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Cost Estimation for Underwater Tunnel Projects based on Uncertainty and Risk Analysis

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Abstract

Cost estimation is a complex and critical process, particularly during pre-investment phases of large undersea tunnel projects, where major decisions must be made under a high level of uncertainty. The high level of uncertainty regarding geological and construction performance aspects, as well as the occurrence of undesirable risk events may certainly affect the actual execution cost, making cost estimation a difficult task to be performed during the early phases.

This work presents a cost estimation model based on uncertainty and risk analysis that may help to obtain more realistic cost estimates. The specific model was designed for Drill and Blast excavation method, and it is focused on the cost estimation of the tunnelling activities. Through standard project management tools, this model estimates the total tunnelling cost (C_{TT}) as a random function of the normal (C_{NT}) and extraordinary tunnelling cost (C_{ET}). The model assumes that normal cost is controlled by geological and construction aspects, while the extraordinary tunnelling cost may be derived for the occurrence of undesirable events. Both are modelled as random processes and integrated in @Risk, which allows performing Monte Carlo Simulations (MCS) and obtain the final cost distributions (PDF).

The model was tested in a specific case study, and the results demonstrate the suitability of the model for determine the total tunnelling cost. Even though the model has demonstrated to be valid, the model robustness and accuracy may be improved by more advanced research in areas related to rock support and water inflow control. Finally, this work has confirmed that the integration of stochastic cost estimation and risk management may provide a powerful tool to improve the pre investment decision process of undersea tunnel projects.

Keywords:

Cost Estimation Process
Uncertainty and Risk Management
Decision Making and Project Performance
Underwater Tunnel Projects

Preface

This master thesis has been developed as part of the course TBA4910 "Project Management, Master Thesis" and it has been submitted to the Department of Civil and Transport Engineering, in partial fulfilment of the requirements for the degree of Master of Science in Project Management at the Norwegian University of Science and Technology (NTNU).

This thesis represented the final and certainly the most challenging task undertaken as a student of this master programme at NTNU, demanding several hours of researching, modelling and analysis. This work has been developed, considering theoretical contents acquired during this specific master programme, a specific theoretical framework, as well as previous knowledge of the author acquired as project engineer in large construction projects.

The main motivation of this work is to integrate standard project management tools in cost estimation of tunnelling activities for undersea tunnel projects, and in this way make an academic and practical contribution in the development of more advanced tools for supporting the decision making process in future undersea tunnel projects.

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This thesis represents the achievement of a specific academic process; moreover it also represents the final point for a personal and human experience, in which I have had the opportunity to discover the Norwegian society, and meet students from different cultures and places, bringing an immensurable knowledge that goes beyond than academic aspects.

In the academic perspective, I am thankful with my supervisor, professor Amund Bruland, who provides useful comments and ideas that help me to improve and shape this specific academic work.

I am also grateful with my officesmates at the Institute of Civil Engineering at NTNU, whom were always open to discuss different aspects related to this work, as well as other daily aspects regarding our life as students. In the same way, I would like to thank all those friends, who certainly did not provide any inspiration or help for this work, but they were always available to share our spare time and make these two years a great life experience.

Infinitely to my family, especially to my grandmother Sofia, who provided the essential for my education and my entire life. Finally to my girlfriend Claudia who encourages me to take this academic challenge and expand my borders as an engineer and as a person.

Abbreviations and Acronyms

The following acronyms and abbreviations are used throughout the chapters of this master thesis and they must be understood according to the specific description given in this section.

Professional or Academic Organisations

APM:	Association for Project Management
ASCE:	American Society of Civil Engineering
ITA:	International Tunnelling and Underground Space Association
MIT:	Massachusetts Institute of Technology
MOP:	Chilean Ministry of Public Works
NPRA:	Norwegian Public Roads Administration
NTH:	Norwegian Institute of Technology
NTNU:	Norwegian University of Science and Technology
NFF:	Norwegian Tunnelling Society
PMI:	Project Management Institute

Professional Bodies of Knowledge

APM BoK:	Body of Knowledge for APM
PM BoK:	Guide for Project Management Body of Knowledge - PMI

Project Management

CSC:	Critical Success Criteria
CSF:	Critical Success Factors
CAPEX:	Capital Project Expenditures
CBS:	Cost Breakdown Structure
LCC:	Life Cycle Cost
OPEX:	Operational Expenditures
PM:	Project Management
PRM:	Project Risk Management
PLC:	Project Life Cycle
RBS:	Risk Breakdown Structure
TCO:	Total Cost Under Ownership
WBS:	Work Breakdown Structure

Project Risk Management

AHP:	Analytic Hierarchical Process
BN:	Bayesian Networks
DAT:	Decision Aids for Tunnelling
ETA:	Event Tree Analysis
FST:	Fuzzy Set Theory
FTA:	Fault Tree Analysis

FM:	Failure Mode
MCS:	Monte-Carlo Simulation
MCDM:	Multi Criteria Decision Models
PT:	Probability Theory
PERT:	Program Evaluation Review Technique
RP:	Risk Policy
RI:	Risk Identification
RA:	Risk Assessment / Risk Analysis
RR:	Risk Response
RM:	Risk Monitoring

Cost Modelling

C_{TT}:	Total Tunnelling Cost
C_{NT}:	Normal Tunnelling Cost
C_{ET}:	Extraordinary Tunnelling Cost

Statistic Theory

RV:	Random Variable
RP:	Random Process
PDF:	Probability Density Function
CDF:	Cumulative Density Function
EV:	Expected Value (Mode)
MV:	Mean Value
SD:	Standard Deviation
LV:	Lowest Value
MV:	Medium Value
HV:	Highest Value

Underground and Tunnelling Projects

D&B:	Drill and Blast or Conventional Method
EPB:	Earth Pressure Balance Machines
NATM:	New Austrian Tunnel Method
TBM:	Tunnel Boring Machine

Executive Summary

Cost estimation is a highly critical process for both; project sponsors and contractors involved in the development of complex construction projects. This process is especially complex and challenging during the pre-investment phases, where a high level of uncertainty and lack of definition deprive to obtain accurate estimations for both capital and operational costs related to specific project alternatives.

From the specific perspective of the project sponsor (i.e.: the owner), pre-investment cost estimations will highly influence two critical aspects related to the project development. Firstly, cost estimations will influence the decision-making process regarding the selection of the preferred alternative to be implemented during the execution phase. Secondly, and during the project appraisals (e.g.: interim or ex-post), the cost estimation considered as the project budget or baseline for the project approval, will usually influence the results regarding project cost performance.

Similarly, contractors and other suppliers involved in the project developments must also face the challenges regarding cost estimation, in order to success in their business strategies and development. Contractors are continuously required, during the bidding process, to obtain realistic contract prices that allow them to undertake the execution of complex projects, within a certain level of utility and risk.

Uncertainty and risk are project attributes that generate disturbances throughout the project life cycle (PLC), which may affect positively or negatively project processes and objectives, especially those related to critical project criteria such as safety, cost, time, and quality. As a consequence of this high sensitivity, uncertainty and risk must be duly managed and assessed, during the whole project development, and especially during the early project phases, where risk and uncertainty are higher.

In order to cope with risk and uncertainty, the Project Risk Management (PRM) has been designed as a project management tool that may help project organizations to increase the probabilities of project success. The PRM allows foreseeing undesired events and reduces consequences over project objectives. It is believed, that the highest value of PRM is obtained, when the PRM activities and outputs are incorporated in other project processes, such as: engineering, supply, construction, safety, planning, and cost estimation. The systematic integration of the PRM will eventually increase the probabilities of projects success through the achievement of realistic cost estimation, well-informed decisions-making process and higher project performance.

When considering complex and high-risk developments, underwater tunnels represent a particular class of engineering project; where aspects regarding cost estimation, risk management and construction performance appear to be more intricate than standard tunnel

projects and other surface projects. Besides the difficulties encountered during the design and execution of underwater tunnels, these structures represent a key part of the public infrastructure that provides an efficient and sustainable solution for current and future demands for the development of the modern society.

As a matter of fact, tunnels projects are rarely achieved on the target values (i.e.: base line or project budget) determined during the pre investment phases, and cost overruns are commonly found after the project execution. Generally speaking, projects overrun are caused by the combination of organisational and technical factors, nonetheless cost underestimation appears to be one of the most common causes, when analysing the repetitive underperformance of underground projects. This cost underestimation is basically due to the systematic application of inadequate estimation approaches, which are not able to capture the random nature and complexity of this class of projects, providing unrealistic project budgets for supporting the project development decisions.

Considering the stochastic nature of the project cost and its relevance during the whole project development, this work proposed a cost estimation model based on uncertainty and risk analysis. This model constitutes an academic effort to contribute with more realistic cost estimation models for undersea tunnel projects, and consequently improve the basis for the decision making-process and performance assessment of this specific class of projects.

The model was designed for drill and blast excavation method and it is primarily focused on the cost estimation of the tunnelling process, which is a highly sensitive cost element in the project cost structure. The tunnelling process is defined in this work, as the all the required construction activities to obtain the main tunnel, without considering the execution of complementary construction activities, such as road and pavement structure, ventilation, drainage, fire, signs, and other operational systems or facilities.

The total tunnelling cost (C_{TT}) is modelled as function of the normal (C_{NT}) and the extraordinary tunnelling cost (C_{ET}), which are considered stochastic or random processes, dependent of specific random variables. The normal tunnelling cost (C_{NT}) is a function of the geological and construction uncertainty; while the extraordinary tunnelling cost (C_{ET}) is controlled by the occurrence of undesirable risk events.

The normal and extraordinary tunnelling costs are modelled using standard project management methods and tools, having focus on the integration of cost and risk management. Firstly the normal tunnelling cost (C_{NT}) is determined using a driver-based estimation approach, where the cost is determined by specific cost drivers, treated as random variables, that capture the uncertainty regards geological and construction performance for the tunnelling activities. Since geological conditions vary along to the tunnel alignment a basic geological model, based on the rock lithology, is also included in order to divide the tunnel in homogeneous zones and obtain better estimation of the normal tunnelling cost.

Similarly, the extraordinary tunnelling (C_{ET}) cost is determined by the systematic application of project risk management tools, such as risk identification, qualitative and quantitative risk analysis of specific undesirable events that may occur during the execution of the tunnelling process. The risk events are also treated as stochastic processes, which are described as a function of the sampled occurrence (i.e.: discrete random variable) and its monetary consequences (i.e.: continuous random variable).

Finally, both models are integrated in a single model built in a specific excel add-in (@Risk), which allows the execution of Monte Carlo Simulation (MCS) and obtaining the respective probabilistic density function for each of the cost under assessment.

The proposed model considers different setups, which allow the estimator to obtain different estimations, depending on the availability of information. The basic stochastic setup, considers the tunnel as a single zone (i.e.: division is not feasible), yet correlation among cost drivers should be assessed if sufficient information is available. The advanced stochastic setups allow estimators to incorporate the correlations among cost drivers, as well as the correlations among the specific homogeneous zones.

In order to test the applicability of the proposed model, a specific case study was introduced and analysed using the proposed model. The case study corresponds to a non-executed project concept for crossing the Chacao Channel in the south of Chile. The results show that the model is valid and suitable for determine the total tunnelling cost, during the pre investment phases.

Although the model results are considered valid, several improvements regarding model robustness and accuracy may be done through more extensive research and collaboration. More advanced research is required in areas, such as rock support and water inflow control, where prognosis model are not available or are not duly updated. Collaboration, between research and project organisations (e.g.: universities, government and contractors) may bring relevant improvements in the accuracy of the model; through the incorporation of more detailed information regard actual execution costs.

Additionally similar effort may be done in the specific field of mechanised excavation (i.e.: TBM), in order to provide a more powerful tool for project organisations, during the earliest phases of the project, where excavation methods are not yet decided.

Finally, after performing this research work, it has been prove that better assessment of the tunnelling cost for undersea tunnels may be achieved through the integration of existing management tools regarding cost and risk management, helping project organisations to increase the probabilities of the project success.

Contents

1. INTRODUCTION

This chapter sets the general framework to understand the relevance and motivation of this research project, and it also provides a clear description about the problem statement, scope of work, objectives and limitations regarding this master thesis.

Firstly, the background information provides reasonable basis to understand the academic and practical relevance of the selected topic for both project management and civil engineering. The first section contains a brief review about the main topics treated in this work (i.e.: underwater tunnels, project risk management and cost estimation), and it explains the relation among these topics, emphasising the need for more advanced research in these specific areas of knowledge.

The remaining sections of this chapter introduce and describe the problem statement and the specific research questions that are addressed throughout this academic work. In these sections is also defined the scope of work, the objectives, and the structure of this research work.

1.1 Background

1.1.1 The Problem of Cost Estimation in Undersea Tunnel Projects

Underwater tunnels represent large investment projects, which aim to overcome specific needs regard public infrastructure to connect urban areas separated for open bodies of water (e.g.: rivers, fiords) or located apart from the mainland (i.e.: islands). Underwater tunnels stand out among other fixed link projects, due to their sustainable features when comparing with other fix-linked project concepts, Pennington (2011).

On the other hand, Pennington (2011) emphasises that underwater tunnels represent one of the most challenging civil engineering endeavours, due to the high level of uncertainty and risk that surrounds this class of projects, which mainly comes from the geological conditions of the sea bed, where tunnels are built. This high level of uncertainty, plus the limited capacity of project organisations (i.e.: project owner and contractors) to anticipate the geological conditions to be encountered during the tunnel construction makes underwater tunnels a challenging enterprise. The uncertain and risk features of undersea tunnel do not only exist during the early project phases (e.g.: front-end and pre-investment), and they remain, throughout the later project phases, such as detailed design, planning, construction, and commissioning.

The high level of uncertainty presents in underground projects, and specifically in underwater tunnels, affects several project management processes, as well as the inputs and outputs related to these processes. As the classical paradox of project development states, major decisions regarding the tunnel execution must be taken, during the early project phases, where uncertainty is especially high and the accuracy of relevant project attributes, such as cost and time estimations trend to be low. Therefore, and as highlighted by Isaksson (2002), Flyvbjerg and Cowi (2004), Oreste (2006) Paraskevopoulou (2012), and Spackova, Sejnoha et al. (2013 a), it is precisely during the pre investment phases where project organisations are challenged to provide sounds basis and inputs for the decision making process and ensure that the best decisions are being made.

As highlighted by Isaksson (2002), Rostami, Sepehrmanesh et al. (2013), and Spackova, Sejnoha et al. (2013 a), one of the most relevant inputs, analysed in the decision making process, is the capital investment cost, which is highly affected by the disturbances generated by the uncertainty and risk that surround the execution of underground developments, making its estimation process a extremely difficult task to be performed.

The capital investment project cost, also known in project management as capital expenditure (also known as CAPEX), represents the whole quantity of financial resources required to obtain the final deliverable. As in any other civil project, the capital investment for a subsea tunnel may be determined as the summation of all the deliverables required to the project completion, and it considers the cost related to all the phases previous to the operation, APM (2006) and PMI (2008).

Following the same reasoning, the cost of the tunnel as single deliverable, will be conformed by the execution costs of tunnelling activities, road, access, and the implementation of operational systems, such as ventilation, fire control, illumination, and drainage. Even though, contemporary road tunnels are complex projects, where more and advanced technology is incorporated, the final construction cost is still governed by the cost related to the actual tunnel excavation. This fact is highlighted by Paraskevopoulou (2012), who states that excavation cost represents from 54% to 72% of the construction cost.

Paraskevopoulou (2012) also emphasises that geology constitutes the key cost driver for tunnelling. This is also support by several studies, such as Einstein (1996), Isaksson (2002), Issakson and Stille (2005), Oreste (2006) and Spackova, Sejnoha et al. (2013 a), where is also emphasised the strong correlation between the uncertainty and risk regard geological conditions and the final cost achieved in underground projects.

Considering all above mentioned, it is possible to state that tunnelling cost, geological uncertainty, as well ad the risk involved in the execution of the tunnelling activities are three elements that affect the total investment cost and therefore they require a sensible assessment and analysis.

As several researches and public reports have demonstrated, see Flyvbjerg, Holm et al. (2002), Flyvbjerg and Cowi (2004), Flyvbjerg (2006), Treasury (2010), the predicted cost of public infrastructure projects is usually underestimated. This means that the actual cost (i.e.:

the cost after the project has been built) normally exceed the approved budget estimated during the pre-investment phases.

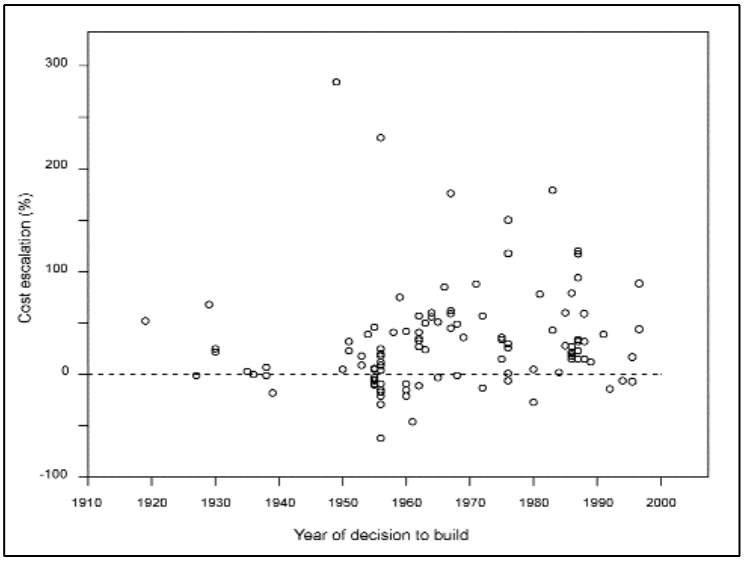

Figure 1.1: Approved Budget versus Actual Project Cost. The line set at zero represents the approved cost for the project and the points represent the actual cost expended at the approved year to build, Flyvbjerg, Holm et al. (2002).

As depicted in Figure 1.1, extracted from the study developed by Flyvbjerg, Holm et al. (2002), the execution of general public transport projects exceed in average 28% the approved cost for execution. Tunnelling projects, as an important part of the transport projects, are not far from the situation describe in the above figure.

When specifically referred to the tunnelling industry, Paraskevopoulou (2012) states that almost 60% of 84 tunnel projects reviewed in the United Stated reported significant cost overruns and contractor claims. In the same line Efron and Read (2012) conclude that every project, over a total sample of 158 projects, experimented cost overruns. A long term research performed by Flyvbjerg and Cowi (2004), the overruns in tunnel projects were estimated in 34%. This notorious difference between the baseline and actual project cost for underground projects is probably one of the main reasons that sustain the "well-known" poor reputation of the tunnelling industry regards construction and project performance.

According to Flyvbjerg, Holm et al. (2002), the causes for underestimation of investment cost in public infrastructure projects respond to a complex combination of technical, economic, psychological and political aspects, which are not treated as part of the scope of this work. Nevertheless, and after reviewing the previous mentioned researches, it is possible to state that cost underestimation is mainly explained by a consistent and systematic neglect of the project uncertainty and risks.

In the specific field of underground projects, the need of incorporate the assessment of risk and uncertainty is highlighted in several research, such as Einstein (1996), Isaksson (2002), and Spackova, Sejnoha et al. (2013 b), who claim for the implementation of more advanced estimation techniques that may incorporate project uncertainty and risk. In most of the previously researches is emphasised that cost estimation for underground projects have usually been performed by deterministic approach, which in the opinion of these authors is not capable to deal with the uncertainty of underground projects. More specifically Spackova, Sejnoha et al. (2013 b) stress that deterministic approach for cost estimation has two main drawbacks that may affect the project development and its performance after execution.

Firstly, deterministic cost estimations do not represent the real complexity of underground projects, and estimations obtained by this approach must be considered unrealistic, which lead in gross mistakes when estimations are incorporated into the decision making process. Secondly, since deterministic cost estimations are unrealistic, they have a great probability to be exceeded during the execution phase, and produce the previously mentioned overruns. Spackova, Sejnoha et al. (2013 b), explain these overruns due to the variation of project cost and the occurrence of undesirable events, which were not duly foreseen during the estimation process. Thus, and as consequence of using unrealistic and poor basis during the decision making process, projects have almost not probability to achieve the target values established at the execution approval.

Fortunately, the continuous development of the Project Management (PM) has introduced several models and tools that may help project organizations to assess projects under a more systematic approach, which provide better basis for the decision making process and for improving the project results and performance. One of the project management tools created to deal with the uncertainty and minimise the impact of undesirable effects over the project objectives, is the Project Risk Management process (PRM), Lessard and Miller (2001), APM (2006), and PMI (2008). The application of the PRM also helps project organisations to support the decision-making process and increase probability of project success.

Even though the PRM has been successfully implemented in several industries, such as: finance, aerospace, and insurance, construction and tunnelling industries have continuously failed in the systematic implementation of this process, and this may be the main cause of several project failures reported in the construction industry Taroun (2013). Specifically in the tunnelling construction industry, the PRM has been partially implemented, and it is usually related to safety management. Nevertheless the safety management constitutes only a single application, among several others, where PRM may be applied, in order to improve the development of underground projects.

During the last 20 years, several authors such as Einstein (1996), Isaksson (2002), Eskesen, Tengborg et al. (2004) have recognised the relevance and criticality that PRM possesses for the success development of underground projects. Isaksson (2002) and Eskesen, Tengborg et al. (2004) have also emphasised that PRM must be incorporated and performed since the earliest project phases, in order to assist the decision making process of underground projects, which eventually may contribute in better project results for all the parts involved in the project development. Nonetheless, the poor cost performance of tunnelling projects, established by Flyvbjerg, Holm et al. (2002), and the recurrent practices of cost estimation under deterministic approaches, it may be understood as a clear demonstration that PRM still remains as a non linked aspects of the project management activities. The need of linking the management process with uncertainty and risk analysis, in the specific field of underground projects, has been claimed by several authors, such as Sturk, Olsson et al. (1996), Reilly (2000), Isaksson (2002), Reilly and Brown (2004), Eskesen, Tengborg et al. (2004), and Spackova (2012).

A full agreement on the need formerly described, was obtained as part of previous research work developed by the author, which is presented in this research as Arestegui (2013). As part of this work was concluded that real value of the PRM is achieved, when the process is fully linked and incorporated with other critical project management processes. This is particularly relevant for those project processes, where uncertainty and risk must be duly assessed, in order to deliver reliable basis for critical processes (e.g.: cost estimation, schedule).

An alternative to link these two processes (i.e.: cost estimation and risk management) is the execution of the cost estimation process by analytic tools based on cost drivers. The driver-based estimating allows estimators to easily incorporate the uncertainties related to the variable that governs the cost of a specific process, Hollmann (2007). Additionally, and as emphasised by Isaksson (2002), Reilly and Brown (2004), Eskesen, Tengborg et al. (2004), Oreste (2006) and Spackova (2012), the use of stochastic tools for quantitative risk analysis, such as Monte Carlo Simulation, may help to better manage and incorporate the effects of uncertainty and risk in the cost estimation process for the tunnelling activities.

Independently of the specific approaches or tools used by the authors previously introduced, they agree that the implementation of new approaches, based on uncertainty and risk analysis, is a clear step for achieving more improvements in the quality of the cost estimations, and therefore in the general management process of tunnelling projects.

As a confirmation of the above mentioned, several stochastic models for estimation of time and cost in tunnelling, based on risk analysis, have been developed during the last 15 years. Some examples of the efforts made by other researchers to incorporate the risk analysis are the works developed by Einstein (1996), Isaksson (2002), Min (2003), Oreste (2006), Spackova, Sejnoha et al. (2013 a), which by using different methods and tools assess the tunnelling cost and time.

All the above-mentioned researches were developed for standard underground projects, nonetheless none research has been found in the specific field of cost estimation of undersea tunnels. The special features of this class of projects and its inherent complexity make these an interesting case for developing a new research projects.

1.1.2 Need for Research

According to the arguments presented in the previous section, the cost estimation process for underwater tunnels may be improved by incorporating project risk management models and tools. As formerly presented the effort for better assessment must be done firstly in those aspects with larger effects in the final outcome (i.e.: total investment cost).

Previous stochastic models, based on uncertainty and risk analysis, which have been specifically developed for underground projects, may serve as valuable foundation and basis for developing a customised model that address the cost estimation problem for the tunnelling activities in underwater tunnel projects.

More advanced research about uncertainty and risk modelling may contribute in the development of more practical, and user-friendly tools that may be incorporated and used for project organisations (i.e.: project owners, sponsors and contractors) to overcome the shortcomings of the models currently used for cost estimation of underground projects. The improvements in the cost estimation modelling may allow project organisations to make better decisions during the pre investment phases and increase the probability of project success after the project execution.

In a more specific point of view, it is believed that more research on the field of subsea tunnels, and particularly in those aspects regarding the cost estimation of the tunnelling process, may give a significant contribution to overcome the lack of cost modelling in this specific area, and provide a valid tool to be deployed during the pre-investment phases.

1.2 Objectives of the Research

The aim of this master thesis is to provide a stochastic cost estimation model for the tunnelling activities of underwater tunnels, based on standard project management tools for uncertainty and risk analysis. Through this model is expected to give specific contribution in the integration of project risk management and other relevant project management processes, such as cost estimation.

The proposed model is built up, through the development and integration of geological, cost and risk modelling, which allow capturing and quantifying the effects of uncertainty and undesirable risk events into the tunnelling cost of undersea tunnel projects. As part of this research project, it also intends to apply specific qualitative and quantitative risk analysis tools, which are integrated as part of the cost estimation model.

In order to obtain the final results of the model (i.e.: the probability density functions), Monte Carlo Simulation (MCS) is incorporated and it is performed by a standard risk management software called @Risk.

The following points summary the objectives of this research project:

i. To understand the fundaments of stochastic cost estimation and risk analysis for tunnelling projects, and establish a theoretical framework that allows the author to create a specific cost estimation model based on uncertainty and risk analysis for undersea tunnels.

ii. To design and provide a practical model for cost estimation of undersea tunnel projects that integrates standard project management tools, and with especial focus on those aspects related to the tunnelling process.

iii. To establish a practical model for the estimation of the normal tunnelling cost, based on analytic and parametric approaches, which may incorporate the uncertainty related to geological and construction performance aspects.

iv. To establish a practical model, based on standard risk management tools, to quantify and incorporate the monetary effects or consequences of undesirable risk events into the total cost of the tunnelling process in underwater tunnels.

1.3 Research Questions

In order to fulfil the objectives of this research, the following questions have been defined and are addressed throughout the development of this research project.

i. How the incorporation of uncertainty and risk analysis may improve the cost estimation process of tunnelling activities for undersea tunnels during the pre-investment phases?

ii. How uncertainty regards geological and construction performance can be captured, quantified, and incorporated into the cost estimation process of tunnelling activities? Is it feasible to perform a cost estimation based on cost drivers? Which parameters can be used as cost drivers in undersea tunnel projects?

iii. How undesirable events can be modelled in order to capture and quantify the monetary consequences in the total tunnelling cost if they occur during the execution of the project?

iv. To what extent uncertainty and risk management may improve the cost estimation process in underwater tunnels during the pre-investment phases?

1.4 Scope of Work

The scope of this work is delimited to design and implement a cost estimation model to determine the total tunnelling cost in undersea tunnel projects. The model has been design specifically for Drill and Blast excavation method and for a given section equivalent of $67m^2$, which is equivalent to the T9.5 section of the Norwegian Standard, see NPRA (2004).

As previously pointed out, the proposed model is specifically designed for Drill and Blast excavation method and it is focused exclusively on the determination of the tunnelling cost. This cost involves all the direct resources, equipment, material, and consumables that are required to perform the actual tunnel. The tunnelling activities considered as part of the total cost are namely: excavation, water control, rock support and tunnel lining.

The total tunnelling cost does not include the cost related to other facilities required by standard road tunnels, such as pavement and road structure, and other operational system, such as ventilation, water drainage and control, fire control, traffic signs, CCTV, lighting, among others. Finally, it is worth mentioning that the cost related to engineering, and project management, during the execution of the tunnel, as well as other general and indirect costs are not included as part of the results of this model.

1.5 Report Outline

This master thesis has been structured in nine (09) chapters, plus the respective references and appendixes. Chapter 1, heretofore presented, considers the basic background information to understand the relevance of this work, scope, objectives and limitations (boundaries). Chapter 2 is focused on describe the methodology deployed by the author and the activities performed in order to achieve the objectives of this research project. A brief introduction about research theory and approaches are also given in this chapter, which supports the methodology utilised by the author in the development of this work.

The theoretical framework of this work is presented in Chapters 3, 4 and 5. The main reason to divide the theory in three different segments is basically due to the extension and relevance of each of the topics treated in these chapters. Chapter 3 is basically devoted to describe the preponderance of project management, emphasising those aspects related to cost estimation and project risk management, especially in underground and tunnel projects.

Chapter 4 provides information regards underwater tunnel projects and it describes the main features of the development this class of projects. A special effort was made, in order to determine the most relevant geological parameters that affect the tunnelling process in drill and blast, and the actual cost of these activities.

Chapter 5 is exclusively dedicated to cost estimation modelling for tunnelling projects. In this chapter, the author synthetises different models previously developed in the specific field of underground works. The first section of this chapter is a description of four (04) stochastic models developed for cost estimation of tunnelling projects. The summaries emphasise the fundamentals, basics, as well as the main results and conclusions obtained as part of these research works. The second section of chapter 5 describes the main features of the cost model developed by the Norwegian University of Science and Technology, which constitutes a core input for this work. The final part of this chapter is basically focus on describing the parameters that control the effort required to perform the tunnelling activities, and were considered relevant for the development of the proposed model.

Chapter 6 introduces the model developed by the author and it describes the fundamental and basis of the model, as well as the main components that constitute the proposed model. Special emphasis is given on describe the selected cost drivers and the proposed cost function to estimate the cost of tunnelling activities.

Chapter 7 introduces the case study selected to test the model and it also presents the results obtained after applying the cost estimation model. The selected case study corresponds to the Chacao Channel Tunnel in Chile, which was a non-executed project concept presented to cross the Chacao Channel.

The discussion and analysis regarding the obtained results are presented in Chapter 8. This chapter also includes the recommendation given by the author for upcoming research works that may improve the results of this work and extent its applicability in real undersea tunnel projects.

The final conclusions of this work are given in Chapter 9, followed by the respective reference list and appendixes. Appendixes have been organised according to the specific order in which these documents are introduced in this report and they are considered an integral part of this report.

2. RESEARCH METHODOLOGY

This chapter basically describes the methodological strategy designed and deployed by the author, in order to perform this research and achieve the objectives of this master thesis.

Since, the selection of methodological approach will certainly affect the quality of the research project, the author considered relevant to devote part of this chapter to briefly describe particular theoretical aspects regarding the research approaches, and analyse its suitability for this specific work.

Considering the above, the first section of this chapter is focused on describing the three main research approaches, as well as their main features, advantages and drawbacks. Considering that the research theory is an extensive and extremely complex topic, this section contains the most relevant concepts that influenced the selection of the methodological approach for this research.

Section 2.2 is devoted to briefly discuss about the validity and reliability of academic researches, and it relevance for assessing the quality of the obtained results. The third section is specifically dedicated to describe the approach, design and method selected by the author, providing the main arguments that sustain its suitability for this particular research.

Section 2.4 present a brief description of the phases and activities performed as part of this project, and where the selected methods were applied. Finally section 2.5 introduces a list of the resources deployed during the execution of this research project.

2.1 Research Approaches

According to Creswell (2009), there are three different approaches for researching, which may be described as follows:

i. Qualitative research: focus on understanding specific social or human problems. This approach involves typically emerging questions, data collection in small samples, and inductive analysis. The researcher makes interpretations about the data collected in order to better understand the complexity of the problem. This approach is based on the constructivism paradigm and it was developed as part of the social science researches.

ii. Quantitative research: focus on testing objective theories by examining the relation among the variables, which are typically measured by instrument and analysed by statistical and numerical procedures. The theories are tested deductively, emphasising the protection against bias and in the replication and generalization of the findings. This approach is based on the positivist and post positivist paradigms, and it constitutes the main or classic approach for scientific research.

iii. Mixed methods research: focus on collecting quantitative and qualitative data, and using distinct designs and methods that may involve both philosophical assumptions and paradigms. The core assumption of this approach is that the combination of both approaches provides a more complete understanding of the research problem. The mixed approach is based on the pragmatism paradigm.

Regardless its differences, research approaches share a common structure based on three main elements, which are namely: i) philosophical worldview, ii) research methods, and iii) research designs. The approaches and tools regarding each of these elements vary depending on the selected research approach, and consequently they present different degree of suitability for particular research projects (e.g.: scientific, engineering, and social).

Figure 2.1 shows the basic elements and some of the tools and perspectives commonly used in quantitative, qualitative and mixed research approaches.

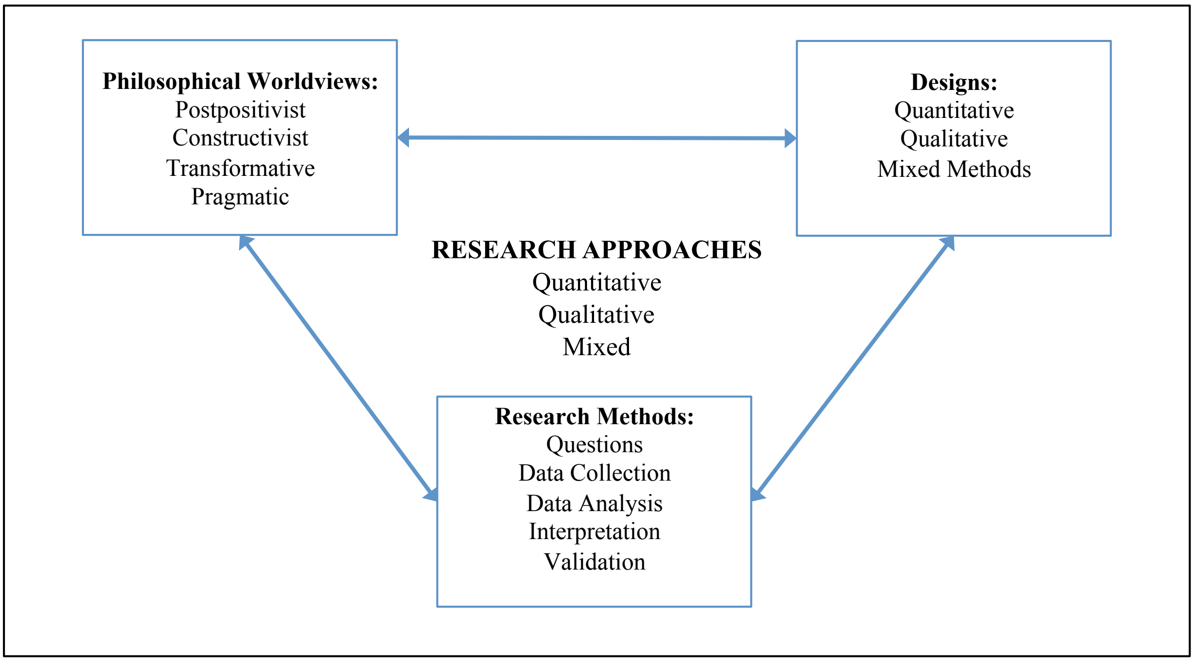

Figure 2.1: Basic Structure of Research Approaches, Philosophical Worldviews, Research and Design Methods constitute the basic element that built up a specific research approach (after Creswell (2009)).

The main features of the components, for each specific research approach, are briefly described bellow:

i. Paradigm or philosophical worldviews Creswell (2009) represents the philosophical orientation about the world and the nature of the research that is performed. There are four main paradigms regard research development, which are: Post positivism, Constructivism, Transformative and Pragmatism.

ii. Research designs are described by Creswell (2009) as types of inquiry that provide specific direction for the procedures in a research design. The research designs may be organised the in Quantitative (e.g.: experimental designs or surveys), Qualitative (e.g.: narrative research, case study) and Mixed (e.g.: convergent, explanatory sequential).

iii. Research methods involve the form of data collection, data analysis, and the final interpretation of this data. Research methods may be divided in the following groups: Quantitative methods (e.g.: closed-ended questions, census data, statistical data, statistical interpretation), Qualitative methods (e.g.: open-ended questions, interview data, observation, text analysis, patterns interpretation) and Mixed method (e.g.: close and open and closed-ended questions, statistical and text analysis, data interpretation).

Creswell (2009) emphasises that the selection of research approach must be done based on three main factors:

i. Nature of the research problem and question,
ii. Personal experiences of the author, and
iii. The audience. (i.e.: the reviewers and sensors)

As previously mentioned, each research approach represents a valid option to perform a research work; nevertheless each approach represents, at the same time, a distinct level of suitability for specific kind of problems (i.e.: scientific, social, economic). This means that prior to start any research project, the researcher must duly assess the factors previously mentioned, in order to determine, which is the most suitable choice for its own work and objectives.

2.2 Quality in Academic Research

In order to ensure the quality of the project research and its results, the quality of the process must be tested throughout the development of the research. This will constitute a core piece of information in order to assess limitations of the work, as well as generalisation and applicability of the results.

According to Golafshani (2003) two relevant concepts related to the quality, especially in quantitative research are validity and reliability. The definitions given by Joppe (2000) for these concepts are as follows.

"Validity determines whether the research truly measures that which was intended to measure or how truthful the research results are".

"Reliability is the extent to which results are consistent over time and an accurate representation of the total population under study and if the results of a study can be

reproduced under similar methodology, then the research instrument is considered to be reliable".

Golafshani (2003) emphasises that both concepts are strongly correlated to the development of quantitative research methods, and are supported by the positivist or scientific paradigm, however they are equally applicable when developing qualitative and mixed approaches. Graphical representations depicted in Figure 2.2 provide an easy way to better understand these concepts.

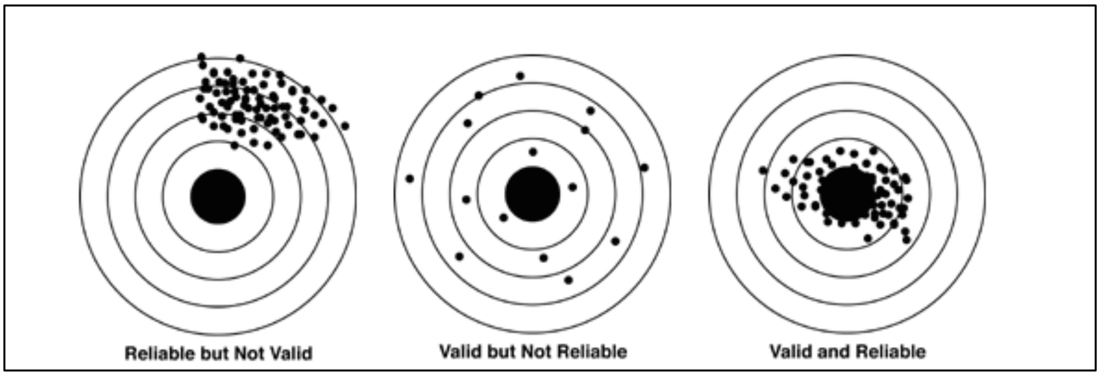

Figure 2.2: Graphical representation of reliability and validity in research methods (source: http://ccnmtl.columbia.edu/projects/qmss/measurement/validity_and_reliability.html).

2.3 The Selected Approach

Considering the factors heretofore mentioned; the author determined that a combination of quantitative and qualitative approach (i.e.: mixed approach) gives the best choice for addressing the objectives of this research project. As highlighted by Creswell (2009) the mixed approach allows researchers to incorporate the strengths of both qualitative and quantitative methods, and consequently overcome potential shortcomings present in these approaches.

Firstly, the *pragmatic paradigm* was selected as the philosophical worldview for this research. The pragmatic approach allows researchers to focus more on the problem and its practical solution, rather than the specific methods and designs deployed during the research. The pragmatic paradigm may use all the available approaches to understand in better manner the research problem and give a wider approach to the final outcome and results of the research project.

Secondly, the selected research design is based on *convergent parallel mixed method*, which allows combining quantitative and qualitative data, providing more comprehensive foundations to analyse the research problem. According to Creswell (2009), one of the main advantages of mixed design lies in its capacity to neutralise the weaknesses present in both quantitative and qualitative data collection, allowing researcher to expand the possibilities for this process (i.e.: data collection). This feature makes mixed research designs an extremely flexible and suitable tool, especially when researching about project cost aspects, where information trend to be very difficult to find if non-cooperation with companies or other organisations is considered as part of the research.

