions too much complex to interrelate. The thesis is indeed focused on the most common different intended uses of tunnels, that in turn produce a controlled number of variables, coherently analysed in this chapter.

5.3.2 - Pre-consolidation systems at the front

Passing through the first phases of tunnel design, related to analysis useful to determine excavation shape and dimensions, the project strategy addressed the most difficult and variable part of the methodology. Consolidation and containment interventions are indeed a fundamental and extremely complex part of the work, having the aim to guarantee not only safety and structural stability of the final construction, but most of all to prevent collapses and subsidence events during the construction phases [24].

The first category of interventions, following the common order of construction activities, is the one connected to pre-consolidation systems at the front. The main objective of this group of activities is to consolidate and stabilize the excavation front of the tunnel before the beginning of the excavation process. To preserve the integrity of the front, there can be different technological solutions, among them the most common are the following.

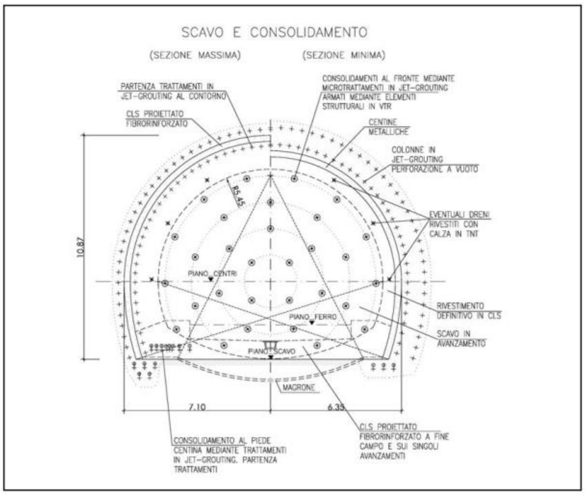

Figure 39 - Common consolidation systems for traditional tunnel section

Drainage pipes

One of the most critical parts of the excavation is the water management of the geological context. This issue risks to be harmful not only during the use phase with structural layer completed, but also during excavation and construction phase. It's fundamental in these cases to maintain a dry and safety working environment, possible only through prevention activities. Temporary drainage systems are indeed applied to the excavation front to divert or pump out groundwater that may accumulate within a tunnel during excavation, consolidating the structural integrity of the mass that is available to dig. Drainage pipes, hydraulic pumps and water storage systems are the elements implemented to play this role.

Figure 40 - Temporary drainage pipe functioning

The linear tools responsible to collect the water flows are pipes applied on the front in a circular way. They are commonly constituted by Polyethylene or PVC, hollow and perforated along the longitudinal development, to perform across their entire length. Following case studies and usage recommendations, the length of these elements is strictly related to the advancement span, and in general is approximately 2.5 times higher than the expected advance range. This characteristic is combined with the conical direction outside the section of the tunnel and lead to a complete and well performed action not only for the mass of the first advancement span, but also for the subsequent ones, which are then overlapped by other groups of drainage pipes, in turn applied to the next advance range. The overlapping of this technical solutions for each advancement span is able by this way to collect water and stabilize terrain with great anticipation on subsequent excavated sections.

Finally, the constraint principally considered influent on this technical element is the water presence. In a simply way they are used only when the presence of underground water is too much complex to handle and can prevent safety and efficiency of the excavation environment.

Fiberglass (VTR) structural elements

From the structural point of view, the stability of the excavation mass is carried out by linear elements driven into the excavation face. In this category there can be two different configurations, suitable to different input parameters and geotechnical conditions. The elements common for both cases are the VTR poles, responsible of the stabilization of the digging mass. Differently from drainage pipes, these tools are fixed parallel to the excavation route, following a smaller conical divergent shape. While, like the pipes, they have the same overlapping longitudinal development, with a length that is double compared to the advancement range. By this way each advancement span, when reached, is already consolidated by previous elements. Being temporary components inserted into the excavation volume, they are then gradually disposed of together with the excavated mass itself. Their use, as they are "disposable", must therefore be well thought out on the needs of each project context.

The use of these features is principally connected to geological context and cross section typology. In fact, they become necessary for traditional excavation with variable conical section, which is in turn triggered by a GSI smaller than 50. A series of interdependent relations regulate this technological class.

The first configuration is constituted only by VTR structural elements fixed with mortars. Their use is implemented when GSI index is between 30 and 50. The second configuration, characterised by micro jet-grouting armed with VTR structural elements, is instead related to worse geological context, and is requested when GSI goes down 30.

Fibre-reinforced concave shotcrete layer

The last technical component useful to make safe and stable the digging mass is the fibre-reinforced concave shotcrete layer, which is intended to create a uniform containment barrier of the excavation front. This element helps to make efficient and safe the work environment during the other pre-consolidation activities mentioned above, and it's put into operation for each field of advancement.

Characterised by 15 cm thickness, the use of this layer is related to geological conditions, and it’s requested when GSI is lower than 50, which coincides with the presence of the conical variable section for traditional excavation.

Finally, it’s important to point out that in the case of mechanized excavation method, pre-consolidation systems at the front aren’t necessary, as it’s the entire shield of the TBM that carries out this type of tasks.

5.3.3 – Boundary pre-consolidation support structures

As explained in the chapter 4.3.3, boundary pre-consolidation class includes two main areas of activities. Injections and support structures has the scope to provide stability and safety before and during excavation. These components are designed to control ground movements and

Kind of support	A	B	C	D	E	F
Rock property	Very good	Good-medium	Medium-weak	Weak-very weak	Very weak	Very weak
RMR	>70	50–70	30–50	30–15	<15	<15
Shotcrete (cm)	25	25	30	30	30	30
Face shotcrete (cm)	–	–	10	10	10	10
Wire mesh	1	2	2	2	2	2
Lattice girder (mm)	H = 136	H = 136	H = 174	H = 174	H = 174	H = 174
Pipe (L = 4 m)	–	–	If needed	Yes	–	–
Umbrella pipe (L = 9 m)	–	–	–	–	At 4.8	At 4.0
Rock bolt	>1.8	0.8–1.2	0.6–0.8	0.4–0.6	0.8	0.8
Soil nail (L = 6 m)	–	–	–	–	0.8	0.8
Excavation round	1.8	0.8–1.2	0.6–1.0	0.4–0.6	0.8	0.8

Figure 41 - Fields of Application for consolidation systems

prevent excessive deformation of the surrounding soil and rock mass. Boundary pre-consolidation is implemented to mitigate effects like stresses and displacements of the underground mass around the excavated volume, which can lead to ground movements and potential instability during the next digging activities [24].

Injections

The first category is represented by injections of different materials, based on requirements imposed by geological context. These are used to improve the ground conditions, enhance stability, and control groundwater during the excavation. The main parameter responsible for the technological solutions chosen is the Granulometry, to which the presence of water and GSI are also added.

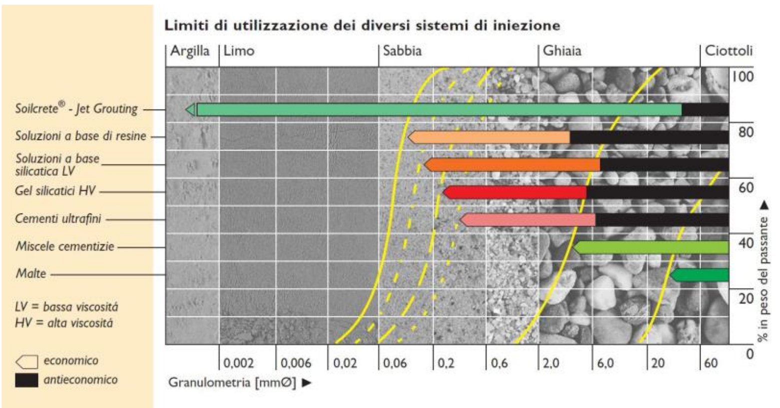

Figure 42 - Injection typologies based on Granulometry.

An initial constraint is the GSI index, responsible for the design of cross section. When GSI is higher than 50, and the cross section is linear non variable with traditional excavation, occurs the use of injections directly applied on the internal excavated surface of the tunnel. A context of good rock like this is usually related to higher granulometry, with stable and bigger rock masses. In these cases, the interventions serve to fill voids and fractures of the adjacent rock volume, giving stability, and furthermore they slow down and mitigate any water flows, waterproofing the rocky portion in contact with the future tunnel structure. After that first distinction, the granulometry index regulates the injection type necessary. Expansive mortar is used with larger granulometry, considering values higher than 20 mm diameter. It's important to fill large fractures and voids, between medium-large rock masses. When granulometry stands between 0.6 and 20 mm, the injection applied is composed by cement-based mortar, with medium interstitial spaces. The last case, with granulometry lower than 0.6

mm, request the employment of ultrafine cement-based mortars, facing smaller rock elements and having to squeeze into increasingly narrow spaces.

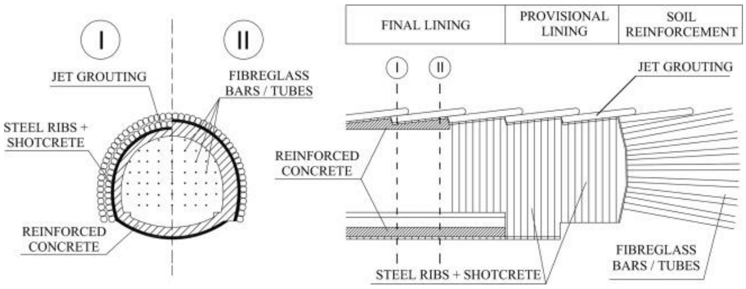

Figure 43 - Jet-grouting disposal explanation

Changing the parameter index GSI, going below 50, the cross section of traditional excavation switch to a more load bearing and consolidating system, with the conical variable section. This permits to have a series of conical consolidation parallel to the excavated surface. The overlapping of these elements increases preventive stability and safety of all the construction activities. With this situation the main intervention applied is the jet-grouting, that consists in the jab of a high-pressure cement mixture into the ground through small nozzles in order to have load-bearing columns made of mortar, rocks and soil. This type of injections is more indicated in critical situations, with high instability of the geological context, and generally when the granulometry of the inconsistent soil is very low. Within this category the parameters influenced by granulometry are related to the distance between each injection and its diameter, intensifying frequency and size as the grain size decreases and the soil becomes increasingly inconsistent. With granulometry higher than 0.006 mm, the interval between injections is 180 cm, and diameter 50 cm. Interval goes down to 160 cm, with 60 cm of diameter, when the input parameter is between 0.002 and 0.06 mm. the last case stands with granulometry lower than 0.002 mm, and requests 140 cm interval and 70 cm of diameter. The jet-grouting columns, overlapped between each advancement field, have a length of approximately 5/3 of the advance range, obtained by other case studies [25].

Finally, its important specify that the frequency of all these injections will increase if the underground context is characterised by water presence, the third parameter input influential for this category, because of the waterproofing action performed by this type of interventions.

Support structures

The other group of interventions is composed by support structures also applied to the boundary of the excavation, with a scope similar to that of the injections, but characterized by a greater structural value. This type of components, installed on the cross-section periphery, is intended to form a safety and stable boundary between the excavated tunnel face and the undisturbed ground. This group principally includes umbrella arc and cellular arc structure, dependent on the cross-section type implemented for the tunnel project.

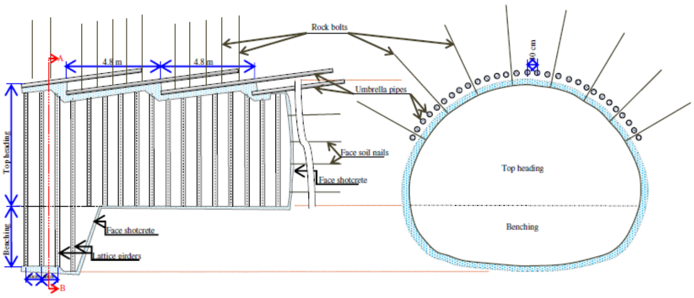

Figure 44 - Umbrella Arch sections

Umbrella arc solution is a support system that has the aim to form a structural umbrella with the insertion of an assortment of longitudinal valved poles above and around the crown of the tunnel face, followed by the consolidation through injection of mortars. It's employed in complex geological conditions, with inconsistent soil, and in general with conical variable cross section. The use is than connected to GSI index and is necessary when the value is lower than 30. When GSI is between 15 and 30, the system has 50 cm interval between each valved pole. While this space of interval decreases to 35 cm when GSI is lower than 15, needing more frequency and consolidation effect [26].

Cellular arch is instead a construction technique, as explained in cap. 4.3.1, that aims to fully consolidate the excavation environment even before starting to dig. This boundary structures, composed by large reinforced concrete pipes arranged above the cap, is ideal to consolidate underground mass with inconsistent geology and low space above the excavation, as often happens in urban contexts. The main parameter responsible for this technological solution is therefore the previous choice made during excavation method and cross section definition, with the design of the cellular arc option [27].

In conclusion it's necessary to highlight that this entire technological class, like it happened for the pre-consolidation at the front, isn't contemplated by tunnel with mechanized excavation, having the TBM the ability to perform all the activities typical of this group of solutions.

5.3.4 - Boundary containment support structures

Unlike pre-consolidation activities, containment works act downstream of the excavation face and perform a function of regulating the deformation phenomena at the boundary of the excavated surface. This containment action takes place through a series of interventions which primary are aimed at preventing the decay of the excavation walls and secondary allow to increase the shear resistance of the soil. The technological solutions capable of performing this function are lattice girders, rock bolts and the external consolidation ring [24].

Lattice girders

Lattice girders are structural elements composed by steel bars arranged in a grid-like pattern, forming a rigid framework that can bear loads and forces of the underground context. These are commonly installed on the perimeter of the excavation, following its shape, and guaranteeing maximum flexibility. Their employments are indeed characterized by a proportional utilization based on GSI index. Frequency of installation and dimensions vary following input parameters, adapting the load-bearing capacity to the needs.

Although there are different types of ribs, only the most common one was considered, namely the HE one, with the aim to not excessively complicate the research on the application fields of each element. Therefore, there are five application field, starting with GSI higher than 60, that requires 170 cm interval, while goes down to 140 cm with GSI from 40 to 60. In both these two cases, the steel ribs have a section with 14 cm height. In the range between 30 and 40, the interval remains constant at 140 cm, while the height of the section raises to 18 cm, following a worse geological scenario. Maintaining a section height of 18 cm, the lattice girders interval decreases to 110 cm, with GSI between 20 and 30, and to 80 cm, with value lower than 20.

Rock bolts

Rock bolts are long anchor bolt used to stabilize the rock mass around the excavated volume, with the capacity to transfer loads from the unstable exterior to the confined, and much stronger, interior of the tunnel. Like happens in the case of lattice girders, this technical solution is extremely flexible and adaptable, having the opportunity to change length and installation pattern, both on longitudinal and radial interval [28].

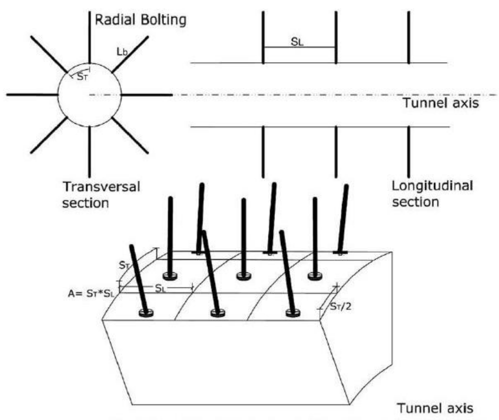

Figure 45 - Rock Bolts pattern distribution

From a general point of view, rock bolts aren’t necessary when the tunnel design strategy goes towards mechanized construction with TBM and cellular arc structure typology. As they are used only for traditional excavation, the other parameter responsible for this technical component is the GSI index. With GSI higher than 80, rock bolts aren’t required. From 60 to 80 rock bolts have 4 m length, 2,5 m for radial interval and 3 m for longitudinal interval. When the value is between 40 and 60, the length increases to 5 m, with a 2,2 for 2,7 m pattern of installation. In the last case, with GSI from 30 to 40, the pattern frequency raises to 1,9 for 2,4 m, and the length to 6 m [29].

GSI	Definition	L_b (m)	S_T and S_L (m) squared pattern assumed	β/λ	β at $\lambda=0.6$	Possible yielding around the tunnel
81–100	Very good		No support required		0.0	No yielding
61–80	Good	2 to 3	2.0–2.5	0.06–0.04	0.038–0.024	Minimal
41–60	Fair	3 to 5	1.5–2.0	0.11–0.06	0.067–0.038	Minimal–major
31–40	Relatively poor	5 to 6	1.0–1.25	0.25–0.11	0.151–0.067	Major
21–30	Poor	≥6	1.0	0.25	0.151	Major–excessive
<20	Very poor	≥6	0.8	0.39	0.236	Excessive

Figure 46 - Rock Bolts dimensions based on GSI

These components are common to both conical variable and non-variable traditional section. In fact, below GSI value of 30, bolts aren't necessary because of inconsistent soil with low granulometry, in which the gripping power of the bolts is lower. This happens in favour of umbrella arc solution, typical for variable section and complex geological conditions.

External consolidation ring

The external ring of consolidation is the last intervention applied as a containment of the excavation boundary. It guarantees stability, partial waterproofing and consists in a layer of cement mixtures, appropriately combined with reinforcement when requested, positioned between the excavated surface and the inner structural layers of the tunnel. The main difference, inside this category, is dictated by the excavation methodology. In the case of traditional excavation this element is composed by a shotcrete reinforced layer, while for the TBM tunnels it become a filling jet shaped on the circular boundary of the construction machine.

The shotcrete reinforced layer, composed of a mixture of cement, aggregates, and water, is projected at high velocity over the excavated surface, guaranteeing more homogeneous and well-distributed final surface, suitable for the subsequent laying of the actual tunnel structure, beyond stability and partial waterproofing power previously cited. At this point the shotcrete implementation is regulated by GSI index, following geotechnical conditions of the underground context. With a GSI above 50, a fibre-reinforced shotcrete layer with 25 cm thickness has enough loadbearing power. With a GSI between 30 and 50, the shotcrete requires 25 cm thickness and the incorporation of a single wire mesh previously settled. The thickness raises to 30 cm when GSI is lower than 30, further requiring a double wire mesh settled before.

Differently from classical shotcrete, the annular gap fill consists in the casting of cement mixtures or other filling materials inside the void space which usually remains between the excavated surface and the segmented structural lining typical of mechanized excavations carried out using TBMs. Its use is therefore strictly related to TBMs excavation methodology. Like happens with shotcrete, also the filling circular layer carries out several objectives, including provide initial waterproofing, structural stability, and cohesion with the excavated surface, ensuring a better redistribution of loads from the geological context to the primary lining.