The flexibility offered by mixed designs is demonstrated in the development of this work, where the cost estimation model was basically built up, considering quantitative information obtained from previous academic works and public reports developed in the specific field of cost estimation for tunnelling projects. On the other hand, expert opinion was used to feed the proposed model. It is worth mentioning that surveys and questionnaires were not considered as part of this work, due to the difficulties encountered to obtain data regarding cost.

The selected research methods for analysing the collected data are basically based on *statistical and text analysis*. Quantitative methods provide the basis required to process large quantity of data collected from previous researches and projects. Statistical analysis also provides the numeric basis to determine the basic element of the model, such as cost drivers and correlations among these variables. Additionally, qualitative methods, such as text analysis and unstructured interview are also used, in order to incorporate the opinion and implicit knowledge from project experts. The experience of the author, for more than 10 years as project engineer in large capital projects, must be also considered as qualitative method that is deployed throughout the development of this work.

2.4 The Research Phases

In order to undertake this research, it was broken-down into four (04) phases, which represent distinctive levels of maturity in the development of the project research. This organisation of the work allowed the author to develop all the required activities in a systematic and well-structured manner, ensuring the consistency of the contents in the final report.

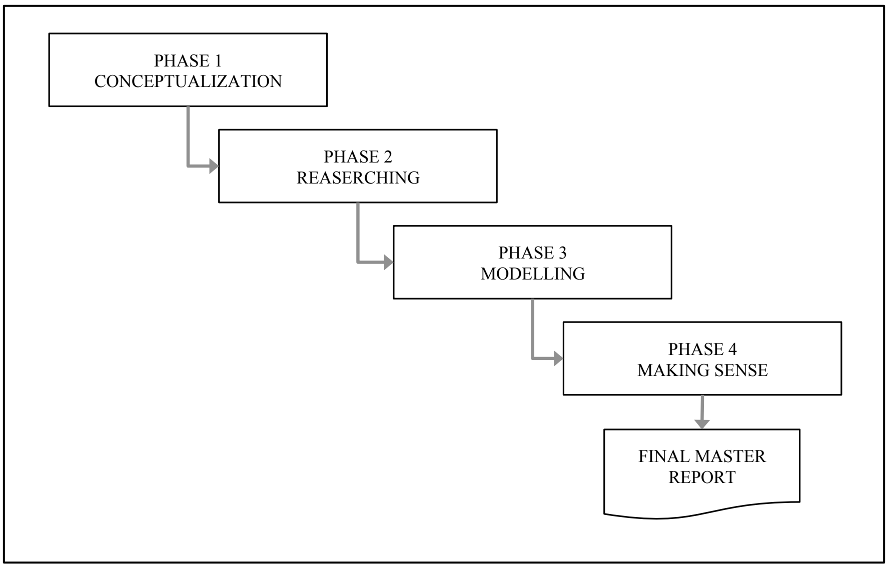

Figure 2.3: Research Project Phases (source: the author)

As depicted in Figure 2.3, the four phases allows the author to obtain the final deliverable that contain the main features of the task and activities developed throughout this project. In each of these phases are also deployed the research designs and methods previously described in section 2.2. The main activities developed in these phases are described in the following sections.

2.4.1 Phase 1 "Conceptualization"

Conceptualization constitutes the earliest phase of this research project; consequently it is focused on deciding the research problem and other essential maters for the research project. The conceptualization phase involves the execution of four (04) different activities, which are depicted in Figure 2.4 and briefly described in the following paragraphs.

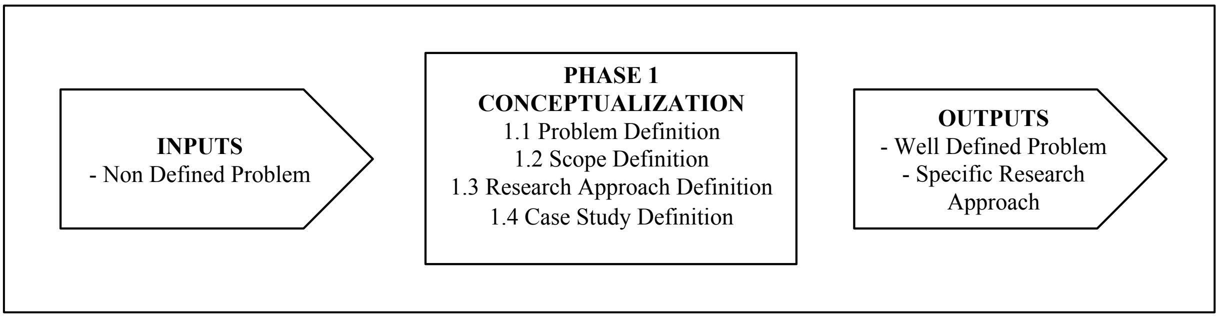

Figure 2.4: Phase 1 "Conceptualization", the inputs, specific activities developed at this phase and the outputs (source: the author).

Activity 1.1: Problem Definition

The definition of the research topic is made basically, considering and balancing personal and academic interests of the author. The relevance for both project management and construction engineering is also considered to made the final decision regards the topic of research. Another relevant aspect, considered to define the final topic, is the previous research project developed as part of the course TBA4530 "Project Management, Specialization Project". A specific conceptual map is used to perform this first activity, see *Appendix A*.

Activity 1.2: Scope Definition

As any other project, the definition of the scope and limitations is necessary to set the boundaries and limitations regarding the final deliverable. The scope of work and limitations of this project are established considering the relevance of the topics involves in the problem and the time constraints defined to perform this academic work.

Activity 1.3 Research Approach Definition

Once the first two activities are already executed, it is possible to assess the most suitable approach to develop the research project. This activity is performed, considering all the matters discussed and presented in sections 2.2 and 2.3 of this chapter.

Activity 1.4 Defining a Case Study

The definition of the specific case study is also completed as part of this early phase. Since this work proposes a cost estimation model for the tunnelling activities, the definition of a case study it is considered mandatory, in order to test the validity and reliability of the model.

As depicted in Figure 2.4, the final output of the conceptualization phase is a well-defined and structured research problem that can be addressed in the following phases by applying the selected methodology approach. The deliverables of this phase are basically reflected in Chapters 1 and 2 of this report.

2.4.2 Phase 2 "Researching"

This second phase is focused on developing a comprehensive theoretical framework that work as a main basis of this research project. The main input to start this phase is obtained from Phase 1 "Conceptualization". A well define problem and research approach allow the researcher to focus on selecting and analysing the most relevant literature that may conform the theoretical framework for the research.

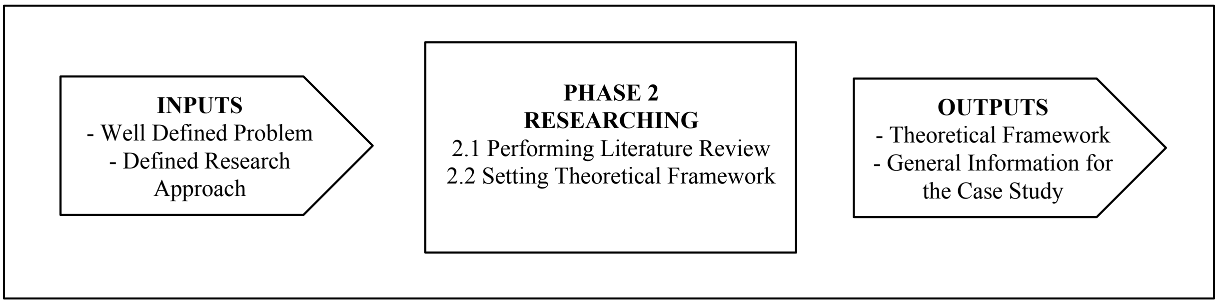

Figure 2.5: Phase 2 "Researching and its inputs, main activities and the final output (source: the author)

As shown in Figure 2.5, the researching phase considers the execution of two (02) main activities, which are described in the following paragraphs.

Activity 2.1: Literature Review

This first step is focused on select and analyse the literature, which help the author to build up a comprehensive and well-structured theoretical framework to perform this work. This process is performed, considering relevant journals and seminal publications, as well as master or doctoral thesis, standards and other documents with regard to cost estimation, risk analysis and underground projects.

The documents, selected to be part of the literature review, are assessed following the recommendations given by VIKO NTNU (www.ntnu.no/viko). Consequently, the papers and publications, which will conform the theoretical framework of this work, fulfil the requirements in terms of Reliability, Objectivity, Accuracy and Relevance.

It is also worth mentioning that a relevant part of the literature review, especially in those aspect regard risk management in underground project, was performed as part of the previous research work developed by the author, Arestegui (2013).

The main method apply to select and analyse the documents was text analysis, which allows the author to analyse large quantity of documents and select the most relevant. Although the main objective of this activity is the analysis of the documents to set the theoretical framework, alternative sources are reviewed and analysed, in order to obtain information about the specific case study (i.e.: Chacao Channel Project).

Activity 2.2: Setting a Theoretical Framework

This specific activity is highly interrelated with the literature review, and it works as a valuable source of feedback, in order to obtain the definitive documents that must be incorporated or eliminated of the literature review activities. The theoretical framework for this work includes the following aspect: project management (Chapter 3), underwater tunnel project (Chapter 4) and cost estimation for underground project (Chapter 5).

As highlighted previously, general information related to the case study is also defined as part of this activity. This information is basically focused on geological aspects and other pertinent aspects for the tunnel design, which is presented in the first section of Chapter 7.

2.4.3 Phase 3 "Modelling "

As the name suggests, this phase is focused on designing the proposed model and applying the model in the specific case study. Figure 2.6 shows the main activities that conform this specific phase. The inputs for this phase are taken from Phase 2, and they are basically conformed by the theoretical framework and information collected regarding the case study.

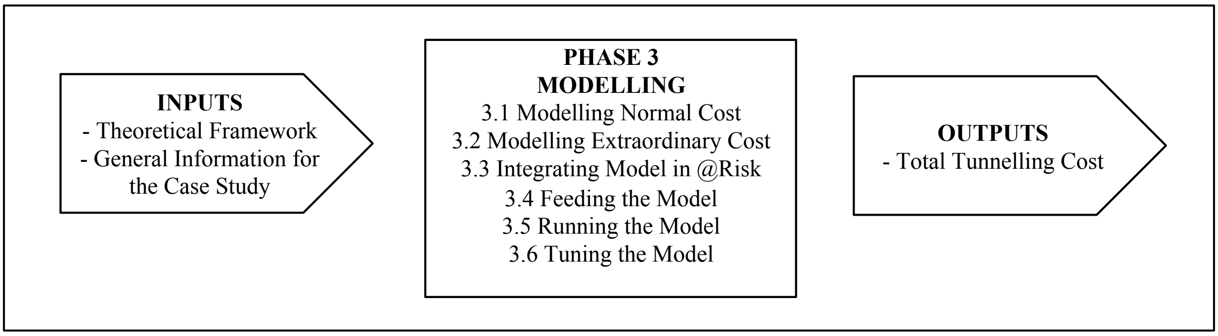

Figure 2.6: Modelling Phase, inputs, activities, and outputs (source: the author)

Activity 3.1 Modelling Normal Tunnelling Cost

This activity consists basically on determining the geological and design parameters that are used as cost drivers. As part of this activity is also considered to define the specific cost functions that will allow obtaining the unit cost for the tunnelling activities.

The design of the normal tunnelling cost (C_{NT}) contemplates the use of statistical (i.e.: correlational) and numerical analysis of quantitative data, as main research methods. Nonetheless qualitative methods, such as text analysis and observation are also required in order to understand some aspects, where lack of data does not allow the use of statistical analysis.

Activity 3.2 Modelling Extraordinary Tunnelling Cost

The extraordinary tunnelling cost is modelled as function of the extraordinary risk events. Correlation analysis is performed in order to understand potential dependencies among risk events related to the tunnelling activities. Text analysis is also deployed as part of this activity, in order to understand the modelling of risk events in previous research works.

Activity 3.3 Integrating the Model in @Risk

Once both models were defined, the model for the estimation of the total tunnelling cost (C_{TT}) is build-up. The integration of both models (i.e.: normal and extraordinary tunnelling cost) was done in @Risk.

To perform the integration of the cost model, quantitative methods, such as data process and calculation are considered; nonetheless it is also considered the participation of the author in seminars related to risk simulation, which is considered an unstructured method to collect data and knowledge.

Activity 3.4 Feeding the Model

Once the model is designed and integrated in @Risk, the model may be fed and consequently the model can be run. In order to feed the model and overcome the lack of detail information regarding the case study (e.g.: regarding cost drivers), this process considers the collaboration of tunnel experts that provide the specific assessment for cost drivers, risk events and correlations. As previously highlighted, qualitative data was required to feed the model, and it was obtain from expert session

Activity 3.5 Running the Model

After setting the model inputs and loading the required data, the next step was to set the number of iteration and simulation and run the model. This activity allows the author to obtain the preliminary results and review the models settings, in order to improve the quality of the results.

Activity 3.6 Model Tuning

In order to assess the results (i.e.: model outputs), cost estimations are compared with previous studies, as well as statistical data obtained for previous projects developed in Norway. During this process is also considered to incorporate the use of expert opinion, which may help to obtain the fine tune of the model. This can be represented as an iterative process that will help to increase the quality of the results, within the time frame of this research.

2.4.4 Phase 4 “Make Sense”

The last phase aims to analyse and discuss the results obtained as part of the previous phases. The make sense phase involves the development of three (03) main activities, which are depicted in Figure 2.7 and described in the following paragraph.

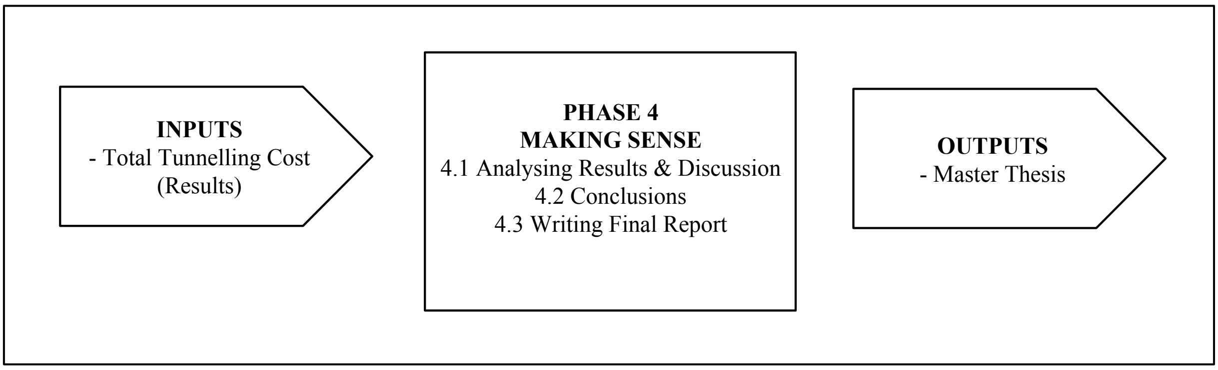

Figure 2.7: Making Sense Phase, activities, and outputs (source: the author)

Activity 4.1 Analysing Model Results Discussion

This activity is extremely relevant since it allows the author to evaluate the obtained results in the light of the theoretical framework of the research, and in this way establish valuable recommendation that may improve the obtained results. This process is performed also considering the analysis of the processes performed and the method deployed during the execution of the research. During this activity, the author points out potential recommendations in regard to further research works that may be undertaken in the same field.

Activity 4.2 Conclusions

This step is basically focused on the analysis of the whole research process and outcomes, in the light of the research objectives. The conclusion should briefly describe the most relevant findings and conclusive notes after performing the project research.

Activity 4.3 Master Thesis Report

This last step is actually performed along to the whole development of the research project, nonetheless it is considered as the last activity, due to its relation with the final deliverable. This step considers all the activities required to fulfil the specific requirements established by the department of Civil and Transport Engineering, as well as those general requirement related to the Master Thesis submission (e.g.: format, uploading, among others).

2.5 Resources

This research project requires the use of standard resources. The most relevant resources to be used during the execution of this work are listed bellow:

Electronic Libraries & Data

- ASCE Library
- PMI Library
- Engineering Village
- Science Direct
- Scopus
- Lectures Material

Search Engines

- Google
- Google Scholar

Software and Hardware

- MS Office (Word, Excel and PowerPoint)
- @Risk (Personal Student Licence)
- End Notes – Reference Editor
- NTNU Printers

Facilities

- Student Office at Department of Civil and Transport Engineering (NTNU)
- NTNU Library

Research Schedule (Actual)

	Actual Resources Hours (MH)					
Phase	***Jan***	***Feb***	***Mar***	***April***	***May***	***Jun***
Phase I	160					
Phase II		180	60			
Phase III			110	120	70	
Phase IV				70	120	90
Partial	160	180	170	190	190	90
Cummulated	160	340	510	700	890	980

Figure 2.8: Research Actual Schedule depicted as researching hours

3. MANAGEMENT AND TUNNELLING PROJECTS

The primary aim of this chapter is to provide a specific theoretical framework regarding project management applied in the field of road tunnel projects. Considering the objectives of this research, this chapter is focused on those aspects related to cost estimation and risk analysis as part of the generic project management process. This chapter also emphasises the evolution of the cost estimation process, during the whole Project Life Cycle (PLC) and the influences and effects that this process may have into the decision making process and in the final assessment of project performance.

3.1 The Project Life Cycle

As any other large investment project, underground projects are executed in discrete phases or stages that allow project sponsors (e.g.: governments, transport ministry, and public agencies) to split the commitments, activities, and especially the risks with regard to development of such endeavours. These project phases are the basic elements that build-up the whole Project Life Cycle (PLC), which represents the complete time line for any project development, from the early initiation (i.e.: front end and concept phases) until its commissioning and final delivery for operation, APM (2006).

Project phases are characterised by different level of management and governance that allows project organizations (e.g.: project sponsors, consultant and contractors) to effectively manage and achieve the final project deliverables considered in the project scope. The project phases are typically completed sequentially, but they may overlap in some project situations or under certain project strategies such as "fast track projects", where engineering and construction trend to be overlapped. The number of phases, level of control and management required in each phase will basically depend on the size, complexity, project impact and internal regulations of the project owner, PMI (2008).

The Extended Project Life Cycle (EPLC) may be represented as a "process" that involves all the phases of a particular project, from its early concept phase to the final de-commissioning. Figure 3.1 depicts the EPLC, which is described according to the Association of Project Management (APM).

As may be observed in Figure 3.1, the EPLC shows a broad perspective of the project development that considers the operation and final de-commissioning of the facilities built as part project. This broad perspective must be always considered when analysing the most suitable project alternatives and its specific Life Cycle Cost Estimate (LCC), GAO (2009).

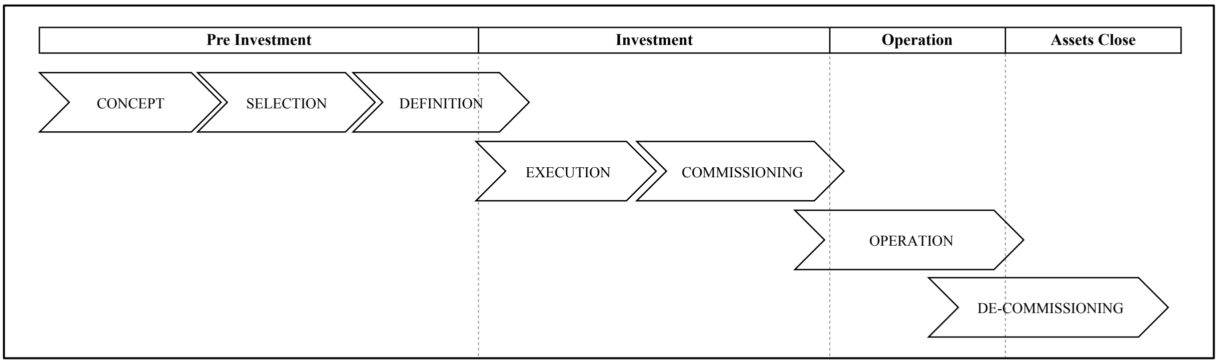

Figure 3.1: Extended Project Life Cycle, which considers all the phases related to the project development, since its earliest phases until the final de-commissioning of the facilities (after APM (2006)).

Nevertheless, in the light of this work the Project Life Cycle (PLC) refers exclusively to the pre-investment and investment phases, which considers all the activities to be performed before the tunnel is ready for operation.

Depending on authors or distinct project organisations, the scope and boundaries of the project phases may differ in its structure and definitions. The definitions given in this work must be understood as a particular reference, and the reader must be aware that these correspond to a discretisation of a complex and continuous process, which may vary from other authors.

The specific project phases considered in this work are shown in Figure 3.2, which are defined by Efron and Read (2012), specifically for the development of tunnelling projects.

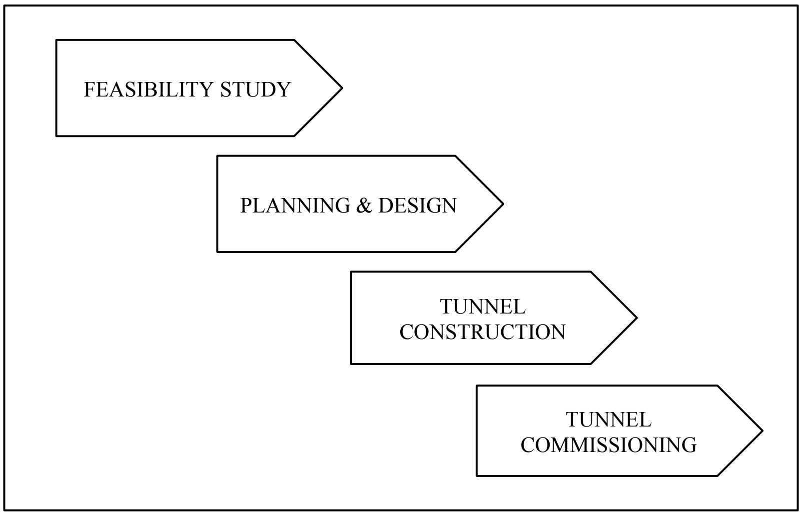

Figure 3.2: Tunnel Project Phases, the feasibility and planning & design may be considered as pre-investment phases, since they do not consider the actual execution of the construction activities. The construction and commissioning represent the investment phases and they are performed after the final approval of the project is obtained (after Efron and Read (2012)).

Considering the definitions proposed specifically for tunnelling projects in Efron and Read (2012) and other generic project management definitions, given by APM (2006), the project phases in this work are defined as follows.

3.1.1 Project Feasibility

This constitutes the initial phase in the PLC, which involves concept development, preliminary drawings, and rough cost estimates. Efron and Read (2012) emphasises that during project feasibility the efforts are concentrated in desk studies and basic site investigations, which allow designers to analyse the geological conditions in which the project will be executed.

The analysis is focused on identify soil, and rock types, as well as other parameters that contribute in potential risk such as faults, shear zones, and ground water. Efron and Read (2012) emphasises that the more information is gathered regarding the geological aspects, the more chance there is for avoiding delays and obtaining more accurate cost estimates.

During the feasibility phase a general design must be obtained and analysed, technically and economically, in order to determine the preferred alternative or business case that will be developed in the next phases, APM (2006).

3.1.2 Project Planning and Design

The main inputs for this stage are the feasibility study and the preferred business case obtained in the previous phase. During this phase, the tunnel design moves from scheme design to detail design, and eventually to the final design for construction. According to APM (2006), the preferred alternative must be always tested against the project requirements for fitness the project purpose and conformance.

As the tunnel design progresses, the owner may start the design and execution of the specific project management plan for the preferred alternative and the level of detail in the project management plan should be sufficient to assist the formal sanction of the project execution. Additionally the owner may start the tender or bid process, in order to select the contractor or contractors that will be involved in execution of the tunnel project.

Once the contractor has been selected, the final investment cost may be obtained and informed in order to continue or not to the project execution. At this phase, and depending on the owner's preferences and contract limitations (i.e.: contract terms and conditions), the selected contractor may be involved in the detail design before drawings are issued for construction.

Efron and Read (2012) emphasises that project planning and design phase is a complicated step since a careful balance between time and detail is required in order to make the final investment decision. Nevertheless at this phase relevant decision must be done, and the construction method for the tunnel must be decided, as well as other relevant aspects, such as definitive tunnel alignment. These decisions must be done in an uncertain scenario, considering all the studies and activities performed in the previous phases.

The final decision is often taken at a formal gate, which the project must pass, to progress to the execution or implementation phase. The final deliverables of this phase are considered the baseline for the project and the APM (2006) emphasises that this phase must be considered as the last point in the PLC, where the project may be cancelled or modified without incurring in more significant costs.

3.1.3 Project Construction

According to Efron and Read (2012) this phase involves the actual construction process and the development of mobilization and field activities. In the definitions given by APM (2006) and Efron and Read (2012), it is clear that the construction, also known execution or implementation phase, is characterised by a significant increment of the economic commitments, mobilisation and use of resources.

At the construction phase the Project Management Process (PMP) must be implemented and monitored by the project owner, in order to ensure that the project will achieve the agreed objectives regarding safety, scope, time, cost, and quality. The execution phase is also characterised by regular reports and communications among project team and other stakeholders, which are commonly focused on the project performance, APM (2006).

The output of the project execution is a set of system and sub-deliverables that constitute the final deliverable (i.e.: undersea tunnel), which must be tested against the acceptance criteria defined during the early stages. At the execution stage, the systems are tested as single units and not as an entity. According to the results obtained in these testing processes, the project organization must decide to enter the next phase, which involve the final handover and commissioning, before starting the operation of the tunnel, Efron and Read (2012).

3.1.4 Project Commissioning

This phase also referred as the Handover and Close out Phase, APM (2006), constitutes the last phase in the PLC and it represents the decision whether or not the project deliverables may pass to the operational phase.

The tunnel, as entire unit or system, is tested in operational mode, in order to set the safely operation of each of the project systems (e.g.: mechanical, electrical, control, and fire systems), Efron and Read (2012). Previous to the final acceptance for operation, the project owner and other pertinent authorities must duly approve all the activities executed during this phase. Some activities that are also part of the handover process are: acceptance of all pertinent documentation, acceptance certificate, transfer of responsibility, and formal transfer of ownership.

3.2 Project Maturity and Decision Making Process

The phases previously described represent distinct levels of maturity and flexibility along to the project development. The level of maturity and flexibility is usually controlled by the degree of uncertainty, stakeholder involvement, and financial commitments regard the project under analysis. The forces present in this phenomena are depicted in Figure 3.3, the blue function represents the level of uncertainty and flexibility to introduce changes and improvement in the project, while the red function represents the project commitments and cumulated cost across the different project phases, Samset (2010).

As depicted in the figure bellow, the project uncertainty decreases, when more and better information became available and the project progresses into the PLC, nonetheless most of the critical decisions regard project investment (go or not go) are made when uncertainty is still high, and limited information is available to provide good and sound basis for the decision making progress.

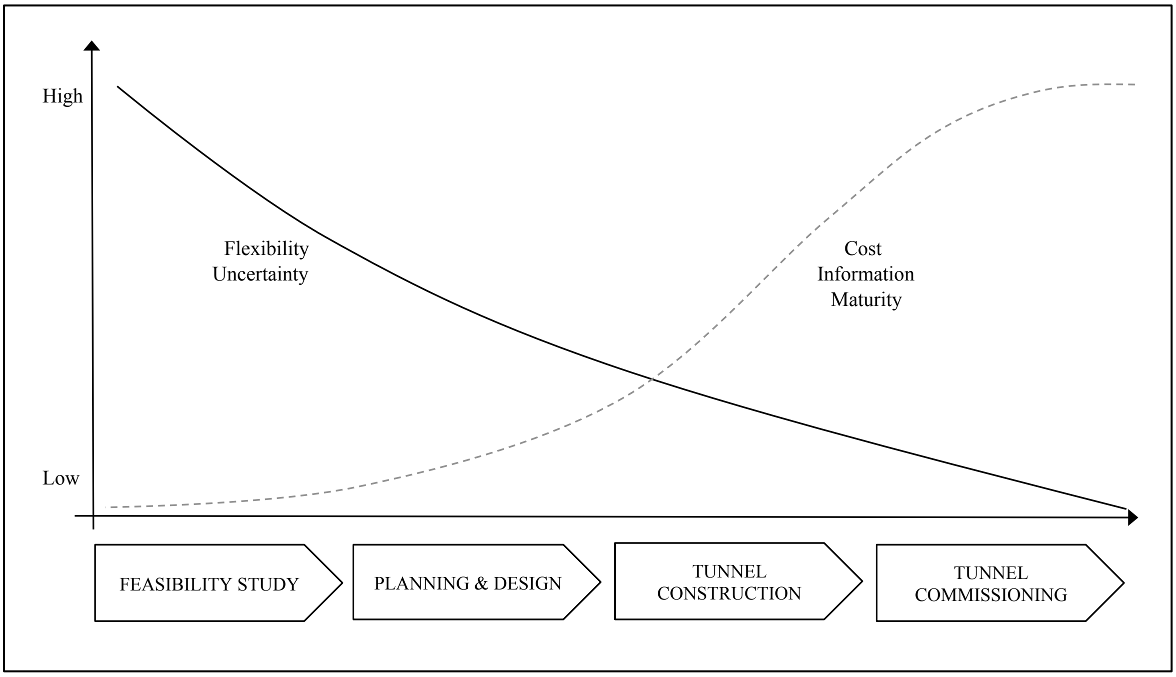

Figure 3.3: Project Maturity and Uncertainty during the PLC (after Samset (2010)).

The phenomena previously described and depicts in Figure 3.3 constitutes one of the main paradox in the project management practice; nonetheless, and as emphasised by Samset (2010), the pre investment phases offer a valuable opportunity to introduce more project management tools and focus, in order to better assess the project concepts and the decisions required in the early project phases. A similar opinion is found in (PMI 2008), where is stated that *"the ability to influence cost is greatest at the early stages of the project, making early scope definition critical"*.

Several decisions are made throughout the pre-investment and investment phases, which imply the assessment of different project criteria. The assessment of these project criteria will determine the viability of the project under analysis and the continuity of the progress in its PLC. Once the project has been approved for execution, medium terms and final project performance reviews will assess the fulfilment of the criteria originally established in the project approval, APM (2006).

During the project phases, different project management processes (PMP) are performed in order to acquire more information that allows decision-makers to evaluate whether a specific project concept must go forward either be held or cancelled. The project management processes are performed with different level of detail at each project phase, consequently the process deliverables (i.e.: outputs) are required to have a certain level of accuracy and precision that must be consistent with the quantity of available information APM (2006), and PMI (2008).

Two important processes that must be undertaken to support the decision making process in large investment projects, such as underwater tunnel projects, are cost estimation and risk management, which are fully describe in the remaining sections of this chapter.

3.3 The Cost Estimation Process

The cost estimation process is an integral part of the project cost management process defined by the Project Management Institute, see PMI (2008), where also are performed the budget estimation and cost control processes.

The cost estimation is defined by PMI (2008) as *"the process of developing an approximation of the monetary resources needed to complete project activities. Cost estimates are a prediction that is based on the information known at a given point in time"*. This estimation are generally given in monetary terms (i.e.: NOK, €, USD); nonetheless it can also be represented as staff hours or times units, in order to eliminate the effects of currency fluctuation

The total amount of resources required by a project is a key piece of information for assessing the project alternatives, and for selecting the preferred alternatives to be executed. The relevance of the cost estimation process is highlighted in general project management literature, such as a PMI (2008), APM (2006), GAO (2009), as well as in more specific documents regarding tunnelling projects, Reilly (2000), Reilly and Brown (2004), and Efron and Read (2012).

Considering the perspective of the above-mentioned documents, the cost estimation is a critical process due to the following reasons:

i. Cost Estimation is a critical input during the pre-investment decision gates for assessing and selecting the preferred project alternatives.

ii. Cost Estimation is critical in the definition of project performance targets, which are later evaluated, during the mid and final project assessments (i.e.: project appraisal)

This specific process interacts with other activities related to the general project management process (PMP), and it occurs at least once in every project, and it may be performed in one or more project phases. The generic cost estimation process may be summarised according to the following figure, which has been taken from the PMI (2008):

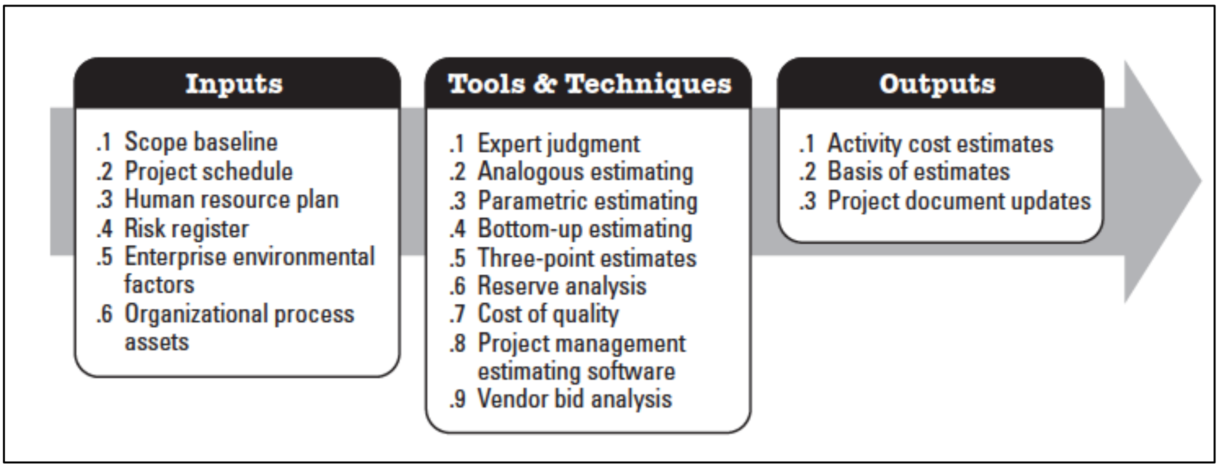

Figure 3.4: Simplified Cost Estimation Process. The left hand box represents the inputs required to perform the process. The middles box exemplified the tools and techniques recommended by PMI to executed the cost estimation, while the right hand box depicts the outputs of the process (PMI (2008)).

As depicted in Figure 3.4, the cost estimation process depends of a certain number of inputs, which must be coherent with the level of cost estimation that is required (i.e.: fit to purposes). As shown in the left hand box (i.e.: inputs), two core pieces of information to perform this process are the project scope baseline (i.e.: which is intended to built) and the risk register, being both important concepts in the remaining sections of this work.

The middle box in Figure 3.4 provides different techniques and tools that may be deployed in order to estimate the project cost. The tools and techniques proposed by PMI (2008) are as follows:

i. Expert Judgment
ii. Analogous Estimating
iii. Parametric Estimating
iv. Bottom-up Estimating

v. Three Point Estimates
vi. Reserve Analysis
vii. Cost of Quality
viii. Project Management Estimating Software
ix. Vendor Bid Analysis

The main outputs of the cost estimation process are the cost estimation itself, the basis of estimates, and the update of project documents. These documents are live documents that reflect the continuous changes in the project development. More specific description of the elements (i.e.: inputs, methods and outputs) that conform the generic cost model introduced by PMI (2008) is given in *Appendix B*.

According to PMI (2008) this process can be executed for the whole project or for individual parts of the total scope (e.g.: deliverables or work packages) and it should be refined during the development of the project and more information is available.

As previously listed, there are different techniques and tools to perform and refine cost estimations and its suitability is highly influenced by the project phase, where the estimation is performed, GAO (2009). There are key aspects that must be always taken in to account, when selecting and applying the tools or methods for cost estimation. Table 3.1 depicts and specific Trade Off Analysis presented in GAO (2009), where the strength, weakness and most suitable application are presented.

Table 3.1: Trade Off among Cost Estimation Methods (source: GAO (2009))

Method	***Strength***	***Weakness***	***Application***
Analogy	- Requires few data - Based on actual data - Reasonable quick - Good audit trail	- Subjective adjustments - Accuracy depends on similarity of items - Difficults to assess effect of desgin change - Blind to cost drivers	- When few data are available - Rough-order-of-magnitude estimate (ROM) - Cross-check
Engineering build-up	- Easily audited - Sensitive to labor rates - Tracks vendor quotes - Time honored	- Requires detailed design - Slow and laborious - Cumbersome	- Production estimating - Project development - Negotiations
Parametric	- Reasonably quick - Encourage discipline - Good audit trail - Objective, little bias - Cost driver visibility - Incorporates real-world effects (risk)	- Lacks details - Model Investment - Cultural barriers - Need to undertands model's behaviour	- Budgetary estimates - Design-to-cost trade studies - Cross-check - Baseline estimate - Cost goal allocation

From Table 3.1, it is possible to deduce that methods and tools must be consistent and coherent with the level of information available at the time, when the estimation is performed.

Additionally, methods must demonstrate consistency with the level of decision that is made, and they should always aggregate value in the estimation process and outcomes.

As shown in Table 3.1, distinct methods have particular strengths and weaknesses that influence its suitability and applicability at different project phases. Nevertheless, each method may offer, when is properly applied, a possibility to contribute in the evolution of the cost estimation through the PLC.

3.4 Cost Estimation Evolution and Maturity

As emphasised by PMI (2008) and GAO (2009), the cost estimation process occurs at least once in every project development and it may be performed in one or more project phases, which means that this process may be executed during the feasibility, planning & design and also during construction phases. Consequently cost estimation must be considered as a repetitive and iterative process, which evolved during the different phases of the PLC.

As previously defined, cost estimates are predictions of the required resources, which are based on the information available and known at a given point in time (i.e.: project phase). It is also highlighted that cost estimates should be refined or updated during the course of the project to reflect additional information that became available. As a consequence of the introduction of more information the accuracy of the cost estimate should increase as the project progress in its PLC, PMI (2008) and GAO (2009).

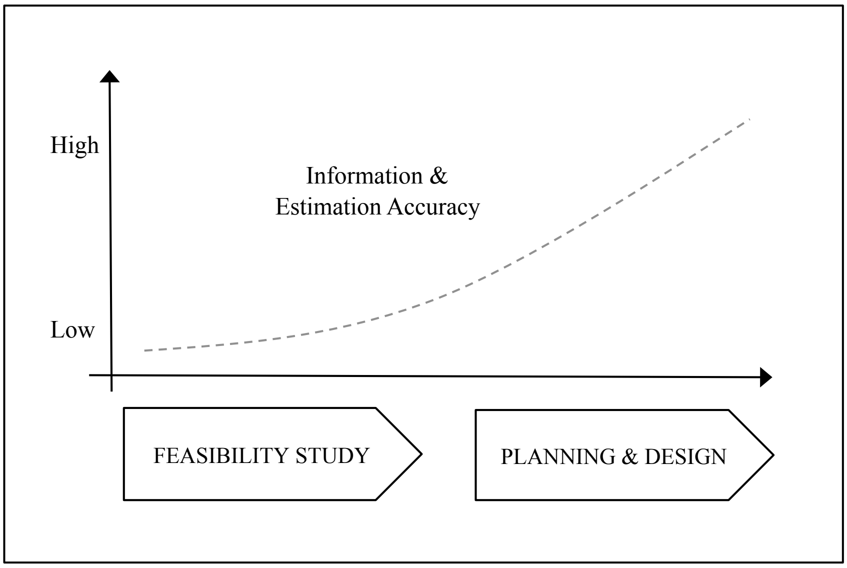

Figure 3.5: Expected Evolution in the Cost Estimation Maturity. The more information is developed and incorporated in the process, the more precision and accuracy are expected in the process output (source the author).

The evolution of the cost estimation is represented in Figure 3.5, which shows the cost process performed at two distinct pre investment project phases. The figure illustrates the normal evolution of the cost estimation process, which represents the rule that the more information is available, the more precision in the cost estimation is expected by the project organisations.

As highlighted by APM (2006) and PMI (2008), organisations may expect distinctive level of accuracy at different project phases or decision gates, nonetheless and as previously indicated, there project organisation will always expect an increment in the accuracy and precision of cost estimation increase as more information became available.

General project management practices have defined different levels precision (i.e.: cost range) for cost estimation across the project phases. A summary of the estimate method and the expected level of accuracy (i.e.: measure of the deviation of the estimation respect to the expected actual value) for each project phases are given in Table 3.2.