5.3.5 - Waterproofing system

As tunnels are typically located below the water table or surrounded by water-bearing formations, preventing water ingress is essential to maintain structural integrity and prevent potential hazards. Waterproofing systems play a fundamental role into the underground environment to ensure that all the elements and technological solutions implemented can actively collaborate in meeting the safety, functionality and above all durability requirements of the infrastructure.

To reach the primary goal of this technological class, the common solution is to create a barrier that effectively seals the tunnel from water intrusion. The main difference inside this category is represented by open and closed systems. The parameters influential on this design choice are related both to the excavation method used, and to the underground water behaviour. Once the presence of water is established in any type of geological and morphological context, it is then the pressure of underground water flows that directs the choice of waterproofing systems.

	Concetto di drenaggio galleria a cielo aperto **Telo sintetico d'impermeabilizzazione incollato su tutta la superficie (coesione con incollaggio)**	**Concetto di drenaggio costruzione sottosuolo** **Sistema drenato**
Descrizione	**Incollato su tutta la superficie, con o senza drenaggio, monostrato** ■ Come impermeabilizzazione contro l'umidità, la sedimentazione e le acque del sottosuolo, come pure contro l'acqua in pressione idrostatica ■ Tramite l'incollaggio su tutta la superficie il sistema è sicuro contro l'infiltrazione posteriore, le eventuali falle possono essere regolate localmente	**Posa flottante, con drenaggio, senza compartimentazioni** ■ Come impermeabilizzazione contro l'umidità, la sedimentazione e le acque del sottosuolo ■ Per prevenire la pressione dell'acqua è necessario un sistema di drenaggio
Pressione dell'acqua	■ Acqua in pressione (esigua)	■ Nessuna pressione ammessa

Concetti della struttura chiusa costruzioni sottosuolo	
Impermeabilizzazione completa – sistema integrato	**Impermeabilizzazione completa – sistema active control**
Posa flottante, senza drenaggio, a uno strato, con compartimentazioni ■ Come impermeabilizzazione contro l'acqua sotto pressione idrostatica ■ Prima dell'innalzamento del livello dell'acqua i nastri per giunti Sika® vengono iniettati con Sika® Injection-201 CE e quindi i campi comparti-mentati vengono riempiti con sospensione di cemento.	**Posa flottante, senza drenaggio, a due strati, con compartimentazioni** ■ Come impermeabilizzazione contro l'acqua sotto pressione idrostatica ■ Sicurezza elevata tramite l'individuazione delle falle nel sistema d'impermeabilizzazione anche durante la fase di costruzione ■ Le compartimentazioni possono, se necessario, essere iniettate
■ Acqua in pressione (esigua)	■ Acqua in pressione (forte)

Figure 47 - Waterproofing system typologies based on Water Pressure Index

Open waterproofing barriers are employed with drainage pipes, liable for collect water infiltrations at the base of the tunnel section. Membrane fabricated with different materials, as bitumen, PVC, or synthetic rubbers, are installed on the tunnel cap extrados forming an umbrella shape capable of removing and conveying water flows to the drainage pipes below. These systems typically include a combination of sumps, pumps, weep holes, and auxiliary channels to control water flow. The current technical solution is suitable for traditional excavation tunnels, both with linear and variable section, included in an underground environment characterized by water presence, but without pressure. The umbrella effect of this element is useful to conveying and removing water but risks falling into crisis if subjected to pressure.

When flows under pressure are added to the common water presence, closed waterproofing systems are more indicated to prevent infiltrations and guaranteeing durability of the construction. These are composed by 360-degree membranes around the whole extrados of the tunnel, which act as a shield to immediately repel water, without having to channel it into drainage systems as happens for open solutions. In this case there can be the implementation with probes and sensors, to control and manage the proper functioning oh the systems. Also, for closed systems, the usage is addressed to traditional excavation methodologies and directly influenced by water pressure indexes. Inside this category water pressure outlines two different situations. With low water pressure, the waterproofing system involves the use of only one membrane layer, while requests a double membrane layer in presence of high-water pressure.

The last case concerns mechanized tunnel excavation methodologies, for which the use of independent waterproofing systems is less common, since the prefabricated ashlars are commonly already prepared and equipped with waterproofing sheaths and profiles, that permits to meet safety, waterproofing and durability requirements of the infrastructure.

5.3.6 - Structural lining

After completing the essential safety operations required for the tunnel, including pre-consolidation measures at the excavation front and boundary, as well as consolidation and support for the excavated surface, the subsequent phase involves constructing the primary lining. This primary lining serves as the central structural ring in an underground infrastructure, ensuring that all consolidation efforts come together to meet the diverse requirements of such civil projects.

In contrast to the highly specialized technological classes mentioned before, this particular class is distinctive for its multifunctionality. Its primary role lies in the effective management of structural loads and deformations within a tunnel, playing a crucial part in ensuring the long-term stability of the structure. When combined with waterproofing layers, it forms an unyielding physical barrier that shields against water infiltrations, particularly when external pressures are applied to the waterproofing systems. Additionally, it is responsible for upholding the overall safety and uniformity of the tunnel's interior environment, which is indispensable for its subsequent use.

The main factors responsible to influence this technological class are firstly related to excavation methodology adopted and cross section diameter, while secondly to geotechnical characteristics of the contexts. These conditions determine material characteristics, technology adopted, dimensions and especially thicknesses of the structural lining. As explained an initial macro subdivision managed by excavation methodologies, set the use of prefabricated modular segments for mechanized tunnel realized with TBMs, while cast-in-place reinforced concrete structures for traditional excavation methods. Since dimensions and thicknesses of these structural elements require a very thorough structural and stress analysis, in this phase it was preferred to generalize and simplify the management of these components, homogeneously proportioning the thickness of the structural lining to the diameter of the cross section.

If from a dimensional point of view, it wasn't possible to better detail this category, regarding reinforcement four fields of application have been generated, all for the prefabricated segments used in TBM tunnels [30]. The ruling parameter is GSI, since also in this case geotechnical characteristics are the principal conditioning. Starting from the worst situation, with GSI index below 30, the use of classical reinforcement bars is required, with a proportion of 160 kg per cubic meter of prefabricated cement. With GSI between 30 and 50, the amount of steel bars decreases to 130 kg, and with GSI from 50 to 70, it decreases further until to 100 kg per cubic meter. Lastly, when GSI is above 70 and the underground context is quite stable and secure, fibre-reinforced concrete ashlars can be used, guaranteeing better sustainability characteristics and lighter elements simpler to implement on site. In this case 45 kg of steel fibres per cubic meter is the amount usually recommended [31].

In light of the significance of this component and the array of technological solutions available, it is essential to undertake thorough analysis and research efforts to pinpoint the optimal choices in dimensions, technologies, and materials. In conclusion, it's important to highlight that with more practical cases and advanced design phase, the analysis efforts accomplished at this stage need to be improved with critical tasks like structural analysis, geotechnical investigations, and numerical modeling, all of which are typically utilized to guarantee that the primary lining aligns with the particular project requirements and standards.

6 STUDY MODEL

6 - Contextualization

6.1.1 - Introduction to Study Model

The importance of an intelligent tool to support tunnelling design is outlined right from the first chapters of the thesis. Difficulties and risks involved in this type of infrastructural works are in fact multiple and characterize all phases of the project's life. The world of construction is characterized in most cases by digital backwardness and lack of solutions for a holistic design that can consider the entire life cycle of the project and at the same time provide a valid support tool for design strategies. This dynamic is particularly evident in the civil engineering sector, where extremely complex projects from a technological, dimensional and management point of view pose serious difficulties for traditional project and information management strategies.

Within this sector, tunnelling activities probably constitute one of the most complicated challenges, having to consider both during the design and execution phases, alignment with the general project requirements and adaptation to the intrinsic characteristics of the geological context where the infrastructure moves. This situation constitutes a source of considerable complexity and uncertainty, with the inevitable propagation of effects resulting from errors and unexpected events. Economic impact and construction times are then the two main elements influenced by this high magnitude effect, with consequences that can often be disastrous given the amount of resources involved. In order to manage the high number of economic and technical resources involved, information management is a crucial part of the adopted process.

The amount of data that develops in complex infrastructure and tunnelling projects therefore requires particular attention during the entire life of the civil work. From preliminary to executive planning, moving on to implementation and finishing with maintenance management, traditional design and management strategies most of the time struggle to keep up with the needs of increasingly complex projects, with players who vary over time and based on the sector of expertise. From this perspective, it becomes necessary to use digital systems that can take into consideration the different moments of the infrastructure's life cycle, collect information, plan activities and update others, always precisely involving the different and multiple figures involved.

Among the digital systems most exploited for this purpose we can find BIM models, which contain within them all the information and geometries representative of the digital twin of the construction, through which it is possible to conduct preliminary studies, design, simulations and checks of various kinds. type. Conducting these activities guided by an information-based process allows to predict potential risks and problems, verify their effects in real time, and obtain key information and results to calibrate the best design decisions. The approach takes particular inspiration from the manufacturing sector, where the product logic is applied to the entire life cycle of the objects, whose digital twin contains all the information necessary for its design and management, including three-dimensional geometries, dimensional attributes, properties and PLM (Product Lifecycle Management) information. Likewise, this sector has long exploited these digital systems also for management and collaboration, ensuring the sharing of information among the stakeholders involved. Collaboration and communication are important features of the new digital systems to support the construction world, allowing you to manage aspects related to the activities, tasks, and notes of each operator, from managers to maintenance workers and through engineers and designers.

By focusing on the tunnelling sector, the subject of the thesis, many of the issues that characterize this new strategic design and management approach become of primary importance. The problems and difficulties previously mentioned outline a picture of absolute clarity in which the need to use advanced digital tools emerges to be able to recollect all the useful data, administer it among the various stakeholders and channel it to make technical, logistical and executive choices. Following this direction, the objective of the thesis therefore becomes the development of an interactive digital model to support design choices in tunnelling projects. Also given the low availability of information related to the sector, this fits halfway between preliminary and executive planning. The intention is in fact to collect enough technical and strategic information on the construction of underground infrastructures, and to recompose them in a BIM environment in order to create a digital twin that can bring together the different dimensions of a project of this type: project pre-requisites, geological context, excavation methods and technological solutions.

The focal point of the model and the primary objective of the thesis work is to introduce a design optioneering process into the tunnelling context. This type of infrastructure in fact incorporates numerous and different inputs, including geological, geotechnical, logistical and usage ones, generating a notable series of possible configurations. A design optioneering mechanism integrated into the BIM environment therefore allows for immediate feedback between the digital model with resulting information and the variations in the inputs.

A fundamental part of this system is the set of information that links the aspects of technological and strategic design to the requirements and parameters of the project itself, structured into categories and technological classes, present within chapter 5.3 of the thesis. The decision support tool is therefore based on experience-based databases, the result of the analysis work carried out on existing projects and research activities. As also anticipated in the previous chapters, the level of detail on the relationships that regulate the planning in the tunnelling field is placed in an intermediate phase between the preliminary and the executive one, with an adequately detailed representation for the mechanism to be reliable, but at the same time distant from the infinitesimal minor variables relating to on-site construction and which can only be addressed with long experience in the field. At the same time, the framework of the relationships between technological design, requirements and inputs remains an important work-in-progress field that can accumulate and interpolate, as already happens for existing ones, further information, technological solutions, and new construction strategies, enriched by the expert knowledge of the sector and new technologies.

An important feature of the thesis work is in fact, due to the awareness of a limited knowledge of the sector, that of being able to constantly implement information and databases that regulate the mechanisms of the decision support tool. The integration of this tool within the BIM environment then makes the model completely autonomous and implementable, placing sector technical knowledge at the service of modern technologies.

6.1.2 - IDeCOM & 3DExperience Platform roles

The thesis work from a practical point of view takes shape, as mentioned above, in the creation of an interactive digital model to support design choices in tunnelling projects. This model arises from research and analysis of the mechanisms that regulate the construction of underground infrastructures and ends with the creation of a model capable of incorporating this information network to create an interactive digital twin in a BIM environment.

From the first stages of the thesis work it was therefore immediately clear how indispensable these two elements were. On the one hand, deep technological and strategic knowledge within the sector to be able to collect and organize all the variable elements that contribute to the multiple configurations of a tunnel. On the other hand, the technical knowledge linked to the creation of a BIM project and the generative design tools necessary to create the model.

The collaboration on the thesis work with IDeCOM s.r.l. is therefore based on these needs. A dual support in order to initially enrich the knowledge acquired in the tunnelling field during research and analysis activities of the state of the art, and subsequently provide the tools necessary to implement the idea of the study model in a BIM environment.

IDeCOM is an engineering company founded in 2016 with the strategic objective of bringing an innovative contribution to the construction sector, focusing on the differentiation of services, internationalization, and continuous technological investment. The main consultancy and integrated design activities are aimed at the field of civil and structural engineering in various sectors: Buildings, Oil & Gas, Power, Infrastructure, Marine and offshore and in the R&D field in the study of composite materials. The company's founding principles share the same values on which the strategic partnership with Dassault Systèmes is based, which over the years has consolidated IDeCOM's role as a strategic technical and commercial partner for the construction sector. As technical and commercial partners of Dassault Systèmes, the company also dedicates training courses on 3DEXPERIENCE Platform™ for a complete implementation of the tool capable of making customers autonomous.

Figure 48 - IDeCOM Logo

Among the services in which the company specializes, those of greatest interest in the context of the thesis are certainly integrated design and BIM. The traditional multidisciplinary design in the construction sector, characterized by the different disciplines that contribute to the project independently, is not very functional and hinders the natural evolution of the project, favouring errors, losses of information, delays and rework. Using models based on Common Data Environment (CDE), IDeCOM is able to provide a multidisciplinary integrated design service that combines the different skills necessary for the development of each project, guaranteeing each collaborator a clear and total vision on the entire project at all times. The management of the CDE takes place through the company's support for BIM coordination and implementation activities, basing its modus operandi on the search for solutions that respect the different business needs, involving all figures, from managers to operators, and providing structured data that they are configured as the only source of truth. Integrated design in the BIM environment, supported by Dassault Systèmes 3DEXPERIENCE Platform™, also allows the use of the most advanced parametric design tools. Finally, the latter constitute a key element for the creation of the Decision Support System in the thesis field, with generative design tools capable of providing adaptive and modifiable solutions in real time to complex architectural and structural problems.

Figure 49 - Partnership Logo

6.2 - Parametric modelling and generative design

6.2.2 - Modelling instruments for design optioneering

Going deeper into specifics, the creation of the interactive model to support design decisions passes using digital tools that allow the definition of design optioneering processes. This is a fundamental element of the study model, as it constitutes the underlying logical scheme on which most of the data management and modelling mechanisms are based. It mainly has the aim to involve, explore and evaluate multiple design alternatives to find the best possible solution based on predefined criteria and objectives. The fields of application of processes of this type are multiple but they reach their maximum expression in the architectural and infrastructural fields, thanks to the numerous possible configurations, both typological and technological, and to the most varied environmental stimuli linked to the context.

Parametric modelling is often an integral part of design optioneering, thanks to the creation of parametric models to generate and assess multiple design options. Is in fact possible, using parameters, constraints, and fields of application, to manipulate models to generate a wide range of design variations quickly. The process is driven by specific design objectives and constraints. These can include factors like cost, energy efficiency, structural stability, aesthetics, and more. By quantifying these objectives, designers can evaluate and compare different design options objectively.

Design optioneering usually also involves the use of computer algorithms to automate the quick variation of the alternatives and the subsequent evaluation of design options. This can include simulations, numerical analysis, and computational design to assess how well each option meets the defined criteria. From this point of view and considering the AEC (Architecture, Engineering and Construction) sector, these instruments are integrated into visualization systems, such as 3D models, renderings, and diagrams, fundamental to correctly visualize all the project dynamics, and to present design options to the stakeholders involved. For this reason, the use of parametric modelling combined with visualization tools, like happens with BIM models, is essential not only to elaborate the design optioneering process, but also to visualize and communicate ideas and scenarios effectively.

Focusing on parametric modelling, it involves a fundamental concept in Building Information Modelling (BIM) that allows to create intelligent 3D models of buildings and infrastructure. Relationships and constraints created within the model enable the project to be more than just a static 3D representation, since it can change and adapt based on modifications to its parameters.

This flexibility is crucial in the design, analysis, and documentation of construction projects. Here are some of the parametric modelling instruments commonly used in BIM software: Within the parametric modelling instruments most useful in BIM environment for AEC sector, it’s important to cite parameter, constraints, parametric objects, schedule and quantity calculations, families, and simulations.

Parametric modelling relies on defining parameters, intended as variables, and constraints, intended as rules and relationships, that govern the model behaviour. Parameters can include dimensions, materials, and properties, while constraints enforce links between elements and parameters. Parametric objects, instead, are usually used in BIM environment to create parametric components of buildings and infrastructures, such as walls, doors, windows, pillars and so on. These objects are very useful with recursive and numerously used objects, based on predefined parameters that can be adjusted to change their size, location, and properties. Parametric objects can also be grouped into families, that are collections of parametric components that can be customized and reused within a project, switching parameters and configurations every time to obtain that request. One of the main outputs easily accessible thanks to parametric modelling is the schedule and quantity calculations, with schedules that automatically update based on model's parameters, which is invaluable for quantity take-offs and cost estimation. Finally, it also allows the integration of analysis and simulation tools, through which it’s possible to perform energy analysis, structural assessment, and other simulations to evaluate the performance of project design under different conditions.

Parametric modelling is closely related to computational design, guaranteeing a wide use in conjunction to create innovative, efficient, and complex designs, especially for architecture, engineering, and other design fields. Computational design involves using algorithms and computer programming to generate, evaluate, and optimize designs. It extends beyond traditional design methods by leveraging the computational power of software to explore a wide range of design possibilities. Algorithms and scripts are written to automate and control various aspects of the design process, capable to generate complex shapes, patterns, geometries or structures based on specific parameters or input. Generative design, within computational design, can be considered as a subset that explores design alternatives based on predefined objectives and constraints. Algorithms generate and evaluate numerous design options, often producing unconventional and innovative solutions. Computational design can also add important activities in optimization processes and performance analysis, enabling stakeholders and designers to make data-driven decisions about the design's efficiency, sustainability, and other factors.

In the context of BIM modelling, parametric design is an essential part of computational design, since it provides a structured framework for defining parameters and relationships that computational design algorithms can manipulate. Parametric models can serve as a feedback loop in computational design, with design iterations that can be automatically updated based on analysis results, allowing for rapid exploration of design possibilities. Unlike what traditional modelling tools can achieve, computational design can push the boundaries of parametric modelling by exploring designs that are too complex to define manually, exploiting algorithms capable to create and implement geometries, patterns, and structures that would be extremely challenging to model using traditional parametric techniques.

Together, parametric modelling and computational design empower designers to create innovative, data-informed, and highly customizable designs, enhancing the efficiency and creativity of the design process in various fields, including architecture, engineering, product design, and urban planning.

6.2.2 - CATIA & X-Generative Design from 3DExperience Platform

The 3DEXPERIENCE platform is a comprehensive business software and digital transformation solution developed by Dassault Systèmes. It operates in the cloud and serves as a collaborative environment that integrates various software applications for product design, engineering, simulation, manufacturing, and data management.

Figure 50 - 3D Experience Platform logo provided by Dassault Sistèmes

The platform involves a wide range of applications and workspaces designed for different aspects of product development, among which the most relevant for the AEC sector are CATIA for 3D modelling, DELMIA for manufacturing and construction operations, SIMULIA for simulation disciplines and ENOVIA for data management. In addition to the applications dedicated to the AEC sector, the platform covers numerous other sectors, called industries, such as Transportation, Aerospace, Marine and Offshore, Goods Retail, Energy and Materials, City and Public Services.

Data management is a core element of the platform, providing tools for secure storage, retrieval, and sharing of product data and related information. It also offers robust simulation and modelling capabilities for engineers and designers to validate product designs before creating physical prototypes. One notable feature of the platform is in fact its ability to create digital twins, allowing for real-time monitoring and analysis of products and processes, which is valuable for predictive maintenance, performance optimization, business process management, resource allocation analysis and key performance indicators assessment. It caters to the various industries previous mentioned with industry-specific solutions to meet sector-specific needs and requirements. With its cloud-based infrastructure, the platform facilitates mobility and remote accessibility, enabling teams to work from anywhere and promoting global collaboration. It represents, unlike the traditional way of working and collaborating on a project, a shift towards a connected, data-driven approach to product design and manufacturing.

3DEXPERIENCE platform is also highly important for Building Information Modelling (BIM) due to several key reasons, promoting collaboration among multiple stakeholders, centralizing data management, integrating various software tools, offering 3D modelling and simulation, managing changes effectively and providing data visualization capabilities. The platform is essential to meet project requirements and supports remote collaboration, making it a crucial tool for enhancing the efficiency, accuracy, and sustainability of construction and building operations in BIM projects.

Within 3DEXPERIENCE Platform, the most useful instrument for the creation of the study model as part of the thesis work was definitely CATIA. This is a widely used 3D design and modelling software developed by Dassault Systèmes, that plays a significant role within the Platform, serving as a core component for 3D modelling and product design. CATIA enables engineers and designers to create highly detailed 3D models of products, including mechanical, electrical, and architectural designs, with the advantages brought by simulation and visualization of product behaviour in different scenarios. The integration within 3DEXPERIENCE platform has other advantages, among which collaboration and data management, fundamental for BIM projects in AEC sector. Furthermore, CATIA supports, beyond construction sector, various industries and applications, from automotive and aerospace to consumer goods and more. Its versatility makes it a valuable tool capable to streamline product design processes and achieve greater efficiency and innovation along complex projects.

Figure 51 - 3DExperience Catia

The modelling of the technological and typological elements that characterize the case study is mainly done using CATIA, but considerable help comes from the

Figure 52 - Visual Scripting application icon

integrated X-Generative Design application, a powerful visual scripting tool. Visual scripting is a programming approach that utilizes visual elements and diagrams instead of traditional text-based code to create and automate processes. It simplifies complex tasks and makes programming more accessible thanks to connections between visual blocks or nodes to create sequences of actions and logic. In visual scripting, users typically work with a graphical interface where they arrange blocks or nodes, each representing a specific input, function or operation, connecting them with lines or arrows to define the flow of the design sequence. Inside 3DEXPERIENCE Platform, this tool guarantees the possibility to custom processes, automate repetitive tasks, and create specialized tools tailored to their specific needs. This not only enhances productivity but also encourages innovation and flexibility in how the platform is utilized, integrating various components and data sources within the platform, enhancing connectivity and data management.

CATIA software and XGenerative Design tool represent in the end the most important and widely used tools in the development of the thesis study model. These are of primary importance since capable of managing at the same time in the same BIM modelling area, both the parameterization of the technological and typological elements typical of the tunnelling sector, and the management of their use and fields of application, linked to the network of relationships that characterize the decision support system.

6.3 - Decision Support System & Design Optioneering: Study Model

6.3.1 - Introduction to Platform modelling environment

Before getting to the heart of the construction of the decision support system, and in particular its study model, it is important to provide a clear and complete overview of the structure and functioning of the modelling environment in 3DExperience Platform. The product logic transversally dominates all work areas, from those of pure modelling to those linked to Product Lifecycle Management, with the simultaneous management of geometries, data and relationships, and for this reason it is essential to understand the elements of the modelling environment and the mechanisms that regulate them.

The first practical considerations necessary to understand the functioning of the Platform concern the combination and integration of cloud-based services and rich client applications, to provide a collaborative and comprehensive environment for product design, engineering, and lifecycle management. Cloud-Based Services enables real-time collaboration from anywhere with internet access, centralizes data storage in the cloud for consistent and accessible information, and finally provides scalability for flexible usage based on project requirements. At the same time Rich Client Applications offer specialized applications for tasks like 3D modelling, simulation, data management and other powerful functionalities, supporting industry-specific needs with applications like CATIA, SIMULIA, and ENOVIA. The integration between these elements guarantee collaborative workflows, allowing team members to work concurrently, using various tools and ensuring interconnectedness across design, simulation, and data management processes. In essence, the 3DExperience platform combines cloud-based collaboration with feature-rich client applications to provide an integrated and efficient environment for product development and lifecycle management.

As regards the development of the study model to support design decisions in the tunnelling field, the use of Rich Client Applications was predominant compared to Cloud-Based Services, as the creation of the case study did not directly involve PLM management of the elements, although it is in any case an aspect that can be implemented starting from the model itself. Among the Rich Client Applications, the most relevant were certainly Building 3D Design for basic 3D parametric modelling, Building and Civil Assemblies for the parts and products assembly, and finally Visual Scripting app for the creation of technological configurations and the Design Optioneering process.

Building 3D Design

Figure 54 - Building 3D Design Logo

Building and Civil Assemblies

Figure 53 - Building and Civil Assemblies Logo

The software is a product lifecycle management (PLM) and development platform, that provides a comprehensive environment for collaborative design, simulation, and data management in a 3D modelling context. The modelling area, like the sections dedicated to information management, is therefore structured to work on PLM products and has a diverse range of different product types, which intrinsically have different attributes and properties. From large to small scales, there are both products typically used as containers to assemble and structure complex projects, such as Site and Building, and smaller technological and structural elements, such as Beams, Pillars and MEP systems. Since the Platform has the bold goal of aligning the world of construction with that of manufacturing through integrated product design, all project components, up to the most detailed ones, can be modelled and characterized. The created products appear, always guided by the product logic, in the modelling area structured into "Trees". These are hierarchical structures that aim to contain everything that BIM design requires, including and relating geometries, information, relationships, formulas, parameters, and attributes to each other.

The connection between Product and "Tree" is also fundamental to effectively identify not only the geometric and informative characteristics of the individual Products, but also to understand and detail, based on project needs, the links between each Product. Tree hierarchies can respond to requirements, regulations, and project choices, gradually becoming more complicated as the level of detail and the quantity of Products contained increases. It also provides a representation of the different components and subassemblies of a “parent” Product, with a hierarchical succession which usually in the construction field starts with a Site, containing Buildings, which in turn contain the Load-bearing Structures, and so on. From these reasons derives the importance of this organization, fundamental to guarantee full management and collaboration on product design and development.

6.3.2 Engineering Template Product functioning

After having briefly contextualized the organization of the Platform and the configuration of the modelling environment, it is necessary to explain the functioning of the Engineering Template. Understanding its potential and mechanisms is fundamental right from this introductory phase, as it establishes some essential basic technical requirements for the effective modelling of the different typological configurations in the tunnelling field.

Engineering Template appear in 3DExperience Platform as a real PLM product like the structural ones as a pillar product can be. This aspect is fundamental because it guarantees full collaboration and possibility of reuse, both at project level and at company level, promoting the users to easily and interactively capture engineering know-how and methodology for highly efficient reuse. As a result, this helps organizations and teams share best practices and avoid duplication of effort. From a practical point of view, this functional product is a combination of predefined set of parameters, configurations, or design elements that can be reused across different projects.

These tools help standardize the design process by providing a predefined structure for different engineering projects, ensuring consistency and adherence to best practices across projects and design teams. The possibility to create templates containing commonly used components and assemblies allows the successful reuse of design elements, reducing redundancy and saving time. By this way it promotes the design process streamlining, by eliminating the need to start from scratch for each project and directly make project-specific modifications, accelerating the overall development cycle. Another advantage of using Engineering Templates is to maintain consistency in design across different works, ensuring that similar types of projects follow the same standards and guidelines, facilitating quality control and regulatory compliance. All these aspects are always inserted in a context of full collaboration, as in the case of 3DExperience Platform, with the potential to work on different aspects of a project while using a shared template, promoting seamless integration and collaboration.

Its functioning is always linked to another starting product, just as in the case of the thesis study model it can be the product of a typological unit of a tunnel. Among the activities that this functional Product can perform, the most important is certainly that of adaptability. This function allows you to instantiate the original starting Product, inserted as a Reference in the Product Template, adapting to certain geometric and parametric inputs. It therefore becomes enormously useful for the AEC sector, where it allows a flexible and functional product capable of adapting to different geometric and parametric stimuli to be reused infinite times. The thesis work clearly also falls into this discussion, where it was necessary to create starting products that covered the different typologies in tunnelling field, and which could be reused in an adaptive way in any situation. From a technical point of view, the essential geometric input in this case was the path of a hypothetical tunnel. All three-dimensionally modelled elements are therefore necessarily anchored to the polyline representing the central axis of the path, which in turn is then inserted as a geometric input in the Product Template. In addition to this, the parameters present in the starting Reference Product can also be reused and inserted into the Template Product, ready to modify and adapt the new instantiated Product.

The use of the Engineering Template Products is therefore one of the key elements regarding the construction of the study model, linking to the peculiarities of the technological and typological development of an underground civil work. A tunnel is in fact characterized by the constant and always varied re-proposition of the construction elements according to advancement fields of excavation, usually in the order of ten meters each. It necessarily requires an adaptive and parametric tool, reusable for long distances on the order of hundreds of metres, which can align itself with the geometry of the route and the needs of the geological context at the same time.

This introductory parenthesis dedicated to the functioning of the Engineering Template is preparatory in the context of drafting the thesis. In fact, it has the objective of framing in advance some fundamental prerogatives that guided the modelling strategy, aligning and preparing the Typological Products for input and output of this tool.

6.3.3 - Modelling of typological Sections general process

Considering all the considerations made regarding the use of the modelling and management tools present in the 3DExperience Platform, the construction of the study model starts with the creation of the different types of sections present in the tunnelling sector. Well outlined in chapter 5 dedicated to constraints, field of application of construction typologies and technological solutions, they play a fundamental role in the economy of the study model. These are in fact modelled partly through the most classic parametric 3D modelling tools, and partly thanks to the use of automated and massive generative design mechanisms. This allowed the final Typological Products to be completely responsive to a series of parameters, also organized and reported in chapter 5 of the thesis, typical of the project requirements and needs dictated by the geological context for the construction of an underground civil works.

As reported in chapter 6.3.2, the construction of each Typological Product is based strategically a priori on the functioning of the Engineering Template, where the starting geometric inputs and parameters guarantee the full adaptivity of all the geometric components linked to the inputs themselves. For this reason, having as a geometric target a polyline sectioned into portions, representing the 3D layout of a tunnel divided into advancement fields, the basic input of each Typological Product is a polyline. This curve, not bound to any other geometric element, thus has the ability, via the Template, to adapt and transform into the geometric target during the assembly phase of the entire tunnel. The remaining geometries relating to the structural elements and technological solutions implemented for each type of section, however, remain strictly bound to the Polyline in question, allowing the instantiated Product to adapt fully based on the geometric Input.

There are therefore some recurring elements in the "Tree" structure present in every modeling environment. These are mainly Geometric Sets, i.e. features that contain groups of non-solid geometries such as Points, Lines, Surfaces and Volumes, and Body, features that can also contain Solid elements. In particular, there is always a Geometric Set renamed "INPUT" containing the Input Polyline, other Geometric Sets that hold skeleton sketches relating to structural and consolidating elements, and finally Body features containing the Solids of the previous elements. In addition to these, the Design Sequences performed with the Visual Scripting app contribute to representing further geometries, which generate new Geometric Sets in an automated, parametric and massive way, especially in the context of consolidation interventions. All the geometric elements mentioned above are finally coordinated and linked to each other through a series of Relations and Parameters, viewable and manageable in the "Tree", which allow the Products to behave adaptively and parametrically in every situation.

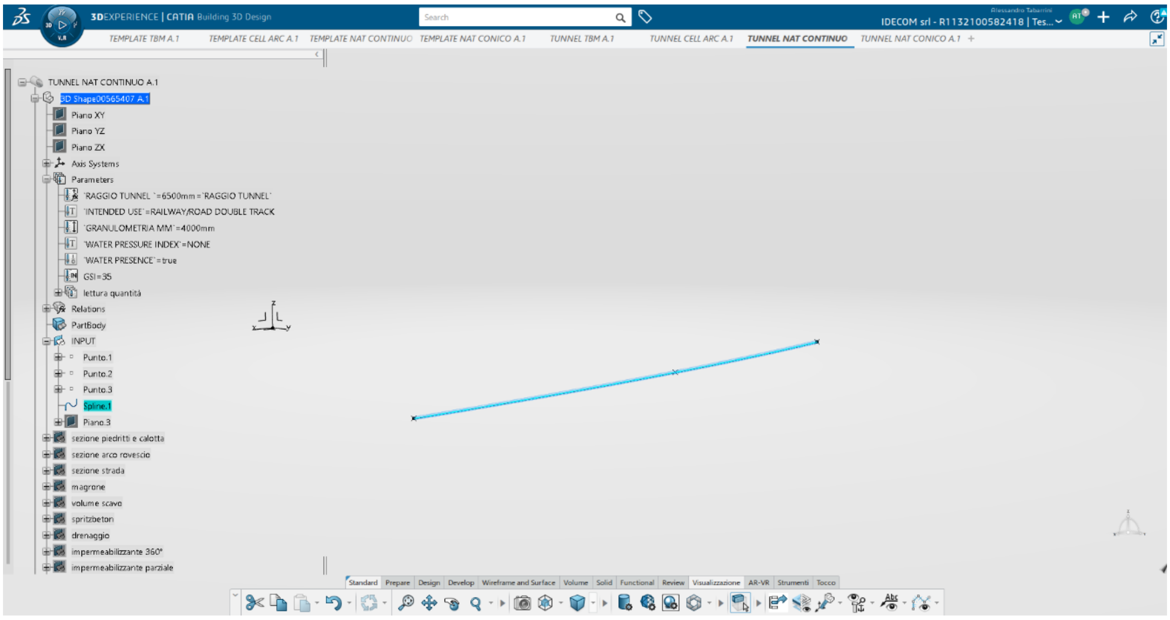

Figure 55 - Geometrical input Tunnel Path

The construction of the four Typological Sections, identified during the development of the thesis and reported in Chapter 5.3 will therefore be described in this Chapter, building through Parametric and Generative Modeling the Design Optioneering mechanisms, founding elements of the Decision Support System study model.

TBM section Product

The series relating to Typological Products starts with the introduction of tunnels created through mechanized excavation using TBM. Summarizing what is fully explained in Chapter 5 dedicated to excavation methodology, it's an extremely expensive digging and construction technique on an economic level given the huge cost of renting or building the mechanized mole. Furthermore, to this is added less executive flexibility compared to traditional excavation methods, ultimately proving to be suitable only over a certain distance to be covered.

The modelling starts, as anticipated, from the creation of the Input Polyline, to which all the subsequent typological and structural elements are then linked. At this point it is important, before creating the geometries, first flat and then solid, to establish which parameters are necessary to establish the different alternative configurations in the case of tunnels made with segmented ashlars prefabricated by TBM. In this particular case, referring to what was done for the definition of the fields of application underlying the Design Optioneering mechanism, it is important to highlight some aspects. There are not many variables to consider regarding the components of the structure itself, as the most complex choices to adapt to the morphological and geological conditions of the ground are precisely those relating to the type of machinery used. The aspects relating to the management of the different types of TBM, with the consequent variations in terms of resources involved and excavation times, remain unrelated to the 3D model and analyzed a priori within the chapter dedicated to excavation methodologies. However, the data relating to the use of the infrastructure and the geotechnical conditions remain influential on the construction components of the segmented rings, represented in the "Tree" respectively by the reference geotechnical parameter GSI and the intended use.

The first Geometric Sets, after the one dedicated to the Inputs, have the task of creating the two-dimensional framework of the model. In this case, there are sketches relating to the intrados of the segmented ring and the components that make up the road surface and its structure. In the latter case, the geometric references immediately become useful for defining the respective 3D solids, extruding the sketches via the initial input polyline. In the case of the Geometric Sets referring to the tunnel intrados, their role becomes that of creating the surface of the entire internal intrados, connecting the start and end references following the Input Polyline. The surface created then becomes the main geometric reference for the subsequent creation and subdivision of the segmented TBM ring via Visual Scripting.

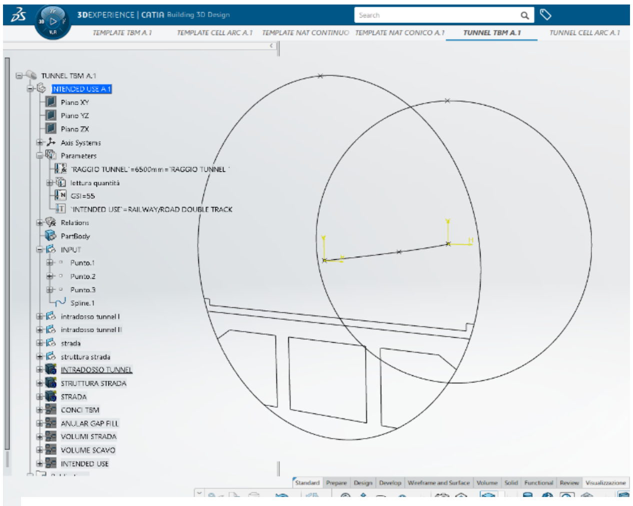

Figure 56 - Geometric wireframe for TBM sections

It remains useful to highlight how the geometric constraints, both within and between the three-dimensional components, are fundamental to making the Typological Products autonomous in the subsequent instantiation phase via Template. In the case of geometries not correctly connected to each other, the result would be to have disconnected parts in the Instantiated Product and an incorrect reading of the emission parameters.