Table 3.2: Cost Estimation Classes, at different project phases. The early project phases are characterised by less accuracy and larger ranges in the cost estimation (source: the author)

Class Name	***Class 5 Factor Estimate***	***Class 4 Factor Estimate***	***Class 3 Semi Detailed***	***Class 2 Detailed***	***Class 1 Detailed***
Methods & Tools	Analogy Expert Judgement	Parametric Analogy Expert Judgement	General Unit Cost Basic Take Off	Detailed Unit Cost Detailed Take Off Detailed Bottom Up Simulation	Detailed Unit Cost Detailed Take Off Detailed Bottom Up Simulation
Expected Accuracy	30% - 40%	25% - 35%	15% - 25%	10% - 15%	5% - 10%
Project Phase Applicability	Project Concept	Project Feasibility	Early Planning & Design	Early Planning & Design	Project Execution

The number shown in Table 3.2, and related to the expected level of accuracy, are fully consistent with general project management literature, such as PMI (2008), GAO (2009) and Samset (2010), which emphasise that cost estimations experiment an evolution during the different project phases. This evolution implies that the mean value should be closer to the expected actual value (i.e.: accuracy), while the standard deviation (i.e.: precision) should be reduced as the project progress in to more advanced stages. This phenomenon denominated as the "cone of uncertainty" in GAO (2009) is depicted in the left hand side of Figure 3.6.

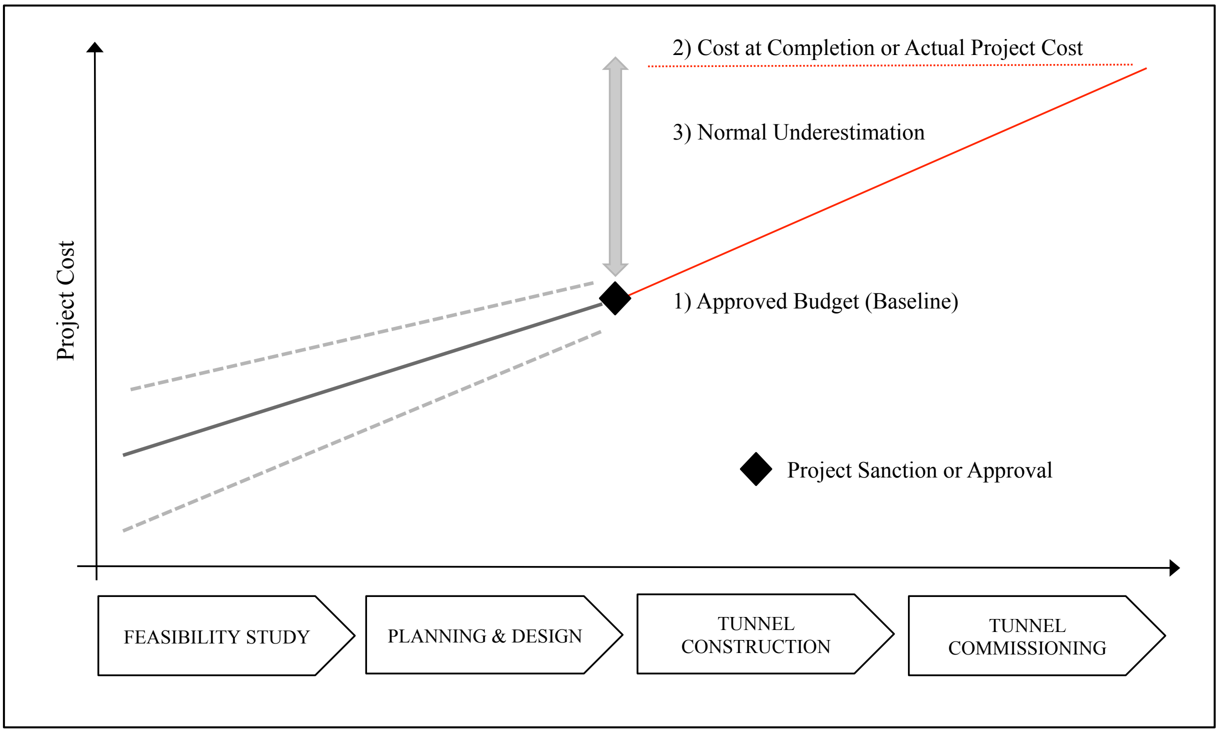

Figure 3.6: Cost Estimation Maturity and Evolution. The black line shows the evolution of the project cost estimation during the pre-investment phases. The dotted lines represent the range of the cost estimation. The red line represents the evolution of the actual project cost, during the investment phases. The difference between the actual project cost (2) and the approved project budget (1) may be understood as the normal underestimation of the project cost (after Samset (2010) and GAO (2009))

Regardless the continuous evolutions of the cost estimation during the pre investment phases, estimations are usually exceeded after the final completion of the project is achieved. Researches and public reports, such as Flyvbjerg, Holm et al. (2002), Flyvbjerg and Cowi (2004), and Treasury (2010), emphasise that cost overrun is a recurrent problem in large investment project, but especially in those large projects related to public infrastructure projects.

When specifically reviewing the performance of tunnelling projects, Efron and Read (2012), Tamparopoulos (2013), and Spackova, Sejnoha et al. (2013 a) highlight that cost estimation for tunnel projects (i.e.: project budget) are also often exceeded. In the opinion of these authors, cost estimation for tunnelling project are likely to be exceed due to the systematic underestimation of the conditions that surrounds the project development.

According to Flyvbjerg, Holm et al. (2002), Tamparopoulos (2013), Spackova, Sejnoha et al. (2013 a), tunnelling projects are normally subjects to the systematic underestimation, mentioned above, due to the high complexity presents in the development of these projects and due to the high willingness of the decision maker to execute these class of projects (i.e.: public infrastructure projects).

Considering all above mentioned, it is possible to state that even though cost estimations evolve considerably during the pre investment phases of the PLC, it still remains as an aspect to be further improved, in both precision and accuracy.

3.5 Cost Estimation Approaches for Tunnelling Projects

In order to undertake the cost estimation process, project organisations may deploy several approaches, which range from standard deterministic estimation to more advance stochastic models. Researchers, such as Petroutsatou, Georgopoulos et al. (2012), Rostami, Sepehrmanesh et al. (2013), Paraskevopoulou and Bernardos (2013) stress that several tools, such as Monte Carlo Simulation (MCS), Regression Analysis, and Neuronal Networks may be deployed in order to obtain the estimation of the tunnelling activities. The tools described in the researches previously are based in broader approaches, which according to Spackova, Sejnoha et al. (2013 b), may be classified as follows.

i. Deterministic analyses
ii. Interval and percentiles estimates
iii. Probabilistic models.

Spackova, Sejnoha et al. (2013 b) emphasise that deterministic approach assesses a single value and neglect the uncertainty regards the estimate. The values used to assess the cost are considered to be close to the mode, which represents the project cost value under an ideal scenario. The total project cost is obtained as the simple summation of the different cost elements that are required to obtain the final deliverable. According to Spackova, Sejnoha et al. (2013 b), the deterministic nature of the estimation is independent of the method used for obtaining the values; therefore deterministic cost estimations may be obtained from analysis of statistical data regards past projects (e.g.: regression analysis), expert opinion or analytic methods.

The main drawback of the deterministic approach is that assumes the project development in ideal conditions, which systematically ignores the occurrence of undesirable events. Consequently deterministic estimations do not allow estimators to incorporate the uncertainty and risk that define the uniqueness and complexity of each project. Single value estimation are considered unreliable, which may lead in underestimation of project cost, Isaksson (2002). Chou, Yang et al. (2009), and Spackova, Sejnoha et al. (2013 b).

The interval approach assesses the project cost estimate in a given interval, which is primarily obtained by expert judgment. The accuracy of this estimate (i.e.: the width of the interval) depends of the project phases and it trends to be wider during the early project phases, Spackova, Sejnoha et al. (2013 b). This approach enables estimators to consider the project uncertainty; nevertheless it does not provide a full probability distribution for the cost estimation.

On the other hand, the stochastic approach to cost estimation recognises the random nature of the cost elements and values are assessed as specific statistic distributions (i.e.: probabilistic density functions), Isaksson (2002). The stochastic approach allows estimators to incorporate the uncertainty and risk that surround projects and, consequently, it provide a method that may be representative of the project complexity and uniqueness. These models represent the tunnel project cost as a full probability distribution, and generally they provide updating tools, which allow estimators to incorporate new information as the project progress in the PLC.

As highlighted before, the main drawback of probabilistic models lies in the necessity of reliable statistical data that must be duly assessed by the estimators. Some of the main problems highlighted by Isaksson (2002) and Spackova, Sejnoha et al. (2013 b) is the difficulty to find and incorporate reliable data in the stochastic models. Tamparopoulos (2013) emphasises that even when information is available, other challenges equally difficult to solve arise. Some of these challenges are: selection of the probability distributions to describe the cost elements, and the determination of correlation among the cost variables involved in the project.

Spackova, Sejnoha et al. (2013 b) emphasise in their conclusions that probabilistic models have not been widely accepted in the practice, basically due to two reasons. Firstly there is not a real demand for quantitative modelling of uncertainty and risk among decision makers, and secondly existing stochastic models do not provide realistic estimate.

During the last 20 years, several models have been developed and applied in the cost estimation of underground projects, see Isaksson (2002), Min (2003), Oreste (2006), Paraskevopoulou (2012), Petroutsatou, Georgopoulos et al. (2012), Rostami, Sepehrmanesh et al. (2013), and Spackova, Sejnoha et al. (2013 a). Each of this research constitutes an academic effort in order to improve the cost estimation process, in tunnelling project. In all these model is also reflected the need to provide better basis for the decision making process, especially in the pre-investment phases of the tunnelling projects. Chapter 5 is specifically devoted to describe stochastic cost estimation models for underground projects.

3.6 Cost Estimation Variables for Underground Projects

According to Isaksson (2002), Efron and Read (2012), among others authors emphasise that are several and significant differences between underground projects and standard heavy construction projects that affect the cost estimation process, which make more complex the cost estimation process, and therefore the decision making process in such as projects.

According to Efron and Read (2012), the main variables affecting the cost of tunnel projects range from the actual geology, where the tunnel will be built, to general commercial aspects, such a type of contract and public support. The variables highlighted by Efron and Read (2012) are depicted in Table 3.3.

Table 3.3: Cost Variables for Tunnelling Projects, Efron and Read (2012).

Cost Variable for Tunnelling Projects	
Geology	Locality
Excavation Method	Labour Cost
Materials	H&S Regulation
Tunnel End Use	Market Competition
Face Area	Client Knowledge
Lining Type	Public Support
Tunnel Depth	Contract Type

Efron and Read (2012) emphasises that the uncertainty, related to all the variables presented above, must be duly assessed, in order to understand its influence in the final cost of tunnelling projects. Since these variables have either direct or indirect effects in the cost estimation process, Efron and Read (2012) refers to them as "project cost drivers".

Specific researches related to cost estimation in tunnelling project, such as Einstein (1996) Reilly (2000), Isaksson (2002), Tamparopoulos (2013), and Spackova, Sejnoha et al. (2013 a), emphasise the need of duly assess and analyse the uncertainties and risk related to these variables and its effects in the final cost of the tunnelling projects.

3.7 Project Risk Management, The Generic Process

As emphasised by Al-Bahar and Crandall (1990), Einstein (1996) and Reilly and Brown (2004), uncertainty and risk are project attributes present during the whole development of construction and tunnelling projects and they influence the project decisions, processes, and certainly project performance and results.

Uncertainty and risk are two concepts vastly discussed in general project management, and it is as well part of the common project management practices. The project risk management (PRM) is a project management tool, specifically designed for dealing with the risk existing in projects.

A simple definition of project risk management (PRM), which is applicable to a wide class of projects, is given by PMI (2008), where is defined as *"the processes of conducting risk management planning, identification, analysis, response planning, and monitoring and control on a project"*. The primary objectives of this process are *"to increase the probability and impact of positive events, and decrease the probability and impact of negative events in the project"*. According to the PMI (2008), the PRM is implemented through the execution of 6 different sub processes, which are depicted in Figure 3.7.

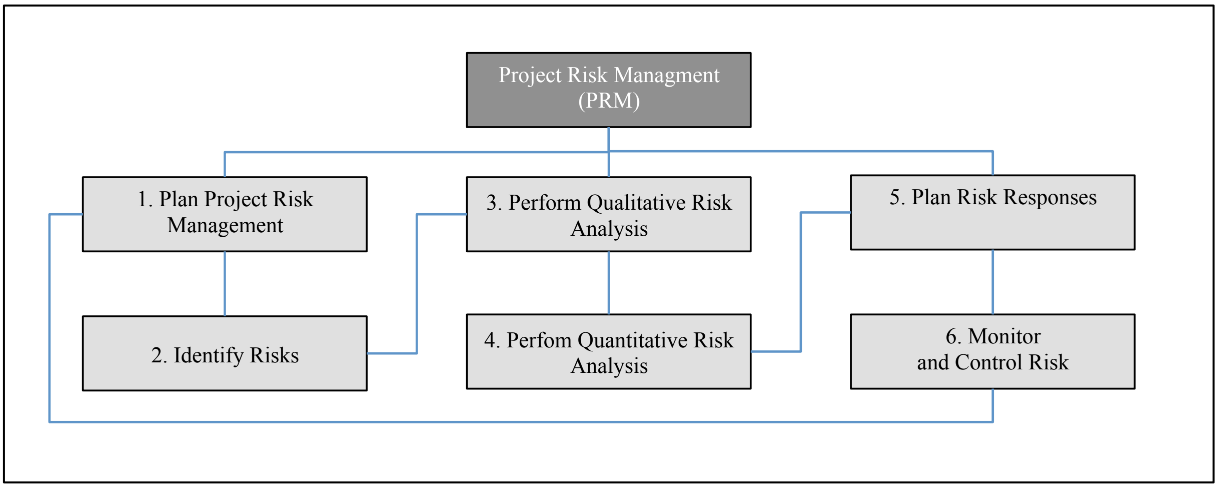

Figure 3.7: Generic Risk Management Process according to Project Management Institute, (after PMI (2008)).

The main features related to these six (06) different sub processes are defined by the PMI (2008) as follows:

i. Risk Planning: the process of defining how to conduct risk management activities for a specific project. It is important to ensure a common understanding in the project team about the importance of risk. Planning provides the required resources for implementing risk management activities. This process should begin as a project is conceived and should be completed in the early concept phase. The output of this process is the project risk policy.

ii. Risk Identification: the process of determining which risks may affect the project and documenting their characteristics. During this process all the project stakeholder and key personnel should take part. It is an iterative process because new risk may be identified as the project is progressing into new phases. The format of risk assessment must be consistent among the identified risks, in order to compare the relative effects of one risk again others. The output of this process is the risk register.

iii. Qualitative Risk Analysis: the process of prioritizing risks for further analysis or action by assessing and combining their probability of occurrence and the impacts. The focus should be on the high priority risks. Qualitative risk assessment is rapid and cost-effective for establishing priorities for other risk process (e.g.: risk response) and it is the foundation for performing quantitative risk analysis. The main outcomes of this process are: risk register update, relative ranking of project risks, list of risk for additional analysis and response.

iv. Quantitative Risk Analysis: the process of the process of numerically analysing the effect of identified risks on overall project objectives. This process is performed on the risk identified and prioritised during the qualitative risk analysis, having focus in their effects. It is also a continuous process that must be repeated after risk response and risk monitor, in order to determine the efficiency of the risk management process. The main outcomes are: risk register update, probabilistic project analysis, prioritised list of risk, trend in quantitative risk, among others.

v. <u>*Risk Response*</u>: the process of developing options and actions for enhancing opportunities and reducing threats to project objectives. It identifies one single responsibility for performing the risk response and risk response must be executed considering the risk priority, and inserting the required resources into the budget, schedule and project management plan as needed. The risk response will consider generally the following measures: Risk Avoid, Risk Transfer, Risk Mitigate and Risk Acceptance.

vi. <u>*Risk Monitor & Control*</u>: the process of implementing risk response plans, tracking identified risks, monitoring residual risk, identifying new risks and evaluating risk process effectiveness throughout the project lifecycle.

The PRM has been incorporated in several industries, such as financing, insurance and aerospace, where the random nature of the project variables, make absolutely necessary the application of this project management tool. Contrarily, and according to Taroun (2013), the construction industry has continuously failed in the systematic application of PRM and it has a poor reputation in risk management, when comparing with other industries.

Several authors such as Al-Bahar and Crandall (1990) and Mustafa and Al-Bahar (1991) have emphasised the necessity to incorporate a systematic approach to risk in the construction industry, in order to deal effectively with the uncertainty and risk that surround construction projects and increase the probability of project success.

The systematic approach claimed for Al-Bahar and Crandall (1990) and Mustafa and Al-Bahar (1991) is reflected in a structured arrangement and execution of the activities that conform the project risk management process. Other authors, such as Eskesen, Tengborg et al. (2004) and Spackova (2012) also emphasises the need for a systematic approach to project risk management in the specific field of underground and tunnelling projects, therefore the following section gives a specific insight of PRM is tunnelling projects.

3.8 Project Risk Management in Underground Projects

The application of the PRM in underground projects is not a novel idea; and an important quantity of researches may be found in this specific field of knowledge, see Einstein (1996), Sturk, Olsson et al. (1996), BTS (2003), Eskesen, Tengborg et al. (2004), Choi, Cho et al. (2004), Sousa (2010), Sousa and Einstein (2011), Likhitruangsilp and Ioannou (2012), Fouladgar, Yazdani-Chamzini et al. (2012), and Spackova (2012).

In these works is underlined that negatives results in relevant project objectives such as safety, time and cost, which are influenced for a high level of uncertainty and risk, have motivated a new perception regarding risk and the preponderance of PRM as a tool for achieving project success.

In order to achieve a good performance in project objectives, professional associations and governmental entities have made persistent efforts to implement the PRM in the development of underground projects. The works published by BTS (2003), Eskesen, Tengborg et al. (2004), and ITIG (2012) are good examples of the increasing relevance that project risk management has taken in underground projects. The risk management processes for underground projects does not present major differences with respect to the generic process described in section 3.7, therefore the definitions previously introduced are totally valid for the implementation of PRM in tunnelling projects.

One of the most relevant aspect emphasised by Eskesen, Tengborg et al. (2004) is that risk management must be developed throughout the project life cycle, being critical during the early project phases, where major decisions such as tunnel alignment and construction method must be done. The implementation of PRM in all the phases of the project development may incorporate relevant information, which allow project organisations (e.g.: project owner, sponsors and contractors) to obtain better basis for the decision making process, Eskesen, Tengborg et al. (2004) and Spackova (2012). As a consequence of this, the PRM must be considered an essential matter for all the parties involved in the project development.

One of the aspect that characterises the high risk of underground project is the limited capacity that project organizations have for forecasting and controlling the risk and uncertainty that involve the tunnelling process, especially those aspects regarding geological and construction performance, Isaksson (2002) and Spackova (2012).

As previously presented in section 3.7, the PRM is composed by several activities, which according to Likhitruangsilp and Ioannou (2012) may be summarised in the following fours activities: risk identification, risk analysis, risk response and risk monitoring & evaluation. Since this work is based on uncertainty and risk analysis, the following section will describe the main approach and tools used to perform this specific activity.

3.9 Risk Analysis Approaches and Tools

The risk analysis process, as part of the PRM, may be executed using different approaches and tools, which will depend among other factors on: the project phase that is being performed, the availability of information, the level of risk under assessment, and the responsible for the risk assessment.

Table 3.4: Approaches and Tools for Project Risk (Arestegui (2013)).

Practitioners Perspective		
Focus on	***Approach***	***Tools***
Overal Project Risk	***Qualitative***	Risk Matrix Risk Register Expert Opinion Engineering Judgement
	Quantitative - Probabilistic	Monte Carlo Simulation
Specific Risk Events	***Quantitative - Probabilistic***	Decision Tree Event Tree Failure Mode Failure Tree

Researchers Perspective		
Focus on	***Approach***	***Tools***
Overal Project Risk	***Quantitative Analytic***	Fuzzy Set Theory Analitical Method (AHP) Topsis
	Mixed Approaches	Fuzzy Event Tree Fuzzy MCS Monte Carlo Simulation
Specific Risk Events	***Quantitative - Probabilistic***	Bayesian Network Decision Tree Event Tree Failure Mode Failure Tree

Depending on the level of risk that is under analysis, approaches may vary from qualitative and quantitative. Table 3.4 shows part of the results obtained as part of the previous research work developed by this author, Arestegui (2013). The above table depicts and summaries the different approaches and tools used by practitioners and researchers, when analysing both overall project risk and specific risk events.

As indicated in the above table, tunnelling practitioners focus the analysis of overall project risk in qualitative methods, based on risk matrix, risk register, expert opinion and engineering judgement. Arestegui (2013) emphasises that even though Monte Carlo Simulation appears as the most common quantitative tools, used by practitioners, this done with a larger number of simplifications that usually reduced the reliability of the results.

One the other hand, researcher performs the analysis of overall project risk, using most sophisticated approaches and tools, such as Fuzzy Theory (FT) and Analytic Hierarchical Process (AHP), which confirm the gap between practitioners and researchers.

This gap is less notorious, when analysing specific risk events. In these aspects both practitioners and researchers deploy similar methods. As conclude by Arestegui (2013), the design of new stochastic models for cost estimate should try to shorten this gap, and offer simple, but reliable means that may be implemented in real practice.

3.9.1 Qualitative Risk Analysis

The main tools used by practitioners to perform qualitative risk analysis are based on risk register and risk matrix. The qualitative risk analysis relies primarily in expert opinion and engineering judgment. The project experts assess the identified risk events, in terms of its probability of occurrence (i.e.: risk frequency) and the consequence if the specific event occurs. The assessment is performed considering relative and predetermined categories (i.e.: verbal scale), such as small, medium and high. The assessment process is carried out through brainstorming sessions held with multi-disciplinary project experts Eskesen, Tengborg et al. (2004).

Once the risk events are assessed, they must be classified according to the magnitude that each risk event represents. The risk classification provides a framework for the decisions to be made regards risk mitigation measures. When the level of risk conflicts with the project acceptance criteria, it is mandatory the identification and implementation of risk response and the responsible. All this information is registered and updates in the project risk register.

Eskesen, Tengborg et al. (2004) emphasises that qualitative risk analysis is a core process that may helps project organizations to acquire awareness about the risk events that are affecting the development of the project and its execution is crucial during the early project phases. Spackova (2012) highlights that the primary objective of the qualitative risk analysis is to evaluate the magnitudes of the risk events affecting the project development and it may work as a valuable basis for the preparation of contracts and allocation of responsibilities among the project stakeholders.

Spackova (2012) state that this method may be used as a basis for the quantification of the overall project risk, and the total project risk may be assumed as the simple summation of all risk events involve in the project. Nonetheless, this author emphasises that this procedure may also lead in incorrect estimation of the overall project risk. The reason of this, it is because single risks are strongly correlated to each other and simple summation does not represent the complexity of the project risk and other approaches must be applied to perform this analysis.

3.9.2 Quantitative Risk Analysis

The quantitative risk analysis must be carried out in situations when specific risk event represents a special interest due to the high level of risk or the relevance of the decision to be made. This class of analysis involves the assessment of the risk, its probability of occurrence and effects, in numerical terms Spackova (2012). The quantitative risk analysis is basically based on the Probability Theory (PT), and consequently most of the principles of this theory are applied in order to assess the project risk.

The execution of quantitative risk analysis requires a clear structuration of the variables involve in the problem, specific analysis of causes and effects, and clear identification and evaluation of the dependencies of the risk events. According to Isaksson (2002), Eskesen, Tengborg et al. (2004), and Spackova (2012), the quantitative analysis of risk provides valuable information for the decision making process and it also represents and effective communication with the project stakeholders involve in the tunnel development.

Some of the tunnel decisions that may be assessed by the implementation of quantitative risk analysis are:

i. Selection of the construction or excavation method
ii. Determine the required budget for tunnel development, (owner)
iii. Determine the bid price for tunnel construction (contractor)
iv. Determine the time required for execution

The most used tools for quantitative risk analysis are described bellow, according to Eskesen, Tengborg et al. (2004):

i. *Fault Tree Analysis (FTA):* tool used to analyse causal relations of negatives events. FTA may be executed with or without quantifying the probabilities related to the events under observation. This tool is suitable for solving complex problems where several interconnected events must be analysed.

ii. *Event Tree Analysis (ETA)*: this tool describes the whole development of a single risk event, considering the cause and all the possible consequences. ETA requires the assessment of the probabilities of occurrence for different outcomes (i.e.: consequences), which eventually will provide a quantitative analysis of the consequences of the considered scenarios

iii. *Decision Tree Analysis (DTA)*: tool used to analyse the best decision, based on information related to probability of occurrence and effects for different risk scenarios. This provides a structured format to analyse decision regards underground construction.

iv. *Monte Carlo Simulation (MCS)*: this tool provides a good solution when several random variables are involves in the problem under analysis, especially when analytical solutions may be very complicated. The first step is to define the variables involve in the problem and the equation that related all these variables. Then distribution (PDF) for each stochastic variables must be defined, and as well as, the correlation that exists between variables. After this, a random machine incorporated in the specific software generates random inputs for each variables of the model (simulation), which eventually allow obtaining an approximate result for the equation.

The result is expressed as a probability density function (PDF), where average value, standard deviation and other statistical parameter may be determined.

3.9.3 Analytic Risk Analysis

The analytic risk analysis is basically based on the Fuzzy Set Theory (FST), and it has been implemented in the risk analysis process in order to overcome some of the shortcoming existing in both qualitative and quantitative methods. During the last three decades, researchers, such as Mustafa and Al-Bahar (1991), Nieto-Morote and Ruz-Vila (2011), and Kuo and Lu (2013), have made a big effort in order to design risk analysis approaches and tools capable to deal with low degree of information and incorporate in a systematic and well-structured way the knowledge of experts.

These analytics models are capable to deal with ill-defined situations and with the high level of complexity that surround the construction risk assessment. Analytical tools are able to process, quantify and incorporate expert opinion into mathematical models that assess the risk in a quantitative manner. The most well know and used analytical tools are:

i. Fuzzy Set Theory (FST)
ii. Analytical Hierarchical Process (AHP)
iii. TOPSIS

Given that analytical model are able to process and obtain a numeric output, they may be classified as quantitative methods, nevertheless these models must be clearly differentiated from the quantitative – probabilistic approach introduced in the previous section.

4. UNDERWATER TUNNEL PROJECTS

This chapter introduces the most relevant characteristics of underwater tunnels and it also analyses the complexity that involves the development of this class of projects. The main features related to the planning and execution phases for undersea tunnels are introduced and analysed, emphasising those aspects where risk and uncertainty trends to be higher, and may negatively affect the cost estimation process, as well as the project performance during execution.

4.1 The Concept again Complexity

Underwater tunnels are underground structures, partially or completely excavated in rock or soil that lie underneath open bodies of water such as: seas, fjords, rivers or lakes. These structures are generally built to connect urban areas located far way from the mainland or to provide industrial facilities under the seabed, NFF (2009).

A specific example of undersea road tunnel, built as part of the public infrastructure, is shown in Figure 4.1. This figure shows the longitudinal section of the Frøya Tunnel Project, which was executed in Norway between 1998 and 1999.

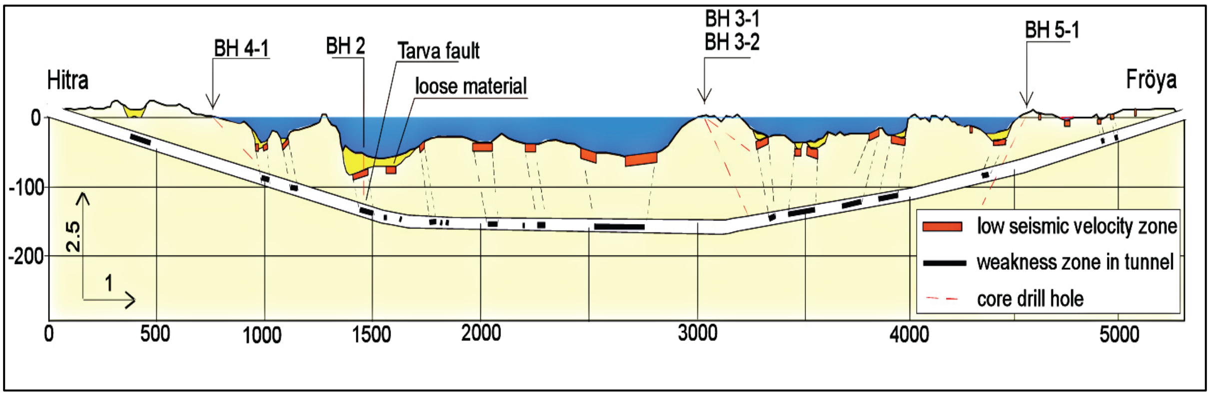

Figure 4.1: Longitudinal Section of the Frøya Tunnel Project (source: NFF (2009)).

Undersea tunnels are complex civil engineering endeavours that usually represent a higher level of complexity and risk than typical surface projects, and also with regard to conventional tunnels, Pennington (2011). Similarly, and according to NFF (2009), some of the aspects that make more challenging the development of underwater tunnel are as follows:

i. Special methods for field investigation are required, due to the difficult location of the tunnel (i.e.: the main part is covered by water). This condition contributes with more uncertainty in the interpretation of the investigations.

ii. Specific locations of underwater tunnels, such as fiords or straits constitute itself fault or weakness zones.

iii. The potential of water inflow is infinite.

iv. The corrosive features of salt water represent problems during the tunnel construction and for the rock support systems (i.e.: steel and concrete).

Regardless the difficulties encountered in the planning and execution of undersea tunnels, civil engineers have developed this concept for more than 150 years, delivering undersea tunnels that symbolise great achievements in the field of the construction engineering. Examples of these projects are the Thames Tunnel in England, built between 1825 and 1843, the Hudson and Manhattan Tunnel, executed between 1873 and 1908, and the Channel Tunnel (1988-1994).

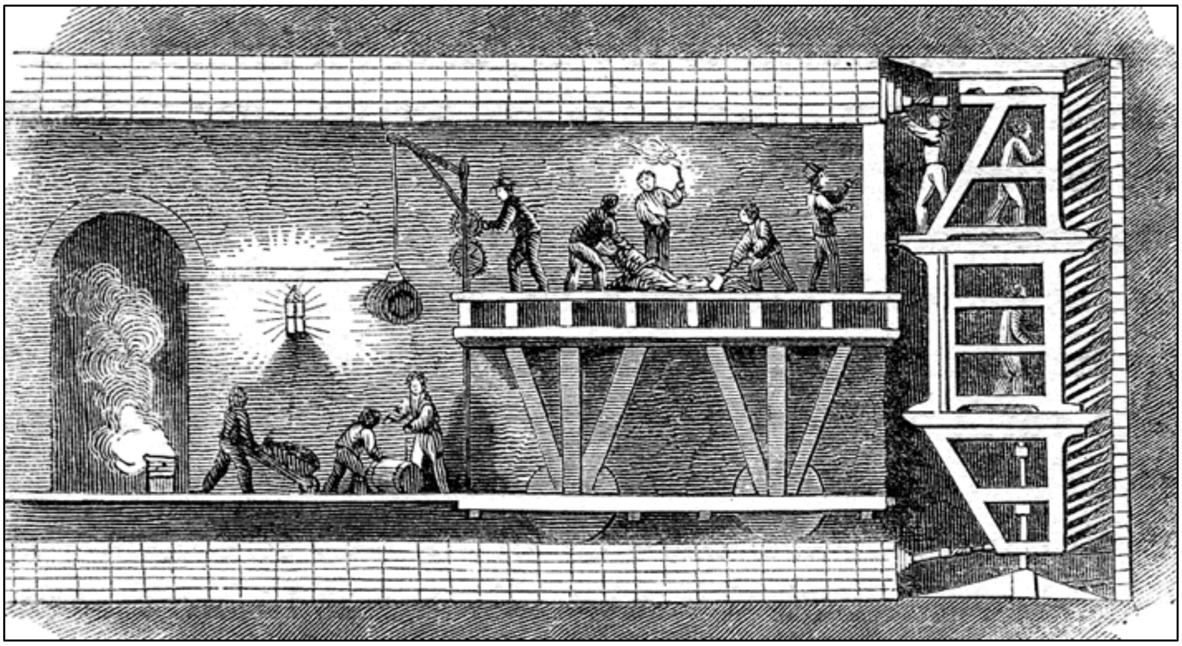

Figure 4.2: Excavation Method in Thames River (source: www.wikipedia.com)

More than hundred years have passed since the first undersea tunnels were built and delivered for operation; and newer and larger developments have continuously extended the relevance of this fixed-link concept, as key component of the public and private infrastructure in different countries around the world.

A good example of the continuous development of this class of projects is Norway, where more than 25 underwater road tunnels have been built during the last 30 years. Examples with regard to other sectors (i.e.: not for public road infrastructure) are others 15 undersea tunnels that have been executed to provide industrial facilities to the Oil & Gas industry and water supply. Table 4.1 provides some key information regarding road tunnel projects undertaken in Norway, since 1981 to 2009.

Table 4.1: Undersea Tunnel Projects built in Norway from 1981 to 2009 (source: NFF (2009)).

Number	***Project Name***	***Opened***	***Main Rock***	***Cross Section*** **m2**	***Length*** **km**
1	Vardø	1981	Shale	53	2,6
2	Kamsund	1984	Greenstone, Sandstone	27	4,7
3	Hjartøy	1986	Gneiss	26	2,3
4	Ellingsøy	1987	Gneiss	68	3,5
5	Valderøy	1987	Gneiss	68	4,2
6	Kvalsund	1988	Gneiss	43	1.6
7	Godøy	1989	Gneiss	52	3,8
8	Hvaler	1989	Gneiss	45	3,8
9	Flekkerøy	1989	Gneiss	46	2,3
10	Nappstraumen	1990	Gneiss	55	1,8
11	Fannfjord	1990	Gneiss	54	2,7
12	Byfjord	1992	Phylite	70	5,8
13	Freifjord	1992	Gneiss	70	5,2
14	Kolssnes (Troll)	1994	Gneiss	70	3,8
15	Hitra	1994	Gneiss	70	5,6
16	Tromsøysund	1994	Gneiss	2*60	3,4
17	Bjorøy	1996	Gneiss	53	2
18	Nord Kap	1999	Gneiss, Sandstone	50	6,8
19	Oslofjord	2000	Gneiss	79	7,2
20	Frøya	2000	Gneiss	52	5,2
21	Bømlafjord	2000	Greenstone, Gneiss	74	7,9
22	Elksund	2007	Gneiss, Gabbro	71	7,8
23	Nordåsstraumen	2008	Gneiss	2*74	2,6
24	Finnfast	2009	Gneiss, Amphibolite	50	5,7 + 1,5
25	Atlanterhavs Tunnel	2009	Gneiss	71	5,7

Regardless the great development of undersea tunnels, during the last years, this fixed-link concept is far away to be considered a low risk endeavour. Supporting this statement, Pennington (2011) emphasises that even though new and modern technologies have made underwater tunnels cheaper, faster, and certainly safer, the complexity, and uncertainty inherent to these projects still remain as difficult aspects to be managed during the entire project development.

The high level of complexity and risk that surround undersea tunnel projects certainly affects the development of all project phases and the specific processes performed in each of these stages (e.g.: engineering design, cost estimation, construction, commissioning, among others). In the same line, Pennington (2011) highlights that underwater tunnel projects posses a high probability to do not achieve their execution targets, in relevant aspects such as safety, cost, and time, especially due to the occurrence of undesired events that arise across the whole project development.

The Publication Nº 18 "Subsea Tunnels", referred in this work as NFF (2009), also recognises that uncertainty and risk affect the project development and it influences greatly the project success.

From the above exposed, risk management appears to be a critical aspects that must be introduced during the early development of undersea tunnel projects, in order to improve the whole project management processes. The incorporation of uncertainty and risk analysis, is especially relevant, in those processes that affect the decision making process and the final assessment of the project performance.

4.2 Geological Investigation in Undersea Tunnels

As in any other construction endeavour, information collected previous to the final decision, to go or not to go, may contribute to built sound basis and foundations to support the decision making process. A well-supported decision making process should ensure that the best alternatives, those with the best value for the project owner and stakeholders, are being selected and implemented. In this sense, geological investigation is an extremely relevant aspect that contributes to better assess the development of undersea tunnels.

Given the location of undersea tunnels, difficulties regard geological investigations trend to be higher than other normal underground projects. Restrictions to access in the proximities of the future tunnel alignment make more restrictive the possibilities to perform field investigation, which certainly contribute in the cost regards this specific project aspect. Therefore, the decision of which pre investigation should be made must always consider those that give more value, during the development of the pre investment phases, Pennington (2011).

The above mentioned is consequent with the opinion of NFF (2009), where is emphasised that pre investigation must be as extensive as possible, in order to ensure that the best engineering choices are being made (i.e.: tunnel alignment, optimum rock cover, selection of excavation methods), and in this way reduce the risk during the construction phase. NFF (2009) also highlights that even though an extensive pre investigation plan may be executed, there is always a probability that actual conditions are less favourable than expected. Therefore, pre investigation must be always evaluated in a conscious and realistic manner, in order to avoid excessive optimism in the planning & design phase. NFF (2009) emphasises that the optimistic interpretation of pre excavation investigations implies the execution of exceptional measures during the construction process and it will increase the costs during the project execution.

The geological investigations to be carried out during the tunnel development may be categorised as function of the time when they are performed. According to NFF (2009) the geological investigation may be organised into the following categories:

4.2.1 Feasibility Pre Investigation

The main objective of the pre investigation at the feasibility phase is to provide the basis for a geological assessment of the expected conditions to be encountered during the tunnel execution, considering different tunnel alternatives. Relevant aspects to be analysed are: feasible tunnel alignments, minimal tunnel overburden, main joints and potential fault zones. The minimum investigations to be considered at this stage are:

i. Analysis of previous Geological Investigations
ii. Analysis of Aerial Photographs
iii. Geological Mapping (scale 1: 5.000)
iv. Soil Cover Analysis (when is possible)

4.2.2 General Plan Pre Investigation

At the general plan is expected to provide the basis for the selection of the definitive tunnel alignment. The investigation should include the revision of all the information previously collected and following information must be added or updated:

i. Topographic Maps and Aerial Photographs (scale 1:5000 – 1:1000)
ii. Soil Cover, Type, Thickness and Depth
iii. Rock Boundaries and Geology of the On-Shore Areas
iv. Bedding and Foliations
v. Joint Pattern (Density, Orientation)
vi. Weakness Zones
vii. Hydrology and Hydrogeology
viii. Quality of the Rock
ix. Geophysical Investigation
x. Core Drilling and other Borehole Investigations

After the plan investigation is carried out and the geological model has built up within sufficient confidence, the pre investigation may be focused on performing more detailed and supplementary information that allow the project organisation increase the level of confidence and enter into the tendering process. During the tendering process all the information collected as well as the owner interpretation of these deliverables must be incorporated in the geological report that is incorporated as part of the tender documents.

In undersea tunnel projects, a relevant role is played by seismic refraction and reflection, which are commonly used for determining potential fault and weakness zones. Directional cost drilling from the shore side are typically used to reach and assess the critical and deepest points, which is typically related to major fault zones in undersea tunnels.

According to NFF (2009), the pre investigation carried out during the feasibility and planning phase should provide sufficient information regards the geological model in order to predict time and project schedule, project cost, tunnelling prognosis, rock support and grout estimates. Nevertheless, it is also emphasises that a sensible assessment of the cost must be done, when designing the investigation plan. This assessment implies that the reduction in the project uncertainty must be higher that the actual value and efforts related to the execution of the investigations.

4.2.3 Construction Investigation

Once the actual excavation of the tunnel is carried out, field investigations continue at the tunnel face. Construction investigation constitutes a core piece of information for the decision making process regarding other tunnelling activities, highly dependent, of the actual rock or soil conditions encountered at the tunnel face. The measures related to the water control and the definitive rock support should be assessed and decide, considering the actual parameters measured at the tunnel face. Some relevant information to be registered at the face rock mapping is as follows:

i. Rock Stresses and Strength
ii. Q Values
iii. Lugeon Value

4.3 The Tunnelling Process

As the tunnel project progress in its cycle, different processes are executed in order to develop the basic concept and obtain more realistic approximation of the project scope. All the information collected as part of the geological investigation is integrated, as valuable input, in the engineering & design and project management processes. The deliverables of both will help decision makers to decide the project execution or its cancellation. More details about the planning and design activities for tunnelling projects are given in *Appendix C*.

Once the decision to build the tunnel is done, the execution phase starts and involves the execution of a large quantity of support and construction activities (e.g.: topography, mobilisations, facilities). It is also, at this phase, when the actual excavation of the tunnel is performed through specific activities, defined in this work as the tunnelling process.

The tunnelling process is defined in this work as the execution of four (04) different activities, which are as follows:

i. Excavation
ii. Ground Water Inflow Control
iii. Rock Mass Support
iv. Tunnel Lining

The activities related to the tunnelling process are highly sensitive to disturbances generated by geological and construction uncertainties. Therefore disturbances, generates in the tunnelling process, affect relevant project criteria such as: cost, time or safety. According to Isaksson (2002), the main reason of this high level of sensitivity to disturbances is due to serial nature of the tunnelling process, which is basically due to the by the following constraints:

i. Limited capacity to change workplace location
ii. Limited capacity to perform parallel activities

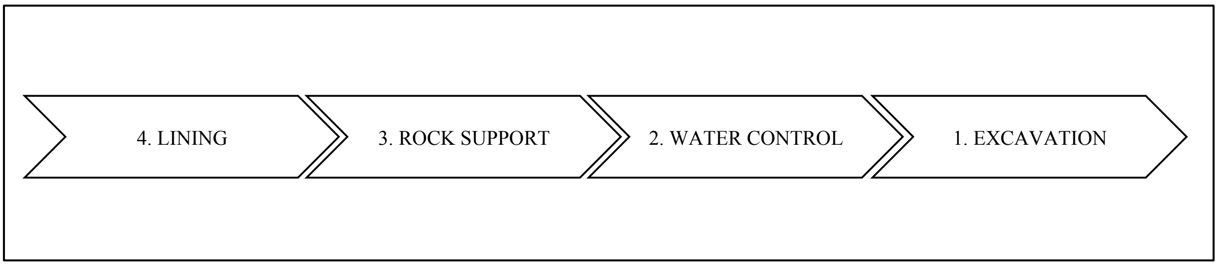

Figure 4.3: Tunnelling Process as a Serial Process. In the left hand side of the process is the excavation process, following for the water control and rock support activities. The lining process is performed as the last activity of the tunnelling process (source: the author).

Figure 4.3 shows the main group of activities that conform the tunnelling process. It is worth mentioning that the serial nature of this process is a rough representation of a very complex process, where several sub process and activities take place and may be to some extent overlapped. This figure depicts all the activities that are required as part of the tunnelling process, which does not include the execution of other activities related to the final deliverable, such as road and pavement structures, ventilation, and other operational systems.

As emphasised by Pennington (2011), all these activities are affected for different sources of uncertainty and risk, therefore it is relevant to understand the main features of each of them, in order to assess the risk that may be involved during its execution and the effects that they may bring to the total tunnel cost.

The following sections are dedicated to describe these tunnelling activities or processes and the main methods and technologies that may be carried to perform these activities.

4.3.1 Excavation

Excavation is the process that removes the rock or soil in order to execute and obtain the actual tunnel. Excavation methods for underwater tunnels do not differ from those used in standard underground projects. According to (Pennington 2011), the primary methods used to excavate underwater tunnels are the following:

i. Conventional Method or Drill and Blast

ii. Mechanised Methods - Tunnel Boring Machines (TBM)

On the light of this work, the excavation process considers the scaling, loading, hauling and other activities that allow continuing the excavation process at the tunnel face.

Figure 4.4: Typical construction face of drill and blast tunnelling, this picture correspond to the construction phase of Grønnlia Tunnel (source: NPRA (2012))

4.3.2 Ground Water Inflow Control

The water inflow control may be considered as part of the excavation process, or as part of the preliminary rock support, nevertheless it has been considered relevant to describe separately. This decision is supported in the high preponderance that water control activities have for both construction and operation of underwater tunnels.

According to NFF (2005) the water control in underground structures is basically due to the following reasons:

i. To prevent an adverse internal environment during the construction and operation of the tunnel
ii. To prevent unacceptable impact on the external surrounding environment
iii. To maintain hydrodynamic containment

Since the water inflow should be considered infinite in underwater tunnels, the first objective is the most relevant. According to NFF (2011), the control of water inflow may be performed by applying the following techniques.

i. Pre grouting
ii. Post grouting
iii. Infiltration
iv. Face Water Freezing
v. Water and Frost Protection
vi. Drainage and Water Pump

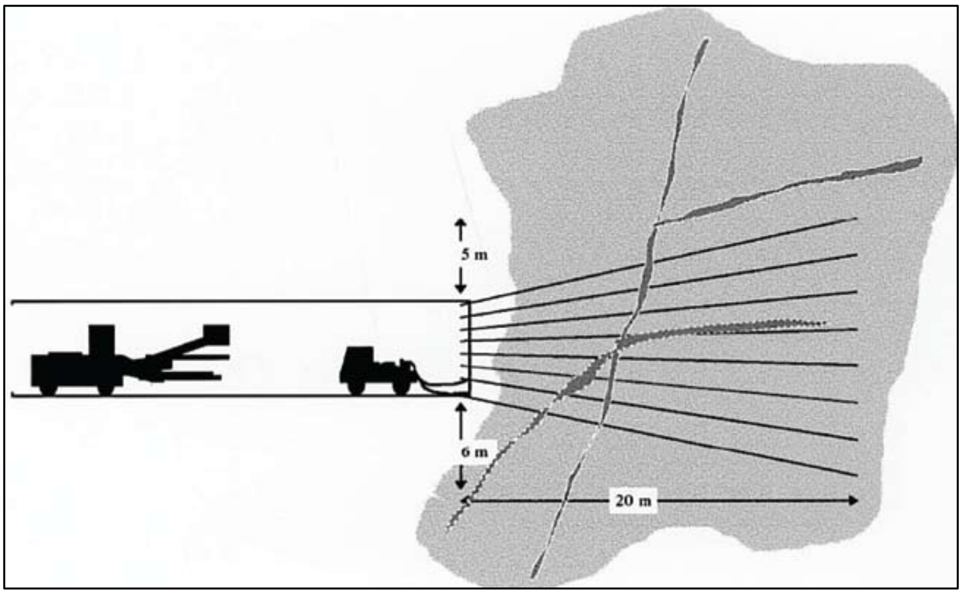

Figure 4.3: Water Control through Pre-grouting. The figure show the principle of pre-grouting cut off, which is performed a head of the excavation activities. According to NFF (2011), this represents a highly efficient system to control the water inflow and it must be systematically executed, when required due to the specific hydrogeological conditions (source: NFF (2011)).

4.3.3 Rock Support

Rock support is the process where the rock mass is stabilised by different means that eventually contribute to achieve a new equilibrium condition in the modified rock or soil mass. According to NFF (2010) the rock support is basically controlled by two conditions: mechanical properties of the rock mass and the safety conditions required for the tunnel construction and operation. NFF (2010) emphasises that rock support is executed as a combination of the following conditions:

i. Competence
ii. Available Site Investigations
iii. Normal Practices
iv. Actual Observations about Rock Conditions during Excavation

According to NFF (2010), rock support includes both preliminary (i.e.: at the work face) and permanent measures (i.e.: heavy rock measures). Preliminary support is carried out in order to provide a safe work environment for the excavation process and it is carried out as part of every single round at the tunnel phase. The main methods used to perform the rock support at the tunnel face are as follows:

i. Spilling and Radial Bolting
ii. Pipe Screens
iii. Injections
iv. Jet Grouting
v. Face Freezing

The definitive rock support is performed behind of the tunnel face and it is not necessary for the continuity of the excavation works, yet it is necessary to provide the structural equilibrium in the tunnel face, which ensure the required level of safety for construction and operation of the facility. NFF (2010) divides the heavy rock support, according to the rock conditions that may be expected the tunnel alignment, where the following categories are highlighted:

i. Rock Spalling Situation
ii. High Rock Tension
iii. Rock with Swelling Clay

In order to control the conditions mentioned above, the following support methods are introduced in NFF (2010):

i. Sprayed Concrete
ii. Reinforced Ribs of Sprayed Concrete (RRS)
iii. Sprayed Concrete Ribs with Lattice Girders
iv. Sprayed Concrete Arcs

According to NGI (2013) the categorisation for permanent rock support can be done according to the level of stability expected in the rock mass (i.e.: Q-Values) and required level of safety in the excavation (i.e.: excavation support ratio, ESR). The possible combinations for rock support, obtained after applying the Q Method are as follows:

i. Unsupported
ii. Spot Bolting
iii. Systematic Bolting and Reinforced Sprayed Concrete
iv. Systematic Bolting, Reinforced Sprayed Concrete and Reinforced Ribs (RRS)
v. Cast Concrete Lining (At the face, Behind the Face)

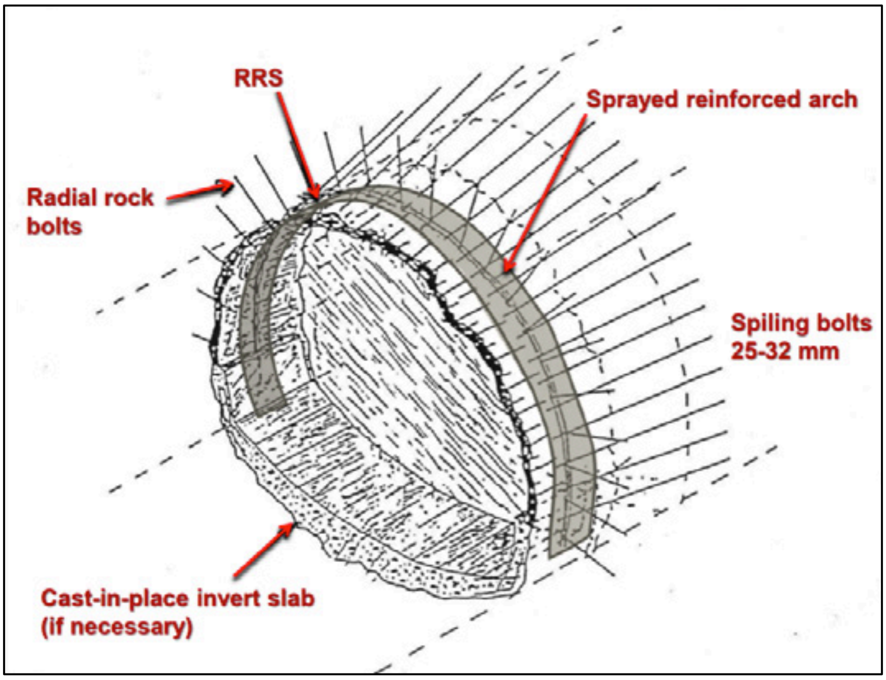

Figure 4.6: Combined Rock Support Principle. The figure shows a combination of methods that can be executed, when rock conditions require a high level of rock supports. This principle presented in NFF (2014) considers: spilling bolts, executed ahead of the excavation round, radial bolts, executed after the excavation round, and the RRS, which are executed after the radial bolts.

4.3.4 Tunnel Lining

Tunnel lining is required when the tunnel section passes across weak zones with heavy rock fall, massive swelling zones, highly crushed rock, and zones with water leakage problems.

As presented by NFF (2010), and under certain rock mass conditions or specific construction strategies, tunnel lining based on in situ concrete lining may be also considered part of the definitive rock support. Similarly, tunnel lining can be considered as part of the water control system, and the structural design can be considered drained or not drained. Contrarily, and even though rock mass and hydrogeological conditions are favourable, tunnel lining might be considered as part of the operational requirements in specific road or railway projects.

Tunnel geometry, soil/rock loads and hydrostatic pressure are relevant parameters to define the final lining design in undersea tunnels. Depending on the construction method, the tunnel lining may be categorised in the following types:

i. In situ Concrete Lining (reinforced and unreinforced)
ii. Pre-casted Concrete Lining (reinforced and unreinforced)

According to NFF (2005), the tunnel lining system may also includes, depending on conditions, the use of impermeable sheets of polyethylene foam located in the tunnel wall and roof.

Figure 4.7: An In Situ Concrete Lining Framework (source: www.ninive.it 28.04.2014).

More details about the concepts presented in section 4.2 "Geological Investigation" and 4.3 "The Tunnelling Construction Process" are given in *Appendix C*.

4.4 Uncertainty and Risk Factors in Underwater Tunnel Projects

As indicated in the introduction of this chapter, undersea tunnels represent in many senses a special and risky class of underground and heavy construction projects. Therefore, it is particularly relevant to analyse and understand the major risk factors that affect the planning and construction processes, which eventually will affect the project cost estimation and the actual cost of the project.

4.4.1 Geological and Hydrogeological Aspects

A remarkable difference, between conventional and undersea tunnels, is the high and complex interaction between the water body and rock mass underneath. This represents one of the biggest challenges, during both the pre investment and construction phases.

In undersea tunnels, both geological and hydrogeological aspects represent extraordinary sources of risk that may contribute in the occurrence of undesired events affecting the project objectives. Some aspects, highlighted by NFF (2009) and Pennington (2011) that should be carefully analysed during the early project phases (i.e.: feasibility, and planning & design) are as follows:

i. *Weakness and Fault Zones*: these represent the most relevant source of risk; therefore, their identification is crucial for the project results. This must include the characterization of the gouge material; especially in those aspects regard water sensitivity (e.g.: active swelling clay as montmorillonite).

ii. *Water Inflow*: the potential of water inflow in undersea tunnel is infinite; therefore a reliable prognoses model must be stated as soon as possible, in order to determine the expected volume of water and its control measures. The high pressure and chemical aspect of the water inflow must be also analysed and considered in the design activities. As previously highlighted in this chapter, the control of water inflow is critical for achieving a good level of advance rate (i.e.: construction performance), but it also relevant for the efficiency of the operation phase of the subsea facilities.

iii. *Type of Soil and Rock*: this aspect also represents a source of risk that may highly influence the project results. Hard and soft soils will require different mechanisms and techniques to perform the tunnelling process, including excavation, water control, rock support and lining.

iv. *Instability Areas*: high stresses zones and poor rock conditions, which may lead in stability problems, such as cave-in during the excavation activities, squeezing or rock spalling, must be identified and measures to avoid it must be taken forehand.

4.4.2 Design and Construction Aspects

Most of the decision regards design (i.e.: engineering), construction and project management aspects are made upon information obtained from the pre-construction and construction investigations. Given the random and epistemic uncertainty that this information has, project organisation should manage in a sensible manner this information, in order to minimise the impacts during the construction phase and in project objectives, such as safety, time, and cost.

Since decisions are based on uncertain basis, Pennington (2011) emphasises that decisions should be considered as a specific risk aspect that eventually will influence one ore more project objectives. Some specific decisions regards design and construction aspects that may be assessed using this approach are as follows:

i. Tunnel Alignment
ii. Construction or Excavation Method
iii. Rock Support Method
iv. Water Control Method
v. Type of Contract

4.4.3 Operational Aspects

Operational requirements must not be disregarded respect risk, and they must be included, as part of the design and construction activities. Some relevant operational aspects that should not be neglect are among others:

i. Safety Requirement
ii. Tunnel Water Tightness
iii. Flood Control
iv. Tunnel Ventilation

4.4.4 Key Aspects for Managing Project Risk in Undersea Tunnel Projects

The successful completion of undersea tunnels in Norway and other countries have allowed to establish a group of measures and lessons learned that will help project organisations (i.e.: project owner, sponsors, contractors) to better manage the development of new undersea tunnel projects.

The following measures are proposed by NFF (2009) and Pennington (2011), in order to manage the sources of risk previously discussed in section 4.4.

i. *Pre-Construction Investigations*: as in other underground projects, pre-construction investigations are crucial for the project success. A sufficient, cost efficient, and coherent pre –construction investigation plan must be developed throughout the project phases, in order to assist the decision making process and the other processes required for the tunnel development (e.g.: engineering design, cost estimation, tendering). According to NFF (2009), pre-construction investigations for undersea tunnels must include geological, engineering geological, geotechnical, hydro-geological and geophysical investigations (e.g.: seismic reflection and refraction). A systematic classification of the rock mass (e.g.: Q system) is highly recommended for quantifying the engineering behaviour of the rock mass under interest.

ii. *Construction Investigation*: a continuous follow-up of pre-construction investigations must be carried-out during the whole tunnel execution. This process must register the actual rock and water conditions found in the excavation tunnel face and analyse respect to the expected conditions. This information may be used for updated the model previously used and in this way prepare updated versions of project documents (e.g.: drawings, specifications, risk register) and incorporate the required changes in contracts and other commercial documentation.

iii. *Risk Management Implementation*: the awareness and readiness for being prepared for unexpected conditions and events during the tunnel execution are also key factors that may contribute to better project implementation. This must be done through a systematic implementation and incorporation of risk management, as part of the project activities.

iv. *Quality Assurance and Quality Control*: this program must be implemented during all the project phases and activities, considering its execution from the early pre-investigations, engineering design, construction and commissioning. The quality assurance and control may help obtaining better project performance and better project deliverables.

v. *Parties Collaboration and Co-Operation*: all the previous measures may not influence the project success if the parties involved do not collaborate to each other and co-work. Project owner, engineering consultant and contractors must integrate their expertise and knowledge in order to obtain better manage the risk regards the project development and obtain better results.

vi. *Sharing Risk*: A fair distribution and allocation of the project risk is essential for the success execution of undersea tunnels. No matter the extent of pre-investigations, the risk will be always present in these projects. Therefore owner and contractors must base their commercial relation on flexible contractual tools that allow introducing the required changes, while maintaining a fair distribution of the parties' liability.

5. COST MODELLING FOR UNDERGROUND PROJECTS

This chapter aims to provide a specific insight about previous researches undertaken in the specific field of cost estimation for tunnelling projects. The model selected to be part of this chapter have been carefully analysed and described, emphasising its basis and fundamentals, the modelling processes (i.e.: input, tools and outputs), the results, as well as the most relevant conclusions and findings obtained in these works.

The first section is focused on describing four (04) models to predict cost of underground projects by stochastic approaches. The models, described in subsections 5.1.1 to 5.1.4, were found relevant examples to be analysed, in order to set the basis for the proposed model. Another four (04) stochastic models for cost estimation are described in *Appendix D*, which have not been included in this chapter.

The second section is devoted to describe the prognoses models developed by NTNU. This prognoses model represents a powerful tool to estimate excavation performance and cost for both: Drill and Blast and Mechanised (i.e.: TBM) methods, especially during the early project phases. The NTNU model is a practical model, which reflects the large experience of the tunnelling industry in Norway.

The last section summaries the most relevant geological parameters that influence the construction activities related to the tunnelling process, which are later incorporated in the proposed model for cost estimation.

5.1 Previous Works on Stochastic Cost Modelling for Underground Project

5.1.1 Model for Estimation Cost and Time in Tunnelling based on Risk Analysis

Isaksson (2002) developed a probabilistic model for cost and time estimation based on risk evaluation for tunnelling projects. This author argues that deterministic cost estimation of underground project does not provide sound basis for decision-making, due to its incapacity to incorporate risk. Therefore, the implementation and use of models that incorporate specific tunnel project risk, such as geological risk, may overcome this situation and improve the decisions made.

Isaksson (2002) emphasises the need to differentiate between normal and extraordinary risk factors. The normal risk factors are defined as *"factors causing deviation in the normal time and cost range"*. According to Isaksson (2002), normal risk factors are related to performance and construction issues (e.g.: quantity variations, deviations in the advance rate, price variations), and they may be described by continuous probabilistic distributions.

On the other hand, the exceptional or undesirable events are defined as *"event that causes major and unplanned changes in the tunnelling process"*. This class of events are more related to geological and hydro geologic conditions (e.g.: tunnel collapses, failure and weakness zones, which are more related to geological and hydrogeological conditions). The exceptional risk events may be defined as non-continuous events (i.e.: discrete distribution), and they are characterised by a small probability of occurrence, but large effects over the project objectives, therefore they should not be neglected.

Isaksson (2002) emphasises that by differentiating the risk a reasonable distribution of the parties' liabilities and responsibilities may be achieved, which may also contribute to minimise disputes and contract claims. Experiences from tunnel construction have demonstrated that the major change of cost are caused by factors that were not considered during the early estimations, due to their small probability of occurrence.

This model is based on the argument that different risk factors have different impacts on project objectives and organisations, therefore a clear differentiation between normal and exceptional risk events must be stated for achieving a better distribution of responsibilities and liabilities among project parties (e.g.: owner, engineer, and contractors). It is also emphasised that risk differentiation may help to improve the basis for the decision-making process in tunnelling, especially in those decisions regard project investment and selection of excavation method.

In order to model the tunnel time and cost, Isaksson (2002) introduces first a theoretical model, in which the normal and exceptional time and cost are estimated separately by statistical and mathematical expression. Secondly, the practical model aims to provide guidance for the application of the theoretical model in both owners and contractors involved in tunnelling projects.

Firstly, the theoretical model introduces the concept of production effort, which is defined as *"time consumption for excavating a tunnel unit with a certain method"*. This parameter is the inverse function of the advance rate and it was selected by Isaksson (2002), given its practical and easy use for cost and time estimation. According to the theoretical model, the normal time and cost is expressed as function of the production effort (denominated as "Q"), which is considered as a random variable that depends of the geotechnical conditions existing along the tunnel alignment. Similarly, the total production effort is obtained as the total add of all the production efforts along the tunnel length.

Isaksson (2002) emphasises that geotechnical characteristics vary along to the tunnel length to one point to another, representing a high level of uncertainty in its assessment. Since uncertainty about geotechnical aspects trend to be high, they are best represented as random variables, which are fully dependent on the specific section that is analysed.

Isaksson (2002) represents all these relations, as stochastic functions, and proposes specific expressions for the expectation (E (y)), and standard deviation (σ_y) of the production effort (y). By considering other statistical relations, Isaksson (2002) also gives specific expressions for the mean total production effort (E(Q)) as a function of the total tunnel length (L), and its standard deviation (σ_Q). Applying the central limit theorem, the total production effort (Q) is considered as a random variable normally distributed ($Q = N(m_Q; \sigma_Q)$) and the total normal cost (C_N) is estimated by a differential equation, in which all the variables are met.

As previously presented, Isaksson (2002) emphasises that exceptional cost (C_E) is caused by the occurrence of undesirable events. Undesirable events may occur due to machinery failure or geological failures, which lead in high consequence on the project cost and time. In order to assess the probability of occurrence of undesirable events, Isaksson (2002) uses Boolean Variables, which eventually help to determine the specific cost for a given undesirable event (C_{ek}) and the total exceptional cost (C_E) expressed as the sum of all undesirable events. Finally the total tunnel cost is represented as the sum of normal and exceptional cost.

Initially, the practical model addresses the modelling of normal variation of cost and time, which are dependent of geological aspects along to the tunnel length. In order to facilitate the cost estimation, Isaksson (2002) proposes to discretise the total tunnel length (L) into different geotechnical zones (with specific length: l), where geotechnical conditions are considered to be similar and the same excavation method is expected to be used. As results of this discretisation, the specific normal cost and time for each geotechnical zones is determined considering the length of each specific zone as a constant (l).

One challenge to be overcome is the assessment of the geotechnical characteristic of each zone and Isaksson (2002) emphasises that the use of previous data in similar project and conditions may helps to achieve this. In case of none data available subjective estimations based on expert opinion have to be made in order to feed the model.

After normal cost and time have been determined, undesirable events must be assessed. Isaksson (2002) proposes a division of the extraordinary events, which include the following classes: production dependent geological events, randomly occurring (geological), randomly occurring (mechanical failures), randomly occurring (gross errors) and miscellaneous.

According to Isaksson (2002) the implementation of systematic risk management activities (i.e.: risk identification and risk analysis) may help to identify and assesses relevant risk events that may affect the project time and cost. The total extraordinary time and cost are estimated as the summation of the cost and time for all the identified undesirable events. Finally, the total cost and time are calculated as a function of normal and exceptional cost and time by applying Monte Carlo Simulation (MCS).

The model proposed by Isaksson (2002) was applied in the Grauholz Tunnel in Bern, Switzerland. The author applied the model for different construction methods and different level of robustness, which were defined as low, high and actual. Isaksson (2002) defines the level of robustness as the total set of measures that are taken, for a given excavation method, in order to improve its construction performance (i.e.: advance rate) and consequently it has a correlation with the expected total cost and time. The simulations included all types of undesirable events.

The results related to project cost are shown is Figure 5.1. This figure shows the comparison among the three different scenarios included in the simulation. Distribution 1 represents the expected cost for a low degree of robustness, while curve 2 and 3 represents a high and actual level, respectively.

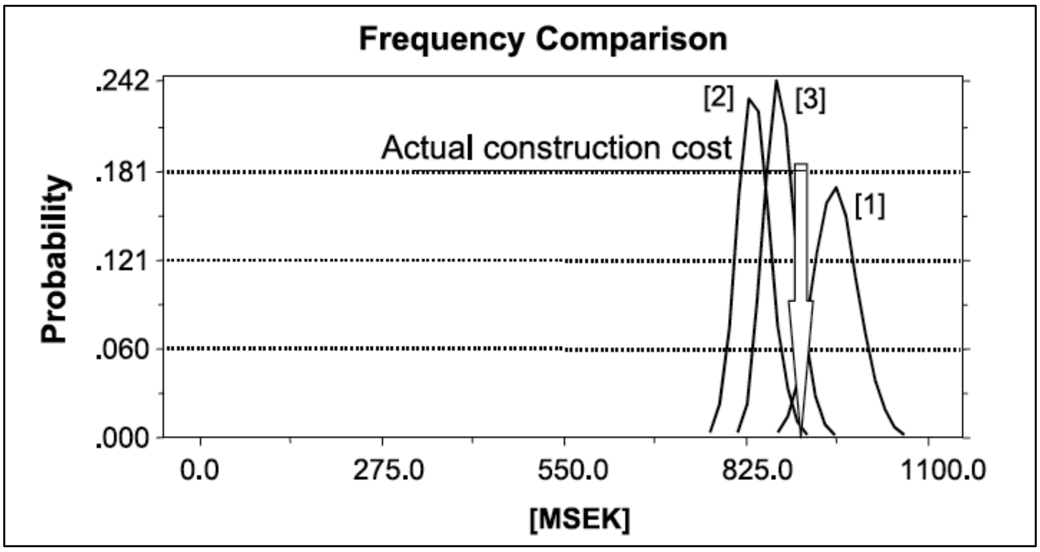

Figure 5.1: Project Cost Estimations obtained by Isaksson (2002). Curve 1 represents the project cost considering a low degree of robustness. Curve 2 represents the cost with a high level of robustness, while Curve 3 represents the actual level implemented at the project execution (source: Isaksson (2002))

According to the results depicted in Figure 5.1, the actual project cost (i.e.: around 900 MSEK) exceed the model estimation made for a high level of robustness (distribution Nº 3), which was estimated in 870 MSEK. This difference may be caused for the late introduction of robustness measures regards the selected excavation method. In the same line, Isaksson (2002) underlines that the early implementation of robustness measures appears to be a profitable decision, since the project cost reduction is higher than the specific cost of the implementation of such as measures.

Some aspects affecting the results, and highlighted by Isaksson (2002) as part of this conclusions are as follows:

i. Correlations among geotechnical characteristic have major effects in the shape of the final distribution of time and cost (i.e.: after simulation is performed).
ii. The number of undesirable events considered in the estimation will affect the total expected value of the project.
iii. The selected excavation method and its different configurations will affect the expected project cost and time.

iv. The level of robustness applied also affects the expected cost and time

Finally, Isaksson (2002) emphasises that the proposed model is realistic and applicable in real projects. It is also accentuated that the differentiation of normal and extraordinary risk may contribute to the transparency of the results and a better allocation of responsibilities among the project parties.

5.1.2 Correlated Probabilistic Analysis of the Excavation Time and Costs in Tunneling

Oreste (2006) introduces a probabilistic model for analysing construction time and cost of tunnelling called PACT (probabilistic analysis of cost and time in tunnelling). In agreement with the previous research work, Oreste (2006) recognises the need to estimate cost and time in tunnelling projects by probabilistic approaches, considering time and cost as two probabilistic and intercorrelated variables.

PACT delivers statistical estimation of excavation cost and time, considering probabilistic ellipses with a certain degree of reliability. This model is based on the discretisation of the tunnel length into homogeneous sections, where cost and time elements are described in analytical terms. The main inputs of PACT are probabilistic variables (i.e.: construction times advance rate), which are described by Gaussian distributions (using the mean and standard deviation of the variables). According to Oreste (2006), the outputs of this model provide an effective comparison of different tunnel alternatives, which eventually allows decision makers to select the most favourable solution, in terms of cost and time, within an acceptable level of reliability.

The geological modelling of PACT is based on the identification of mining and support classes in each of the homogeneous sections defined in the tunnel length. The identification of mining and support classes leads to "excavation classes", where specific configuration respect to mining scheme, support requirements and organisation of the construction activities are determined.

Considering the above, Oreste (2006) reduces the geological problem to define specific excavation classes in each of the homogenous section of the tunnel. After doing this, specific parameters are defined in analytical terms. The parameters required by the model are as follows:

i. Times of each site operation
ii. The mean velocity of advance
iii. The overall time to progress in each excavation class
iv. The quantity of material per unit length in each excavation class
v. Other cost, including materials, personnel, equipment depreciation and fixed cost

The above parameters are expressed by multivariable functions, where tunnelling operations (e.g.: borehole drilling, tunnel support, among other) are described as a function of all the basic activities (i.e.: elemental parameters or activities) that are required to perform the specific operation.

Considering all the activities required to complete the excavation process and the specific excavation class, the cost per tunnel meter in each zone may be assessed. The elemental parameters (e.g.: drilling velocity, explosive loading time) are treated as random variables, with a normal distribution. A final joined probabilistic analysis allows assessing the standard deviation of cost and time and the correlation coefficient between cost and time. The main steps of this model may be summarised as follows:

i. Definition of Tunnel Geometry (i.e.: section, length and depth)
ii. Characterisation and zoning of the rock mass, based on geomechanical and lithological characteristics
iii. Definition of the mining classes in homogeneous section of the tunnel, based on geomechanical and lithological features
iv. Support dimensioning and definition of the support classes in homogeneous section of the tunnel, on the basis of geomechanical aspects (e.g.: Q Value)
v. Definition of the excavation classes in homogeneous sections of the tunnel, based on mining and support classes (considering the previous iii and iv)
vi. Definition of the site operation and determination of the construction time for each excavation class, this is made by specific formulas proposed by Oreste (2006)
vii. Determination of the unit cost and cost for each excavation class, which are function of quantity of material and prices
viii. Determination of the total times and the total costs of the tunnel
ix. Definition of the variability intervals of each single uncertainty parameter
x. Joined probabilistic analysis of the total time and cost,
xi. Analysis of the required level of reliability

The PACT was applied by Oreste (2006) to evaluate construction time and cost of a 6.3 km enlargement tunnel in Italy. This tunnel was excavated in calcareous schist and geomechanical characteristics of rock mass were available (i.e.: RMR and uniaxial compression strength) for different sections of the tunnel.

According to the geological conditions of the project 6 excavation classes were defined and along the tunnel. During the application of the model, 95 elementary parameters were considered, while 25 parameters were considered as probabilistic variables. These variables were described by the mean value and standard deviation (i.e.: normal distributed).

Additionally these variables were analysed, in terms of its partial derivatives respect total time (T_{tot}) and total cost (C_{tot}). Oreste (2006) emphasises that this analysis help to understand which parameters have the maximum effect on the uncertainty of cost and time estimation. The partial derivative analysis allows establishing the time and cost covariance and the correlation coefficient, which is a measure of the sensitivity of the variables in the final output (i.e.: tunnel cost and time).

The results regarding construction cost, represented as a probabilistic distribution function, are depicted in Figure 5.2. The expected total cost for the tunnel was estimated in 80.500.961 € with a standard deviation of 4.567.231 €. The distribution for the tunnelling time resulted in a mean duration of 1.779 days with a standard deviation of 115,8 days.

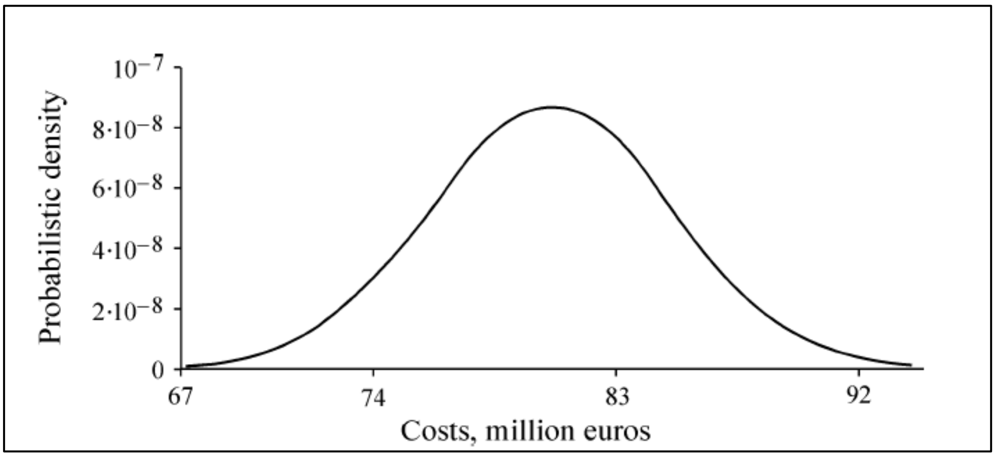

Figure 5.2: PAC Model Output. The Final Cost Estimation of the Project is represented as a Probability Density Function (PDF), which presents a mean value of €80.500.961. (Source: Oreste (2006)).

Since the correlation coefficient for total time and cost is known, as well as the level of required reliability, the model also provides the joined probability function for cost and time. Figure 5.3 depicts the obtained probabilities ellipses, considering two different levels of reliability, which were set at 90% (red) and 80% (green).

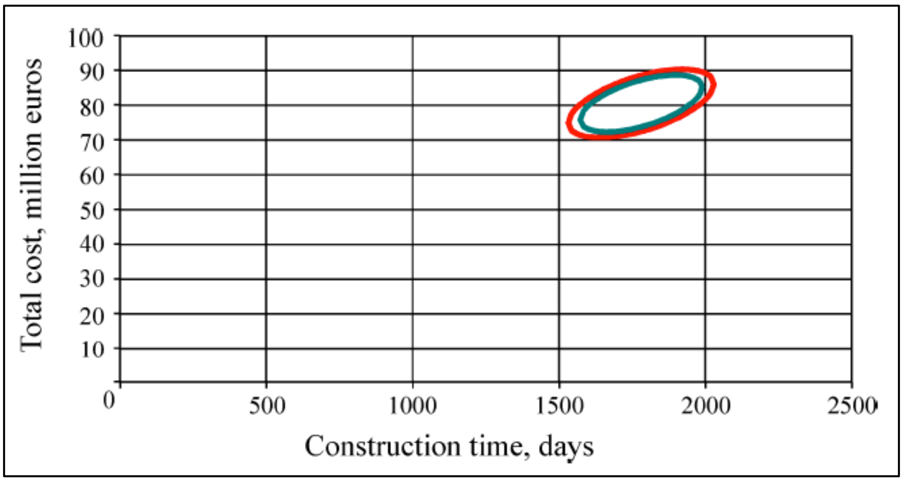

Figure 5.3: PAC Model Output. The Final Cost Time Estimation of the Project is represented as Probabilities Ellipses for two distinct level of reliability. (Source: Oreste (2006)).

According to Oreste (2006) this model allows to set different hypothesis for the tunnel execution (e.g.: different number of machines, shifts, different equipment), which helps project organisations (e.g.: project owners and contractors) to choose the best execution solution, in order to minimise cost and time execution.

5.1.3 Cost Estimation of Large Construction Project with Dependent Risks, A Study on the Brenner Base Tunnel

The research developed by Tamparopoulos (2013) introduces a model for cost estimation with dependent risk variables that was applied on the Brenner Base Tunnel. This model is based on the Probabilistic Cost Analysis (PCA), which is a stochastic approach for cost estimation, where risk factors are considered as individual cost elements.

According to Tamparopoulos (2013) PCA offers several advantages over traditional deterministic methods, which often yield in underestimation of the project cost. PCA allows the use of both quantitative and qualitative information obtained from experts, which may help estimators to reflect the complexity and uniqueness of the project.

This model (i.e.: PCA) involves the development of four main groups of activities, which are as follows:

i. Determination of cost elements and value assessment
ii. Representation of the cost element by specific probabilistic density functions (PDF)
iii. Determination of the dependencies and correlation among the cost elements, and
iv. Integration of the total cost by simulation process (MCS).

According to Tamparopoulos (2013) the first activity of the process is extremely relevant, since it offers the possibility to obtain information from expert, which in many cases may help to overcome the lack of information existing during early project phases. Additionally elicitation of expert knowledge allows reflecting the complexity and uniqueness that exist in specific projects. Tamparopoulos (2013) emphasises that knowledge elicitation involves vagueness, specially in the assessment of the boundaries (e.g.: minimum and maximum values), consequently, the author proposes to perform a "calibration process", which may help estimators to obtain unbiased values based on the existing information and well structured theoretical framework.

To sustain the selection of probability density function (PDF) for the specific cost elements (i.e.: steps Nº 2), the author reviewed and analysed several probabilistic distributions, such as: Uniform, Triangular, Beta, Trapezoidal, Normal, Lognormal, and Weibull. According to Tamparopoulos (2013), each of the reviewed distributions posses advantages and disadvantages, from theoretical and practical point of view, therefore this may be a difficult task to be executed. The author also emphasises that each distribution represents different challenges regarding the collection of information and statistical handling. Tamparopoulos (2013) recognises that the selection of a specific distribution is a highly controversial matter, especially when boundaries represent a sensitive and critical piece of information for decision-makers. Finally, the author selects the Beta distribution to represent individual risks, which according to his opinion, gives a high degree of flexibility respect to the required attributes (i.e.: unimodal, finite range, shaped), especially in those regard low and upper bounds modelling (i.e.: modelling extreme values).

The third phases related to the determination of the dependences of the cost elements, which is usually simplified for cost estimators, trends to be complex and even more relevant than the selection of the distribution (PDF). According to Tamparopoulos (2013), this is a fact that cannot be neglected and oversimplification must be avoided in models where the focus is on "safer" values (i.e.: upper quantiles), such as the model based on PCA.

Tamparopoulos (2013) emphasises that the treatment of dependence must be done combining deterministic and statistical approaches. In order to overcome the challenges regard the correlations among model variables, Tamparopoulos (2013) uses Kendall's Tau for measuring association between pairs of risk (i.e.: cost elements) and the Gaussian Copula for modelling the dependences structure of the total model of cost.

The author highlights that even though, probabilistic density function (PDF) for each cost element are defined, and the correlation among cost elements are duly established, the total cost of the project cannot be obtained straightforward by the simple summation of the single cost elements. Therefore, the total cost must be calculated by complex simulation techniques, such as Monte Carlo Simulation (MCS), which requires the uses of specific softwares and powerful computational means. MCS allows estimators to obtain specific distribution regards the total cost, in which several scenarios may be evaluated, in order to obtain reliable, realistic and valid results.

In order to understand the differences and effects of correlations, the model was run considering two scenarios: fully correlated variables and full independence among cost variables. Figures 5.4 and 5.5 show the results for both cases, where is possible to observe that mean values of expected costs do not vary in a large extent, nevertheless bigger differences are presented in the cost spread (i.e.: standard deviations). While, the full corraleted case, shown in figure 5.4 , has a mean value of 540 M€ and a standard deviation of 65,5 M€, the full un-corraleted case presents the same mean value (i.e.: 540 M€) and a standard deviation of 54,2 M€.

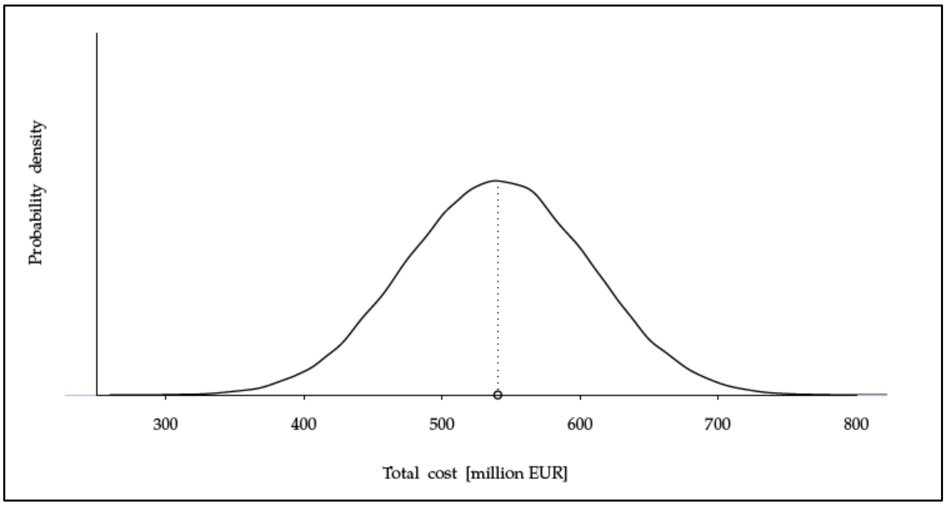

Figure 5.4: PCA Output. The Estimated Cost for Full Correlated Variables is shown as a specific Probabilistic Density Function (PDF) witn mean value of 540 M€ and standard deviation of 65,5M€.