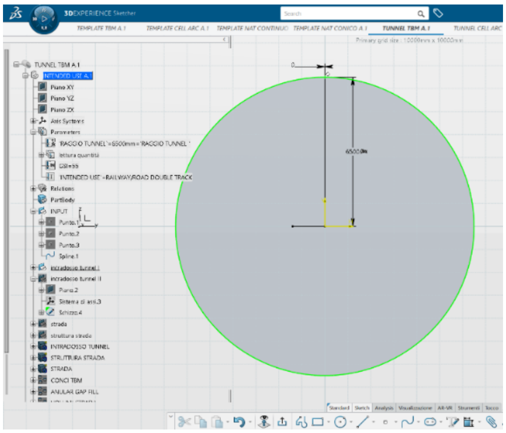

Figure 58 - Intrados Sketch

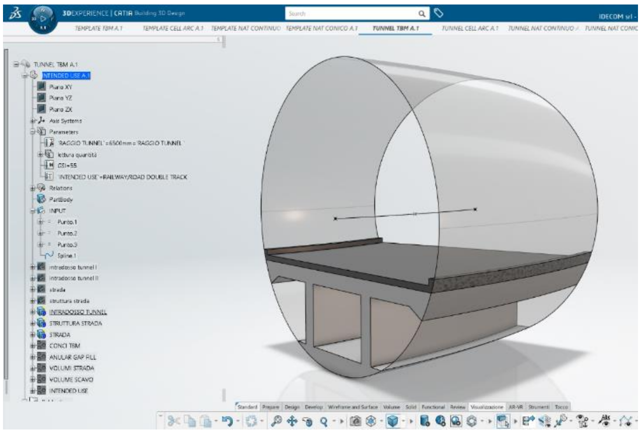

Figure 57 - Geometrical features to create Segmental Ring

The geometric structure of the Typological Product now needs to modulate dimensions and components based on the present parameters.

The management phase of the technological solutions and fields of application of each component is processed by Design Sequences using Visual Scripting. The first case to mention concerns the management of the parameter relating to the intended use. In this instance, four reference cases were identified, related to the dimensional ranges reported in the methodology. A radius of the tunnel intrados equal to 3.5 meters in the case of subways, 5 meters for single-track railway tunnels, 6.5 meters for two-way railway and road tunnels, and finally 7.5 meters of radius in the case of tunnels intended for highways. These dimensions constitute the Input parameter which regulates the radius of the tunnel within the Geometric Sets of the tunnel intrados. When the string parameter that defines the use of the infrastructure is modified, a computational design sequence automatically generates the reference geometric parameter, immediately updating the three-dimensional model and all the geometries linked to the modified objects. Below is the Visual Script sequence that independently manages the variation of the Input parameter and the consequent generation of the output parameters that update the model.

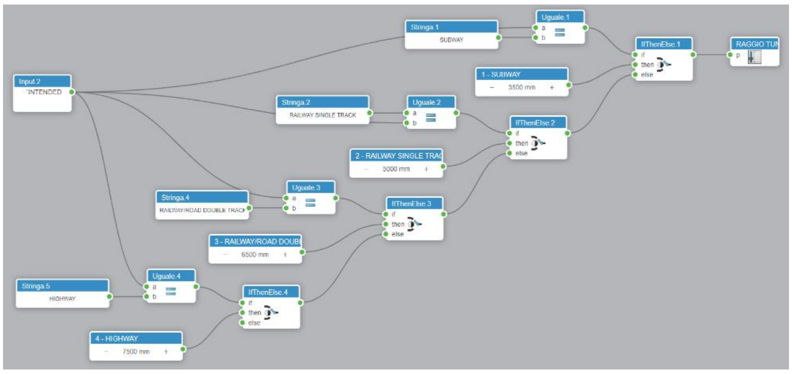

Figure 60 - Visual Script: generation of Intrados Radius based on Intended Use

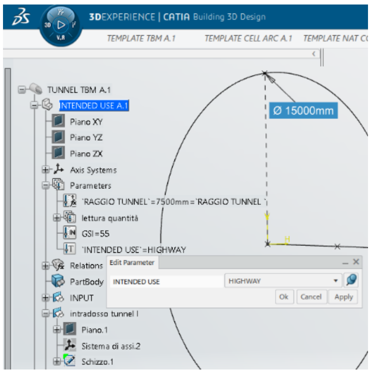

Figure 59 - Intrados based on Radius

The second important dynamic to describe is related to the management of the geotechnical reference parameter GSI. Also, in this case based on the different fields of application identified in chapter 5 dedicated to the methodology, four ranges of use have been identified for as many technological alternatives. As the GSI Input parameter varies, the types of segments inserted into the model vary, differentiated by colour, and consequently also the type of reinforcement embedded in the prefabricated modules, with performances that increase as the Geological Strength Index worsens. From here the different application bands outline the use of reinforcements of 160, 130 and 100 kg per cubic meter respectively, ending with the use of fibre-reinforced concrete in the most stable geological context, containing 45 kg of metal fibres per cubic meter. The Visual Scripting sequence that regulates its operation is also responsible for the creation of some emission parameters relating to the modelled quantities, reported in a set of reading parameters into the "tree", obtaining the volume of the prefabricated segments and the mass of the reinforcements involved. In addition to these, other scripts work in a similar way, obtaining the quantities of other 3D components designed through classic modelling tools and

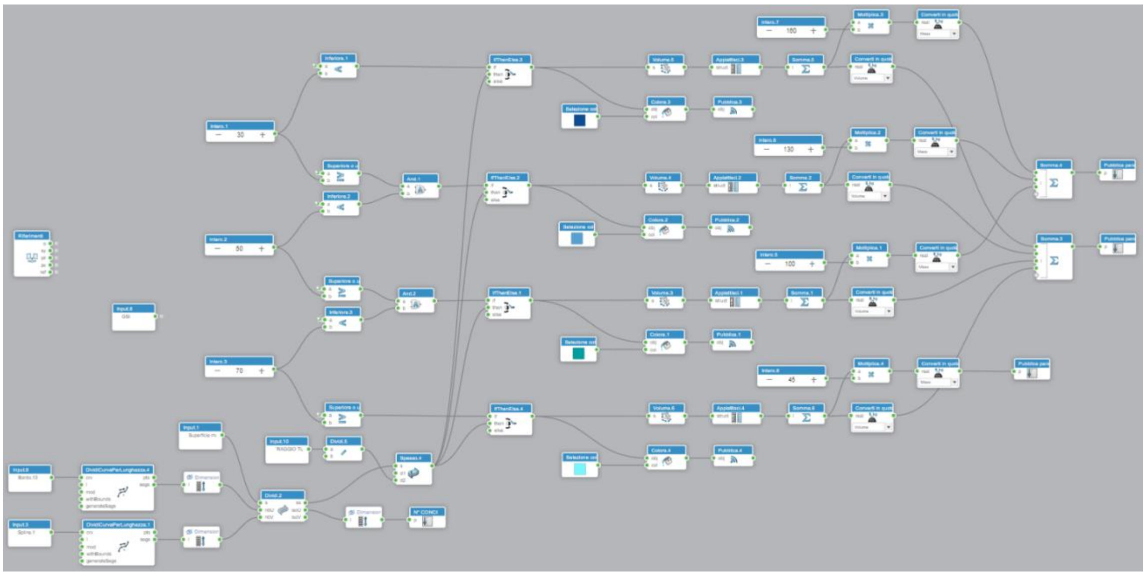

Figure 61 - Visual Script: generation of parametric TBM Segmental Ring geometries and quantities

present as solids in the Body Features, including the total volume of excavation and that of the annular gap fill between the segmented ring and the ground.

Below are some possible final configurations that best exemplify the mechanism that manages the variation of the input parameters and the consequent outputs, both geometric with the updating of the modelled components, and informational with the updating of the reading parameters that report the modelled quantities. The mechanism, not excessively complex for this Typological Product, therefore, highlights the general technical modelling approach that constitutes the Design Optioneering process.

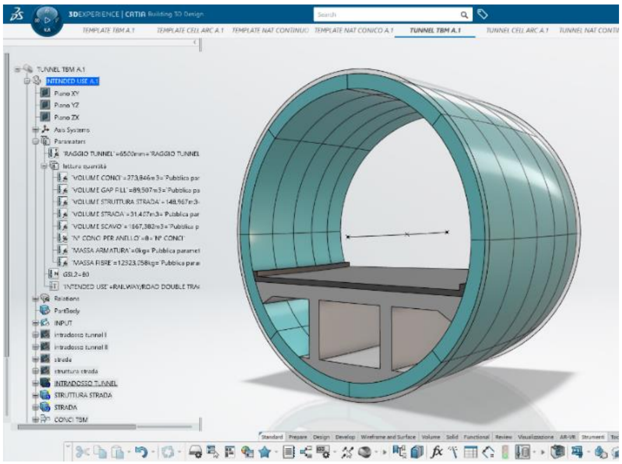

Figure 62 - Example 1 final configuration for TBM typology

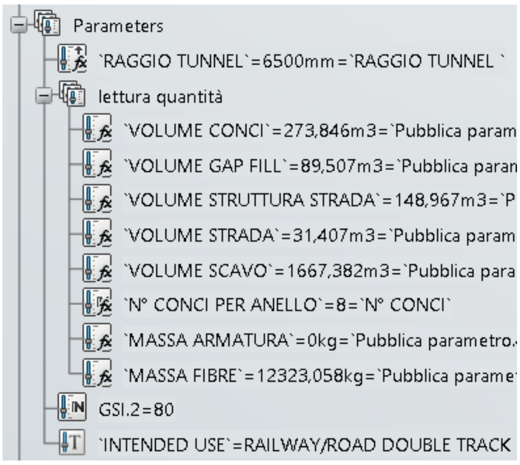

Figure 63 - Reading Parameters: quantity take-off 1

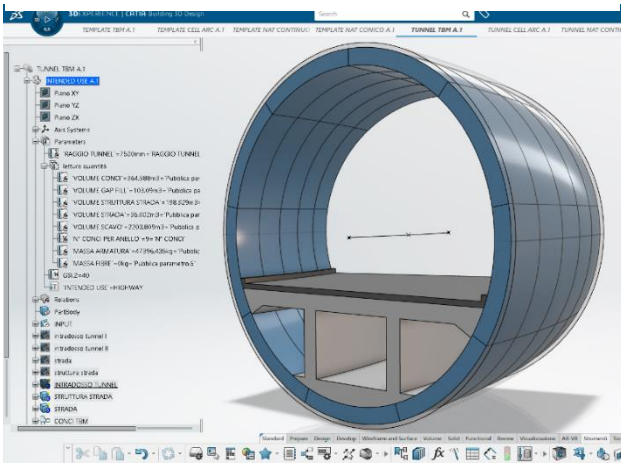

Figure 64 - Example 2 final configuration for TBM typology

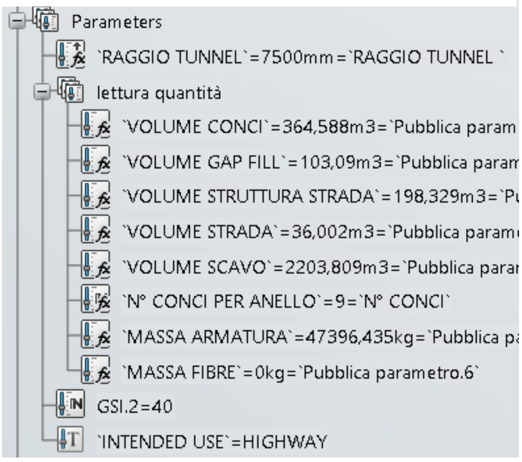

Figure 65 - Reading Parameters: quantity take-off 2

Cellular Arch section Product

The second construction typology analysed concerns the excavation and consolidation technique of the cellular arch. Its use, as previously described, occurs in extremely particular and complex contexts, where the low ground cover and the poor geotechnical performance require a very conservative and careful strategy. For this reason, the ideal application environment remains the city one, where the spaces pertaining to the infrastructures are limited and the soils are extremely fragile and not very cohesive.

Since the application of this typological section is well framed by the needs described above, it has not been further explored in terms of the influencing parameters. For this reason, the main parameter that determines the geometries and emission parameters of the model remains the intended use. As for the previous Typological Product, the string parameter relating to the use of the infrastructure is processed by the relevant Visual Script sequence, consequently updating the dimensional parameter which determines the radius of the section's intrados. This procedure, as for other construction typologies, creates the geometric and parametric reference wireframe which serves as the basis for modelling the subsequent three-dimensional construction elements. From here the modelling takes two different paths, using the basic tools for the composition of not particularly complex elements such as abutments, inverted arch, concrete lean, excavation volume and upper consolidation.

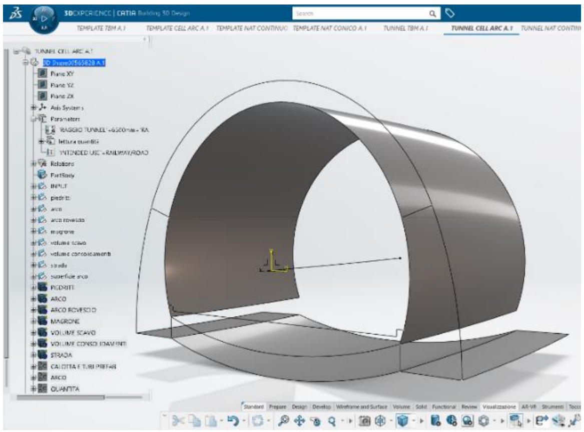

Figure 67 - Geometrical basic features for Cell Arc

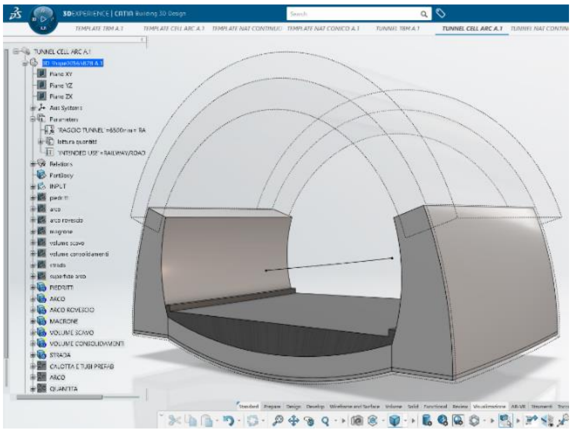

Figure 66 - Solid geometrical features created with basic modelling tools.

The second modelling methodology concerns other elements of structural consolidation of the cellular arch, divided into processing and implementation phases identified in the methodology. Among these there are therefore the prefabricated upper consolidation tubes, their relative filling, the cap, the consolidation castings on the extrados and finally the transverse arches that structurally connect the previous elements. In this case, the approach switches to generative design via Visual Script, which, as shown in the following images, recovers the geometric references previously constrained in the Geometric Sets and exploits them by adding and generating the necessary new and complex geometries.

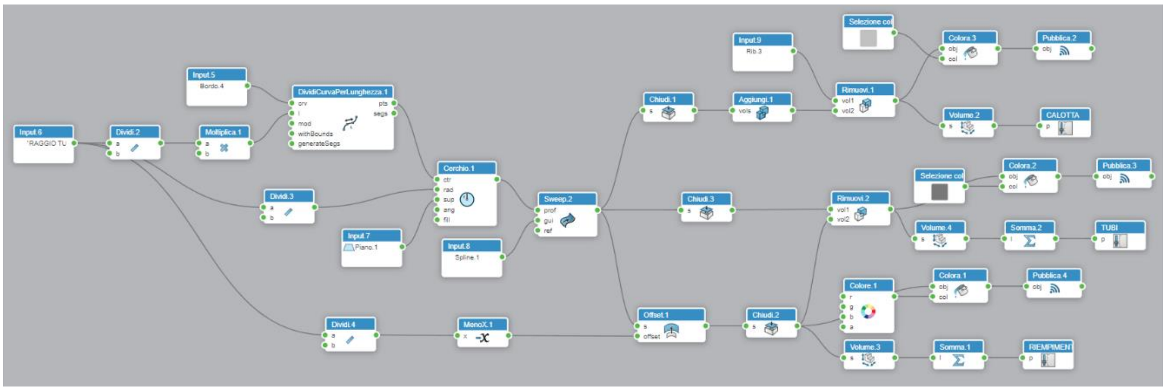

Figure 69 - Visual Script: generation of parametric Cap and consolidation precast concrete Pipes

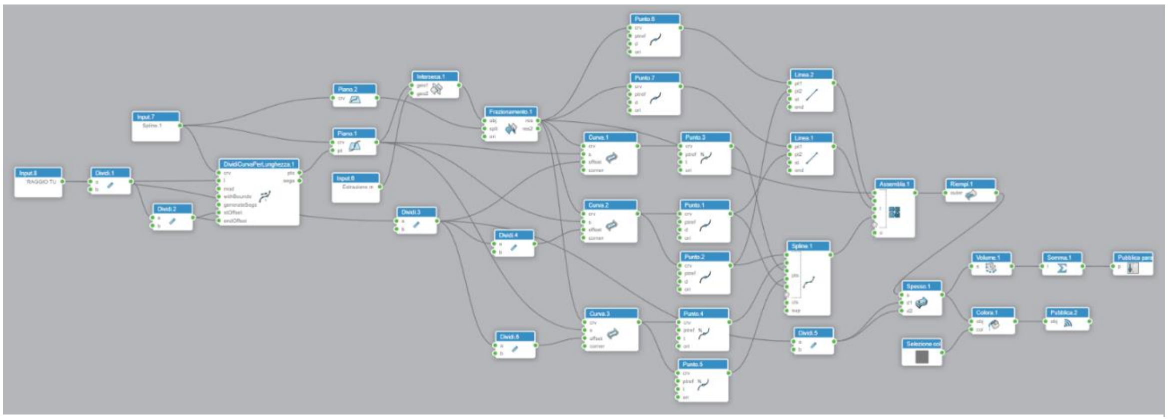

Figure 68 - Visual Script: generation of parametric reinforced concrete Arches

The basic parametric modelling and the computational design sequences therefore allow the different three-dimensional components of the model to adapt autonomously to the variation of the intended use parameter, consequently also updating reading parameters of the interested quantities. Then follow some images that show the ability of the modelled geometries and the information collected to update automatically as the input parameters change.