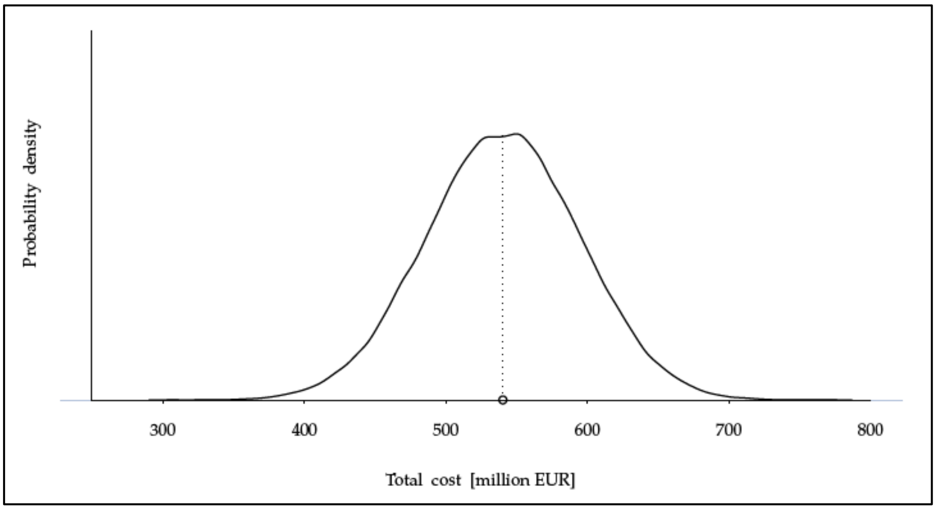

Figure 5.5: PCA Output fot Estimated Cost for Full Un-correlated Variables is shown as a specific Probabilistic Density Function (PDF) witn mean value of 540 M€ and standard deviation of 54,2 M€.

According to Tamparopoulos (2013), these results may be explained due to the following reasons:

i. Unrealistic determination of minimum values it was set in zero)
ii. Large epistemic uncertainty, implies highly skewed distributions, which eventually lead in long tails for low probabilities
iii. Large number of dependencies remains unassessed in the preliminary project phases

As part of the conclusion of this work, it is recognised that probabilistic cost analysis is a complex process, where verification and validation measures must be applied, in order to obtain results that may be analysed with a certain level of confidence. This level of confidence must represent the phenomenon of interest with a degree of accuracy consistent with the intended use of the model (e.g.: decision making process).

Additionally Tamparopoulos (2013) emphasises the critical importance of the information confined in expertise and experience of project experts and the methodologies that allow incorporating this information, in an unbiased way, into the model for obtaining realistic project cost estimation.

In this sense, PCA provides a flexible tool that can be updated as new information is obtained regard specific cost elements. Finally, the author highlights that the final outcome of the process (i.e.: cost estimation) is clearly affected by the epistemic and aleatory uncertainties regard projects, therefore evaluation of the credibility of these estimates must be performed for those interested in this information.

5.1.4 Probabilistic Assessment of Tunnel Construction Performance based on Data

The study performed by Spackova, Sejnoha et al. (2013 a) presents a probabilistic model for cost estimation in tunnelling projects. This model is based on the Dynamic Bayesian Network (DBN), which allows estimators to incorporate data obtained from past projects.

The model developed by Spackova, Sejnoha et al. (2013 a) is limited to the prediction of conventional tunnel method (i.e.: drill and blast), and it includes the execution of the following activities: excavation, mucking, and the primary support (i.e.: bolts, steel ribs and sprayed concrete). According to Spackova, Sejnoha et al. (2013 b) construction methods, support patterns and construction – tunnelling cost depend primarily of several factors that may be summarised as follows:

i. Geological and hydrogeological conditions
ii. Tunnel requirements (i.e.: geometry, overburden, operational constraints)
iii. Quality of the planning & design and construction phases.

It is also highlighted that the real construction process is affected by 3 main sources of uncertainty, which are categorised in the following groups:

i. Geotechnical Uncertainty
ii. Construction Performance Uncertainty
iii. Extraordinary Risk

According to the authors, all these sources of uncertainty must be analysed and incorporated, when estimating cost and time. In order to incorporate this elements in the time and cost estimation, Spackova, Sejnoha et al. (2013 a) develop a model based on Dynamic Bayesian Network (DBN), which is suitable for modelling stochastic processes. In the model, all the uncertainties presented above are described as a set of random variables. The level of detail in each of these groups must be balanced and consistent among them, this means that a detailed geological model does not necessarily lead in accurate results, if construction performance is not detailed at the same extent. The generic process considers the execution of the following steps.

i. Modelling Geotechnical Uncertainty
ii. Modelling Construction Performance
iii. Modelling Extraordinary Events
iv. Selection of the Segment Length
v. Evaluation of the DBN

The geotechnical modelling considers the analysis of geological and hydrogeological conditions of different zones of the tunnel. These zones are considered to have homogeneous properties (e.g.: lithological and geomechanical); therefore the parameters are modelled as constant in each zone or as a homogeneous stochastic process (i.e.: variables may be describe through continuous probabilistic distributions). A specific variable summarise the parameters selected, which is denoted as “ground class”. In each ground class is expected to use the same excavation technology and strategy.

The construction performance is modelled using variables related to tunnel geometry, construction method (i.e.: excavation and support pattern), unit time and human factors. Tunnel geometry as well as construction methods are defined deterministically, while unit time (i.e.: inverse function of advance rate) are described as random processes, and its distribution may be assessed by previous data or expert judgment.

According to Spackova, Sejnoha et al. (2013 a), extraordinary events are defined as events with large effects. Examples of extraordinary events are cave-in collapses, tunnel flooding or public obstruction to the project development, which eventually represents failures in the construction process. In the opinion of Spackova, Sejnoha et al. (2013 a), this class of events are dependent of ground classes and human factors and may be described by a specific failure rate function.

The segments length of the tunnel are represented by slices of the DBN, where it is assumed that conditions can only changes among different segments, but not in the same segment. This also implies that the conditions are fully dependent within each segment. In each segment, it is assumed that time and cost are independent. In order to keep the assumptions made, the authors decided to set the segment length in 5 metres (i.e.: $\Delta l = 5$).

Finally the evaluation of the DBN establishes the marginal probability distributions of the selected variables regard time and cost. This is performed using specific inference algorithms, which may vary from simple to very complex, according to the features of the variables under analysis.

In order to assess the tunnel performance, Spackova, Sejnoha et al. (2013 a) propose three different categories: Normal Performance, Small Disturbances, and Extraordinary Events. By considering statistical data from previous and on going project, the researchers assessed the statistical behaviour of each performance category.

The unit time (T), which is the required time for excavation a segment of the tunnel, represents the performance under normal and small disturbances. This parameter was analysed from data collected in several project in the Czech Republic. The unit time is considered to be dependent of construction method and it is modelled as a stationary random process. Using the law of total probability, the expected value of T is estimated for a specific segment length (Δl). The unit time was assessed for different sequencing of the tunnel heading, which also include a correlation analysis. As a result of the statistical analysis of the Unit Time, the researchers presents and specific probability density function (PDF) and cumulative density function (CDF), which fit with the data available.

Extraordinary events were also analysed as part of this research. Firstly, Spackova, Sejnoha et al. (2013 a) analyse the delay caused by a single failure. They assume that extraordinary events causing major delay may often be described by a shifted exponential distribution. By analysing the data provided by Sousa (2010) and specific fitted distribution (D_k) is proposed by the authors. Secondly, they analyse the failure rate per unit length (λ) of the tunnel tube.

The results of the application of the model are shown in Figure 5.6, where is possible to observe that the mean value for the excavation time is equal to 197 days, with a standard deviation of 38 days. The result depicted as total time (T_{tot}) considers the effects of extraordinary events and does not show big differences with the cumulative time, which excludes extraordinary events. This small difference in the mean value is according to the authors, due to the small probability assign to the occurrence of extraordinary events; nevertheless the standard deviation shows a larger spread when comparing both scenarios.

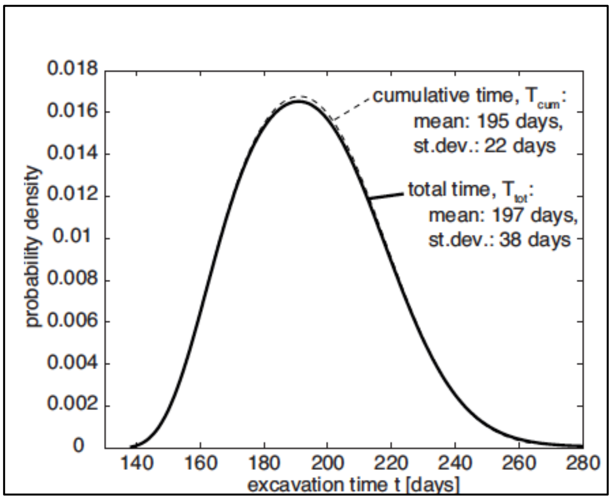

Figure 5.6: Cumulative Density Functions for Excavation Time. The continuous line represents the total time (i.e.: including extraordinary events) and dotted line represents the time, excluding the occurrence extraordinary events.

The conclusions of this research emphasise the relevance of using data from previous projects in order to obtain more realistic cost and time estimates. It is also emphasised the need to combine statistical inputs with expert knowledge, which may help to better describe the variability in the construction performance and the effects of small and extraordinary events.

5.2 NTNU Prognosis Model

The Norwegian University of Science and Technology (NTNU) has systematically collected large quantity of information regards the tunnelling development in Norway. This information encompasses geological, construction performance (i.e.: time) and other management aspects, which have served as the main basis to develop specific prognoses model for different excavation methods and other tunnelling activities (e.g.: rock support)

These models constitute a systematised approach to assess and evaluate the tunnelling activities, especially in the following aspects regards the decision making process.

i. Economic Dimensioning
ii. Choice of Alternative (i.e.: tunnel alignment)
iii. Time Planning
iv. Cost and Tender Estimates
v. Choice of Excavation Method and Equipment

These prognoses models can be considered a deterministic means, since model inputs and results are represented by single values. Most of the outputs are determined graphically, using different plots provided in these models, which help estimators to obtain in a simple and straightforward manner early estimations of performance and cost for tunnelling activities.

As previously introduced, these models have been developed, considering large quantities of data, collected in the Norwegian tunnelling experience. The systematic approach to data collection may be considered one of the most relevant strength of this model. As indicated in NTNU2B-05 (2006), the results obtained by this mean may be considered representative of well-defined and structured tunnelling operations. This implies that singularities and other relevant aspects of the specific project must be duly treated and incorporated in the results obtained by this model.

The following sections (5.2.1, 5.2.2, and 5.2.3) introduce the main features regard the prognosis model developed by NTNU for Drill and Blast, TBM, and Tunnel Rock Support, respectively, emphasising those aspects related to cost estimation. More detailed information regards these three models are presented in *Appendix E "NTNU Prognosis Model"*.

5.2.1 NTNU Drill and Blast Tunnelling Model

The last version of the NTNU Drill and Blast Prognoses Model was submitted in 2007 and it is composed by three reports, which are as follows:

i. Drill and Blast Tunnelling, Blast design (2A-05)
ii. Drill and Blast Tunnelling, Advance Rate (2B-05)
iii. Drill and Blast Tunnelling, Costs (2C-05)

The model has been built and updated, considering data from several tunnelling project performed in Norway and it considers the latest advances in equipment and method up to the issue date of these reports. Data incorporated in the model was normalised and it is representative for a well-organised tunnelling process. The cost model presented in report, NTNU2A-05 (2006), considers the following items with regard to the drill and blast tunnelling process:

i. Elemental Cost
ii. Total Construction Cost

The first group of cost (i.e.: elemental cost) includes the following group of activities.

i. Drilling, charging and scaling
ii. Loading
iii. Hauling
iv. Additional Works
v. Labour
vi. Niches

The Elemental Cost are estimated based on the assessment of two geological parameters (i.e.: drillability and blastability), and the combination of other inputs regards tunnel geometry, excavation equipment, and materials. In general terms, elemental cost includes all the required cost to obtain the basic tunnel, without considering tunnel road (i.e.: pavement structure), installations, systems and other tunnel facilities.

It is worth mentioning that elemental cost does not consider risk related to the tunnel execution, therefore the final estimation is corrected using a specific correction factor, which has been set as 10%. A final correction is also required, which depends of the cost index published by the Institute of Civil and Transport Engineering of NTNU. The correction of the elemental cost by these two parameters allows obtaining the standard tunnelling cost (i.e.: elemental cost corrected by unforeseen events and price level).

On the other hand, the total construction cost includes all the remaining cost required to perform the tunnelling activities and it considers the following items.

i. Work Site Operations & Cost, Mobilisation and De mobilisation
ii. Project Planning
iii. Project Administration
iv. Interest during the construction and interest rate

v. Standard Tunnelling Cost

It is worth mentioning that the total construction cost does not include costs regard road pavement, traffic signs, and other technical installation applicable for road tunnels and it must be also corrected by unforeseen events, which in this case is specifically set as 7%.

In this manner the NTNU prognoses model, described in NTNU2A-05 (2006), allows project organisations to obtain a reasonable estimation of the investment regard the execution of a tunnel project, which may be used, as complementary source, during the early project stages to assess the decision making process.

5.2.2 NTNU Hard Rock Tunnel Boring Model

The last update of this report was submitted in 1998, and it is built up in the following reports related to hard rock tunnel boring.

i. Hard Rock Tunnel Boring, Design and Construction (1A-98)
ii. Hard Rock Tunnel Boring, Advance Rate and Cutter Wear (1B-98)
iii. Hard Rock Tunnel Boring, Costs (1C-98)
iv. Hard Rock Tunnel Boring, Geology and Mapping (1D-98)
v. Hard Rock Tunnel Boring, Performance Data and Back-mapping (1E-98)
vi. Hard Rock Tunnel Boring, The Boring Process (1F-98)

As well as the Drill and Blast Prognosis Model, the main objective of these reports is to provide sounds basis for assessing the construction performance and cost for rock excavation and tunnelling, during the early project stages.

The model considers data from 35 different job sites and it compromises more than 250 km of tunnel performed in Norway and abroad. The data involved in this report was systematised and normalised, being representative of a well-structured tunnelling process. The model, presented in NTNU1C-98 (1998), considers the following cost items regards to the excavation process:

i. Normalised Cost
ii. Total Construction Cost

Following the same criteria than the previous model, the normalised cost includes all the activities required in order to obtain the basic tunnel structure and it compromises the following items.

i. TBM Assembly and Disassembly
ii. Boring
iii. Back Up Equipment

iv. Muck and Transport
v. Other Cost
vi. Labour Cost

As well as in the Drill and Blast Model, the TBM normalised cost must be corrected by unexpected conditions (10%) and adjusted for the respective price increase. Finally the estimation of normalised cost must be corrected by the efficiency factor, which reflects the variation in aspects such as productivity, project location, climatic conditions, among other factors. The main inputs used in the estimation of the normalised cost are tunnel length, TBM diameter, net penetration rate, number of cutter, among other specific inputs.

The total construction cost for TBM is estimated using the same principle than the previous models, and consequently it represents all the items required to perform the construction activities, including at least the following items.

i. Site Preparation
ii. Site Operations
iii. Tunnel and Other Construction Works
iv. Planning and Management of Owner
v. Planning and Management of Contractor
vi. Interest Rate during Construction
vii. Unforeseen Events (set as 7%)

5.2.3 NTNU Tunnel Rock Support

The NTNU Tunnel Rock Support model is the least updated model, among this series of reports, and it was submitted in 1991, considering the following reports.

- Tunnel Rock Support, Bolting (10A-91)
- Tunnel Rock Support, Shotcrete (10B-91)
- Tunnel Rock Support, Concrete Lining (10C-91)

These reports are submitted in Norwegian language, where each report contains the technical and cost aspects for each specific support method.

The cost regards rock bolting, introduced in NTNU10A-91 (1991), is given as function of bolting method (i.e.: at the face or behind the face), bolt length, bolt types, and times (i.e.: bolting performance). The cost estimation is given in NOK/bolt and it considers direct and additional cost regards down times during the execution of the tunnelling activities. The cost estimation excludes other cost such as planning, administration and unforeseen events.

For the shotcrete or sprayed concrete method, presented in NTNU10B-91 (1991), the cost is divided into two main categories, which are manually and mechanical sprayed. For each of these categories a second categorisation is done, respect of the addition and content of fibres in the concrete mix. The cost for these activities is given in NOK/m2 and it considers the direct and additional costs regard shotcrete activities, nonetheless other cost such as administration, planning and others cost, such as unforeseen cost, are not included as part of the estimation.

Finally the cost for full concrete lining, introduced NTNU10C-91 (1991), is given as function of the concrete thickness, cross-section, and lining method (i.e.: at the face or behind the face), and the values are given in NOK/m. As in the previous models, the estimation considers direct and additional cost, and it does not includes other indirect cost such as planning, administration and others not specifically specified as included.

Unfortunately the prognoses models developed by NTNU do not consider yet, a specific model for water control during the tunnelling activities, which is a critical activity to be considered as part of the cost estimation process, due to this high influence for the construction performance and for the final operation of the tunnel facilities.

The next section of this chapter describes the most relevant geological aspects that affect the tunnelling process, and it will try to set those aspects that may work as cost driver for the tunnelling activities.

5.3 Variables Affecting Cost of Tunnelling Process

As heretofore presented, large number of variables may affect the construction performance and cost of the tunnelling process. These variables may belong to diverse groups of aspects, such as geological, hydrogeological, construction and even organisational aspects, having different level of influence in the final cost of the tunnelling process. Furthermore, each of these variables represents a distinct level of uncertainty and risk that may affect the project objectives, and should be considered, when analysing the expected cost of tunnelling activities.

These variables may be considered deterministic or stochastic and they may be represented as independent variables of a vector that describes a specific attribute of the tunnel project (e.g.: tunnelling cost, total project cost, execution time) that are considered the dependent variables.

Considering the above, the cost of the tunnelling activities may be described as a function, which depends on several random variables (x_i) and other constant or deterministic parameters (a_i). This approach to the tunnelling cost estimation is originally presented in Isaksson (2002), where the cost of tunnel activities is represented by the following expression.

$$C_T = f\,(x_1;\, x_2;\, x_3;\, a_1;\, a_2)$$

Since this work is focused on the cost estimation of undersea tunnel projects, and especially on estimate the total cost of tunnelling activities, the next sections are focused on introducing those parameter that may better describe the tunnelling process, as well as the random and epistemic uncertainty of the geological and construction performance aspects.

5.3.1 Variables Affecting the Drill and Blast Excavation Process

The performance of the drill and blast excavation process is governed by a large group of variables, which is not possible to describe in detail in this report. These variables belong to different tunnel aspects, such as lithological (i.e.: type of rock), geomechanical features of the rock mass, and other specific design aspects (e.g.: tunnel length, section, among others) that eventually influence the unit cost of this process, NTNU2B-05 (2006).

According to NTNU2B-05 (2006), it is possible to state that the excavation cost is basically governed by the efficiency of two main sub processes, which are namely: the drilling and blasting activities. The drilling process is basically controlled by the equipment capacity and rock mass properties. Both aspects may be measured through the "Drill Rate Index" (DRI), which is obtained from the Brittleness Value (S_{20}) and the Siever J Value (SJ), NTNU2B-05 (2006).

Table 5.1: Different Classification of Rock, according to Drill Rate Index (source: NTNU2B-05 (2006)).

Classification	*DRI*	*Rock Examples*
Good Drillability	65	Micha Scist
Medium Drillability	49	Granite
Poor Drillability	37	Gneiss

As shown in Table 5.1, different level of drillability may be assigned to singular type of rock. This must be considered relevant, since this correlation between rock type and drillability may help to assess during the early phase the suitability of the rock for the drill and blast process.

Regards the blasting process, this is basically controlled by geological aspects, such as, mechanical strength of the rock, degree of jointing, density of rock mass, and anisotropy of rock mass. All these characteristic of the rock mass can be assessed using the Rock Blastability Index (SPR). This parameter also will control other sub process regard the tunnelling excavation, such as: hauling, loading and mucking.

Several aspects influence the Blastability Index (SPR) some of the most relevant are anisotropy, density, mineralogy and degree of rock fracturing. As in the Drillability Index, different type of rock may have distinct levels of blastability; Table 5.2 shows examples of good, medium and poor level of SPR.

Table 5.2: Different Rock Classification, according to the Rock Blastability Index (source: NTNU).

Classification	***SPR***	***Rock Examples***
Good Blastability	0,38	Coarsed-grained Granites, Synite, and Quartz Diorites
Medium Blastability	0,47	Gneiss
Poor Blastability	0,56	Methamorphic Rock, such as Mica Schist

The previous parameters may be considered the basic geological inputs for the cost model developed by NTNU and previously described in section 5.2.1, which provides sound basis to assess construction performance and cost, when tunnelling is performed in “normal” rock conditions. When poor rock conditions are faced, another parameters, which take into account the rock mass quality (e.g.: Q-Values), must be analysed and incorporated, in order to correct the results obtained by the NTNU model.

On the line of more advance research on the relation of rock mass quality and tunnelling performance, Kim and Bruland (2009) analysed the variation on advance rate and time construction for different Q-Values. The results show that gross advance rate (i.e.: the meter excavated per week) may decrease around 50% for Q-Values from 10 to 0,01. Since advance rate and cost are extremely correlated, the variation of Q-Value must be duly analysed when analysing of tunnelling cost.

Larger effects of Q-Value in the tunnel time and cost are also emphasised by NFF (2014), where important increment are suggested as a consequence of extraordinary low Q-values. Figure 5.7 shows the results obtained as result of the research performed by Barton et al (2001).

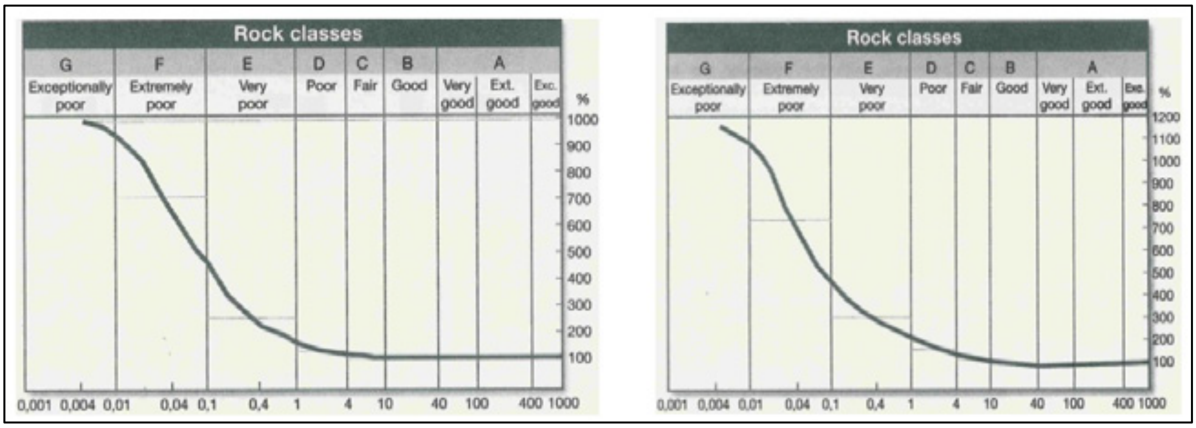

Figure 5.7: Effects of Q-Value in excavation performance, left hand side, and excavation tunnelling cost, right hand side (source: (NFF 2014)).

5.3.2 Variables Affecting the TBM Excavation Process

According to NTNU1B-98 (1998) the TBM performance is controlled for several rock mass and machines parameters, which are depicted in Table 5.3. As presented in this table, the performance of TBM may be summarised as function of the Net Penetration Rate and the Cutter Wear, where many of the rock mass and machines parameters are considered.

Table 5.3: Rock Mass and Machines Parameters affecting the Net Penetration Rate and the Cutter Wear in TBM Excavation Method (after NTNU1B-98 (1998)).

Net Penetration Rate	
Rock Mass Parameters	***Machine Parameters***
Fracturing, frequency and orientation	Cutter Thrust
Drilling Rate Index	Cutter RPM
Porosity	Cutter Size and Shape
	Intalled Cutterhead Power

Cutter Wear	
Rock Mass Parameters	***Machine Parameters***
Cutter Life Index	Cutter Diameter Cutter Type and Quality Cutterhead Diameter
Contents of Abrasive Minerals	Cutter RPM Number of Cutters on the Cutterhead

The Net Penetration Rate (I_n) is defined as the metres tunnel bored per hour while the cutterhead rotates with thrust against the face. This parameter constitutes an important factor in the weekly advance rate of the boring machines, influencing at the same time the cutter life and the final excavation cost, therefore it is a core aspect to be assessed when analysing the use of TBM for tunnelling.

As presented in Table 5.3, the Net Penetration Rate and the Cutter Wear are affected by rock and machine parameters, some of them are briefly described bellow.

i. *Degree of Fracturing*: this is the most relevant parameter for tunnel boring, (NTNU1B-98 1998). The higher degree of fracturing in the rock mass will contribute to a greater penetration rate. The rock mass fracturing may be categorised in different classes, which is dependent of the distance of planes of weakness (measured in centimetres). This parameter is represented by the fracturing factor (k_s)

ii. *Rock Drillability*: this parameter is determined considering the Drilling Rate Index (DRI) and the Cutter Life Index (CLI). Different types of rock present distinct levels of DRI and CLI, consequently by assessing these values, it is possible to determine the rock drillability properties.

iii. *Rock Abrasiveness*: the abrasiveness is basically governed by the contents of quarts in the rock mass. This parameter can be measured from rock specimens, which must be representative of the tunnel location and it is highly influent in the cutter life.

iv. *Average Cutter Thrust:* this is one of the most relevant machines parameters and the larger thrust capacity the larger penetration rate may be obtained on the site. Since larger cutter thrust implies larger efforts in the cutters, this factor is also strongly correlated to the cutter life.

Reviewing NTNU1B-98 (1998), NTNU1C-98 (1998), NFF (2000), as well as other researches regarding TBM excavation method, it is possible to state that the tunnelling process based on TBM is extremely dependent on the actual geological conditions of the rock mass, resulting in a more complex process to be assessed. Since this report is focus on the estimation cost of drill and blast method, no more information is provided regarding TBM system.

5.3.3 Variables Affecting the Water Inflow Control Process

Hydrogeology aspects of the rock mass will govern the water inflow in a tunnel, and therefore it will also determine the efforts and resources (i.e.: time, material, equipment, cost) that must be applied in order to control this aspect. One significant feature with regard to water inflow is that will have major effects during both the actual tunnel excavation and during the operation of the tunnel facilities.

According to NFF (2005), one of the most important variables affecting the water inflow is the rock mass Hydraulic Conductivity (K), which depends on lithological aspect of the rock body, but overall on the features of the joints pattern of the rock mass. Typical values of rock mass Hydraulic Conductivity, according to NFF (2005) may normally be located in the range of $1*10^{-8}$ (m/sec) to $5*10^{-8}$ (m/sec). The target values to be achieved after grouting process is performed are close to $3*10^{-9}$ (m/sec).

Table 5.4: Quantitative and Qualitative Classification for Rock Mass Hydraulic Conductivity "K", according to NFF (2005).

Rock Mass Hydraulic Conductivity "K" (m/sec)				
Very Low	***Low***	***Moderate***	***High***	***Very High***
1,00E-09	1,00E-08	3,00E-08	5,00E-08	8,00E-08

The hydraulic conductivity of the rock mass (K) is difficult to predict during the pre investment phases, especially in the early phases of subsea tunnels, where the pre investigations rely heavily on seismic reflection and refraction, NFF (2005). Event though, seismic methods may provide an indication of potential location of water inflow zones (i.e.: lower velocities carry more water); they do not provide sound basis to assess expected water inflow and values regarding K. More over and as can be deduced from Table 5.4, values of hydraulic conductivity (K) reside in extremely low values, which eventually difficult the expert assessment process of this parameter, when required.

Besides of the difficulties encountered to assess the hydraulic conductivity of the rock mass (K), during the feasibility and planning & design phases, there are not researches that prove the correlation among others geomechanical rock parameters and material consumed during the execution of the water control activities (e.g.: quantities of grouting, surface of froze protection).

Morgan (2004) concludes that there is not a strong correlation between actual Q-Values and quantities of grout material used during the execution of water control activities. This conclusion was taken from a specific project (i.e.: JA1 Skaugum Railroad Tunnel in Norway), therefore this may be considered, but it must no be generalised or considered conclusive. Similar results are shown by NFF (2005) where not correlation was found between actual Lugeon Values measured on the field and used grout material (i.e.: cement).

Other important factor that influences the water inflow is the hydrostatic pressure existing at the tunnel contour. Due to the particular location of the tunnel structure, the hydrostatic pressure trends to be higher in subsea or underwater tunnels. Consequently, this parameter must be considered, when assessing the expected water inflow in the tunnel. According to NFF (2005), an specific formula, which consider the hydrostatic pressure can be used in order to related the Hydraulic Conductivity (K) and the potential expected water inflow (q). Table 5.5 shows specific values obtained for a given tunnel geometry (i.e.: tunnel radius) and a specific hydrostatic water pressure (i.e.: equivalent to h = 250 m).

Table 5.5: Expected Water Inflow "q", given different Hydraulic Conductivity (K) ranges and tunnel geometry (after NFF (2005)).

Rock Mass Hydraulic Conductivity "K" (m/sec)				
Very Low	***Low***	***Moderate***	***High***	***Very High***
1,00E-09	1,00E-08	3,00E-08	5,00E-08	8,00E-08

Expected Water Inflow "q" (lt/min/km)				
Very Low	***Low***	***Moderate***	***High***	***Very High***
20	203	610	1016	1625

5.3.4 Variables Affecting Rock Support Process

Rock Support is highly dependent of the actual rock mass quality that is being excavated. In this sense, rock mass quality specifically refers to the geomechanical properties and rock mass stability. Summarising, the rock support will highly depend on the self support capacity of the rock mass, this means that the final design of rock support must be done through comprehensive structural analysis, considering the actual rock conditions, safety requirements, and the geometry of the tunnel, NFF (2010).

Several parameters affect the stability of the rock mass, the most important according to NFF (2010) are as follows:

i. *Degree of jointing or block size*: this is controlled by the join pattern, join orientation and join spacing. The joint pattern of rock mass can be always identified at the surface and often 2 to 4 joint direction will describe the joint characteristic of the rock massif. Stability will generally decrease, when the number of joint set increase and the joint spacing decrease.

ii. *Joint frictions*: friction along the joints contributes significantly to the rock mass stability. Rough joints with little or not content of fill mineral (e.g.: clay) will present higher level of stability than smooth joints filling with soft material.

iii. *Rock Stress*: The relation between rock stresses (i.e.: tectonic and topographic) and rock strength will influence the rock mass stability. Moderate levels of rock stress are usually favourable for rock stability, while low stresses are usually unfavourable. The anisotropy on the rock mass will also influence the decision regards rock support.

One practical approach to determine the tunnel support requirement is the Q-Value, which is a description of the rock mass stability. The Q-Value may be determined from the earliest pre investigation (i.e.: geological mapping on the surface) or for more advance investigation performed during the planning and design phase (i.e.: core logging), NFF (2010). This offers a good possibility to quantify the rock mass stability, event during the earlier phase of the project.

Nevertheless, designers and engineer, involved in the project development, must be aware on the fact that Q-Values obtained during the pre-investigation or estimated from data (i.e.: values do not come directly from the underground opening or face mapping) involve a great level of epistemic uncertainty. Therefore, these values should be carefully applied in the design process, and only as a basis for the estimation of rock support, Palmstrom and Broch (2006). The Q-Value is determined by six (06) different rock mass parameters obtained during geological mapping. Depending on the Q-Values the rock mass can be classified in six (06) classes, which are depicted in the following table:

Table 5.6: Rock Mass Stability Classes, according to Q-Value (after: NFF (2010) and NGI (2013)).

Rock Mass Classification ***Rock Mass Stability***	***Class***	***Q-Values*** ***Minimum***	***Maximum***
Exceptionally Good		400	-
Extremely Good	A	100	400
Very Good		40	100
Good	B	10	40
Fair	C	4	10
Poor	D	1	4
Very Poor	E	0,1	1
Extremely Poor	F	0,01	0,1
Exceptionally Poor	G	0,001	0,01

Considering the values presented in Table 5.6, and one specific parameter regarding the tunnel spam, which is known as the Excavation Support Ratio (ESR), nine (09) support categories are defined, NGI (2013).

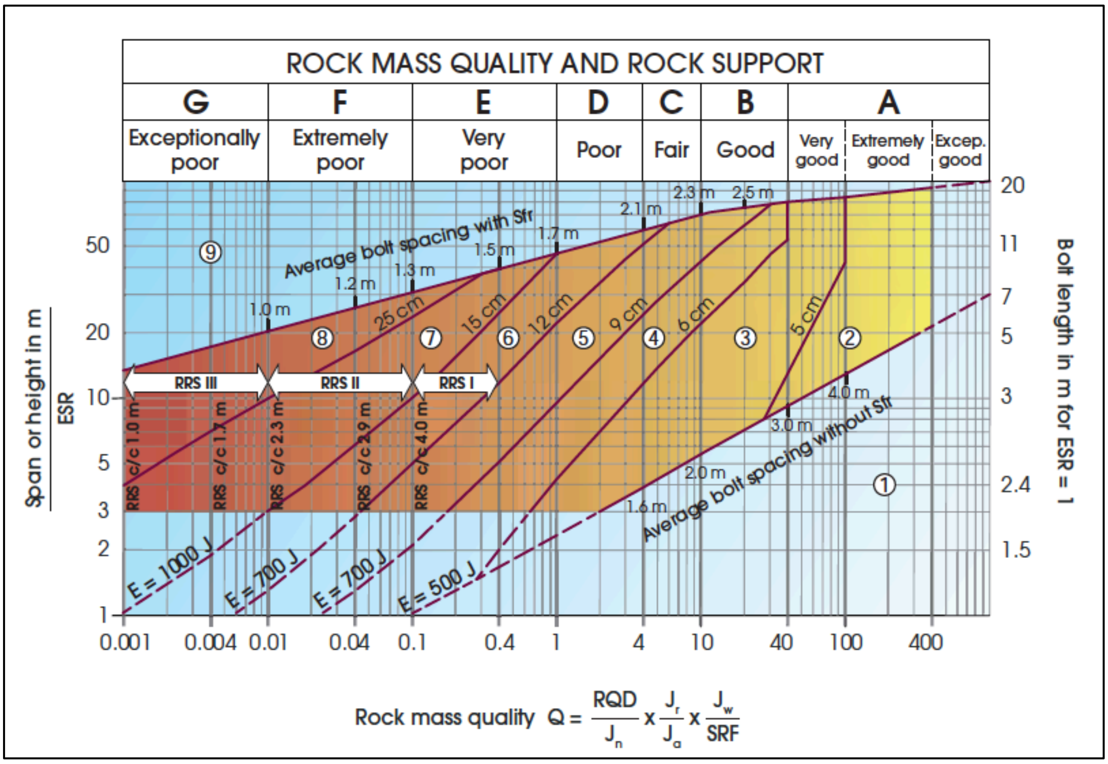

Figure 5.8: Q System for Rock Mass Classification and Rock Support (source: NGI (2013)).

5.3.5 Variables Affecting Tunnel Lining Process

As previously presented in Chapter 4, the tunnel lining may be considered as a specific measure for rock support, especially when extraordinary levels of rock instability are presented (e.g.: weakness zones, faults) or when high level of water inflow is presented. Consequently, the parameters and variables previously introduced and analysed for water inflow control (5.3.3) and rock support (5.3.4) process may be applicable for assessing the requirement related to the tunnel lining.

When the tunnel lining is a specific project requirement (i.e.: it is not optional), the lining requirement may be considered independent on the geological parameters, and this activity will be mainly controlled by technical specifications, such as material, concrete thickness, reinforcement, construction method (i.e.: at the face or behind the face) and the technology selected to carry out this activity (i.e.: cast on site or pre cast panels). Commercial aspects, such as material and labours prices will also influence the final cost of this activity.

6. THE PROPOSED COST MODEL

This chapter introduces the specific model developed by the author. The model has been built up, considering the most relevant aspects previously reviewed in the theory chapters, as well as standard knowledge regards probabilistic models and personal author's experience regarding cost estimation, and uncertainty and risk modelling.

6.1 Model Basis and Fundamentals

The main objective of modelling is to represent, as accurate as possible, a given process and simulate its outputs in a realistic manner, Tamparopoulos (2013). Therefore the complexity of the model may be understood as a direct function of the process under analysis and the purposes of the model. In this sense the proposed model aim to contribute, as a complementary tool, with more realistic estimations during the pre investment phases.

As presented in the theoretical framework, the cost estimation process for underground project is in reality a complex multivariable problem, where several random and deterministic variables that belong to different aspects are involved and interact to each other. The interaction among these variables contributes to create complex levels of dependency (i.e.: statistical correlation), which must be duly analysed, in order to better describe the process and obtain realistic outputs.

When considering the features above mentioned, the modelling process appears to be a challenging and demanding task itself, especially for complex project such as undersea tunnel projects, but also when considering the time frame established to perform this research work, which is about six months.

In order to overcome these difficulties, the proposed model introduces certain number of simplifications, which are duly described throughout this report, as well as in the specific appendixes. The simplifications, made in some particular aspects of the model, do not imply that these elements (i.e.: those simplified) are not relevant for the problem under analysis; consequently, simplifications must be understood as a specific need to achieve the objectives of this research project, within the mentioned time frame.

The general layout for the proposed model is shown in Figure 6.1, which contains the main components and sequence of activities that allow obtaining the total tunnelling cost, as well as the final cost estimation for a given undersea tunnel project (i.e.: project budget).

The area highlighted in blue corresponds to those aspects that are treated as part of the scope of this work, which are specifically related to the tunnelling process. In more specific words, the main efforts of this research were done in modelling the excavation, water control, rock support and lining processes, which is referred as the tunnelling process.