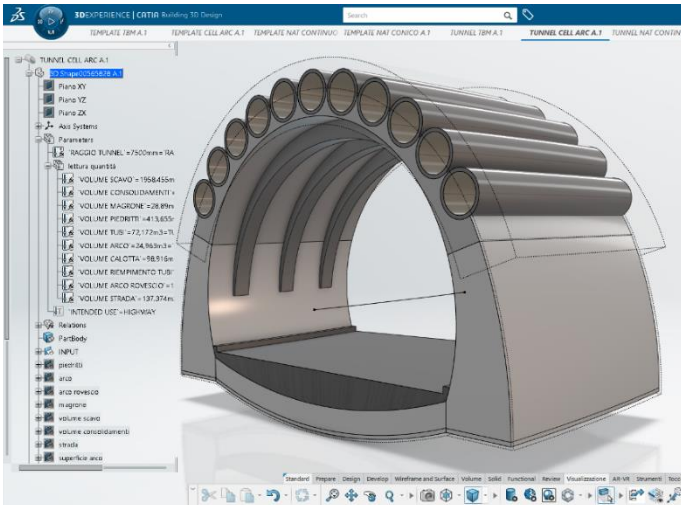

Figure 70 - Example 1 final configuration for Cell Arc typology

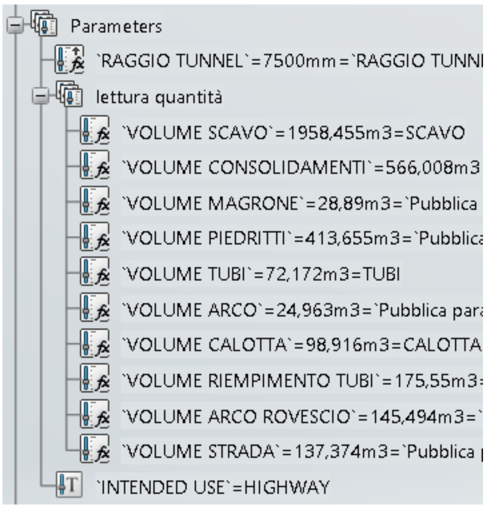

Figure 71 - Reading Parameters: quantity take-off 1

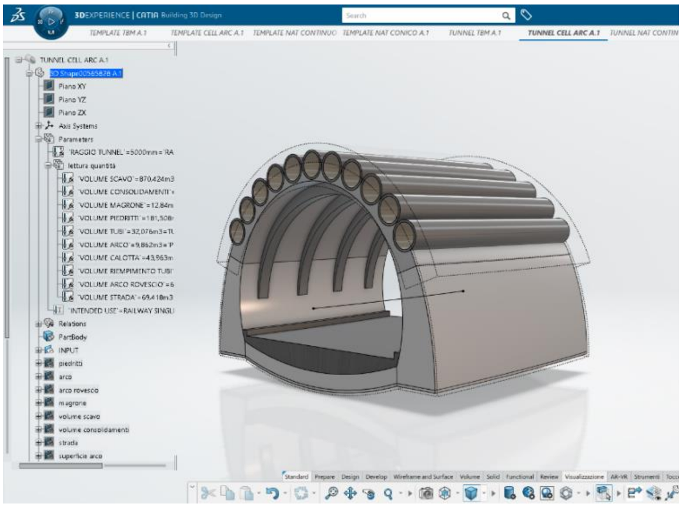

Figure 73 - Example 2 final configuration for Cell Arc typology

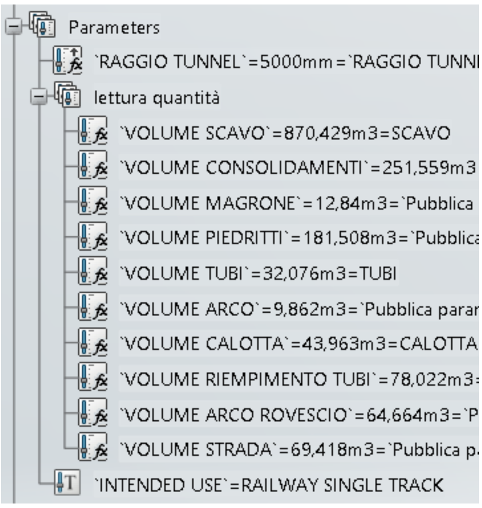

Figure 72 - Reading Parameters: quantity take-off 2

Traditional Linear section Product

After describing the functioning of the Design Optioneering mechanism applied to the BIM models of the previous Typological Products, the excavation methodology with traditional techniques is introduced in this phase. As described in the methodology, these techniques tend to overlap with the use of TBMs with regards to the geotechnical parameters of the context, and the main distinction concerns the size of the infrastructure to be built. If on the one hand they involve a much smaller movement of resources, on the other they remain less performing than TBM constructions, attributing the choice between the two strategies to other more detailed variables also mentioned in the chapter dedicated to the methodology.

A macro distinction in this construction typology concerns the installation of two types of sections. In the first case it is a typology with a constant section along the advance field, the use of which can be found in stable and high-performance geotechnical conditions, with a Geological Strength Index greater than 50. For construction typologies derived from excavations with traditional methods, the influence of the geotechnical parameters and the hydrogeological context have a greater impact than the segmented rings in the context of mechanized excavations, giving rise to a greater variety of possible external stimuli and technological configurations. The parameters that influence the different technical solutions include the intended use, the GSI geotechnical parameter, the granulometry of the surrounding soil, the presence of groundwater and its pressure index.

The construction of the reference geometric skeleton follows the same methodology used for the previous Typological Products, starting from the parametric Sketches of the section of the cap, piers and inverted arch, all related to the intended use parameter which regulates the sizing of the radius at the intrados. This geometric wireframe then provides, with the creation of some surfaces that follow the development of the initial Input Polyline, the geometric constraints for the solid modeling of the technological components involved.

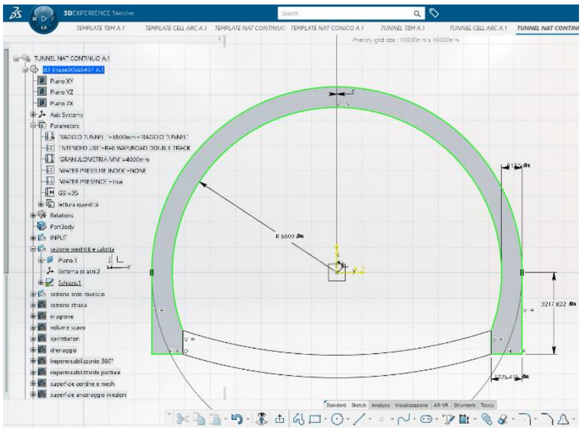

Figure 75 - Basic parametric Sketch for cross-section

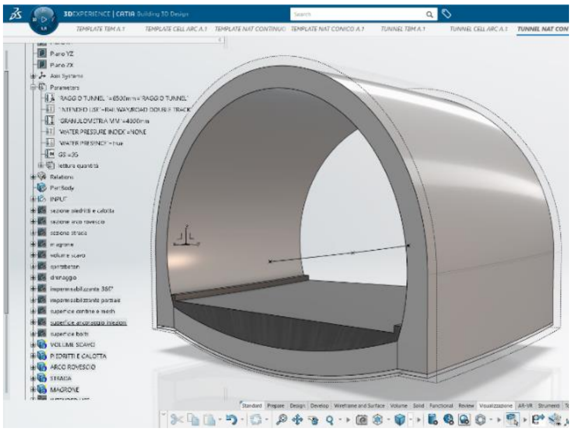

Figure 74 - Solid geometrical features created with basic modelling tools.

Also, for this Typological Product the modelling then takes two different directions, creating through basic tools the solids relating to the elements not conditioned by the parameters subsequent to that of the intended use. This is the case of structural components such as the abutments, the cap, the inverted arch, the road section, the concrete lean and the excavation volume. As regards the solutions aimed at consolidating the tunnel, subject to the parameters previously mentioned and inserted in the Product "tree", their modelling follows generative design processes using Visual Script. From these it was possible to integrate the creation of three-dimensional models and their fields of use based on the set of parameters derived from use and context conditions.

Among these, the generation of ribs and rock bolts is anchored on geometrical set referred to cap and piers surface, both depending on GSI parameter and vary by modifying the length, thickness and frequency of the elements created, following the computational processes reported below.

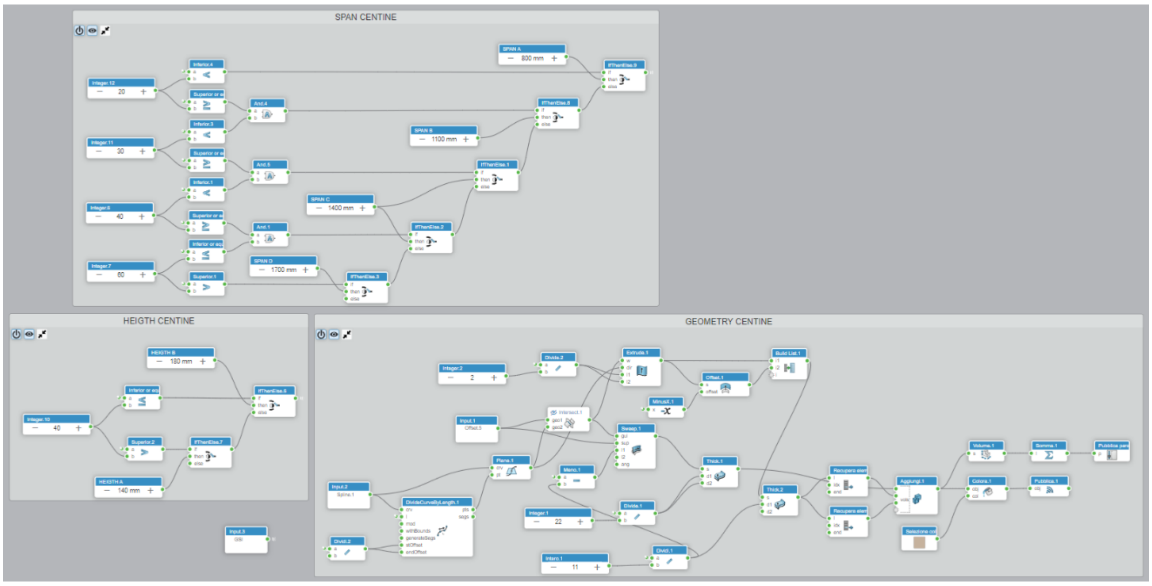

Figure 76 - Visual Script: generation of parametric Lattice Girders and quantities

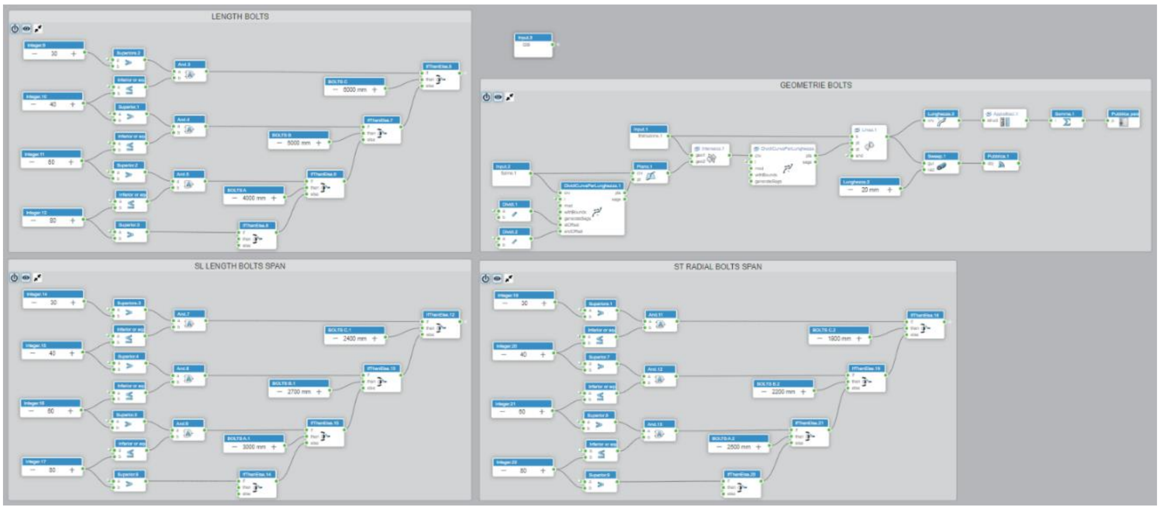

Figure 77 - Visual Script: generation of parametric Rock Bolts and quantities

Computational design processes also generate other technological solutions in a similar way, in particular linked to underground hydrogeological conditions, one of the elements that most affects construction dynamics in the tunnelling sector. Among these there are the consolidation injections at the extrados of the entire section, conditioned by granulometry and presence of underground water. The waterproofing layers, which depend on the water pressure index, and respectively present three possible configurations: umbrella drainage system and waterproof system on the entire extrados, with one or two layers. Finally, to these is added the presence of insertion pipes with a draining function of the mass to be excavated, an important pre-consolidation solution aimed at lightening the hydrostatic load in the excavation context.

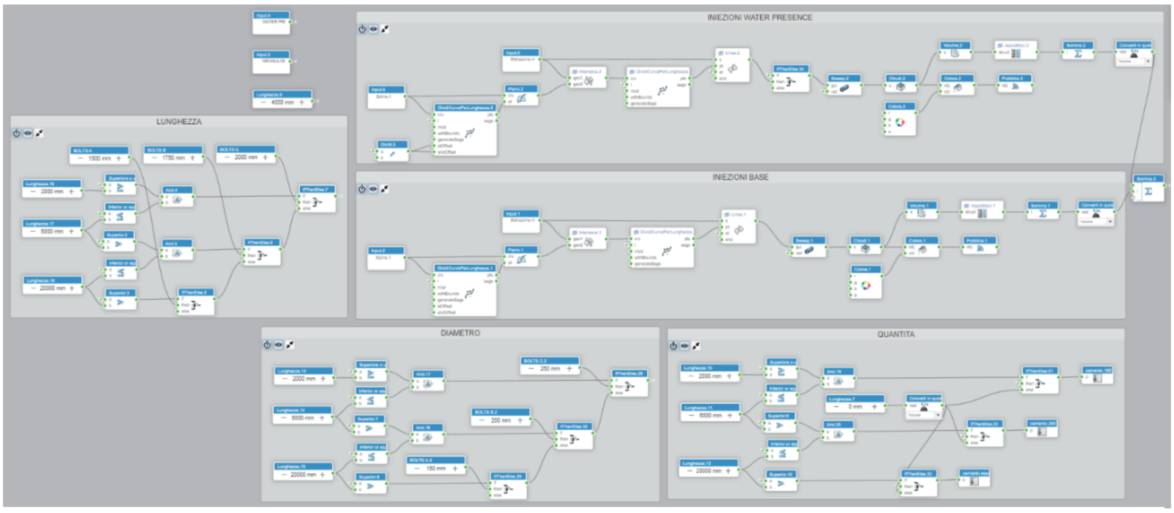

Figure 79 - Visual Script: generation of parametric consolidation Injections

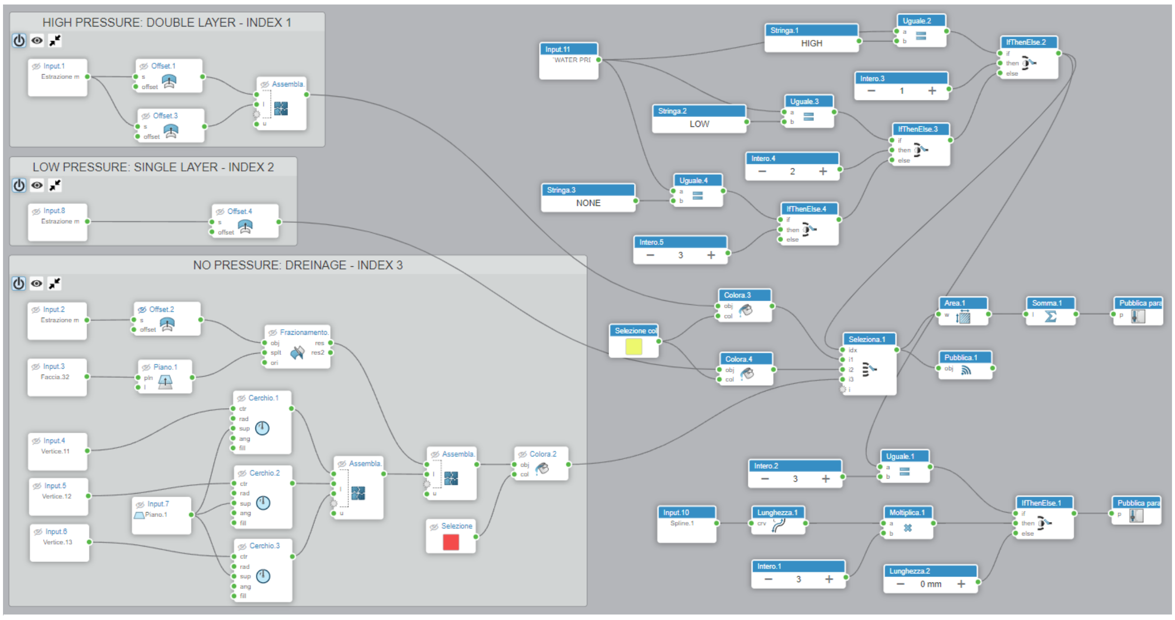

Figure 78 - Visual Script: generation of parametric Waterproofing Systems

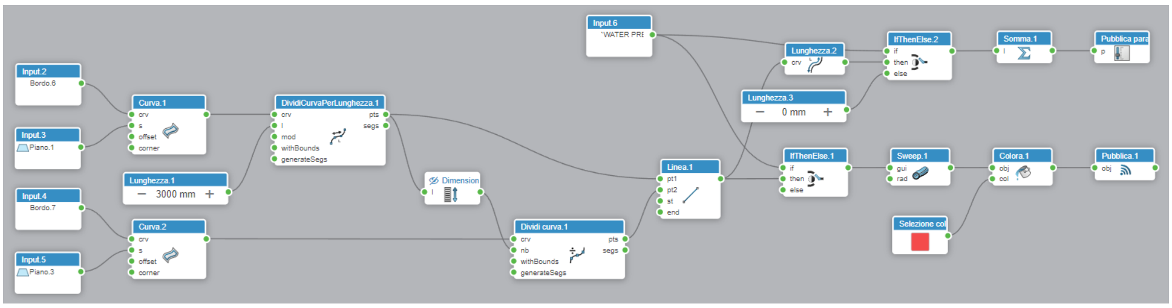

Figure 80 - Visual Script: generation of parametric Drainage Systems

Finally, there remain to mention other components managed and generated using Visual Script tools, less complex and articulated than the previous ones, including shotcrete on the excavated perimeter, the wire mesh embedded inside it, and the necessary quantity of each modelled element. The structure thus created through the processes described allows us to have a three-dimensional model capable of obtaining a considerable amount of possible different configurations, as shown in the following images.

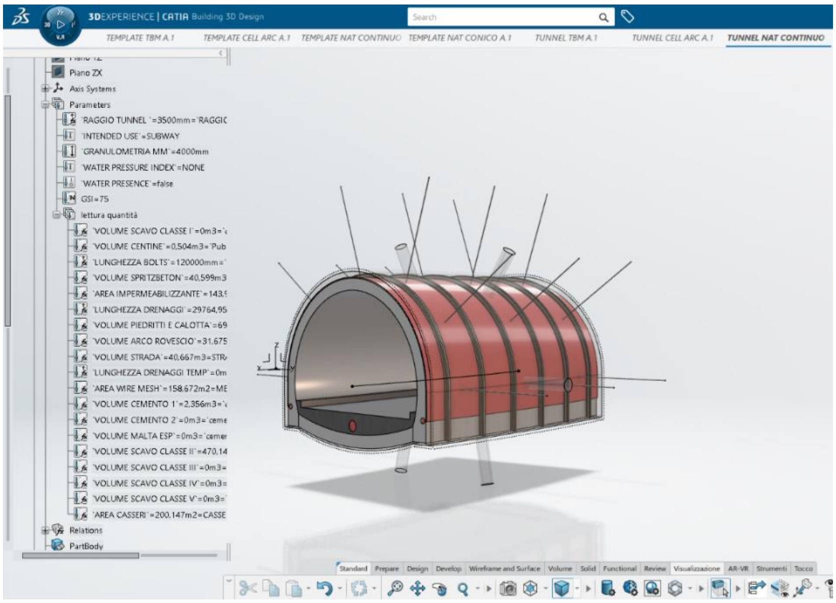
Figure 84 - Example 1 final configuration for Continuous Traditional Section typology

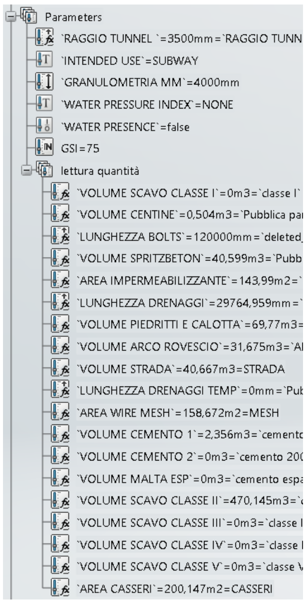

Figure 83 - Quantity take-off 1

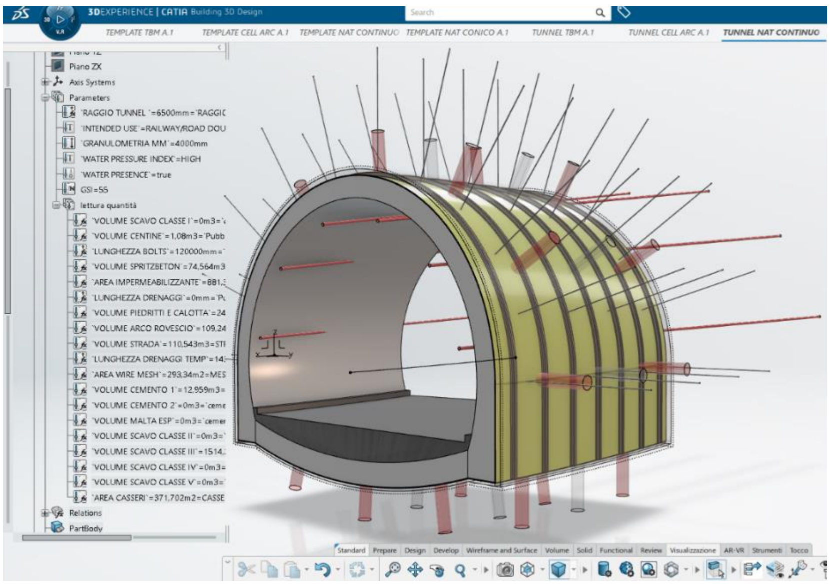
Figure 81 - Example 2 final configuration for Continuous Traditional Section typology

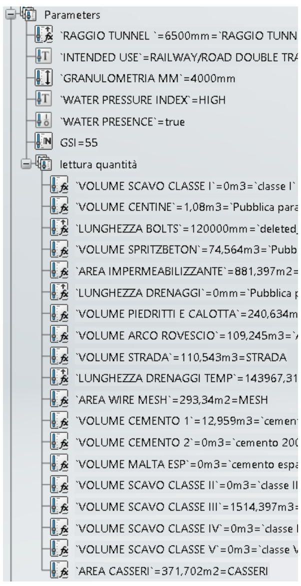

Figure 82 - Quantity take-off 2

Traditional Conical section Product

Remaining in the field of typological sections derived from traditional excavation methods, the macro distinction previously reported identifies a second construction typology composed of a variable conical section along the advancement field, favouring the addition of further arched consolidation elements. This system is in fact used in more complex contexts, characterized by unstable and poorly cohesive geologies, with a GSI lower than 50.

The architecture of the Product remains very similar to the structure that makes up the previous one. Unlike the wireframe created for the linear Typological Section, with constant calibre, this Product requires a conical profile, made possible by a final section with structural thicknesses greater than the initial one. Among the basic modelling tools, it was the Multi-Section Solid that joined the two Sketches to obtain the three-dimensional structure with a conical variable section.

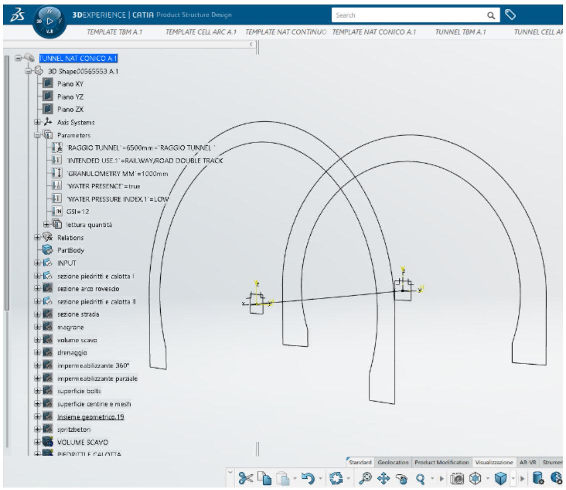

Figure 86 - Geometrical wireframe for Variable Section

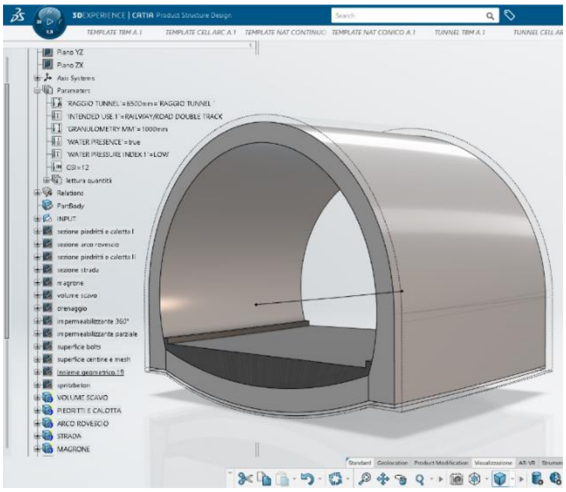

Figure 85 - Solid geometrical features created with basic modelling tools.

In the same way, the modelling of the other solid elements continues, which vary based solely on the intended use and the intrados radius. As regards the creation of the remaining pre-consolidation and containment elements, the methodology followed is the same used for the development of the Linear Section. This applies to several common technological solutions, including ribs, rock bolts, wire mesh, waterproofing systems, boundary shotcrete and temporary drainage. Given the application of this typology in contexts of greater complexity, new elements are added to the common technological systems previously described.

These are pre-consolidation systems at the face and consolidation structures supporting the boundary which, thanks to their conical shape, allow the overlap between successive advancement fields of the systems that run parallel to the surface of the cap. As regards the pre-consolidation systems at the face, in addition to the temporary drainage systems, two new technological solutions have been added, necessary to stabilize and bind the soil being excavated before starting the operations and both modelled through a sequence of Visual Script. The sequence of structural fiberglass tubes guides their distribution following a radial pattern of variable size and frequency based on the size of the cross section and therefore on the intended use parameter. The layer of shotcrete cast at the excavation face follows the geometric trend of the beginning and end sections of the Typological Product in the same way.

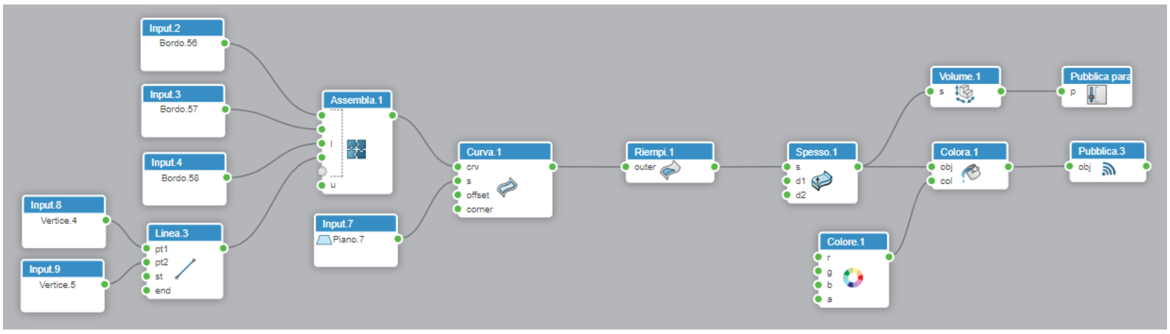

Figure 88 - Visual Script: generation of Shotcrete layer at the front

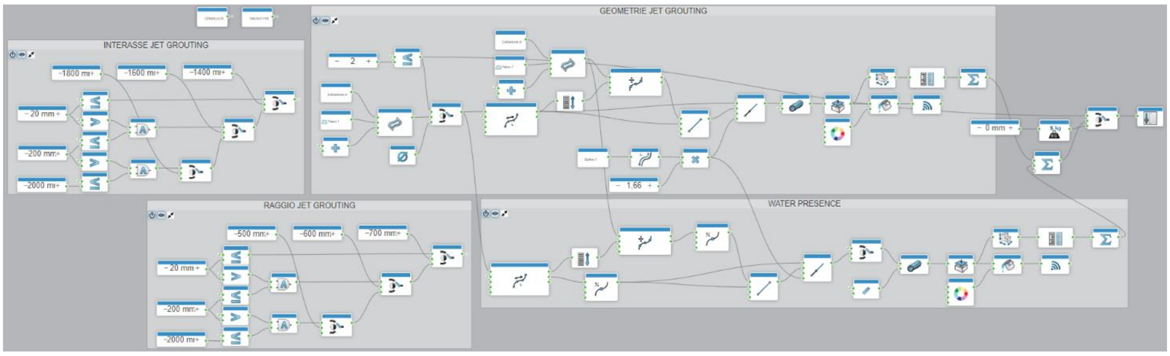

Figure 87 - Visual Script: generation of parametric Jet-Grouting consolidation

As regards the consolidation structures supporting the excavation boundary, the Visual Script sequences follow processes similar to those used for VTR sub-consolidations, given the radial distribution which extends from the advancement field and overlaps with the next one. In this case, however, the management of the Design Optioneering mechanism that guides the generation of three-dimensional elements becomes more complex. In the first instance, boundary injections via jet grouting are influenced by two parameters, namely granulometry and presence of groundwater. The grain size parameter identifies three bands of use, with frequency and radial dimension that increase as the cohesion of the soil and the granulometry decrease. At the same time, the parameter relating to the presence of groundwater requires greater waterproofing capacity on the part of the jet grouting injections, and when active it consequently increases the frequency of initiations by adding new ones. The second technological solution that contributes to the consolidation of the excavation contour is the umbrella arc, subjected to the variation of the GSI parameter. Its presence in the model is activated when the parameter drops below the value of 30, exactly when the use of rock bolts is deactivated, required according to the methodology followed with GSI values greater than 30 and more consolidated rock masses in which to grip. The frequency of the hollow valved tubes that constitute the umbrella arc increases as the reference parameter decreases and the geological stability decreases.

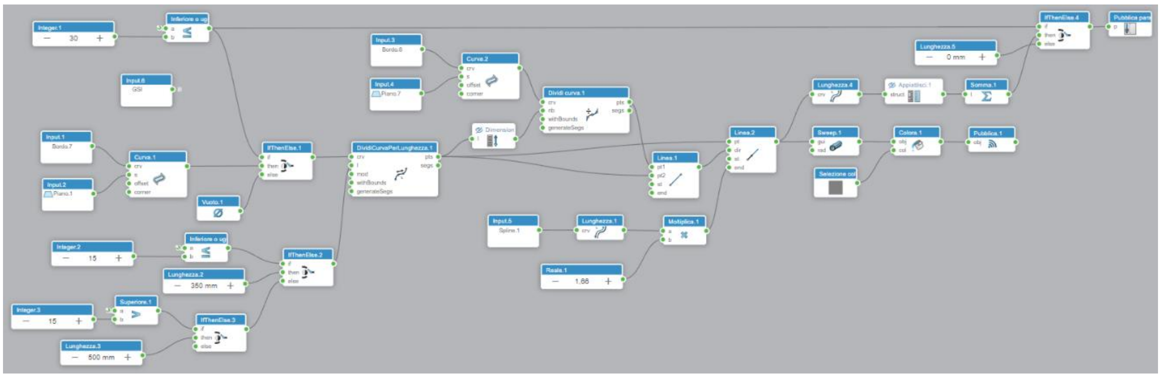

Figure 90 - Visual Script: generation of parametric Umbrella Arc

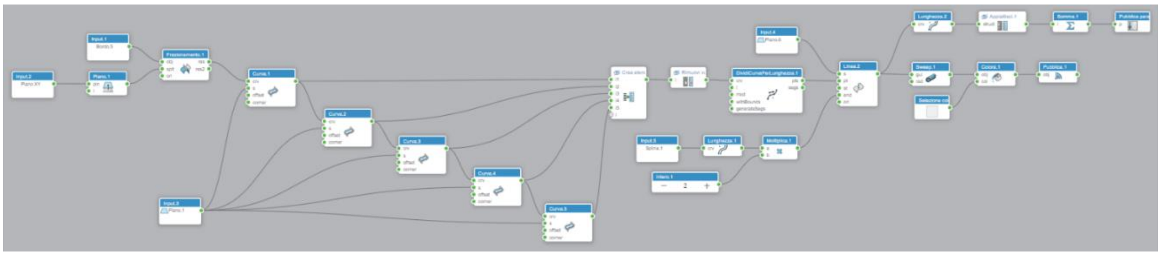

Figure 89 - Visual Script: generation of parametric VTR temporary structural elements

This last Typological Product finally becomes extremely useful and communicative for the purposes of understanding the Design Optioneering mechanism which relates the input parameters representing the geological context stimuli to the geometries of the modelled technological components and to the emission parameters necessary to evaluate their impact. For this reason, images are reported below and show, as in the previous cases, some different possible final configurations.

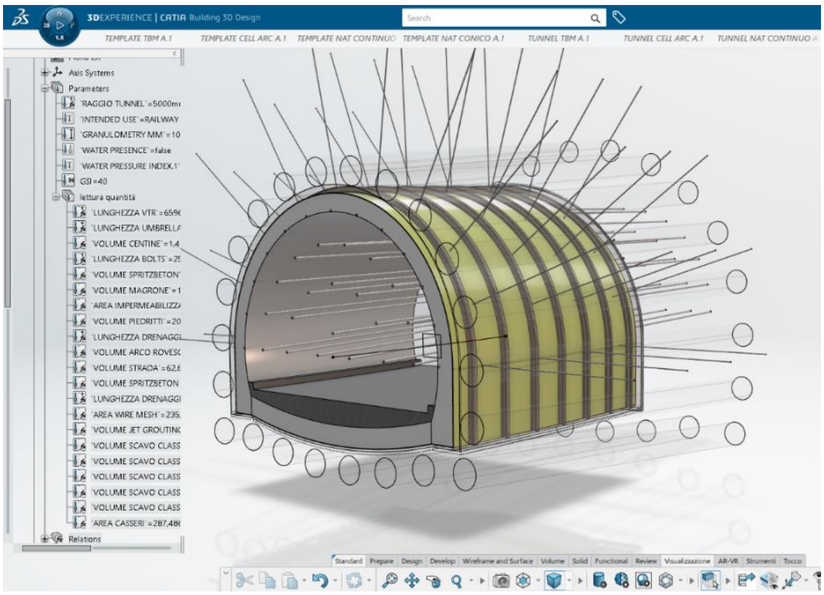

Figure 91 - Example 1 final configuration for Variable Traditional Section typology

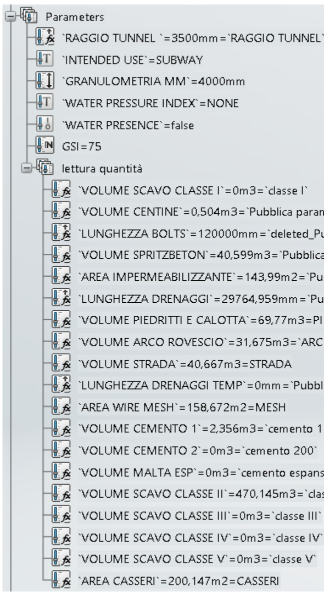

Figure 92 - Quantity take-off 1

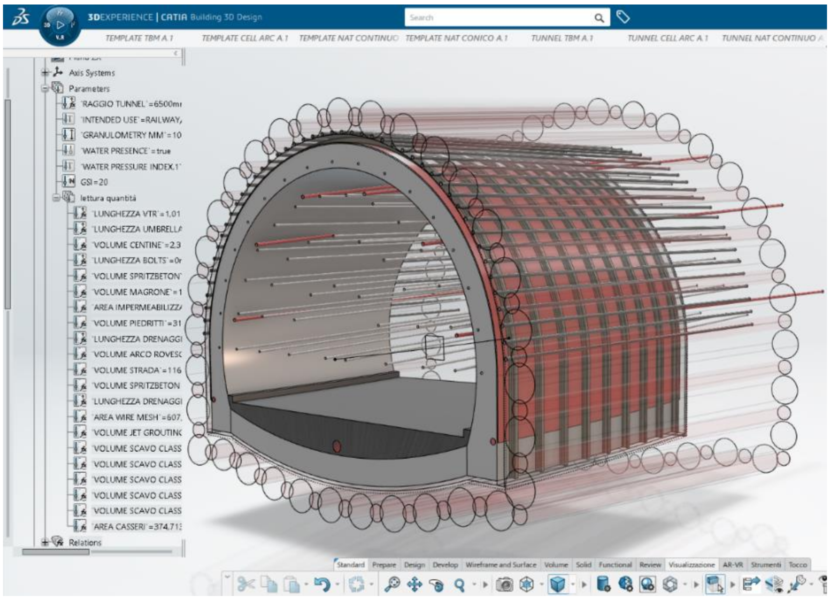

Figure 93 - Example 2 final configuration for Variable Traditional Section typology

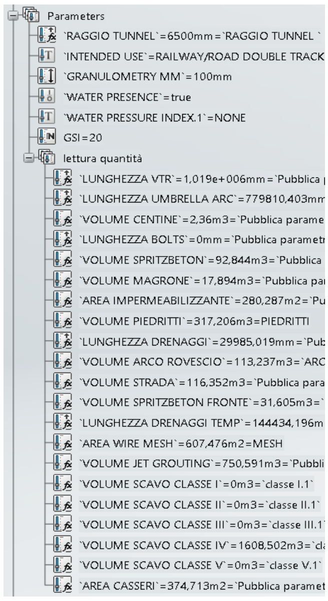

Figure 94 - Quantity take-off 2

6.3.4 – Component Based Design functioning (automated and recursive adaptive template)

Summarizing what has been said in the Chapter so far, the Typological Products derived from the study carried out to define the methodology were modelled in a BIM environment using parametric modelling and generative design tools. This is done by considering them as ready-to-use modules, to be applied to assembly paths through the instantiation of the Adaptive Product Engineering Template, whose operation is described in Chapter 6.3.2. For this reason, the structure of the models follows recurring characteristics that allow the adaptivity of the Template to be successfully achieved, including the creation of a starting Input polyline, the parameterization of the reference geometries, and the automated computational generation of all the typological and technological solutions present. To make the application of the study model complete and scalable on larger overall projects, however, it is necessary to make the assembly of the Products via Template as recursive and automated as possible. The Component-Based Design method was created exactly with this objective, always in the context of 3DExperience Platform.