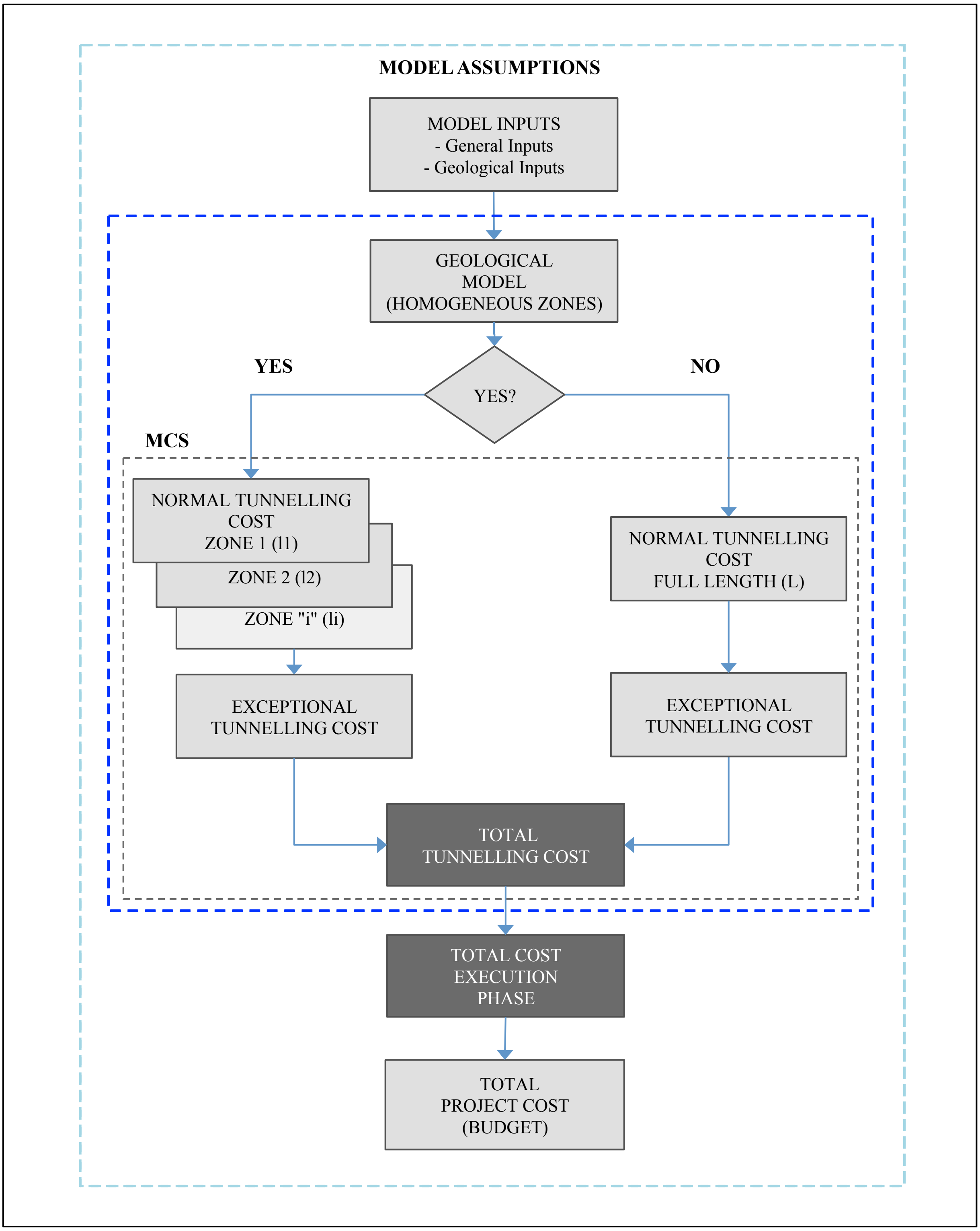

Figure 6.1: Stochastic Undersea Tunnel Cost Model Lay Out (source: the author)

As depicted in the model lay out presented in Figure 6.1, the cost model for tunnelling activities was designed, considering two main subsets of costs, which are namely the normal (C_{NT}) and extraordinary tunnelling costs (C_{ET}). Bearing on mind these two groups of cost, it is believed that the effects of uncertainty related to the geological and construction performance aspects, as well as, the effects of undesirable events may be better captured, quantified and incorporated in a single cost model.

Other aspects with regard to the total construction cost (i.e.: road structure, facilities, and tunnel systems), as well as those costs regarding field engineering and project management, during the construction phase, are not estimated in this model. Nevertheless Appendix H presents a proposed model for estimating the total project budget.

The following sections are devoted to describe the most relevant aspects of each of the model elements shown in Figure 6.1.

6.2 Model Assumptions

As previously explained, the proposed model considers some assumptions that are relevant to make clear, before describing the complete model. Potential model users are asked to carefully review these assumptions when applying the proposed model, as well as those specific prices considered in the model.

The assumptions are divided, according to their scope and applicability. The first group correspond to general assumptions that affect the complete model and cover a broader perspective. Specific assumptions are related to more detail information required to set the cost functions for each of the tunnelling activities.

6.2.1 General Assumptions

i. General aspects regarding the tunnel design are known (i.e.: length and required section).
ii. General information regards geological conditions is known (i.e.: geological profiles, lithology, and potential fault zones), consequently a basic geological model can be determined.
iii. General information regards the body of water and channel bathymetry are also known (i.e.: maximum and minimum tidal, and maximum depth).
iv. The unit normal cost of tunnelling activities may be derived using specific cost drivers and cost functions, which can be expressed as univariable equations.
v. The normal tunnelling cost (C_{NT}) represents the uncertainty related to geological and construction performance aspects.
vi. The extraordinary tunnelling cost (C_{TE}) represents the cost regards the occurrence of undesirable risk events with low probability and large consequences in the tunnelling process.
vii. A group of project experts is available for performing the assessment process.

6.2.1 Specific Assumptions

As previously explained, specific assumptions have been made regards each tunnelling process, in order to determined the specific cost functions. This specific assumptions are related to design and construction aspects, and further details about these assumptions may be found in *Appendix F "Cost Drivers for Tunnelling Process" and Appendix G "Cost Estimation Functions"*.

6.3 General Model Inputs

As highlighted in the model assumptions, general information regarding basic design aspects of the tunnel are known. The general inputs required for the proposed are shown in Table 6.1, where is specified the respective units and symbols used in the model.

Table 6.1: General Model Inputs, Values and Units

Input ID	***Input Name***	***Abbreviation***	***Model Values***	***Unit***
G.I.01	Total Tunnel Length	L	9000	m
G.I.02	Tunnel Section	S	67	m2
G.I.03	Unit (Tubes)	N	2	unit
G.I.04	Tunnel Class (According to NPRA)	Class	T9.5*2	NA

6.4 Geological Modelling

The geological model assumes that the total tunnel length (L) can be divided in "homogeneous zones" with specific length (l_n). It is assumed that in each homogeneous zone, similar values for the selected geological engineering parameters (i.e.: cost drivers) may be used. As depicted in Figure 6.1, if information, at the time of assessment, is not sufficient to divide the tunnel in homogeneous zones, the tunnel must be assessed as one (01) single zone (with total length $l_1 = L$), considering the average conditions expected in the tunnel alignment.

For each homogeneous zone, it is assumed that the same construction methods may be used to perform the tunnelling activities. This means that expected construction performance and unit cost (NOK/m) are considered to be identical for each homogeneous zone.

The determination of homogeneous zones is done based on lithology aspects (i.e.: type of rock) expected in the project location. The assessment of the geological parameters, required by the model, is done based on the specific type of rock determined for a specific homogeneous zone (i.e.: lithology). This simplification is justified in the fact that statistical data, collected during different projects and researchers, has demonstrated that specific values of geological parameters may be assumed for a given type of rock (i.e.: representative values).

It is believe by the author that the simplifications made in the geological model are suitable during the feasibility and planning & design phases (i.e.: pre investment phases). Nonetheless, these simplifications must be reviewed when more information become available and more advanced modelling can be achieved.

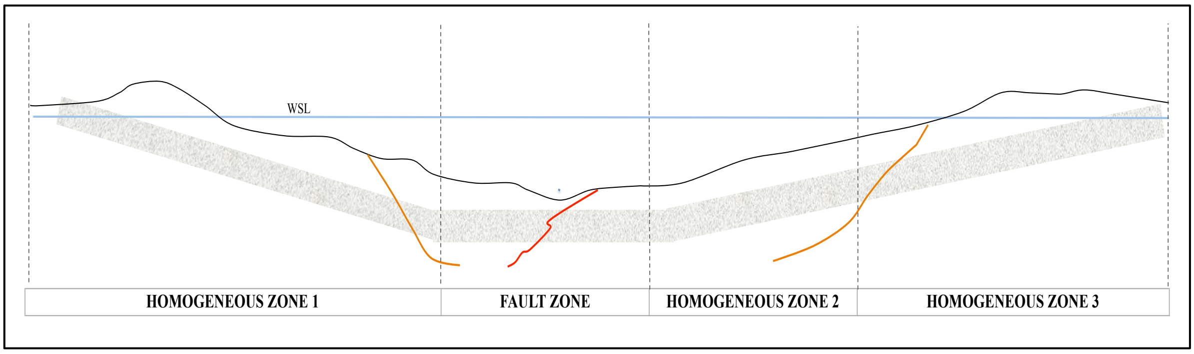

Figure 6.2: Simplified Geological Model for Undersea Tunnel Cost Estimation, each homogeneous zone represents distinct value of the geological parameters and the same construction methods may be executed.

6.5 Normal Tunnelling Cost (C_{NT})

The proposed model considers that the normal tunnelling cost (C_{NT}) may be determined as a function of geological and design parameters (i.e.: cost drivers). These cost drivers are able to capture the uncertainty regarding geological aspects and they are considered random variables that control the unit cost of the tunnelling activities. The activities considered as part of the estimation of the normal tunnelling cost are: excavation, water control, rock support, and tunnel lining.

For each of the tunnelling activities, the unit cost, expressed in (NOK/m), is determined using the specific cost drivers and cost functions described in sections 6.3.1 and 6.3.2 respectively. Once the unit cost for the activities is estimated, the tunnelling unit cost for a specific homogeneous zone "i" (UC_{Ti}) can be determined, using the following expression.

$$UC_{Ti} = UC_{Ei} + UC_{WCi} + UC_{Si} + UC_{Li}$$

Where:

UC_{Ti}: *Unit Cost of Tunnelling in the homogeneous zone "i"*
UC_{Ei}: *Unit Cost of Excavation in the homogeneous zone "i"*
UC_{WCi}: *Unit Cost of Water Control in the homogeneous zone "i"*
UC_{Si}: *Unit Cost of Rock Support in the homogeneous zone "i"*
UC_{Li}: *Unit Cost of Lining in the homogeneous zone "i"*

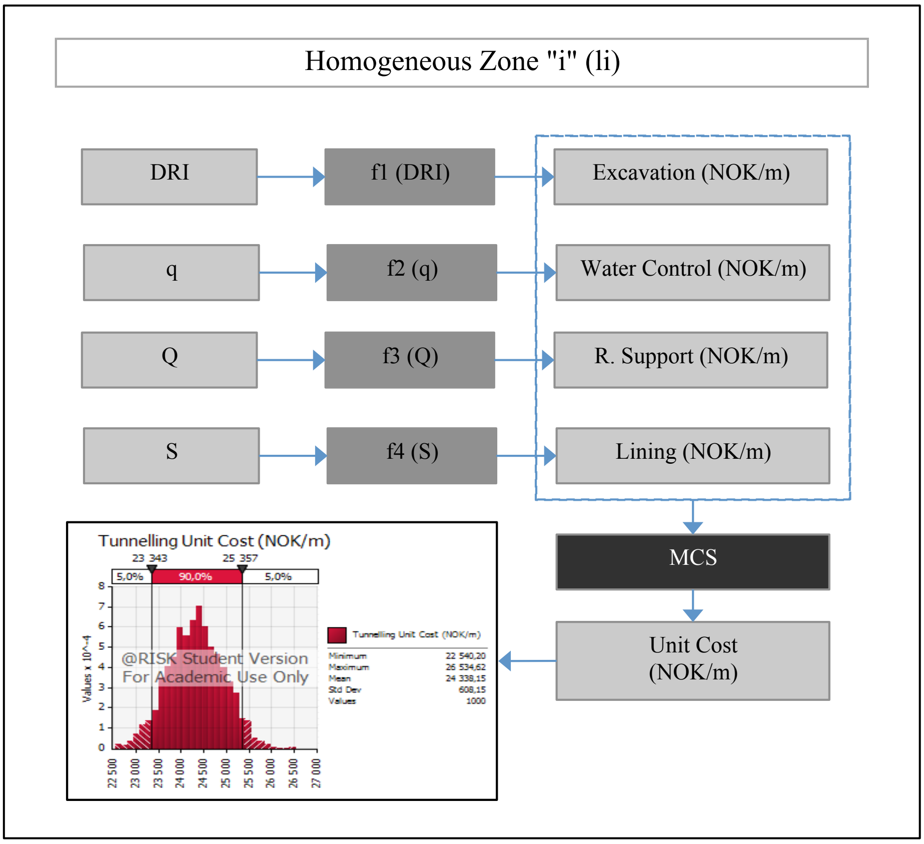

Figure 6.3: Normal Unit Cost for the Tunnelling Process in a specific homogeneous tunnel zone "i" (Source: the author).

As depicted in Figure 6.3, the determination of UC_{Ti} is performed through Monte Carlo Simulation (MCS) and it is carried out for each homogeneous zone, determined in the geological modelling. Once the unit cost for each homogeneous zone is estimated, the normal cost of tunnelling for a given zone (C_{NTi}) is obtained as the product between the zone length (l_i) and the tunnelling unit cost (UC_{Ti}).

$$C_{NTi} = UC_{Ti} * l_i$$

Where:

C_{NTi}: *Normal Tunnelling Cost for the homogeneous zone "i"*

UC_{Ti}: *Unit Cost of Tunnelling in the homogeneous zone "i"*

l_i: *Length of the homogeneous zone "i"*

Eventually, and when the cost for every zones has been assessed, the total tunnelling normal cost for the tunnel length (C_{NT}) can be determined through Monte Carlo Simulation. The total cost is determined as the summation of the single cost of the homogeneous zones (C_{NTi}).

$$C_{NT} = \sum_{i=1}^{n} C_{NTi}$$

Where:

C_{NT}: *Normal Tunnelling Cost for the Total Length*

C_{NTi}: *Normal Tunnelling Cost for the homogeneous zone “i”*

As in the previous step, Monte Carlo Simulation allows obtaining the respective results, which are depicted as statistical distributions, for each of the analysed costs. These processes are further explained in section 6.9 “Estimation Process and Simulation”.

6.5.1 Tunnelling Cost Drivers

As previously presented, the proposed model is based on a mixed approach of analogic and parametric cost estimation methods. As introduced in the theory, both methods represent suitable tools when specific information about the project is still not available, but data can be obtained from past experience, Hollmann (2007), and Paraskevopoulou (2012).

Consequently, the proposed method defines specific cost drivers that are used to derive the unit price of tunnelling activities and in this way assess the normal tunnelling cost (C_{NT}). It is worth mentioning, that the unit cost derived from the specific cost drivers includes all the equipment, labour, material and others consumables directly related to the execution of the tunnelling activities, therefore other cost related to general expenses, site work, management and project administration are not included.

The task of deciding whether or not, model variables must be considered relevant or representative of the tunnelling cost is at least complex; nonetheless correlation analysis, as well as the revision of previous models may provide sound basis or hints to derive and select the definitive cost drivers. A specific aspect evaluated for selecting the cost drivers was the possibilities to obtain information about these variables. In this sense, the selected cost drivers must offer enough flexibility to be assessed by using different methods.

Balancing the points previously exposed, the cost drivers, selected in this work, fulfil the following conditions:

i. To present a positive or negative correlation to the tunnelling cost.
ii. To offer flexibility for the assessment process along different project phases.
iii. To represent the uncertainty regards geological and construction performance of the tunnelling activities.

The cost drivers are assumed to be stochastic variables (i.e.: random variables), which can be described by representative values and specific probabilistic density function (PDF). The representation of geological and geotechnical aspects as a random variable is sustained in several previous works regarding tunnelling cost and time estimation, such as Isaksson (2002) and Spackova, Sejnoha et al. (2013 b), but also in general theory for dealing with uncertainty in geotechnical engineering, see Fenton (1997), Fenton and Griffiths (2002) and Nadim (2002).

Table 6.2: Selected Cost Drivers for the Drill and Blast Tunnelling Construction Process (source: the author).

Cod. ID	*Tunnelling Activity*	*Cost Driver*	*Unit*
A.01	Excavation	DRI	NA
A.02	Water Control	q	lt/min/km
A.03	Rock Support	Q-Value	NA
A.04	Tunnel Lining	Thickness	mm

As shown in Table 6.2, most of the activities regarding the tunnelling process are assessed through geological parameters. The only exception for this is the tunnel lining process, which is assessed as a function the concrete thickness.

These cost drivers represent the independent variables of specific functions that will allow obtaining the unit prices for the activities related to the tunnel excavation. More information regards the selected cost drivers may be found in *Appendix F "Cost Drivers for Tunnelling Process"*.

6.5.2 Cost Functions

In order to determine the unit cost of the tunnelling activities, the author has defined specific cost functions ($y = f_y(x)$), where cost drivers represent the independent variables (i.e.: cost drivers = x), while the unit cost for the tunnelling activities represents the dependent variables (i.e.: unit cost of the specific activity = y), which is expressed in monetary terms per metre excavated (NOK/m). Since the inputs of these specific equations (i.e.: cost drivers) are random variables, the functions may be considered as random processes that eventually deliver random outputs (i.e.: unit cost), which are also represented by specific probabilistic distributions.

The equations were established through a detailed analysis of the most relevant parameters that affect the unit cost of each tunnelling activities, and expressed as a univariable equations. It is worth mentioning that the equations presented in this report correspond to those estimated for a specific tunnel section (i.e.: T9.5) and for a given tunnel length (i.e.: 9 km). The same process can be performed for different standard sections of road tunnels, according to the classification given by the Norwegian Road Administration.

Following sections provide more detail information related to the specific cost functions determined for the tunnelling activities.

i. *Activity A.01: Excavation*: A total number of 15 equations were determined for the excavation unit cost, and it corresponds to different excavation class. Each excavation class corresponds to a combination of different values of Q Values and Blastability

Index (SPR); consequently the effects of these two parameters may be considered included in the final results. The equation obtained for the specific inputs considered in the model are presented in Table 6.3.

Table 6.3: Cost function for different excavation classes. This cost equation are valid for the specific general inputs considered in this model, i.e.: Tunnel Length: 9.000 metres and standard section 67 m^2 (source: the author)

Excavation Class	***Q-Method***	***Blastability SPR***	***U.CA01***
E1	A, B, C	H	-2346*ln(DRI) + 24707
E2	A, B, C	M	-2344*ln(DRI) + 24932
E3	A, B, C	L	-2344*ln(DRI) + 25156
E4	D	H	-2933*ln(DRI) + 30884
E5	D	M	-2930*ln(DRI) + 31165
E6	D	L	-2930*ln(DRI) + 31444
E7	E	H	-3744*ln(DRI) + 39427
E8	E	M	-3740*ln(DRI) + 39785
E9	E	L	-3740*ln(DRI) + 40142
E10	F	H	-5027*ln(DRI) + 52944
E11	F	M	-5023*ln(DRI) + 53425
E12	F	L	-5023*ln(DRI) + 53905
E13	G	H	-8379*ln(DRI) + 88237
E14	G	M	-8371*ln(DRI) + 89038
E15	G	L	-8371*ln(DRI) + 89838

ii. <u>*Activity A.02 Water Control*</u>: The water control function was determined considering all the activities that are required to achieve this activity. The independent variable for this equation is the expected water leakage (q) to be found before performing the water control activities, which is measured in lt/min/km.

$$U.C_{A02} = 4309 * e^{0,0013*q}$$

iii. <u>*Activity A.03 Rock Support*</u>: The rock support function was determined using a similar approach than the previous equation; therefore this considers all the activities that must be performed in order to achieve the stabilisation of the rock mass that surrounds the tunnel. The independent variable is rock mass quality index (Q-Value), and the cost function was determined for a given tunnel geometry (radius) and specific safety factor (SFR).

$$U.C_{A03} = 16601 * Q^{-0,245}$$

iv. *Activity A.04 Tunnel Lining*: As already explained, the tunnel lining is considered a fixed requirement of the model; nevertheless different construction strategies, such as cast in place or precast concrete element may be selected. Considering distinct combinations between these two aspects, fours different lining classes were determined, where concrete thickness (S) is considered the independent variable. The cost functions are depicted in Table 6.4.

Table 6.4: Cost Function for Lining Activities (source: the author)

Lining Class	***Description***	***U.CA04***
L1	Cast in Place + Behind the Face	93,14*S - 27,16
L2	Cast in Place + On the Face	117,78*S + 0,91
L3	Pre Cast Unreinforced	130,39*S - 38,02
L4	Pre Cast Reinforced	156,47*S - 45,62

More details about the cost functions may be found in *Appendix G "Cost Estimation Functions"*.

6.6 Extraordinary Tunnelling Cost (C_{ET})

The proposed model assumes that the extraordinary cost of the tunnelling process (C_{ET}) may be determined as a function of the project risk events (i.e.: undesirable events) that may occur during the development of the tunnelling activities.

Undesirable events are defined in this work as an accident with complete or partial breakdown of equipment, excavating works, or structures that is accompanied by a prolonged interruption of the tunnelling process. Undesirable events are considered to carry financial losses, and in some cases injuries or death for the work force, which affect the excavation process and consequently the tunnelling cost.

Some examples of undesirable events are machinery or equipment failures, gross human errors, cave in events, tunnelling flood, and other events that present low probability of occurrence, but that may cause large effects into the tunnelling cost.

The assessment of extraordinary events and the cost related (C_{ET}) is basically carried out using standard project risk management tools, such as risk identification and qualitative and quantitative risk analysis. The risk identification and analysis is performed through the risk register, where undesirable events that may occur during the execution of tunnelling process are duly identified and assessed in term of their probability of occurrence and consequence, using both qualitative (to determine risk levels or class) and quantitative approach (to determine the extraordinary cost of the project).

The "preliminary" extraordinary tunnelling cost (C_{ETp}) is modelled as a random process, which is the result of the interaction of two random variables. The random variables that conform this random process are the occurrence and consequences of a single risk event. The cost of a single cost event (C_{ETi}) is expressed according to the following expression.

$$C_{TEi} = O * C$$

Where:

O: *Occurrence of the undesirable events (0 = does not occur, 1= occurs)*

C: *Cost involves if the risk occurs*

C_{ETi}: *Actual Cost if the event "i" occurs*

The above formula can be considered identical to the standard approach used for risk analysis (i.e.: R = P * C), where the risk is modelled as the static product between likelihood (P) and monetary consequences (C); nevertheless the proposed model considers a dynamic approach, which provide a more realistic estimation of the extraordinary tunnelling cost.

In order to better represent the random nature of undesirable events, its occurrence is modelled using discrete random distributions (i.e.: probability mass function), which allow assessing in more realistic manner the effects produced by risk events. Table 6.5 shows some of the distributions found suitable to describe the random behaviour of risk events. More details about statistical these distributions are given in *Appendix M "Probability Theory, Fundamentals".*

Table 6.5: Suitable Statistical Distributions for modelling the occurrence of different types of undesirable events.

Risk ID	***Risk Category***	***Suitable Statistical Distribution (Ocurrence)***
R.01	Natural Dissaster	Bernoulli, Binominial
R.02	Machine and Equipment Failure	Poisson
R.03	Geological Events	Poisson
R.04	Human and Organisational Errors	Gamma

The model assumes that occurrence of undesirable events is independent of the homogeneous zones, where the tunnelling activities are being performed (i.e.: simplification of the reality); therefore their occurrence is assessed considering the total length of the tunnel, and it implies that the specific geological features of homogeneous zones do not affect the level of risk of the undesirable events.

The second element of the random process (i.e.: the monetary consequences of undesirable risk events) is modelled as continuous random variables, where PERT or Triangular distributions are used in order to describe the continuous behaviour of the cost. The consequences are assessed in term of the potential cost, if the risk event occurs, and they are expressed in MNOK.

Finally, the occurrence and expected cost of each undesirable event (C_{ETi}) are estimated using Monte Carlo Simulation. The total cost related to extraordinary events (C_{ETp}) is consequently obtained as the summation of the "n" specific events that happen in a given simulation process. It is worth mentioning that this approach assigns discrete value between 0 and 1, therefore the estimated cost includes the whole quantity of resources that will be required if the events occurs during the tunnelling development.

$$C_{ETp} = \sum_{i=1}^{n} C_{ETi}$$

Where:
C_{ETi}: *Actual Cost if the event "i" occurs*
C_{ETp}: *Extraordinary Tunnelling Cost (before risk mitigation is performed)*

The output of this process is called "preliminary" extraordinary tunnelling cost (C_{ETp}), which is represented as a specific probability density function (PDF). The term "preliminary" is used to distinguish the extraordinary cost before and after the risk mitigation plan.

For those aspects identified during the qualitative risk analysis within an unacceptable level of risk, specific measures are designed in order to reduce their overall risk to acceptable levels. The measures considered in the mitigation risk plan are also treated as continuous random variables regard its cost. The cost of the measures is assessed in term of low, medium and maximum values and a specific distribution. The cost of the risk mitigation plan is estimated according to the following expression.

$$C_{MP} = \sum_{i=1}^{n} MC_{ETi}$$

Where:
MC_{ETi}: *Mitigation Cost Event "I"*
C_{MP}: *Total Cost of the Mitigation Plan*

Finally, once the mitigation risk plan is designed and assessed in term of its cost, a new simulation is executed to obtain the final extraordinary cost (C_{ET}), which is estimated using the following expression:

$$C_{ET} = \sum_{i=1}^{n} C_{ETcorrected} + C_{MP}$$

Where:

C_{ET}: *Extraordinary Tunnelling Cost*

$C_{ET\ corrected}$: *Extraordinary Tunnelling Cost (after risk mitigation plan is executed)*

C_{MP}: *Total Cost of the Mitigation Plan*

6.7 Total Tunnelling Cost

By assessing the normal (C_{NT}) and extraordinary tunnelling cost (C_{ET}), the total tunnelling cost (C_{TT}) is given by the following expression:

$$C_{TT} = C_{NT} + C_{ET}$$

Where

C_{TT}: *Total Tunnelling Cost*

C_{NT}: *Normal Tunnelling Cost*

C_{ET}: *Extraordinary Tunnelling Cost*

Figure 6.4 shows the total tunnelling cost (C_{TT}), represented by the red distribution, and the normal tunnelling cost (C_{NT}), which is denoted by the blue distribution.

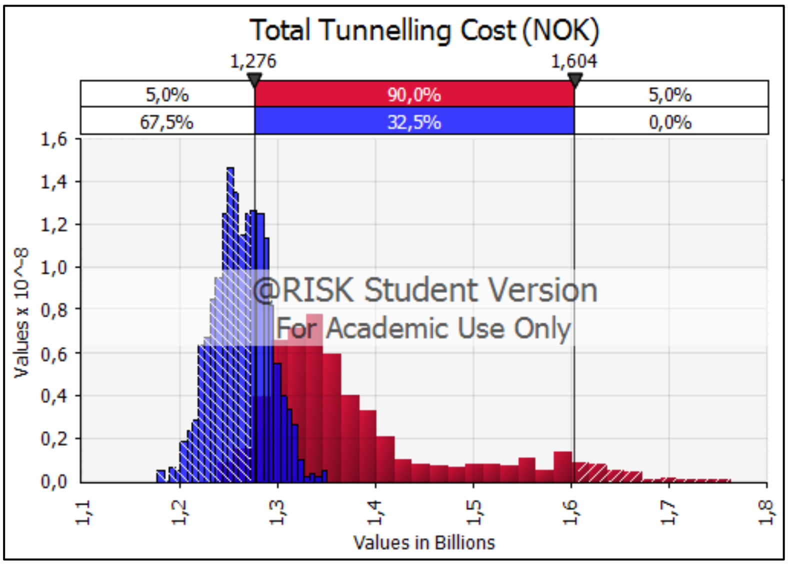

Figure 6.4: Probability Density Functions (PDF's) of Normal and Total Tunnelling Cost.

6.8 Generic Model Setup and Updating

The proposed model contemplates the use and application of three different setups for the estimation of the normal tunnelling cost (C_{NT}). The model setups are denoted using Roman numbers, and the main groups are as follows:

i. Setup I: Deterministic
ii. Setup II: Basic Stochastic
iii. Setup III: Advanced Stochastic

In order to incorporate and understand the effects of statistical correlation in the model outputs (i.e.: cost estimation), a secondary level of differentiation was introduced in the stochastic setups, which are denoted with the capital letters A and B. Considering this, five different setups were defined and they are depicted in Table 6.6.

Table 6.6: Model Setups for Normal Tunnelling Cost (C_{NT})

Model Setups for Normal Tunnelling Cost (C_{NT})			
Name	***Approach***	***Cost Driver Correlation***	***Geological Correlation***
Setup I	Deterministic	Not Applicable	Not Applicable
Setup II-A	Stochastic	Not Considered	Not Applicable
Setup II-B	Stochastic	Considered	Not Applicable
Setup III-A	Stochastic	Not Considered	Not Considered
Setup III-B	Stochastic	Considered	Considered

In the opinion of the author, distinct model setups may give valuable information in different perspectives. In the practical point of view (i.e.: when applying the model), these setups provide the required flexibility to incorporate different levels of information, which reflects the degree uncertainty faced at different project phases.

Secondly, the application of these three setups may provide sound basis to understand the differences among the process output (i.e.: cost estimation) of deterministic and stochastic methods. This information is a valuable input to discuss to what extent the application of simple stochastic tools may provide better information than deterministic models.

Finally, the use of different level of correlation may help to understand the relevance of this aspect, and the effects of correlation in the final cost distribution, especially in the range of the estimation and the extreme values of the probabilistic distributions.

6.8.1 Model Setup I

As shown in Table 7.4, this model setup may be considered as the simplest way to estimate the normal tunnelling cost. The estimation of the normal tunnelling cost (C_{NT}) is carried out using single figures (i.e.: one value) for the required cost drivers, and considering the tunnel as an entire zone.

The extraordinary tunnelling cost "C_{ET}" is determined as a specific percentage of the normal tunnelling cost (i.e.: 10%). Since the cost drivers are assessed as deterministic values and the total tunnel length is considered as a single zone, correlations are not applicable.

It is important to mention that the unit costs for the tunnelling activities and therefore the normal tunnelling cost (C_{NT}) are obtained using identical cost functions than those used in the stochastic setups (i.e.: II and III). Consequently the values incorporated in the assessment of the cost drivers may represent, the perception of the estimators regarding the tunnelling execution. In order to capture and estimate the worst and best possible cases, Setup I allows introducing optimistic, medium, and pessimistic values, and obtain single cost estimations for these 3 different project scenarios.

6.8.2 Model Setup II

This setup is considered the basic stochastic approach for estimating the normal tunnelling cost (C_{NT}). The values related to cost drivers are obtained by triple point assessment. The normal (C_{NT}) is then obtained by simulation process, considering the total length of the tunnel as a one single zone. This setup is suitable when available information regarding geological aspects does not provide a reliable basis for dividing the tunnel length into homogeneous zones.

Since the tunnel is considered as a single zone, geological correlation is not applicable. Regarding correlation among tunnelling cost drivers, the setup II-A does not consider this correlation, and while setting II-B requires the determination of correlations among the cost drivers.

The main outputs of this specific setup are given as specific probability distribution functions (PDF) for the normal and total tunnelling cost.

6.8.3 Model Setting III

This must be considered as the advanced stochastic setup, this setting considers the division of the tunnel alignment into different homogeneous zones along the tunnel alignment. The assessment of the cost drivers is performed using the same procedure than Setup II (i.e.: using triple point assessment).

Setting III-A does not consider correlation among cost drivers, either geological correlation among homogeneous zones. Contrarily, Setup III-B contemplates the determination of correlation among all the elements of the model (i.e.: cost drivers and homogeneous zones). The values assumed for the correlation among the model elements are incorporated in specific matrixes available in the model.

Figure 6.5 shows a simplified representation of the assessment of correlation in Setup III-B.

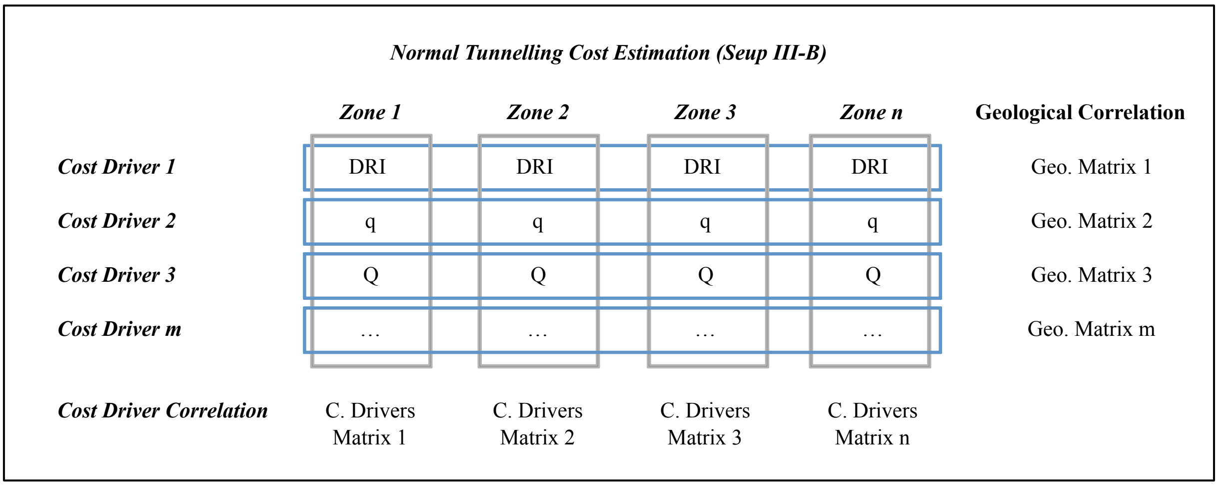

Figure 6.5: Generic correlation outline. The first group of correlation (i.e.: among the different cost drivers), represented by the grey boxes, must be assessed for each homogeneous zone (n). The geological correlations, depicted as the blue boxes, are determined for the same cost driver (m) along the tunnel alignment.

As concluded from the theory, the author agrees on the relevance to incorporate the effects of correlation in the final cost estimation. As depicted in Figure 6.5, the proposed model considers the analysis of correlation among cost drivers in a single zone and the analysis of geological correlations along the tunnel length.

The first group tries to incorporate the complex correlation that different cost drivers have to each other and in the specific tunnelling cost of a particular zone. The second group try to incorporate the effects of variability of a single cost driver along different homogeneous zones.

The main outputs of this specific setup are given as specific probability distribution functions (PDF) for the normal and total tunnelling cost.

6.9 The Estimation Process, Expert Assessment and Simulation

Expert assessment is required in this model, when specific information is not available from other sources, such as pre investigations or statistical data from previous projects. The expert assessment helps cost estimators to obtain the parameters required for both the normal and extraordinary tunnelling cost and consequently is a key element of this model.

Several studies, see for example Vatn (2013), analyse the theory regarding expert assessment and the differences against engineering judgment, some highlights may be found in *Appendix N "Expert Assessment, Basic Concepts"*.

The determination of the total tunnelling cost (C_{TT}) requires the execution of different activities, which can be summarised as follows:

i. Determination of Homogeneous Zones (when is possible)
ii. Estimation of the Normal Tunnelling Cost (C_{NT})
iii. Estimation of the Extraordinary Tunnelling Cost (C_{ET})
iv. Estimation of the Total Tunnelling Cost (C_{TT})

The following sections describe the most relevant features of each of the activity previously mentioned.

6.9.1 Determination of Homogeneous Zones

This activity is performed considering the geological and hydrogeological information that is available. As previously explained in section 6.4 "Geological Modelling", this activity is basically performed considering the lithology of the rock mass, where the tunnel is planned. If information is not sufficient to perform the division of the tunnel, the estimator should focus in the use of model Setup II.

6.9.2 Estimation of the Normal Tunnelling Cost (C_{NT})

In order to determine the normal tunnelling cost (C_{NT}), the cost drivers of the model are assessed through expert opinion. Each cost driver is described by certain values (Low, Medium, High) and a given statistical distribution (i.e.: probabilistic density function PDF).

Considering that values for each parameter have been obtained from elicitation of expert knowledge, Triangular and PERT distributions were found as good candidates to describe the variables under analysis. Since the extreme values (i.e.: the lowest and highest) of these parameters are more relevant for the cost analysis, the author decided to represent the cost drivers by Triangular distribution, which gives more weight to the extreme values (i.e.: in the tip and tail of the distribution). The last step, before performing the simulation process, is to set the specific correlation matrices.

The assessment process is performed for each homogeneous zone, and the information obtained from the expert is specifically introduced in the model. It is worth mentioning that when more data is available, values, distributions and correlations must be obtained from direct statistical analysis.

Once the parameters have been assessed for all the homogeneous zones of the tunnel length and the respective values insert in the model, the simulation process is initiated. The simulation engine used to perform the process is Latin Hyper curve, which is set in the software selected for this purpose (i.e.: @Risk). The generic process above described is represented in Figure 6.6.

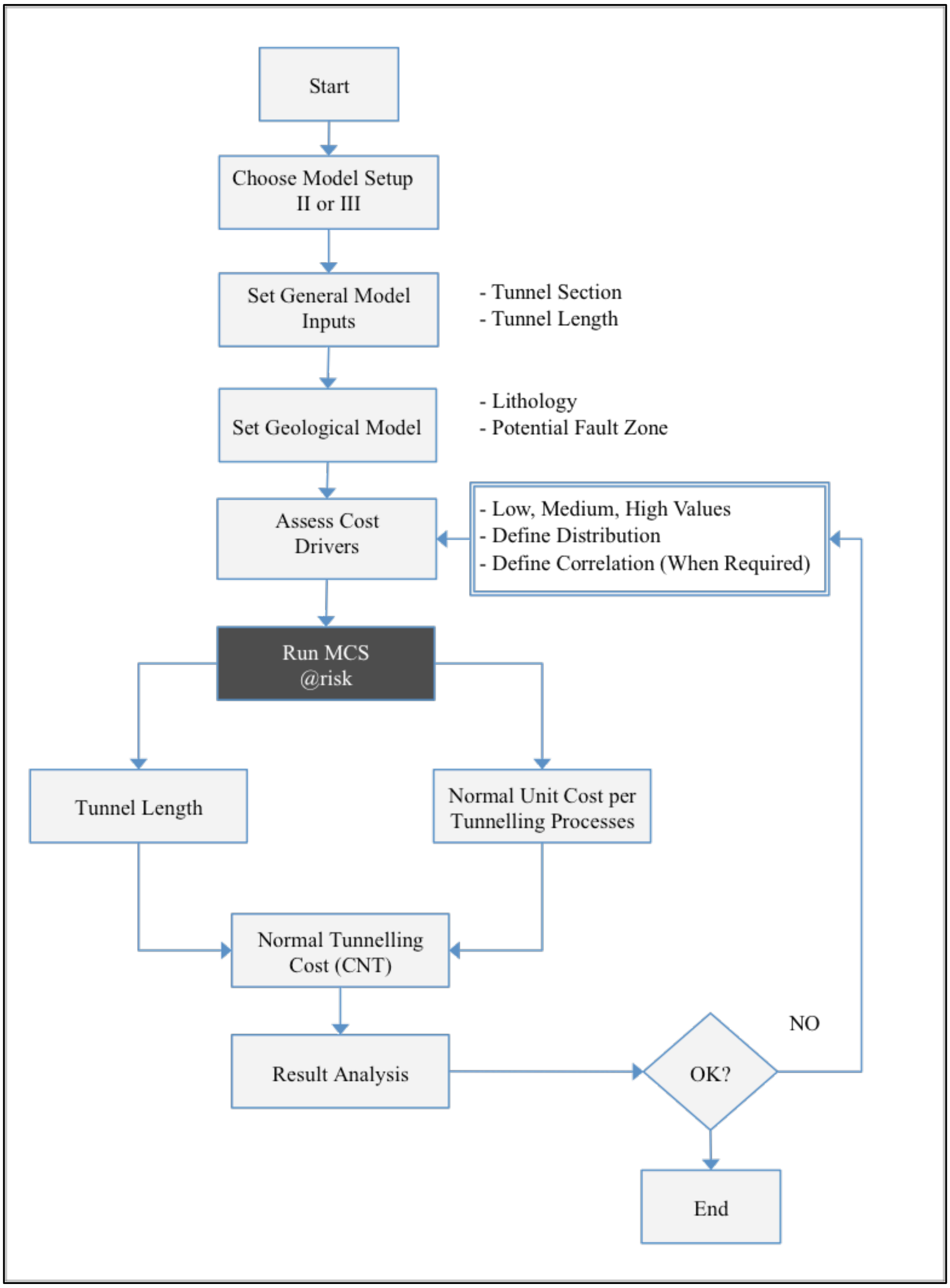

Figure 6.6: Estimation Process for the Normal Tunnelling Cost (C_{NT}).

6.9.3 Estimation of the Extraordinary Tunnelling Cost (C_{ET})

As previously described, and as depicted in Figure 6.7, during this process the experts are asked to identify different risk events that may occur during the execution of the tunnelling activities. These events are structures under predetermined categories, based on standard Risk Register, which are set in the model. At this stage, the experts are required to analyse the risk events by qualitative and quantitative approaches. The qualitative assessment involves the analysis of the probability of occurrence and consequences, which are if assessed by standard expression such as Very Low, Low, Medium, High and Very High and using standard means, such as Risk Matrix.