Within the Platform, Component-Based Design refers to the approach of creating and managing design elements as modular components that can be reused across different projects or within the same project. This approach exploits the systematic reuse of different types of resources, including an Engineering Template product, to apply it to a series of targets according to precise rules and geometric constraints, and at the same time following lists of parameters that influence their behaviour. This methodology enhances automation, efficiency, and consistency in product and assembly development.

It can therefore be summarized that its operation requires three main components: a Geometric Set which constitutes the reference target, one or more sets of parameters based on needs, and the product, Template in the thesis study model, which constitutes the module basis to replicate and instantiate. Before introducing the assembly process of the Typological Products of the case study, a reduced example is provided to better understand its basic functioning.

Thanks to PLM management, the system exploits modularity entities that encapsulate specific design functionalities or features. These components can range from simple parts to complex assemblies. It's also possible to put into practice the reverse process, breaking down a design into modular components, it becomes easier to manage, update, and reuse them across different projects. One of the key advantages of component-based design is reusability, guaranteeing Designers to create libraries of components that capture best practices, standard parts, or commonly used features, easily reusing these components in new designs, saving time and ensuring consistency across projects. In addition to this, the platform provides tools for managing configurations of components, particularly important in scenarios where a product has multiple variants or configurations. Component-based design allows for efficient management of these variations, ensuring that changes made to one configuration do not affect others unintentionally. It constitutes, in its modular and replicable nature, an important evolution of the Template approach, making it automated and scalable on large assemblies.

7 RESULTS AND DISCUSSION

The field of tunneling civil engineering is inherently and remarkably complex, requiring timely and carefully considered decisions to ensure the success of large-scale underground projects. The thesis is rooted in this need and aims to develop a decision support system (DSS) designed to address the unique challenges present in this type of civil works. Through the integration of advanced modeling technologies, decision analysis, generative and computational design, the interactive model object of the case study becomes an intelligent tool capable of autonomously responding to environmental constraints by automatically generating the feasible and most compliant technological configurations. The development of the study model is part of a preliminary design phase and aims to provide the designers involved with informed and targeted decisions. From here the analysis of alternative scenarios becomes the means through which it was possible to evaluate the effectiveness of the model, addressing each time the uncertainties and dynamic variables that characterize the underground environment. The main objective therefore remains to improve the accuracy of forecasts, optimize resource management, and reduce the risks associated with the construction of underground infrastructure. The development of the DSS within the Thesis adopts a complete methodological approach, starting from the consolidation of the state of the art and arriving at the analysis of the results obtained, including the design of advanced algorithms and innovative design approaches.

The results presented in this section resume what was shown in Chapter 6 with the parametric and computational modeling of the typological sections involved. The real-time response of the geometric model and the reading of data and quantities reflect the effectiveness of the system, capable of generating typological and technological configurations from time to time at the service of design decisions in realistic test conditions. The interactive model is inserted, as anticipated in the methodology, in an intermediate design phase, where the results are immature to be able to constitute a complete executive project, but at the same time rich enough in solutions and information to provide effective decision-making support for the preliminary design. This will be an opportunity to examine the performance of the Decision Support System through different simulated scenarios, highlighting its prediction and dynamic adaptation capabilities to changing subsurface conditions.

To introduce the simulations based on the different scenarios it is important to show the procedure followed, which is linked to the functioning of the Component Based Design described at the conclusion of the previous chapter.

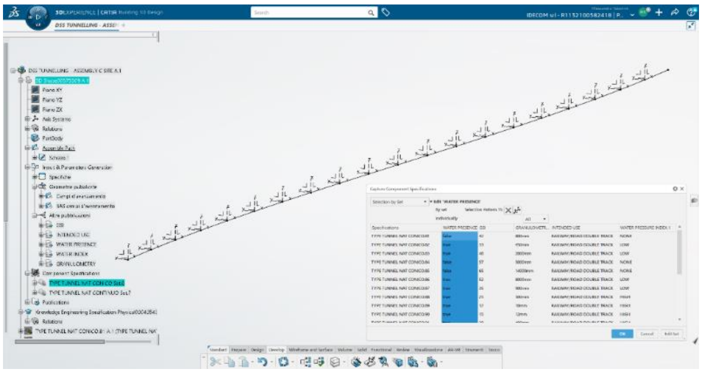

Figure 95 - Polyline sketch: infrastructure alignment path

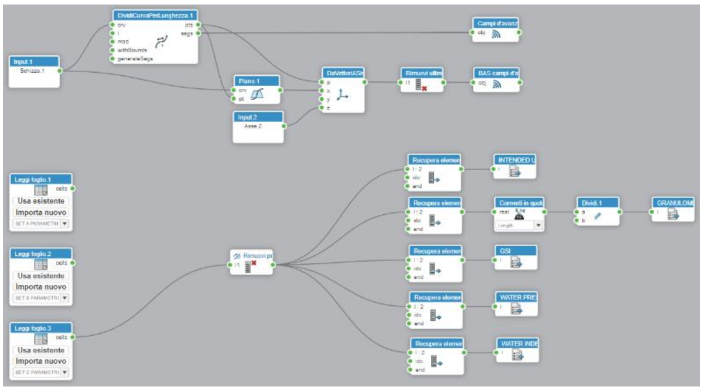

Figure 97 - Visual Script: generation of target Input geometrical sets and input Parameters list

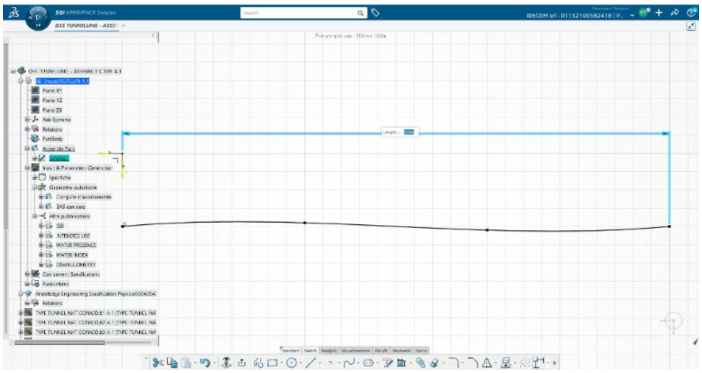

Figure 96 - Alignment path subdivisions and component-based design application

Through this methodology it is in fact possible to automate the serial and massive creation of the products modeled at the start, instantiating them on reference target geometries that correspond to the geometric input chosen via the Engineering Template, previously analyzed in Chapter 6.3.3.

The starting point for creating the scenarios is the Polyline which represents the alignment path of the infrastructure. For the analyzed study scenarios, a Polyline of approximately 300 meters with double curvature was created, which will subsequently allow us to effectively demonstrate how the Products created adapt to the curvatures of the general reference route. The second phase that characterizes the preparation of the simulation context concerns the creation of the Inputs and Parameters necessary to implement the Component Based Design methodology in the interactive model. To this end, a design sequence created using Visual Scripting allows you to perform two fundamental operations. The first consists in dividing the Polyline of the alignment route into smaller sections which represent the progress field of the excavation and construction operations. Each of the traits thus identified becomes the reference Input target on which the Typological Product will be created and adapted. In particular, the case in question reports twenty advancement spans, which will correspond to twenty instantiated Products. The second operation instead allows you to break down the Excel table containing the Input Parameters derived from the geological and geotechnical study of the excavation context, obtaining an independent list for each Parameter. The final configuration of the setup of each scenario therefore presents all the factors necessary to process the Component Based Design, grouped in lists of twenty elements, each of which provides the values necessary for the parameterization of each instantiated Product.

7.1 - Scenario A

The table below describes the oscillation of the geological parameters along the section of tunnel examined. The performance of the individual fields examined is further described through the graphs which, along through the scenarios, will retain the indication of the behavior of the parameters in the previous scenarios to underline position and field of uncertainties. The intended use of the tunnel remains constant along its entire lenght.

INTENDED USE	GRANULOMETRIA (mm)	GEOLOGICAL STRENGTH INDEX	WATER PRESENCE	WATER PRESSURE INDEX
RAILWAY/ROAD DOUBLE TRACK	1400	65	false	NONE
RAILWAY/ROAD DOUBLE TRACK	800	60	false	NONE
RAILWAY/ROAD DOUBLE TRACK	500	57	false	NONE
RAILWAY/ROAD DOUBLE TRACK	350	48	false	NONE
RAILWAY/ROAD DOUBLE TRACK	280	43	false	NONE
RAILWAY/ROAD DOUBLE TRACK	250	55	false	NONE
RAILWAY/ROAD DOUBLE TRACK	150	52	true	LOW
RAILWAY/ROAD DOUBLE TRACK	80	45	true	LOW
RAILWAY/ROAD DOUBLE TRACK	40	40	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	40	35	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	50	55	false	NONE
RAILWAY/ROAD DOUBLE TRACK	70	52	false	NONE
RAILWAY/ROAD DOUBLE TRACK	100	60	false	NONE
RAILWAY/ROAD DOUBLE TRACK	250	40	false	NONE
RAILWAY/ROAD DOUBLE TRACK	300	40	false	NONE
RAILWAY/ROAD DOUBLE TRACK	400	54	false	NONE
RAILWAY/ROAD DOUBLE TRACK	700	48	false	NONE
RAILWAY/ROAD DOUBLE TRACK	1000	55	false	NONE
RAILWAY/ROAD DOUBLE TRACK	2200	62	false	NONE
RAILWAY/ROAD DOUBLE TRACK	2400	68	false	NONE

Figure 98 - Table of Geological parameters to the different sections

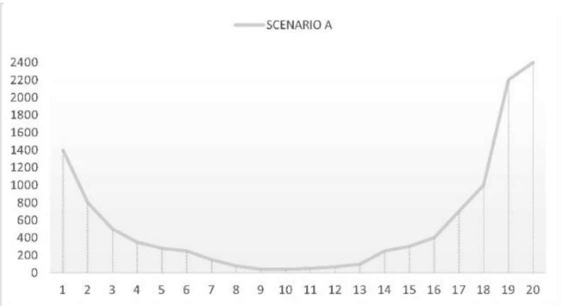

Figure 102 - Granulometry to different sections

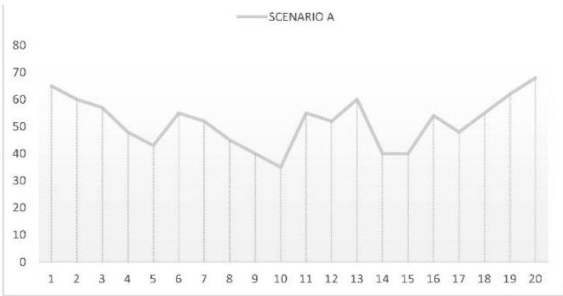

Figure 100 - GSI to different sections

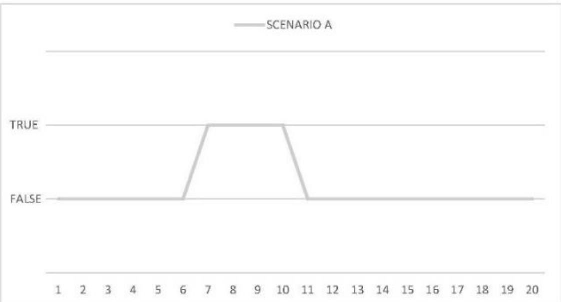

Figure 101 - Water presence to different sections

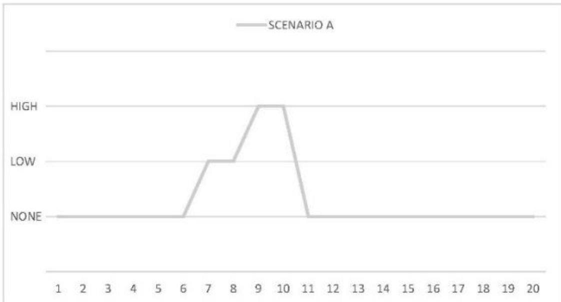

Figure 99 - Water pressure to different sections

To create an adequate dataset to prove the achievement of the set objectives, reference was made to the parameters previously indicated as mainly responsible for the implementation of specific solutions such as Granulometry, Geological strnght index, water presence and water pressure index. A field analysis phase was then simulated in which, associated with the data collected, an uncertainty is also predicted that is more pronounced the more the portion of the rock mass being analyzed is internal and difficult to reach for standard sampling means.

Figure 103 - Plan view, scenario A

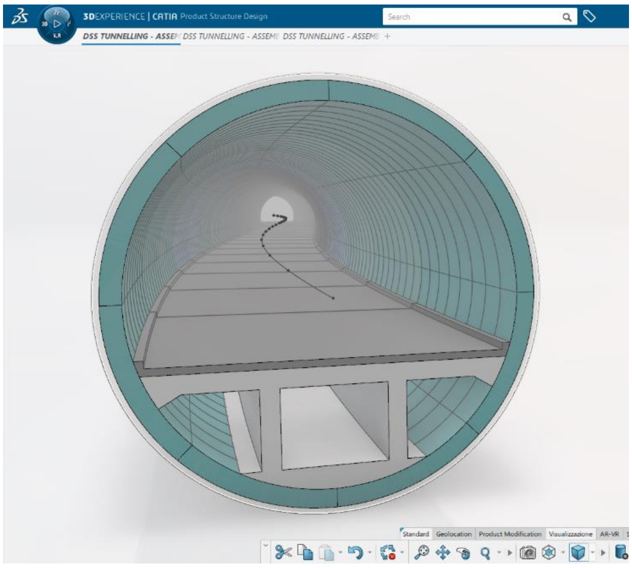

Figure 104 -Section view, scenario A

The data collected has a constant trend. A lowering of the GSI also corresponds to a lowering of the grain size. Likewise, the trend of water presence and pressure below is constant. Given the analysis of the data, net of the uncertainties, the scenario emerges as suitable for the TBM. The DSS is receptive to the input of the dataset and models the inserted products, accordingly, span by span. The development of the tunnel with TBM is by its nature quite static, given the ability of the segmented ring to perform a variety of tasks.

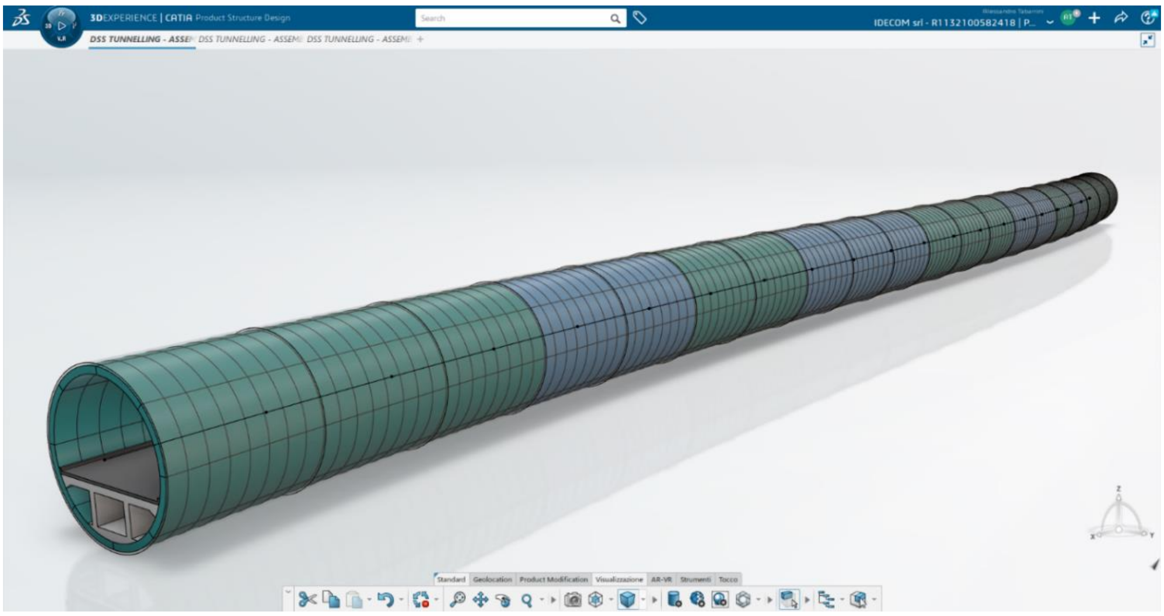

Figure 105 - Perspective view, scenario A

7.2 - Scenario B

INTENDED USE	GRANULOMETRIA (mm)	GEOLOGICAL STRENGTH INDEX	WATER PRESENCE	WATER PRESSURE INDEX
RAILWAY/ROAD DOUBLE TRACK	1400	65	false	NONE
RAILWAY/ROAD DOUBLE TRACK	800	60	false	NONE
RAILWAY/ROAD DOUBLE TRACK	500	57	false	NONE
RAILWAY/ROAD DOUBLE TRACK	350	48	false	NONE
RAILWAY/ROAD DOUBLE TRACK	280	43	false	NONE
RAILWAY/ROAD DOUBLE TRACK	210	55	true	NONE
RAILWAY/ROAD DOUBLE TRACK	80	35	true	LOW
RAILWAY/ROAD DOUBLE TRACK	50	25	true	LOW
RAILWAY/ROAD DOUBLE TRACK	1	12	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	1	15	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	40	28	true	LOW
RAILWAY/ROAD DOUBLE TRACK	70	52	false	NONE
RAILWAY/ROAD DOUBLE TRACK	100	60	false	NONE
RAILWAY/ROAD DOUBLE TRACK	250	40	false	NONE
RAILWAY/ROAD DOUBLE TRACK	300	40	false	NONE
RAILWAY/ROAD DOUBLE TRACK	400	54	false	NONE
RAILWAY/ROAD DOUBLE TRACK	700	48	false	NONE
RAILWAY/ROAD DOUBLE TRACK	1000	55	false	NONE
RAILWAY/ROAD DOUBLE TRACK	2200	62	false	NONE
RAILWAY/ROAD DOUBLE TRACK	2400	68	false	NONE