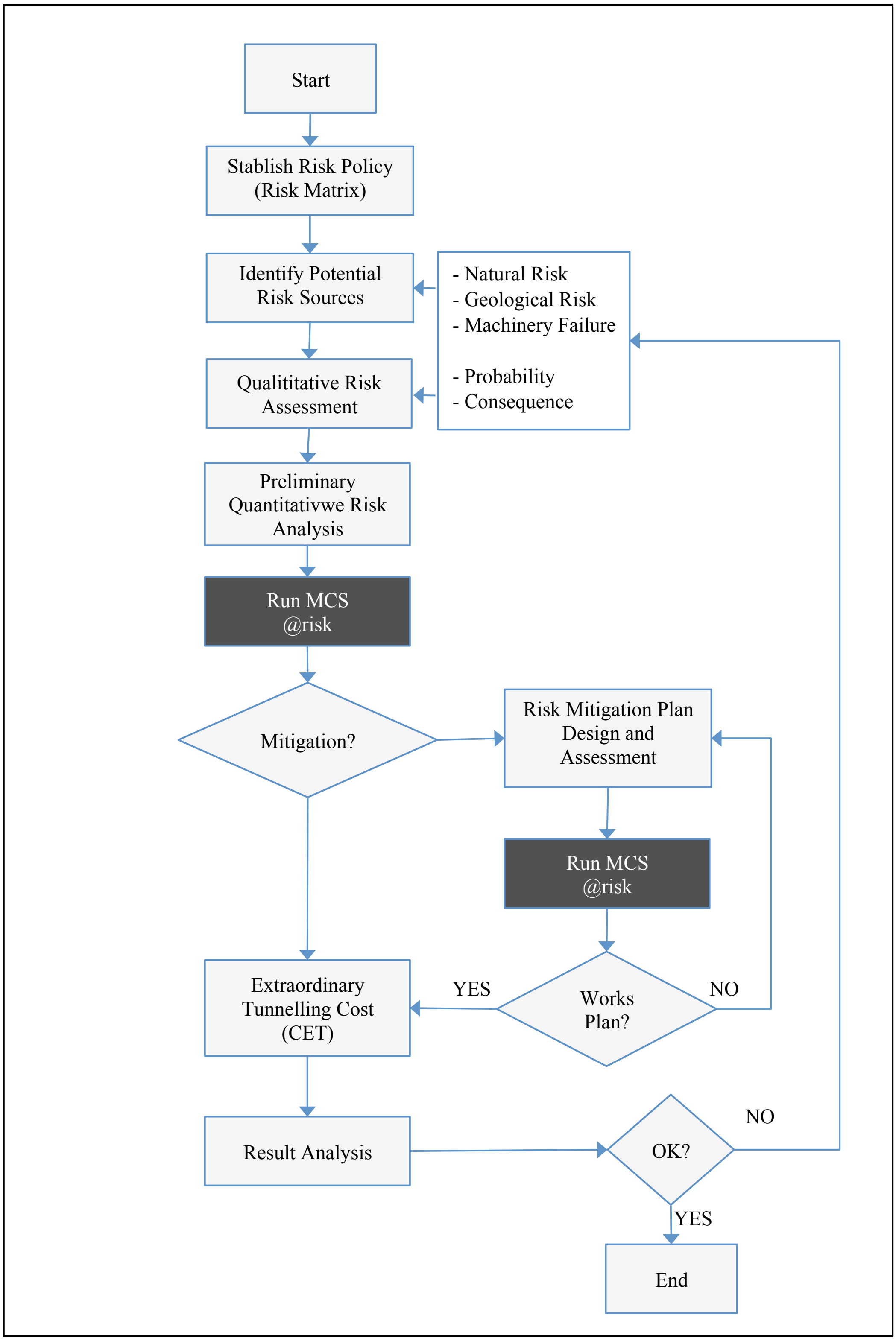

Figure 6.7: Estimation Process for the Extraordinary Tunnelling Cost (C_{ET})

During the execution of the quantitative analysis, the consequence of the risk events are assessed as triple point estimation and measured in monetary terms (i.e.: MNOK). Experts must also assess the probability of occurrence in numerical terms and defining the specific distribution that fit for the specific risk events.

After the extraordinary risk events have been identified and assessed in term of its monetary effect and occurrence, the correlation among these different events should be also evaluated. In the specific case of this research the undesirable events are independent. As part of this process, the experts are also asked to identify the measures that should be implemented in order to minimise the impacts of extraordinary risk events. The cost of the mitigation risk plan, are treated as random variables; consequently they are assessed in term of low, medium and maximum values and its specific distribution (i.e.: PDF).

6.9.4 Estimation of the Total Tunnelling Cost (C_{TT})

After values have been agreed among the experts, for both the normal (C_{NT}) and extraordinary tunnelling cost (C_{ET}), the simulation process for the total tunnelling cost may be initiated and the final estimation can be obtained and analysed. The simulation is performed using specific software called @ Risk, which is a standard add-inn of MS Excel sheets, which is detailed in *Appendix O "@Risk".*

6.10 Model Outputs and Report

The main outputs of the proposed model may be summarised according to the following groups.

i. Probability Density Function (PDF)
ii. Cumulative Density Function (CDF)
iii. Sensitivity Analysis Tornado Analysis
iv. Fitted Probabilistic Distribution

Appendix I contains more information regards generic model outputs and reports that can be obtained as part of the cost estimation process.

6.11 Revision of the Model Results

Once the model outputs are obtained, these must be reviewed in order to check the validity and reliability of the cost estimations. In practical terms, the results of the model can be compared with historical data obtained from previous projects, which may provide a good insight, but certainly it cannot provide a decisive assessment. Another practical way to assess the results of the process is the comparison against the results obtained by applying different means (i.e.: other models) that may be available. In academic terms, this task may be performed through the comparison of other model based on probabilistic approaches or applying other theories that have been developed to deal with uncertainty and decisions. Some theories that may help to check the consistency of the results are Fuzzy Theory, Possibility Theory and Interval Analysis.

7. THE CASE STUDY, CHACAO CHANNEL TUNNEL

In order to test the proposed model and analyse the capabilities and potential applicability of this model in the cost estimation of undersea tunnel projects, a specific case study was selected and it is briefly presented in the first section of this chapter. The following sections are devoted to describe the application of the model, as well as the assessment process performed to feed the model. The last section of this chapter presents the main results obtained for the specific case study.

7.1 General Description

The selected case study was a project alternative presented during the conceptual phase of the Chacao Chanel Project, in Chile. This project represents one of the biggest infrastructure issues for the commutation and infrastructure in the south region of Chile, and it was established as one of the most emblematic project, due to its political relevance.

Currently, the Chilean Ministry of Public Works (MOP) has approved the execution phase of a suspension bridge, under the contract modality of design and construction, within an approximate investment cost of 740 MUSD (i.e.: total construction cost), which is about 4.300 MNOK, according to current exchange rates at May of 2014.

Information collected throughout the development of this research, as well as unstructured interviews with professional involved in the early project phases of this concept, demonstrates that the undersea tunnel was never considered as a feasible alternative to overcome this infrastructure issue. The main reasons that sustain the low interest on this concept was the high risk involved in the execution of this class of projects and the higher cost in comparison with the selected alternative.

Before describing the different project aspects considered to apply the model, it is worth mentioning that most of the information regarding the development of the Chacao Channel Project is focused on the design and construction of the selected alternative (i.e.: suspension bridge); therefore specific geological and geotechnical aspects regarding tunnel design are extremely limited, and restricted to the specific area that surrounds the alignment of the projected bridge. Even though information is limited, the author has considered that is representative of the pre-investment phases and sufficient to apply the proposed model in its different setups.

7.1.1 Geological Aspect of Chacao Channel

According to Duhart and Adriasola (2008), the Chacao Chanel (74ºS; 42ºW) is geographical accident product of a high and complex tectonic and glacial interaction. The channel is part of the Ancud Gulf Failure (described in geological maps as FGA), which is considered an active seismic failure.

The seabed of the Chacao Channel is covered for a thick layer of cemented glacial deposit (-100 m.b.s.l) follows by a secondary layer of soft volcanogenic sedimentary rock with an estimated thickness of 300 metres. A tertiary level composes by sedimentary conglomerates is expected to lie under this layer, without evidence about its thickness and either evidence of metamorphic structures. As part of the geotechnical prospections carried out during the prefeasibility and feasibility study of the bridge, it is possible to confirm the existence of low to high compacted clastic glacial deposits located at the sea bed of Chacao Channel.

Table 7.1: Geotechnical description of Chacao Channel seabed (source: Chilean Ministry of Public Works, MOP).

Depth (m)	***Geotechnical Description Seabed***
0 - 30	Good to high cementation, medium to fine grained sands with fine coarse gravel, cementation drops with depth.
30 - 57	Sand with medium cementation and low in parts, with different amounts of gravel with small layers of silt. The low cemented sands are very dense (SPT does not penetrate).
57 - 89	Hard or cemented silt of yellow to light brown colour with some layers of fine cemented sand.
89 - 100	Medium sand, very densely compacted, with low particle cementation, dark grey colour, with some thin layers of embedded silt.

Considering the geotechnical data presented above, and the geological report reviewed as part of this research, it is possible to infer that a layer of soft sedimentary rock may be located at 200 metres depth approximately. This layer is mainly composed by immature volcanogenic sandstone so called Cancagua rock. The geological profile defined after the revision of the available data and considered as a geological input of the proposed model is as follows:

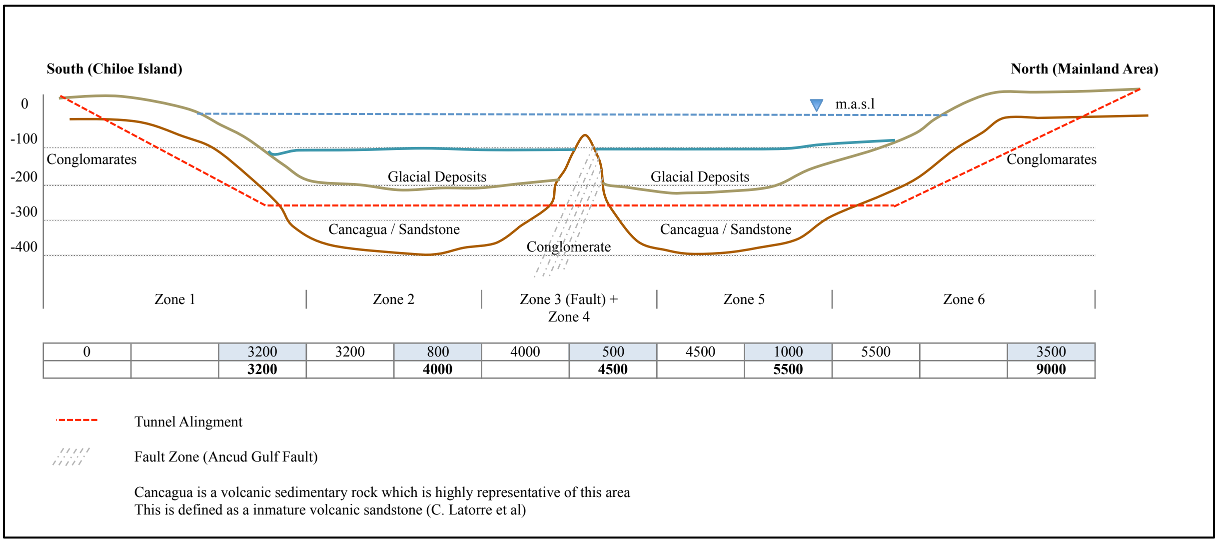

Figure 7.1: Chacao Channel Geological Profile (North – South alignment).

7.1.2 Basic Design Aspects

Considering the information presented in the previous section (i.e.: geological aspects), the basic geometrical aspect of the tunnel were determined. The author has set the technical features of the tunnel, considering the standard design restrictions regard maximum slopes (i.e.: 6% - 8%) and minimum rock overburden (>50 metres), NFF (2009).

Table 7.2: General Features for the Chacao Channel Undersea Tunnel.

Technical Feature	***Value***	***Unit***
Channel Width at the Tunnel Algnment	2.155	m
Expected Tunnel Length	9.000	m
Maximum Channel Depth (Seabed)	120	m
Maximun Tunnel Depth	275	m
Maximum Gradient of the Tunnel Alignment	8	%
Minimum Overburden	50	m

A representation of the vertical profile of the proposed tunnel is shown in Figure 7.1 (red dotted line). Figure 7.2 shows the proposed horizontal alignment, which follows the alignment of the selected project alternative (i.e.: suspension bridge). It is worth mentioning that this alignment has been selected due to the availability of information, nevertheless other alignments may also be assessed in order to optimise the project cost. Assuming the selected alignment, the maximum distance to be crossed reaches 2.155 metres. The remaining 7.000 metres of tunnel are required to achieve the gradient restrictions regarding heavy traffic (e.g.: truck and lorries).

Figure 7.2: General Layout of the Chacao Channel Tunnel. This figure was originally developed as part of the feasibility study for the bridge project that is being developed. The tunnel alignment follows

the same strategy to cross the channel at the shortest distances (source: Chilean Ministry of Public Works, MOP).

7.1.2 Geometrical Design (Cross Section)

In order to determine the cross section required for the tunnel project, the Average Annual Daily Traffic (AADT) was obtained from public reports issued by the Chilean Ministry of Public Works, MOP (2002). This report set the traffic demand up to 2031, and it considers 16.000 vehicles per day.

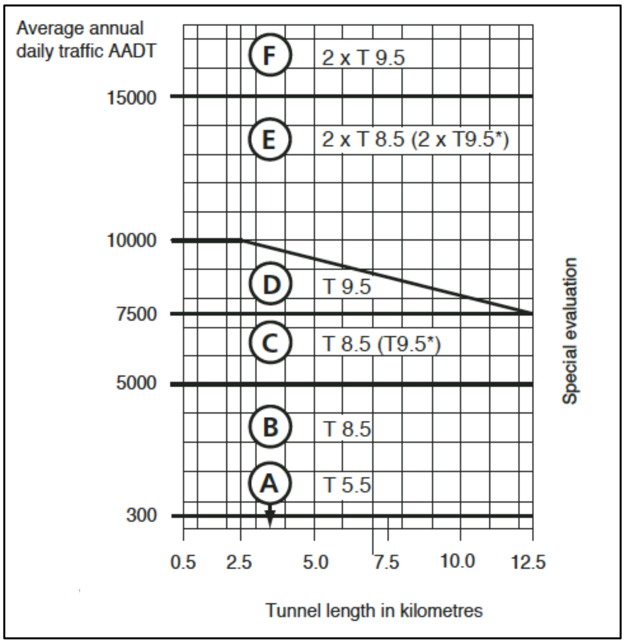

Figure 7.3: Norwegian Road Tunnel Categories (source: NPRA (2004))

According to this information, the project requires a tunnel category F, which implies the execution of two (02) independent tunnel sections T9.5 (i.e.: 2*T9.5). Table 7.3 summaries the information previously presented.

Table 7.3: Parameters considered for the preliminary design of Chacao Channel Tunnel (source: Chilean Ministry of Public Works)

Design Parameters	***Value***	***Unit***
Average Annual Daily Traffic AADT (2014)	4.721	vehicles/day
Expected Average Annual Daily Traffic AADT (2031)	16.879	vehicles/day
Tunnel Category	F	-
Proposed Tunnel Section (According to NPRA)	2*T9.5	-
Nominal Tunnel Section (1 Tube)	54	m2
Actual Tunnel Section (1 Tube)	67	m2

For further information regarding the case study see *Appendix J "Case Study, The Chacao Channel Tunnel"*.

7.2 Total Tunnelling Cost of Chacao Channel Tunnel

Using the information previously introduced and the model setups described in section 6.8, the estimation of the total tunnelling cost was performed. According to the original design, described in Chapter 6, it is considered the participation of tunnelling experts to assess the required model inputs. Unfortunately, none experts were found available to perform this task, therefore the expert session was not possible to be performed as originally designed.

In order to overcome this issue, the author applied its own engineering judgement and experience as project cost engineer. Considering the lack of expertise in tunnelling projects, the author performed a deep study of the geological and geotechnical conditions of the project area, as well as an exhaustive revision of tunnelling experiences in similar conditions (i.e.: tunnel projects in soft sedimentary rock and under high hydrostatic pressure). Then the assessment of the required inputs was done taking into account all the aspects reviewed and applying a realistic approach. Regardless the rigor applied during this process, the author recognises that the assessment of the model's variables by single opinion incorporate a great level of bias in the model results.

Considering all above, the model was fed using the generic displays incorporated in the model, and consequently the normal (C_{NT}) and the extraordinary tunnelling cost (C_{ET}) were obtained for each model setup.

7.2.1 Cost Drivers and Normal Tunnelling Cost (C_{NT})

Figure 7.4 and 7.5 show the generic display created for assessing the normal tunnelling cost (C_{NT}) in the Setup I "Deterministic". It can be observed; in Figure 7.5 that cost drivers are introduced as single values, which are considered representative of the tunnel alignment.

1.0 GENERAL MODEL INPUTS			Pessimistic	Normal	Optimistic
1.1 MODEL INPUTS					
Manual Input	Standard Section (According to NPRA)	-	T9.5	T9.5	T9.5
Manual Input	Section (Excavated Section)	m2	67	67	67
Manual Input	Average Tunnel Length (One Single Line)	m	9.000	9.000	9.000
Manual Input	Nº of Lines	units	2	2	2
Manual Input	Total Tunnel Length	m	18.000	18.000	18.000
Manual Input	Zone Length (distribution)	-	Not Apply	Not Apply	Not Apply
Manual Input	Blastability	qualitative	LOW	MEDIUM	HIGH
Manual Input	Rock Mass Category (based on Q Values)	qualitative	G	D	A, B, C
Manual Input	Excavation Class	qualitative	E15	E5	E1
Manual Input	Lining Strategy	Cast in place behind the face	L1	L1	L1
1.2 LITHOLOGY					
Manual Input	Main Rock Type	-	Sedimentary	Sedimentary	Sedimentary

Figure 7.4: General Model Inputs Setup I "Deterministic". The cells in blue highlight the inputs that are required for the model.

2.0 COST DRIVERS ASSESSMENT			Pessimistic	Normal	Optimistic
2.1 EXCAVATION COST DRIVER			**Value**	**Value**	**Value**
CD.01	Drilabillity (DRI)	-	15	50	100
2.2 WATER CONTROL COST DRIVER			**Value**	**Value**	**Value**
CD.02	Expected Water Leakage (q)	lt/min/km	1600	600	20
2.3 ROCK SUPPORT COST DRIVER			**Value**	**Value**	**Value**
CD.03	Q-Value	-	0,001000	4,000000	100,000000
2.4 LINING COST DRIVER			**Value**	**Value**	**Value**
CD.04	Lining thickness (S)	mm	300	300	300

Figure 7.5: Cost Drivers Model Inputs Setup I "Deterministic". The cells in blue highlight the inputs that are assessed and introduced in the model.

In Figures 7.4 and 7.5 is possible to distinguish how three different assessments were performed for the deterministic case. The left hand side column considers the most pessimistic evaluation, and as depicted in Figure 7.5 all the general parameter and cost drivers have values that reflects the most pessimistic scenario. Similarly, the medium column reflects a normal scenario in all the parameters that are assessed. Finally the right hand side column incorporates optimistic values in all the required inputs.

Figures 7.6 and 7.7 show the display designed for the assessment of normal tunnelling cost (C_{NT}) in the Setup II (A and B). The first display contains the general inputs of the model, while cost drivers are assessed in the second display shows in Figure 7.7.

1.0 GENERAL MODEL INPUTS					
1.1 MODEL INPUTS					
GI.01	Standard Section (According to NPRA)	-	T9.5		
GI.02	Section	m2	67		
GI.03.01	Tunnel Length (Tube 1)	m	8 900,00	9 000,00	9 200,00
			Triangular	E(L1) =	9 019,00
GI.03.02	Tunnel Length (Tube 2)	m	9 000,00	9 100,00	9 300,00
			Triangular	E(L2) =	9 069,56
GI.04	Zone Length (distribution)	-	Not Applicable		
GI.05	Blastability (SPR)	qualitative	MEDIUM	SPR	
GI.06	Rock Mass Category (based on Q Values)	qualitative	D	Q-Value	
GI.07	Excavation Class	qualitative	E5	Excavation Class	
GI.08	Lining Strategy		Cast in Place	Behind the Face	L1
1.2 LITHOLOGY					
GI.09	Main Type of Rock	-	Sandstone - Conglomerate		

Figure 7.6: General Model Input Setup II "Basic Stochastic". The cells in blue highlight the inputs are assessed and introduced in the model. This example corresponds to the basic stochastic (Setup II A and B). As depicted in the figure the tunnel length were assessed using triple point estimates and triangular distribution. The software (i.e.: @risk) reproduces the expected value for this specific parameter.

2.0 EXPERT ASSESSMENT OF COST DRIVERS					
2.1 EXCAVATION COST DRIVER			**L**	**M**	**H**
CD.01	Drillability (DRI)	-	15,00	50,00	100,00
			Triangular	E(DRI) =	67,02
2.2 WATER CONTROL COST DRIVER			**L**	**M**	**H**
CD.02	Expected Water Leakage (q)	lt/min/km	20,00	600,00	1 600,00
			Triangular	E(q) =	905,67
2.3 ROCK SUPPORT COST DRIVER			**L**	**M**	**H**
CD.03	Q-Values	-	0,00100	4,00000	100,00000
			Triangular	E(Q) =	58,03
2.4 LINING COST DRIVER			**L**	**M**	**H**
CD.04	Lining Thickness (S)	mm	300,00	350,00	400,00
			Triangular	E(S) =	362,65

Figure 7.7: Expert Assessment of Cost Drivers for Model Setup II "Basic Stochastic". The values assessed are identical for Setup II-A and II-B. In Setup II-B correlation among cost drivers is assessed using the specific correlation matrix incorporated in the model.

Finally Figures 7.8 and 7.9 show the assessment of general inputs and cost drivers for two different homogeneous zones considered in the cost estimation, when using Setup III-A and III-B.

1.0 GENERAL MODEL INPUTS		ZONE 1 (South)			ZONE 2		
1.1 MODEL INPUTS							
GI	Standard Section (According to NPRA)	T9.5			T9.5		
GI	Section	67			67		
GI	Tunnel Length (Tube 1)	3 100	3 200	3 300	700	800	900
		Triangular	E(L1) =	3 165,55	Triangular	E(L1) =	756,73
		Triangular	E(L2) =	3 165,55	Triangular	E(L2) =	756,73
GI	Zone Length (distribution)						
GI	Blastability (SPR)	LOW	SPR		LOW	SPR	
GI	Rock Mass Category (based on Q Values)	D	Q-Value		F	Q-Value	
GI	Excavation Class	E6	Excavation Class		E12	Excavation Class	
GI	Lining Strategy	Cast in Place	Behind the Face	L1	Cast in Place	Behind the Face	L1
1.2 LITHOLOGY							
GI	Main Type of Rock	Conglomerates (Sedimentary)			Sandstone - Cancagua		

Figure 7.8: Expert Assessment of General Model Inputs for Set III "Advanced Stochastic". As in the previous setup, the values assessed are identical for Setup III-A and III-B.

2.0 EXPERT ASSESSMENT OF COST DRIVERS			ZONE 1 (South)			ZONE 2		
2.1 EXCAVATION COST DRIVER			L	M	H	L	M	H
CD.01	Drillability (DRI)	-	30,00	50,00	70,00	15,00	50,00	90,00
			Triangular	E(DRI) =	43,87	Triangular	E(DRI) =	50,40
2.2 WATER CONTROL COST DRIVER			L	M	H	L	M	H
CD.02	Expected Water Leakage (q)	lt/min/km	500,00	600,00	700,00	800,00	900,00	1 200,00
			Triangular	E(q) =	641,03	Triangular	E(q) =	874,24
2.3 ROCK SUPPORT COST DRIVER			L	M	H	L	M	H
CD.03	Q-Values	-	1,0000	4,0000	10,0000	0,0100	0,0500	0,1000
			Triangular	E(Q) =	4,05	Triangular	E(Q) =	0,07
2.4 LINING COST DRIVER			L	M	H	L	M	H
CD.04	Lining Thickness (S)	mm	300,00	300,00	300,00	300,00	350,00	400,00
			Triangular	E(S) =	300,00	Triangular	E(S) =	350,30

Figure 7.9: Expert Assessment of Cost Drivers for Set III "Advanced Stochastic. As in the previous setup, the values assessed are identical for Setup III-A and III-B. Correlations among cost drivers and geological zones are assessed in Setup III-B.

More specific information regarding the specific inputs incorporated in the assessment of the normal tunnelling cost (C_{NT}) can be found in *Appendix K "Case Study, Experts Assessment and Model Inputs"*.

7.2.2 Undesirable Risk Events and Extraordinary Tunnelling Cost (C_{ET})

Specific displays were created to introduce information regards the assessment of undesirable risk events and assess the extraordinary tunnelling cost (C_{ET}) Since the Setup I considers the cost related to extraordinary risk as a function (i.e.: percentage) of the normal cost, the display showed bellow were applied exclusively in Setup II and III.

Figure 7.10 shows the generic matrix for the quantitative risk analysis performed in Setups II and III. As previously described in Chapter 6, the required inputs at this stage are the potential risk events that may occur during the development the tunnelling activities.

7.0 PRELIMINARY QUANTITATIVE RISK ANALYSIS (without risk mitigation)							
RISK DESCRIPTION		**LIKELIHOOD**		**IMPACT (MNOK)**			
Risk ID	**Extraordinary Risk Event**	**Probability**	**Occurs?**	**Low**	**Medium**	**High**	**Risk Severity**
R.1.0	**Natural Events**						
R.1.1	Earthquake during the tunnelling process	0,01	0,00	100,00	150,00	200,00	149,35
R.1.2	Large flood during the construction	0,10	1,00	200,00	250,00	300,00	251,92
R.1.3	Fire during tunnelling process	0,10	0,00	100,00	150,00	300,00	155,09
R.2.0	**Machine Failures**	**Failure Rate**					
R.2.1	Failure of Excavation Rig	5,00	1,00	1,00	1,50	2,00	1,58
R.2.2	Failure of the Grouting Rig	5,00	6,00	1,00	1,50	2,00	1,40
R.2.3	Failure of the Rock Support Equipment	5,00	5,00	1,00	1,50	2,00	1,54
R.2.4	Failure in the Lining Erection Equipment	3,00	3,00	0,50	0,60	1,00	0,77
R.3.0	**Geological Events**						
R.3.1	Major Rock Fall at the Face	3,00	2,00	1,00	1,20	2,00	1,78
R.3.2	Major Collapse at the Face (Cave In)	2,00	3,00	2,00	3,00	4,00	3,24
R.3.3	Major Rock Fall behind the Face	1,00	0,00	0,50	0,60	1,00	0,74
R.3.4	Major Collapse behind the Face	1,00	0,00	1,00	1,50	2,00	1,38
R.3.5	Excesive Tunnel Deformation (Squeezing)	5,00	4,00	1,00	1,50	2,00	1,70
R.3.6	Rock Burst / Spalling	5,00	1,00	1,00	1,50	2,00	1,83
R.3.7	Unexpected Water Inflow - daylight collapse	3,00	1,00	1,00	1,50	2,00	1,67
R.4.0	**Human Errors**						
R.4.1	Large Human Error with Life Losses	0,50	0,00	10,00	15,00	20,00	13,36
R.4.2	Large Human Error without Life Losses	2,00	1,00	20,00	30,00	40,00	28,21

Figure 7.10: Display for assessing undesirable risk events and extraordinary tunnelling cost.

More detailed information regarding the specific inputs incorporated in the assessment of the extraordinary tunnelling cost (C_{ET}) can be found in *Appendix K "Case Study, Experts Assessment and Model Inputs"*.

After the model setups were fed for both normal and extraordinary cost, the simulation process (i.e.: MCS) was executed to obtaining the total tunnelling cost (C_{TT}).

7.3 Results

This section presents a summary of the results obtained for the specific case study. This section is exclusively devoted to introduce the results, which are lately discussed in Chapter 8. It is worth mentioning that the proposed model offers a wide set of reports; nonetheless this section is focused on those reports that depict the probabilistic distributions obtained for the normal (C_{NT}), extraordinary (C_{ET}) and total tunnelling cost (C_{TT}).

More detailed information regarding the results obtained for the specific case study may be found in Appendix L "Case Study, Model Results".

7.3.1 Results Setup I

As presented before, this setup corresponds to the deterministic approach. The normal tunnelling cost (C_{NT}) was estimated using three different scenarios and in this way was possible to establish the best, base, and worst deterministic cases. These results are summarised in Table 7.4 "Outputs Model Setup I".

Specific Cost	***Setup I (MNOK)***		
	Best Case	***Base Case***	***Worst Case***
- Normal Tunnelling Cost (C_{NT})	929,03	1.239,08	3.955,68
- Extraordinary Tunnelling Cost (C_{ET})	92,90	123,91	395,57
- Total Tunnelling Cost (C_{TT})	**1.021,93**	**1.362,99**	**4.351,25**

Table 7.4: Outputs Model Setup I (deterministic). The table shows the unit cost for each of the tunnelling activities (NOK/m), as well as the normal tunnelling cost (C_{NT}) and the extraordinary tunnelling cost (C_{ET}). Each column presents the different scenarios where the total tunnelling cost was estimated.

As depicted in Table 7.4, the base case for the total tunnelling cost (C_{TT}) reaches 1.362,99 MNOK. This cost corresponds to the simple summation of 1.239,08 MNOK for the normal cost (C_{NT}) and 123,91 MNOK for the extraordinary cost (C_{ET}). Similarly, the best case for the total tunnelling cost (C_{TT}) was estimated in 1.021,93 MNOK and the worst case in 4.351,25 MNOK, respectively.

7.3.2 Results Setup II-A

Figure 7.11 shows the normal tunnelling cost (C_{NT}) as the blue distribution, and the total tunnelling cost (C_{TT}), red curve, for the stochastic Setup II-A that does not consider correlation among cost drivers. The blue distribution corresponds to the normal tunnelling cost, while the red distribution represents the total tunnelling cost, which includes the occurrence of undesirable events. The vertical lines shown in this plot, set in 1.021,93 MNOK and 1.362,99 MNOK, represent the best case (left hand side) and base case (right hand side) obtained for the total tunnelling cost (C_{TT}) in Setup I.

Figure 7.12 shows the specific distribution obtained for the extraordinary tunnelling cost (C_{ET}) related to the Setup II-A. The extraordinary cost present a mean value of 119,63 MNOK with a standard deviation of 97.73 MNOK.

Table 7.5 summaries the main results related to the cost estimation, considering the Setup II-A. As presented in Table 7.6, the main value of the total tunnelling cost reaches 1.431,74 MNOK and it presents a standard deviation of 148,75 MONK. In order to compare these figures with the results obtained from Setup I (base case), these figures are presented in the left hand side column of the same table.

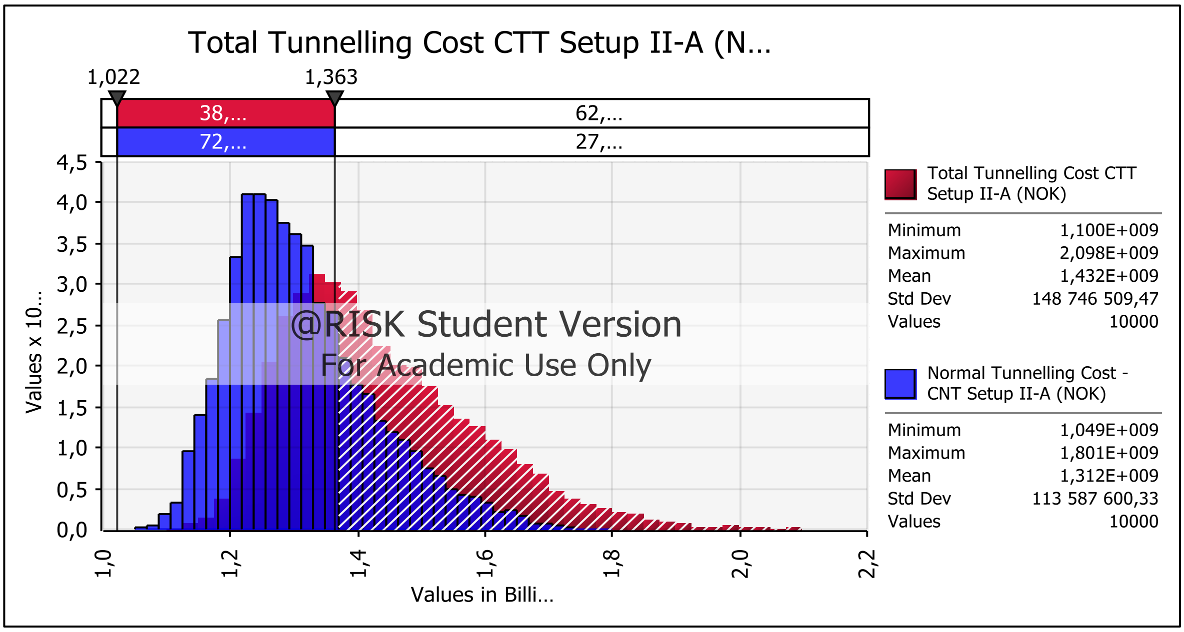

Figure 7.11: Normal and Total Tunnelling Cost Setup II-A (after 10.000 iterations)

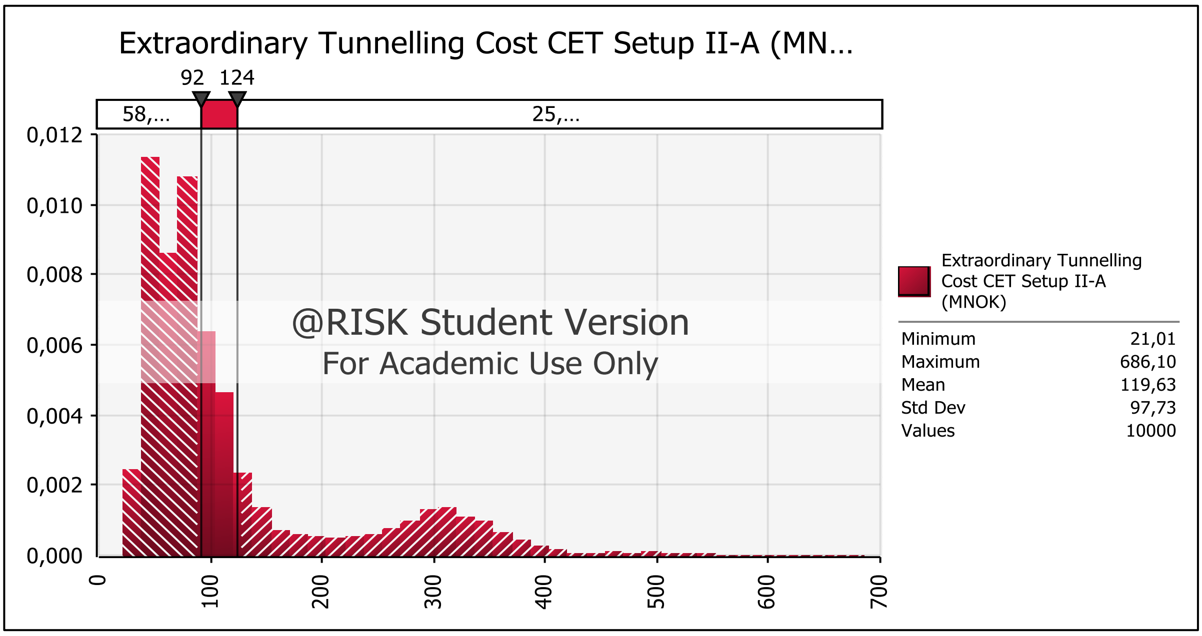

Figure 7.12: Extraordinary Tunnelling Cost Setup II-A (after 10.000 iterations)

Table 7.5: Summary Results Model Setup II-A (Non correlated cost drivers)

Specific Cost	***Setup I***	***Setup II-A (Uncorrelated)***		
	Base Case	***Min***	***Mean***	***Max***
- Normal Tunnelling Cost	1.239,08	1.049,00	1.312,11	1.801,00
- Standard Deviation	0,00	-	113,59	-
- Extraordinary Tunnelling Cost	123,91	21,01	119,63	686,10
- Standard Deviation	0,00	-	97,73	-
- Total Tunnelling Cost	**1.362,99**	**1.100,00**	**1.431,74**	**2.098,00**
- Standard Deviation	**0,00**	**-**	**148,75**	**-**

All Values in MNOK (2014)

7.3.3 Results Setup II-B

Figure 7.13 shows the normal tunnelling cost (C_{NT}) and the total tunnelling cost (C_{TT}) obtained for the stochastic Setup II-B, which considers the correlation among cost drivers. As previously presented, the vertical lines shown in this plot, set in 1.021,93 MNOK and 1.362,99 MNOK, represent the best case (left hand side) and base case (right hand side) obtained for the total tunnelling cost (C_{TT}) in Setup I.

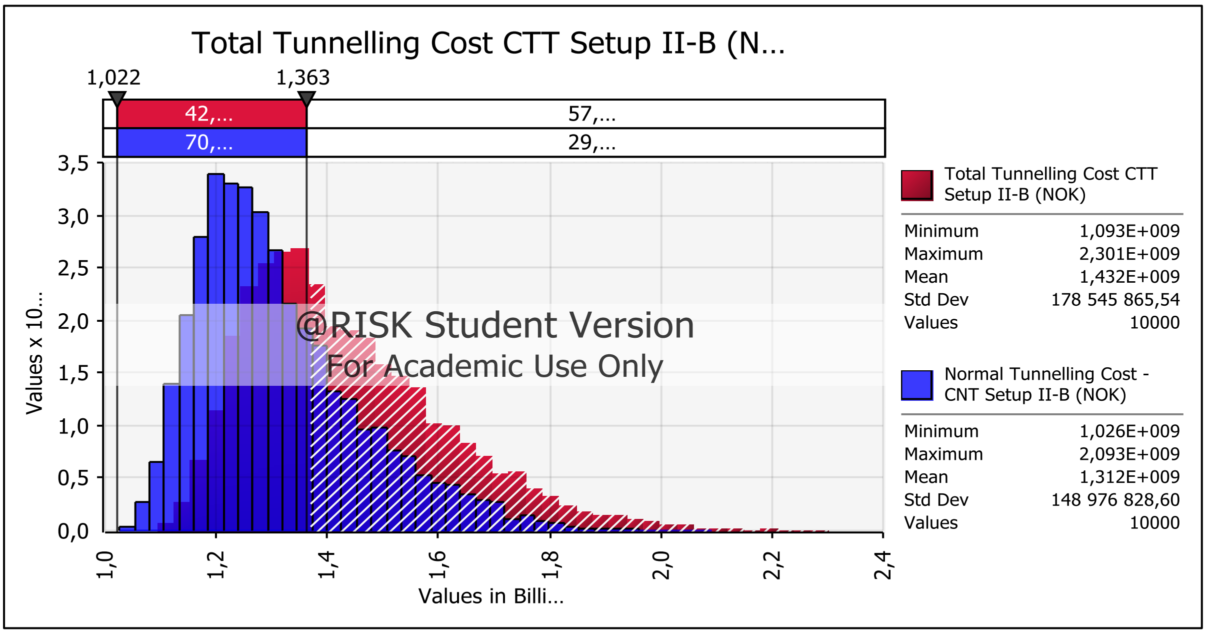

Figure 7.13: Normal and Total Tunnelling Cost Setup II-B (after 10.000 iterations)

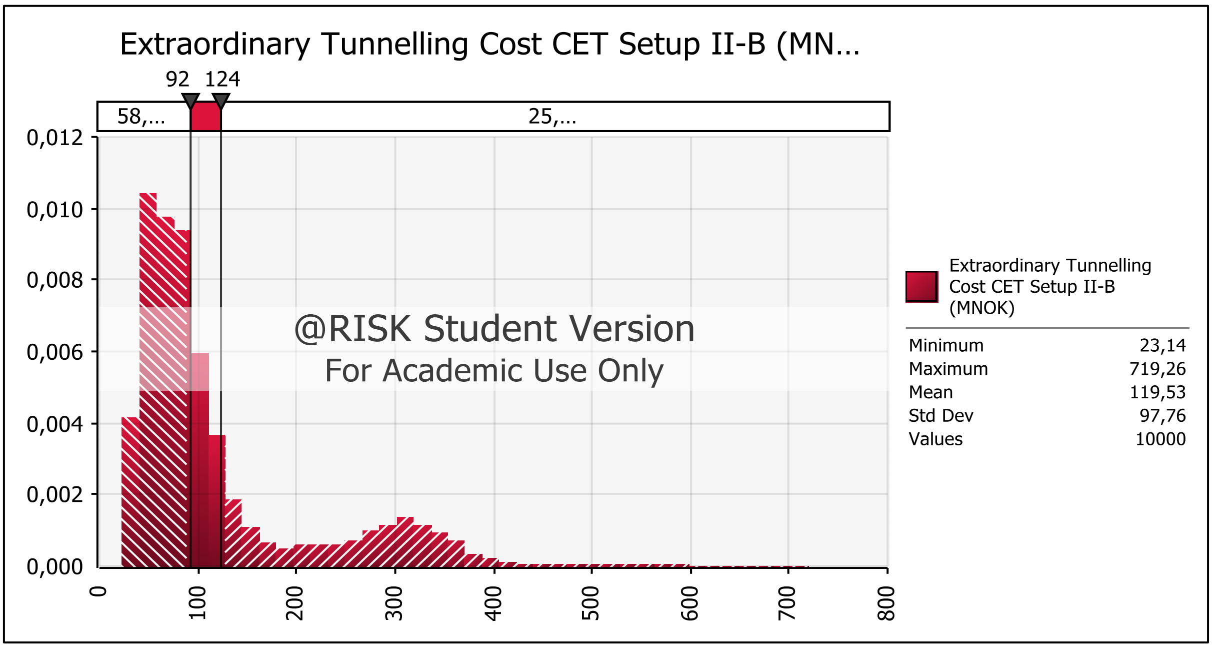

Figure 7.14: Extraordinary Tunnelling Cost Setup III-B (after 10.000 iterations)

The summary of these results is presented in Table 7.6, where are compared with the results obtained from the deterministic setup (i.e.: Setup I Base Case).