Figure 109 - Table of Geological parameters to the different sections

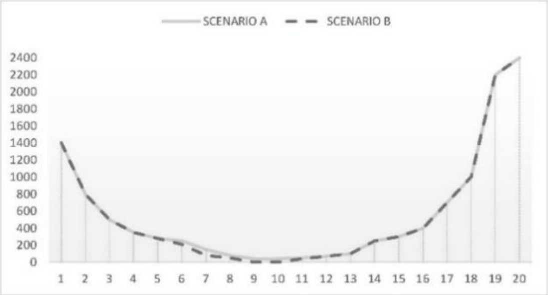

Figure 110 - Granulometry to different sections

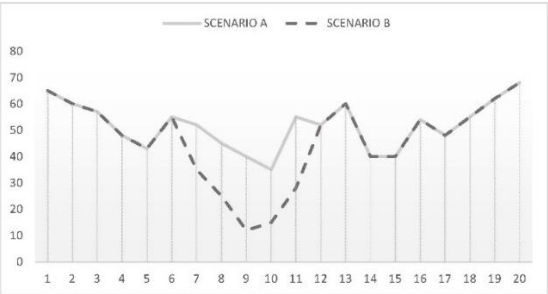

Figure 107 - GSI to different sections

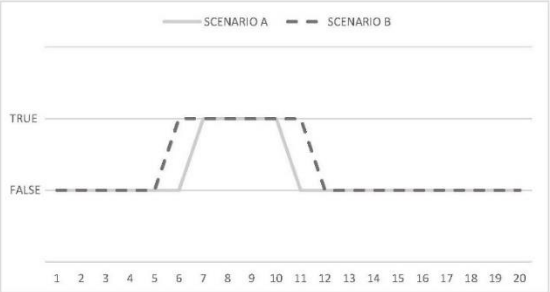

Figure 108 - Water presence to different sections

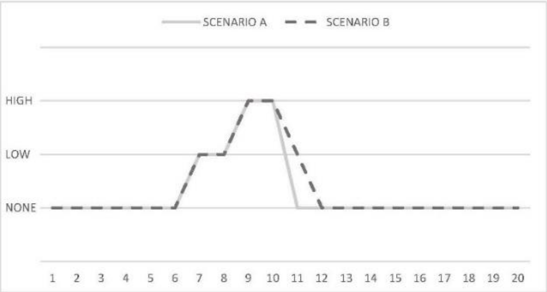

Figure 106 - Water pressure to different sections

With the creation of scenario B, the concrete possibility is introduced that the forecasts made for scenario A worsen in some points where the uncertainty of the data collected opens the possibility of a significant variation across multiple fields typical of the central part of the rock mass. As can be seen from the graphs of the trend of the parameters, in fact, the central portion is subject to a lowering of the level of static stability of the rock which materializes in the valley of the GSI, in the presence of water for a more prolonged stretch and of a greater pressure. The overlap between the two scenarios is interrupted in a localized portion and this may require the use of other types of excavation and construction.

Figure 111 - Plan view, scenario B

Although TBM machinery performs well, it remains very sensitive to geological variations of the context. When there is a decisive change in conditions, the probability of it leaving the field of existence increases considerably. From here another typological section comes into play which adapts to the critical conditions of the portion and resolves the section in question. The use of the TBM on most of the route is not questioned since the points of discontinuity are limited and the rest of the route remains constant and therefore justifies the initial costs of using the machine. Through the analysis of the scenario in question it is possible to carry out a first step of evaluation on the feasibility of the project, in fact the additional costs generated by the implementation of the technologies necessary for drilling with traditional techniques and the related construction technologies are automatically calculated by the DSS.

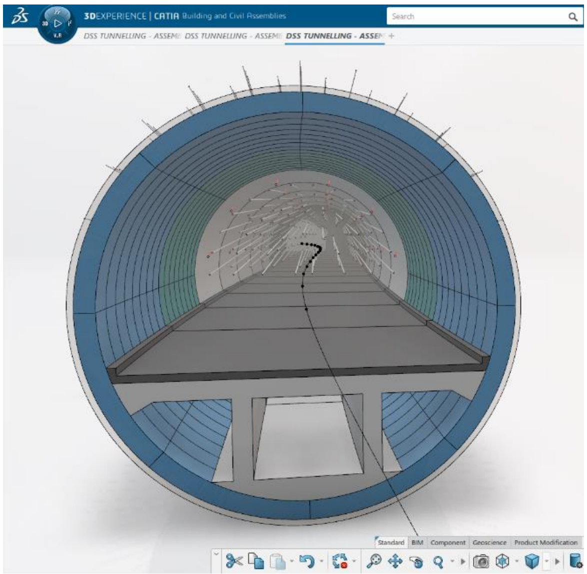

Figure 112 - Section view, scenario B

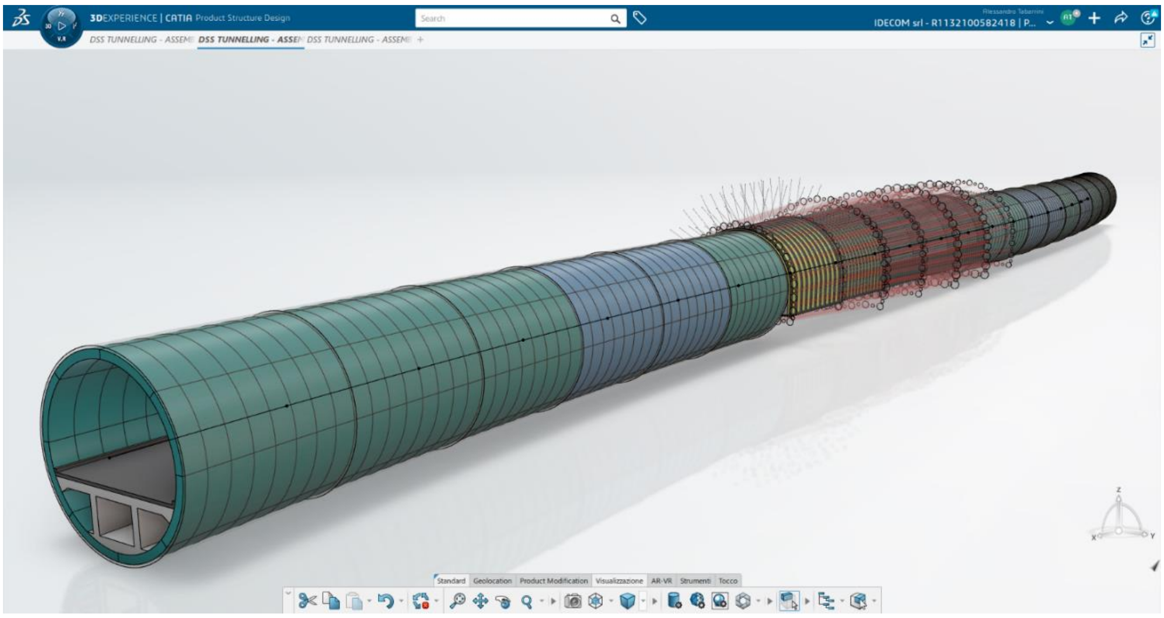

Figure 113 - Perspective view, scenario B

7.3 - Scenario C

INTENDED USE	GRANULOMETRIA (mm)	GEOLOGICAL STRENGTH INDEX	WATER PRESENCE	WATER PRESSURE INDEX
RAILWAY/ROAD DOUBLE TRACK	80	42	false	NONE
RAILWAY/ROAD DOUBLE TRACK	45	33	true	LOW
RAILWAY/ROAD DOUBLE TRACK	200	48	true	LOW
RAILWAY/ROAD DOUBLE TRACK	500	57	false	NONE
RAILWAY/ROAD DOUBLE TRACK	1400	65	false	NONE
RAILWAY/ROAD DOUBLE TRACK	800	52	true	LOW
RAILWAY/ROAD DOUBLE TRACK	90	35	true	LOW
RAILWAY/ROAD DOUBLE TRACK	50	25	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	1	12	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	1	15	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	40	28	true	HIGH
RAILWAY/ROAD DOUBLE TRACK	70	52	true	LOW
RAILWAY/ROAD DOUBLE TRACK	100	60	true	LOW
RAILWAY/ROAD DOUBLE TRACK	60	44	true	LOW
RAILWAY/ROAD DOUBLE TRACK	150	48	false	NONE
RAILWAY/ROAD DOUBLE TRACK	400	59	false	NONE
RAILWAY/ROAD DOUBLE TRACK	2200	75	true	LOW
RAILWAY/ROAD DOUBLE TRACK	1000	63	true	LOW
RAILWAY/ROAD DOUBLE TRACK	50	45	true	LOW
RAILWAY/ROAD DOUBLE TRACK	120	35	false	NONE

Figure 117 - Table of Geological parameters to the different sections

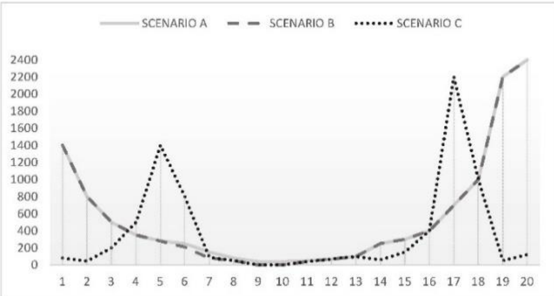

Figure 118 - Granulometry to different sections

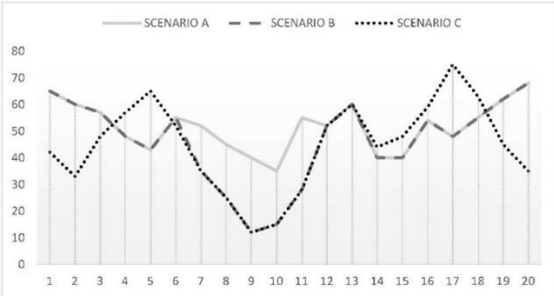

Figure 116 - GSI to different sections

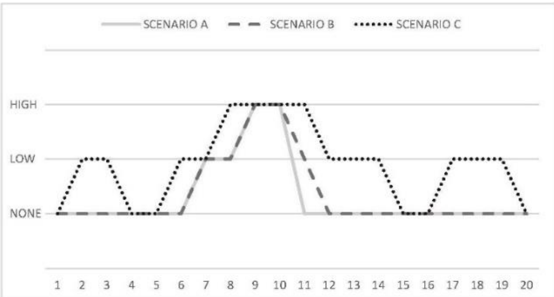

Figure 114 - Water presence to different sections

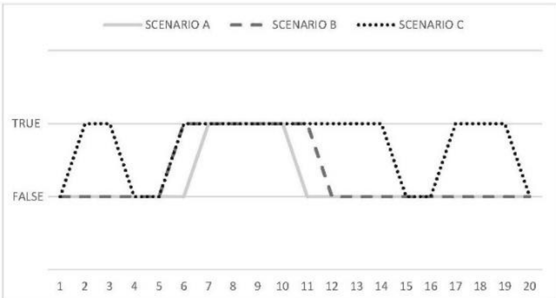

Figure 115 - Water pressure to different sections

In this case, however, we want to show the feedback in the design and instantiation of technological solutions by the DSS in the face of the presence of large quantities of water expected in several sections accompanied by the natural consequent lowering of the static stability of the rock mass. The TBM is no longer suitable given the unconventional nature of the data and geological conditions parameters. Consequently, the entire scenario is approached with traditional techniques that are consistently less sensitive to changing conditions. In this case the DSS proposes different typological sections depending on the tightness of the rock mass in the specific portion, alternating linear section and conical section.

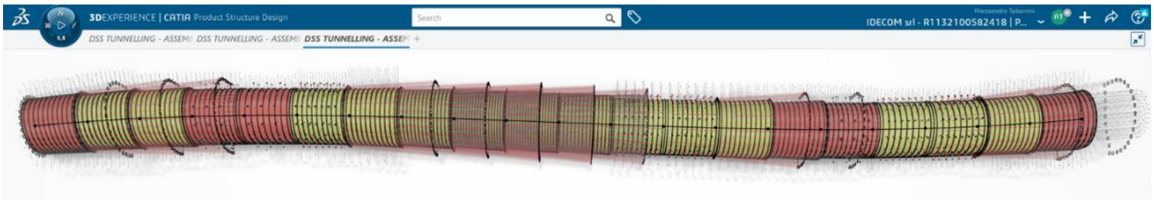

Figure 119 - Plan view, scenario C

As can be seen from the images in this context, the DSS adopts all the technological solutions aimed at counteracting the weaknesses of the context, not only with the use of the suitable typological section but by implementing different pre-consolidation patterns and rock bolt densities.

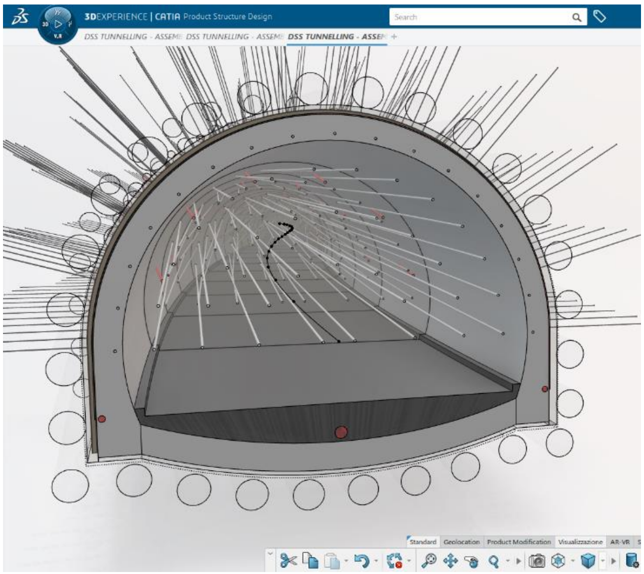

Figure 120 - Section view, scenario C

Through the comparison with these three exemplary scenarios, we wanted to try to demonstrate the effectiveness of the developed device. The examples shown are very close to a concrete situation and with the presence of further and more precise data can constitute an even more effective use of the DSS.

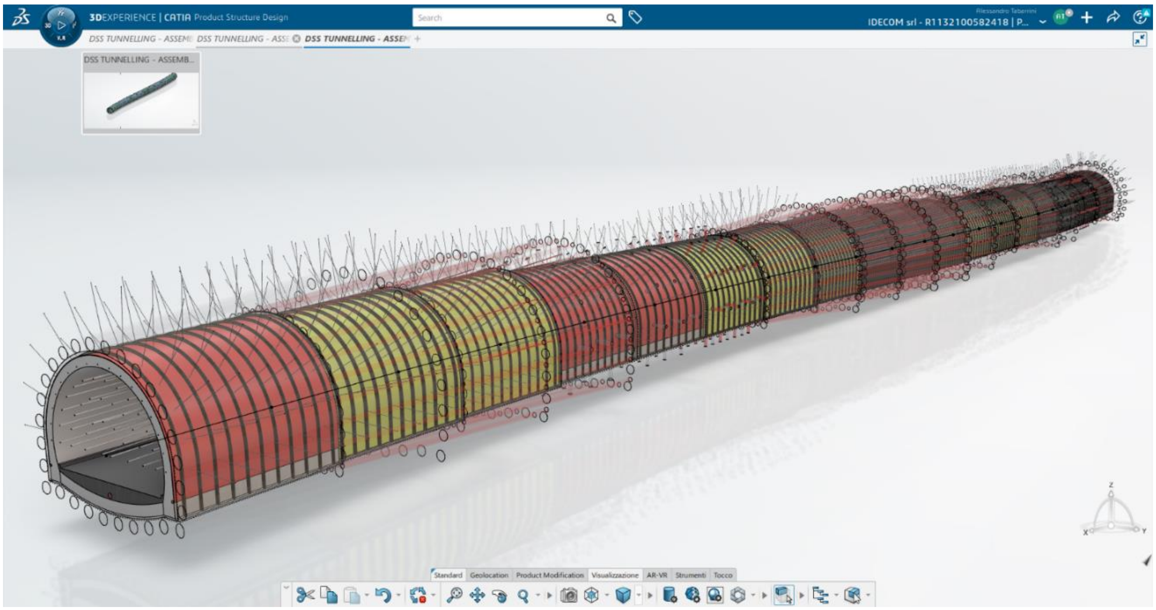

Figure 121 - Prospective view, scenario C

8 CONCLUSIONS

Achievements

This study initially defined as its objective the creation of a DSS capable of accompanying designers and engineers in the evaluation of the impacts relating to the selection between different technological and technical alternatives to facilitate the decision-making phase by providing the user with the information necessary to evaluate in real time and interactively the consequences resulting from the variation of the context; the results exposed in the previous chapter highlight how at the end of the succession of bibliographic, methodological and applicative study processes the device created proved capable of creating a model, adaptive to the three-dimensional curve provided as input, instantiating the appropriate construction technologies scenario by scenario . Furthermore, despite the automated instantiation process, it was possible to achieve the further objective of preserving the properties of the components which, thanks to the parametric design of the model, are declined by applying to them the geometry imposed by the context.

Considering the results obtained, the thesis comes to completion from a methodological point of view while remaining aware of how much the topic addressed can be further explored, an aspect which highlights another strong point of the work carried out, namely its open nature to implementation. In fact, with the work carried out we intend to outline an approach, proven effective by the results obtained, which is based on the authors' knowledge of the topic. The future implication is certainly visible in the expansion of the repertoire of available technological solutions, in the refinement of the selection mechanisms and finally in the inclusion of a database of completed projects so large as to minimize the margin of errors due to inexperience.

Secondly, it is possible to imagine how the constraint-based criterion could be translatable to the development of any other project, even outside the sector of civil infrastructures and even construction itself, as the work environment is so suited to the sharing of files and data across the entire chain of professional figures involved.

The development of the thesis allowed us to deal with the design of a rich and complex work aimed at functionality and durability, the result of the interaction of a large number of different professional figures and which therefore represents the perfect field of application of what was learned during the years of study culminating in a journey carried out entirely together.

The analysis of the performance of excavation techniques and technological components has allowed us to learn detailed nuances of the complex mechanism of infrastructure design where each of the subjects involved has different interests and objectives and a different consideration of the success of a project. Overall, the writing of the thesis was a profoundly enriching experience on a professional and personal level in which, through interaction with various companies active in the field of study, it was possible to broaden the awareness of the functioning of the sector where we would both one day like to find space.

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