Table 7.6: Results Model Setup II-B (Full correlated cost drivers)

Specific Cost	Setup I Base Case	Setup II-B (Correlated) Min	Mean	Max
- Normal Tunnelling Cost	1.239,08	1.026,00	1.312,11	2.093,00
- Standard Deviation	0,00	-	148,98	-
- Extraordinary Tunnelling Cost	123,91	23,14	119,53	719,26
- Standard Deviation	0,00	-	97,76	-
- Total Tunnelling Cost	**1.362,99**	**1.093,00**	**1.431,64**	**2.301,00**
- Standard Deviation	**0,00**	**-**	**178,55**	**-**

All Values in MNOK (2014)

7.3.4 Results Setup III-A

The normal (C_{NT}) and total tunnelling costs (C_{TT}) for setup III-A are presented in Figure 7.15, while the extraordinary cost (C_{ET}) is depicted in Figure 7.16. These figures represent the final estimations for the tunnelling process, when correlation among cost drivers and among the homogeneous geological zones are not incorporated in the model.

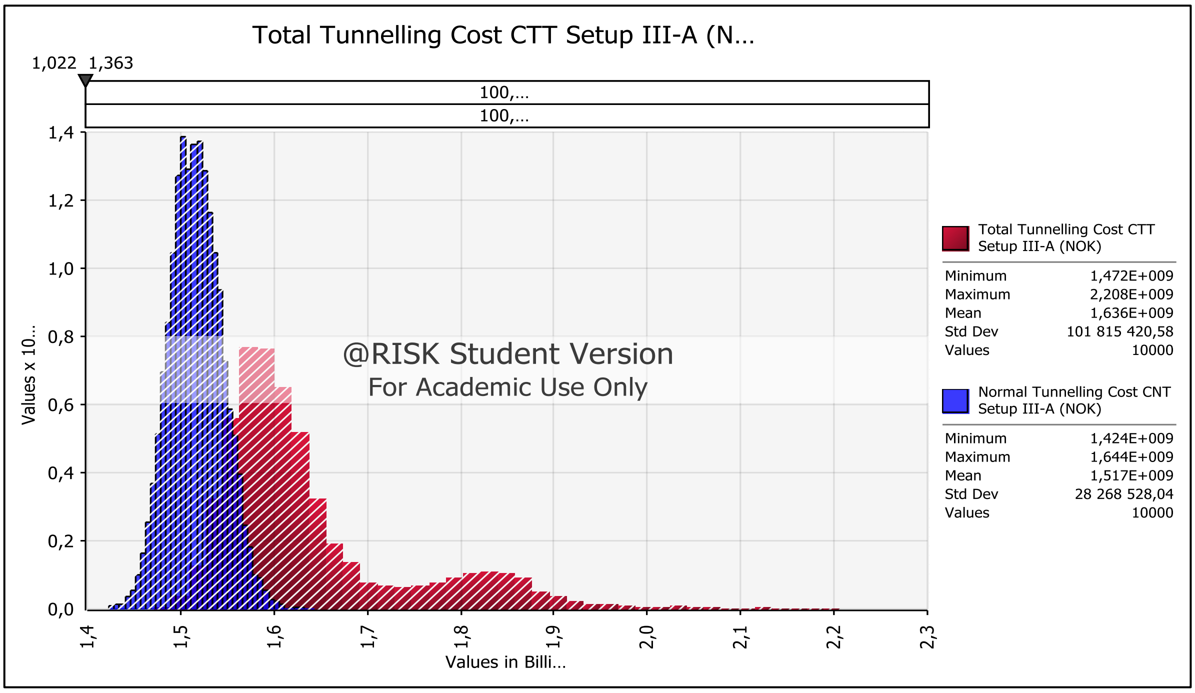

Figure 7.15: Normal and Total Tunnelling Cost, Setup III-A (uncorrelated)

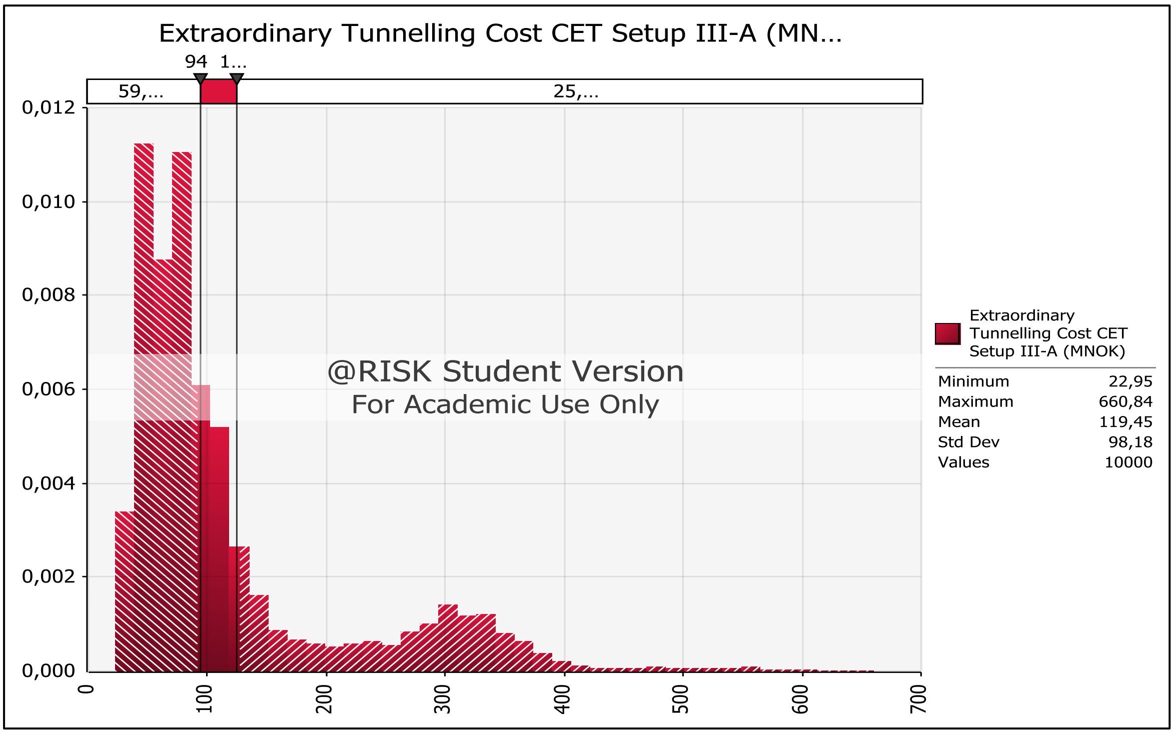

Figure 7.16: Extraordinary Tunnelling Cost, Setup III-A (uncorrelated cost drivers)

According to Figure 7.15, the main value for the total tunnelling cost (C_{TT}) reaches 1.636 MNOK with a standard deviation of 101,82 MNOK. The same figures for the normal tunnelling cost, which is represented in the blue distribution, are 1.517 MNOK and 28,27 MNOK respectively.

As presented in Figure 7.16, the extraordinary tunnelling cost presents a mean value of 119,45 MNOK and a standard deviation of 98,18 MNOK. All these figures and its comparison with the base case of the Setup I are depicted in Table 7.7.

Table 7.7: Results Model Setup III-A (Uncorrelated cost drivers and zones)

Specific Cost	***Setup I***	***Setup III-A (Uncorrelated)***		
	Base Case	***Min***	***Mean***	***Max***
- Normal Tunnelling Cost	1.239,08	1.424,00	1.517,00	1.644,00
- Standard Deviation	0,00	-	28,27	-
- Extraordinary Tunnelling Cost	123,91	22,95	119,45	660,84
- Standard Deviation	0,00	-	98,18	-
- Total Tunnelling Cost	**1.362,99**	**1.472,00**	**1.636,00**	**2.208,00**
- Standard Deviation	**0,00**	**-**	**101,82**	**-**

All Values in MNOK (2014)

7.3.5 Results Setup III-B

The results for the Setup III-B are presented in Figure 7.17 and Figure 7.18. These figures represent the final value for the tunnelling process, when correlation among cost drivers and among the homogeneous geological zones are fully incorporated into the model.

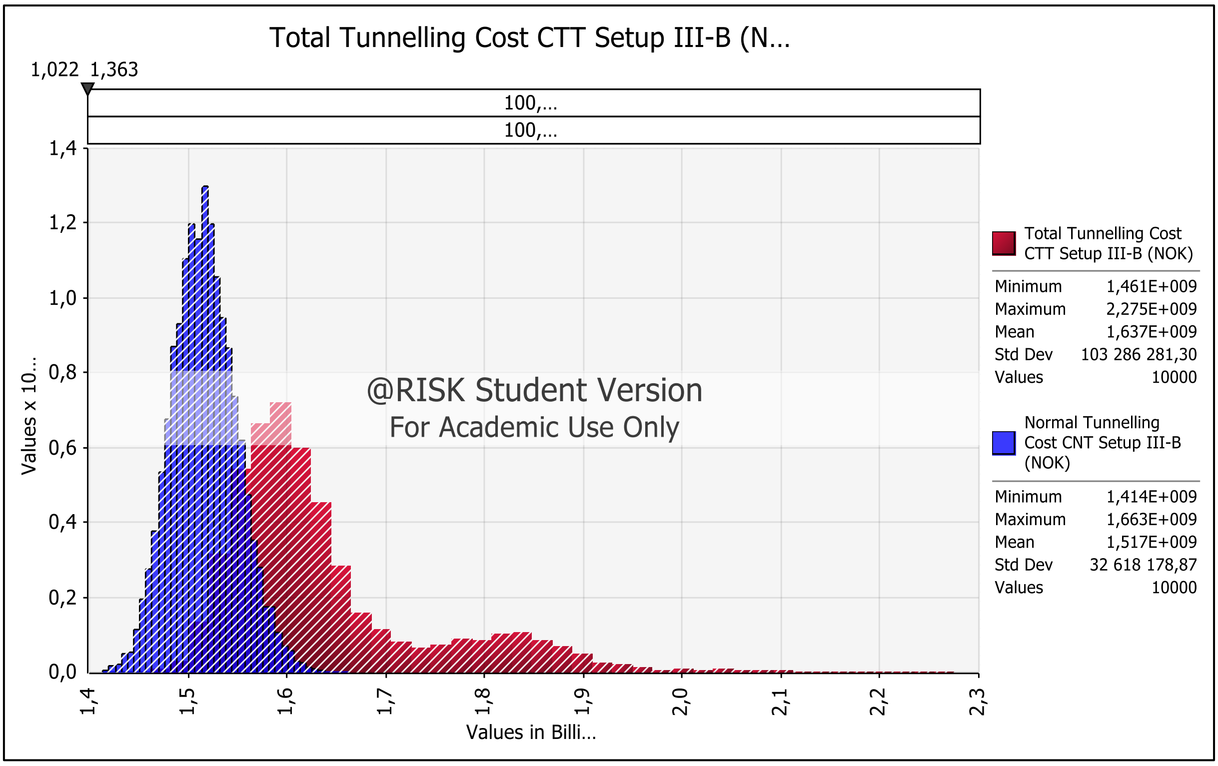

Figure 7.17: Normal and Total Tunnelling Cost, Setup III-B (correlated)

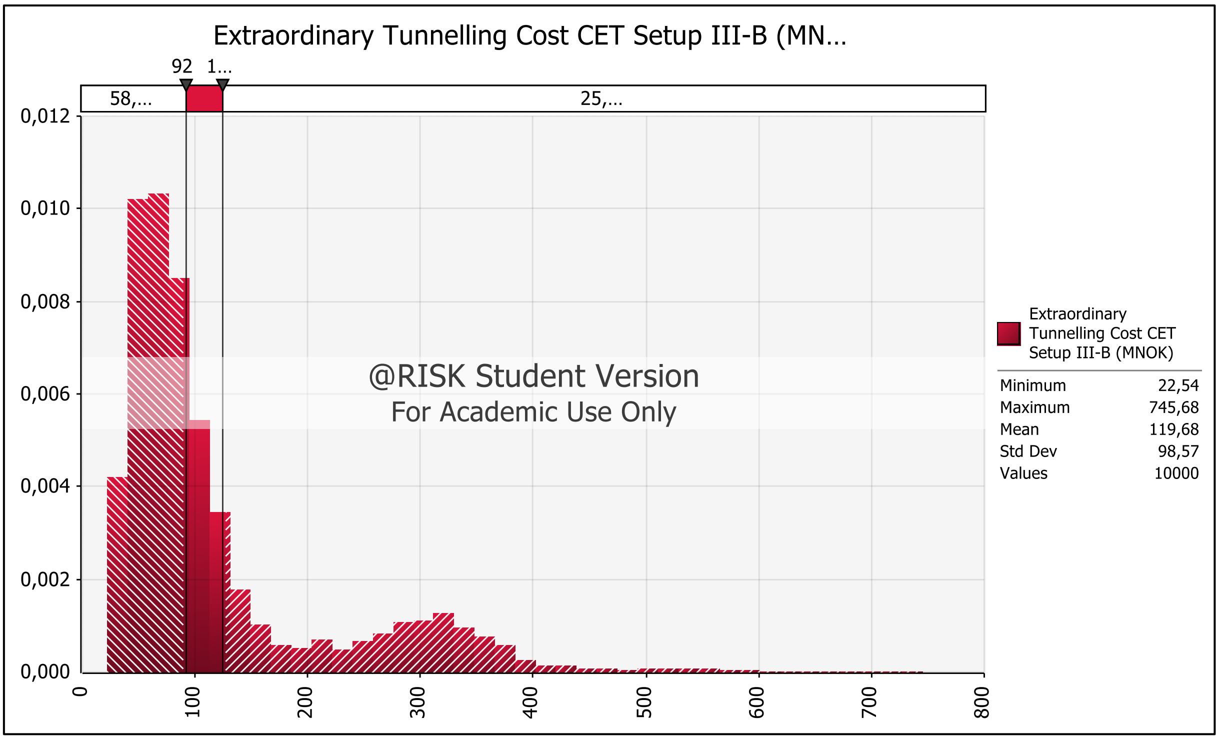

Figure 7.18: Extraordinary Tunnelling Cost, Setup III-B (correlated cost drivers and zones)

According to Figure 7.17 the main value for the total tunnelling cost (C_{TT}) reaches 1.637 MNOK with a standard deviation of 103,27 MNOK. Similarly, the figures for the normal tunnelling cost (C_{NT}) are 1.517 MNOK and 32,62 MNOK respectively.

The extraordinary cost regarding the occurrence of undesirable events, which is depicted in Figure 7.18, presents a mean value of 119,68 and a standard deviation 98,57 MNOK. A summary of these results is presented in Table 7.8.

Table 7.8: Summary Results Model Setup III-B (correlated cost drivers and zones)

Specific Cost	***Setup I***	***Setup III-B (Correlated)***		
	Base Case	***Min***	***Mean***	***Max***
- Normal Tunnelling Cost	1.239,08	1.414,00	1.517,00	1.663,00
- Standard Deviation	0,00	-	32,62	-
- Extraordinary Tunnelling Cost	123,91	22,54	119,68	745,68
- Standard Deviation	0,00	-	98,57	-
- Total Tunnelling Cost	**1.362,99**	**1.461,00**	**1.637,00**	**2.275,00**
- Standard Deviation	**0,00**	**-**	**103,29**	**-**

All Values in MNOK (2014)

Detailed information regarding the outputs obtained for both model settings is given in Appendix L "Case Study, Model Results".

7.3.6 Results Summary

Considering the results presented in the previous sections, Table 7.9 presents a summary for the different cost estimations (i.e.: normal, extraordinary and total tunnelling cost) and the respective model setups. Additionally, this table presents the cost per unit meter (NOK/m) of tunnel and per cubic meter (NOK/m3), which can serve as comparison with other model or industrial cost drivers for this type of structures.

Table 7.9: Results Summary, including all model setups and unit cost (NOK/m) and (NOK/m3)

Model Setup	***Tunnelling Cost (NOK)***			***Unit Cost (NOK)***	
	C_{NT}	***C_{ET}***	***C_{TT}***	***NOK/m (*)***	***NOK/m3 (**)***
Setup I (Base Case)	1.239.082.366	123.908.237	1.362.990.603	75.722	1.130,17
Setup II-A (Mean Values)	1.312.110.000	119.630.000	1.431.740.000	79.541	1.187,18
Setup II-B (Mean Values)	1.312.110.000	119.530.000	1.431.640.000	79.536	1.187,10
Setup III-A (Mean Values)	1.517.000.000	119.450.000	1.636.450.000	90.914	1.356,92
Setup III-A (Mean Values)	1.517.000.000	119.680.000	1.636.680.000	90.927	1.357,11

(*) For a total length of 18.000 metres
(**) Cost for a specific section T9.5 (67 m2 nominal area)

7.4 Tunnelling Cost in Norwegian Undersea Tunnelling Projects

This section has been incorporated as part of the model results, in order to obtain a realistic basis for comparing the results obtained for the specific study case.

The data analysed in this section was obtained from public information available in different reports of the Norwegian Public Road Administration (NPRA). According to NPRA (2002), the construction unit cost (NOK/m) of undersea tunnel vary from 35.000 (NOK/m) to 120.000 (NOK/m), considering a level price at year 2000.

The cost range mentioned above was obtained from a sample of 21 undersea tunnel project executed in Norway, which are depicted in Figure 7.19. The unit cost presented in this table correspond to the final cost, after execution, and it includes all the cost related to the construction activities (i.e.: tunnel, road and systems), whilst planning and other field activities are not include in this numbers

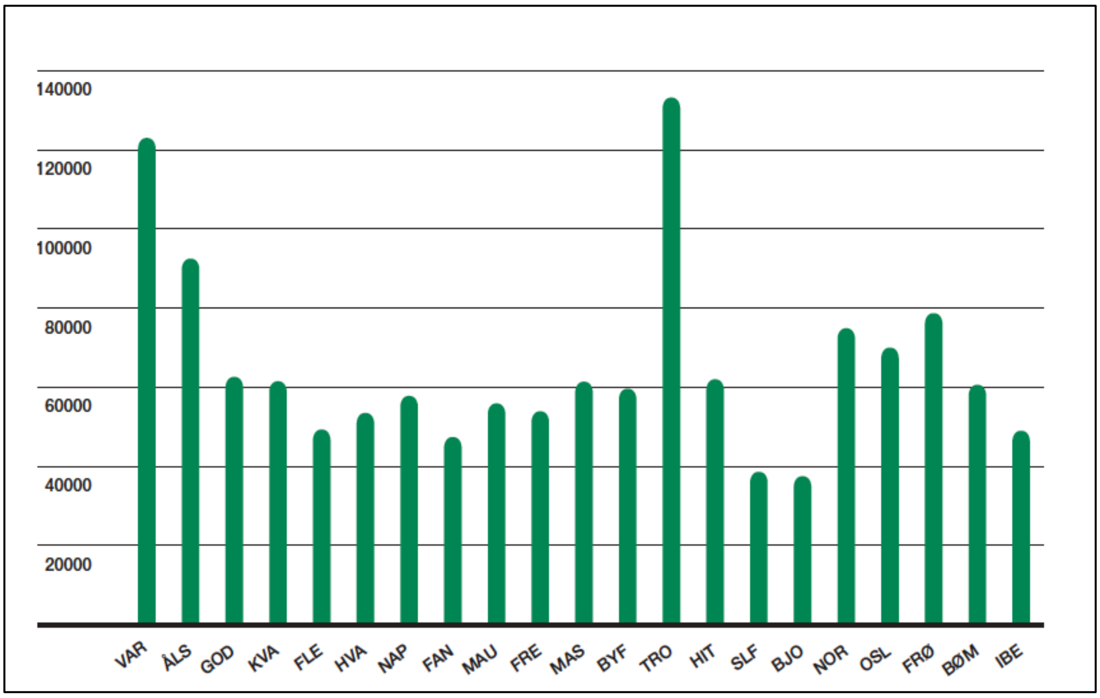

Figure 7.19: Construction Unit Cost in Norwegian Undersea Tunnel Project (executed until 2002). The unit price are depicted in (NOK/m) and corresponds to the level price at year 2000 (source: NPRA (2002))

Using the same information, the figures were updated according to the construction index 2014, and they are depicted in Table 7.10. Additional information, regarding tunnel section, was included in this table in order to provide a more specific insight respect to the unit cost per cubic meter of tunnel (NOK/m^3)

Table 7.10: Updated Construction Unit Cost in Undersea Tunnel Project in Norway. The table also considers the price per cubic meter of tunnel (NOK/m^3)

ID	Project Name	Tunnel Section (m2)	Unit Cost (All construction activities (**)) 2.000 (NOK/m)	2.014 (NOK/m)	2.014 (NOK/m3)	Unit Cost Tunnelling Activities 2014 NOK/m	2014 NOK/m3
1	Vardø	53	120.000	213.512	4.029	*128.107*	*2.417*
2	Ellingsøy - Valderøy	68	120.000	213.512	3.140	*128.107*	*1.884*
3	Kvalsund	43	60.000	106.756	2.483	*64.054*	*1.490*
4	Godøy	52	60.000	106.756	2.053	*64.054*	*1.232*
5	Flekkerøy	46	50.000	88.963	1.934	*53.378*	*1.160*
6	Hvaler	45	55.000	97.860	2.175	*58.716*	*1.305*
7	Nappstraum	55	59.000	104.977	1.909	*62.986*	*1.145*
8	Fannefjord	54	49.000	87.184	1.615	*52.310*	*969*
9	Maursund	54	58.000	103.198	1.911	*61.919*	*1.147*
10	Byfjord	70	60.000	106.756	1.525	*64.054*	*915*
11	Mastrafjord	54	60.000	106.756	1.977	*64.054*	*1.186*
12	Freifjord	70	57.000	101.418	1.449	*60.851*	*869*
13	Hitra	70	61.000	108.535	1.551	*65.121*	*931*
14	Tromsøysund (*)	120	135.000	240.201	2.002	*144.121*	*1.201*
15	Bjorøy	53	39.000	69.391	1.309	*41.635*	*785*
16	Sløverfjord	54	38.000	67.612	1.252	*40.567*	*751*
17	Nordkapp	50	77.000	137.004	2.740	*82.202*	*1.644*
18	Oslofjord	79	70.000	124.549	1.577	*74.729*	*946*
19	Frøya	52	79.000	140.562	2.703	*84.337*	*1.622*
20	Ibestad	54	49.000	87.184	1.615	*52.310*	*969*
21	Bemlafjord	74	60.000	106.756	1.443	*64.054*	*866*

(*) *Double Tube Tunnel*
(**) *All construction activitities are included, planning and field activites are not included*

Since the updated cost obtained from NPRA (2002) includes all the construction activities related to the execution of the tunnel facility, these values are not directly comparable with the results obtained for the case study. In order to obtain a basis for comparison, the unit cost for the tunnelling has been considered equal to 60% of the respective construction cost, obtaining the results highlighted in italic and depicted in the right hand side of Table 7.10.

After performing a simple statistic analysis of the updated data, it was possible to set the main figures for the tunnelling unit costs. The figures obtained in this process are depicted in Table 7.11 ant it considers the main value, standard deviation, and extreme values of the distributions.

Table 7.11: Estimated Tunnelling Cost from Previous Undersea Tunnel Project in Norway.

Results	Total Tunnelling Cost NOK/m	NOK/m3
Mean Value	71.984	1.211
Standard Deviation	27.964	408
Minimum	40.567	751
Maximum	144.121	2.417
Best Fit Distribution	Loglogistic	Exponential

Figure 7.20 shows the fit distribution for the tunnelling cost per meter (NOK/m), while Figure 7.21 depicts the fit distribution of the tunnelling cost per cubic meter (NOK/m3).

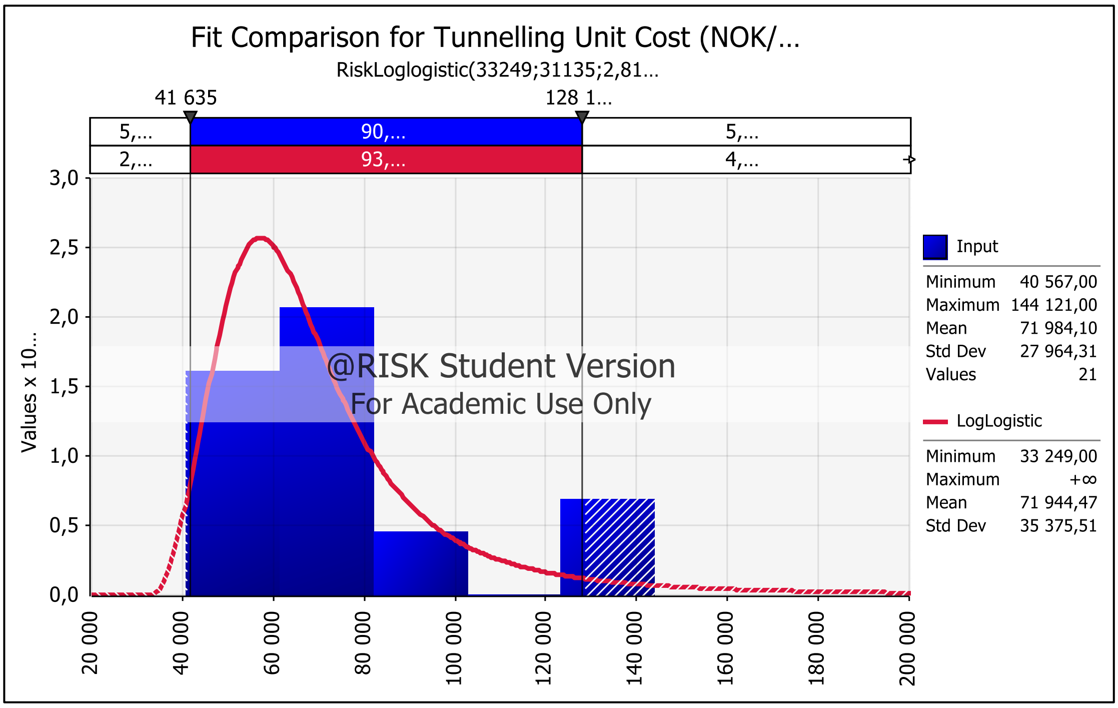

Figure 7.20: Best Fit Distribution for the tunnelling cost per meter (NOK/m), obtained from a sample of 21 projects executed in Norway.

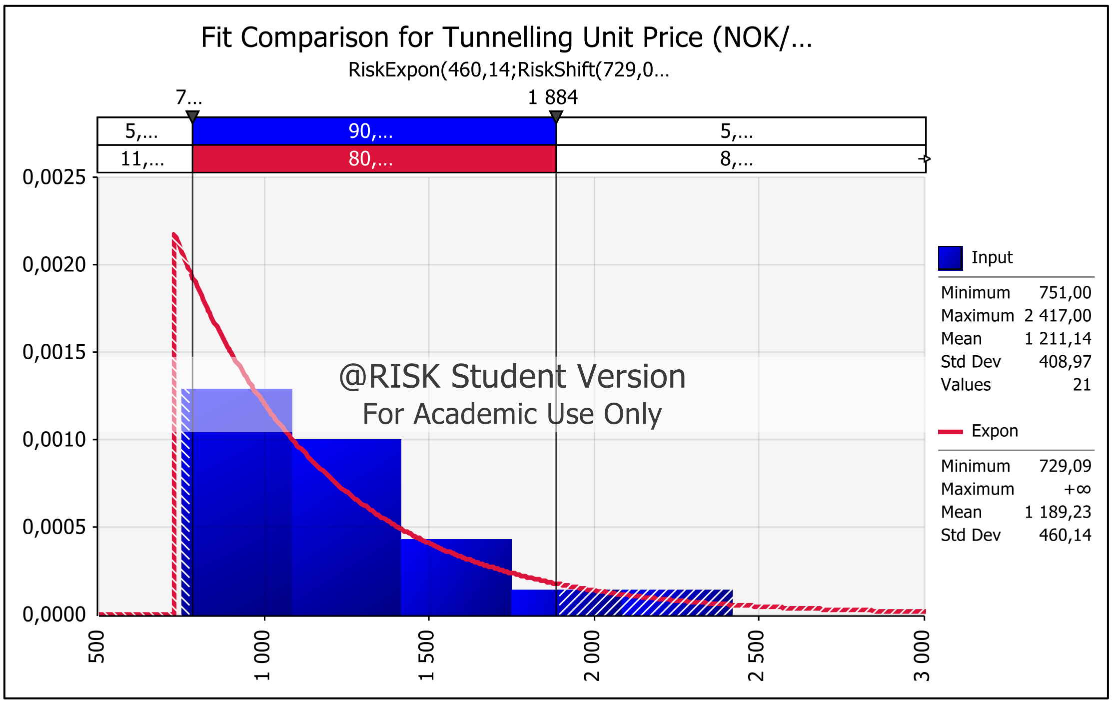

Figure 7.21: Best Fit Distribution for tunnelling cost per cubic meter (NOK/m³), obtained from a sample of 21 projects executed in Norway.

8. DISCUSSION

The discussion of this work has been broken down in five sections, which address specific aspects regarding the development of this research project. The first section is devoted to discuss the particular results obtained for the case study, after applying the proposed model. The analysis is focused on describing the results, in terms of mean values and standard deviations, as well as emphasising those aspects in agreement with the models previously introduced and analysed in this work (Chapter 5).

The second part is mainly devoted to analyse the general modelling process, as well as the difficulties and challenges encountered during the entire modelling process. The third part is focused on assessing those aspects regards the quality of the proposed model, in terms of its validity and reliability. This analysis is essential for assessing the potential applicability of this model in other cases studies or real industrial problems. Section 8.4 is focused on analysing the research questions that address this research work, and it provides a comprehensive overview about the conclusive remarks of this academic work.

Finally, section 8.5 is focused on establishing a group of activity that may be considered as part of futures research projects, in order to improve this model and expand the application of stochastic models in the cost estimation of underground projects.

8.1 Analysing the Model Results

The normal (C_{NT}), extraordinary (C_{ET}), and total tunnelling costs (C_{TT}) for the Chacao Channel Tunnel Project have been estimated using the model developed as part of this research work. The application of the model has been done, using specific model setups that represent distinct levels of uncertainty existing at different project phases. As previously stated, the estimation model was specifically designed for the drill and blast method and it was applied in a tunnel section equivalent to 2*T9.5 and 9 km length.

After the application of the Setup I, it was possible to obtain three different values for the normal (C_{NT}), extraordinary (C_{ET}), and total tunnelling costs (C_{TT}), which are considered as the best, base and worst cases for the execution of the tunnelling activities. These values were obtained, assuming that the parameters involved in the estimation of the normal tunnelling cost (i.e.: cost drivers) take, in a single assessment, the same level of values (i.e.: all optimistic, either all medium or all pessimistic). Even though this "tandem" behaviour of the cost drivers is not realistic, it is assumed that gives a suitable basis to set the boundaries, where the estimations of the stochastic model should exist. The values obtained after applying the deterministic setup are summarised in Table 8.1.

Table 8.1: Deterministic Cost Estimations for the Chacao Channel Project. The table shows the best, base and worst cases estimated using single point assessment.

Specific Cost	***Setup I (MNOK)***		
	Best Case	***Base Case***	***Worst Case***
- Normal Tunnelling Cost (C_{NT})	929,03	1.239,08	3.955,68
- Extraordinary Tunnelling Cost (C_{ET})	92,90	123,91	395,57
- Total Tunnelling Cost (C_{TT})	**1.021,93**	**1.362,99**	**4.351,25**

As can be observed in Table 8.1, the extreme values for the deterministic total tunnelling cost (C_{TT}) may vary from a minimum value of 1.021,93 MNOK to a maximum of 4.351,25 MNOK. The base case is set in 1.362,99 MNOK that may be considered the expected cost related to the most frequent conditions along the tunnel alignment.

In most of the comparisons performed along this discussion, the deterministic base case is used as the main reference point. This decision is sustained in the full agreement of the author with Spackova, Sejnoha et al. (2013 b), who emphasise that deterministic cost estimations usually assume values close to the mode (i.e.: the most frequent value in a sample), and therefore they represent some kind of ideal case.

For the Setup II-A the total tunnelling cost has a mean value of 1.431,74 MNOK with a standard deviation of 148,75 MNOK. When comparing the results of Setup II-A, with the deterministic cost estimation (i.e.: base case equal to 1.362,99 MNOK), the values appear to be relatively close to each other; nevertheless this appreciation changes, when the probability of not being exceeded is taken into account. The deterministic value has only a 38% chance to be achieved (i.e.: the deterministic value has a 62% chance to be exceeded), when is compared respect to the total tunnelling cost obtained for the Setup II-A (red distribution).

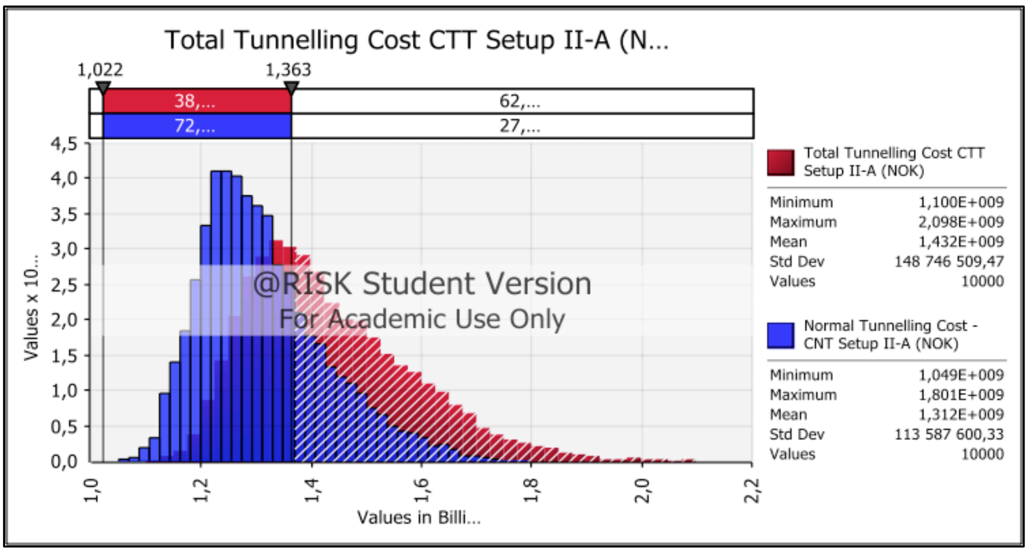

Figure 8.1:Model Outputs Comparison, including Deterministic Base case and Set II-A.

When correlations among cost drivers are incorporated into the model (i.e.: Setup II-B), the results behave in concordance with other stochastic models, such as Isaksson (2002), Tamparopoulos (2013), and Spackova, Sejnoha et al. (2013 a). This means that even though the mean value remains almost constant (i.e.: close to 1.432 MNOK) the standard deviation of the total tunnelling cost increases from 148,75 MNOK up to 178,54 MNOK, reflecting in a better way the uncertainty that is presented this early cost estimation. The relevance of correlation, among model variables, and its effects into the total cost distribution are topics also highlighted by Isaksson (2002), Issakson and Stille (2005), Min (2003), among other researchers reviewed as part of this work.

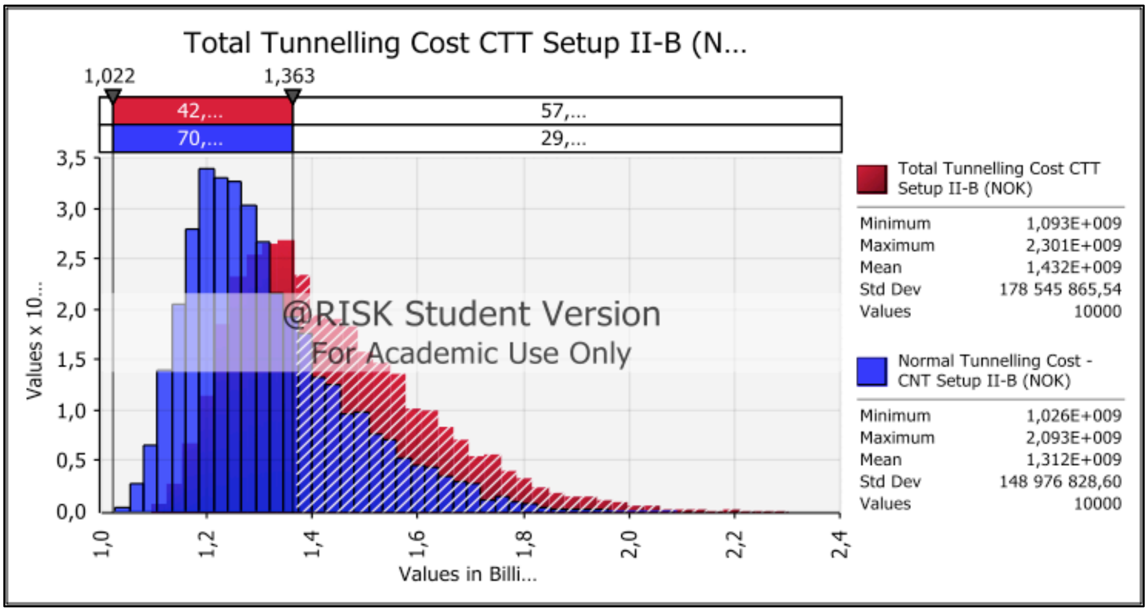

Figure 8.2: Model Outputs Comparison, including Deterministic Base case and Set II-B.

The probability density function for the total tunnelling cost of Setup II-B (red function shown in Figure 8.2) is flatter than the distribution obtained for Setup II-A, which reflects the expected increment in the total range of the cost estimation. The lowest boundary (i.e.: the minimum) moves from 1.100 MNOK (Setup II-A) to 1.093 MNOK for Setup II-B, whilst the upper boundary moves from 2.098 MNOK to 2.301 MNOK.

Even though correlations were incorporated exclusively in the cost drivers and risk events remains uncorrelated, the effects of correlations in the total tunnelling cost are noticeable in both sides of the distribution, demonstrating the relevance of the uncertainty of geological aspects (i.e.: cost drivers) in the final results.

Even though the range of the normal tunnelling cost increase, when incorporating the correlation among cost drivers, the author is totally aware that this simplification (i.e.: to do not assess correlation among risk events) implies that other relevant effects are not introduced in extraordinary tunnelling cost, which controls the values in the tail of the total cost distribution (i.e.: the maximum) and consequently is not reflecting the most realistic scenario for the maximum values.

As a ratification of the inconsistencies generated for the simplification previously analysed, the chance of not being exceeded for the deterministic base case increased from 38% (II-A) up to 42% (II-B), which means that after correlation were introduced, the deterministic estimation has more chances to be achieved. Therefore, when using the model Setup II, the analysis of the correlations among risk events will help estimators to better assess the extreme values regarding the total tunnelling cost.

When sensitivity analysis is performed for the results of Setup II-B, the results shows that cost drivers are the most sensitive inputs in the total tunnelling cost (C_{TT}), while undesirable risk events have less influence in the variation of the final tunnelling cost.

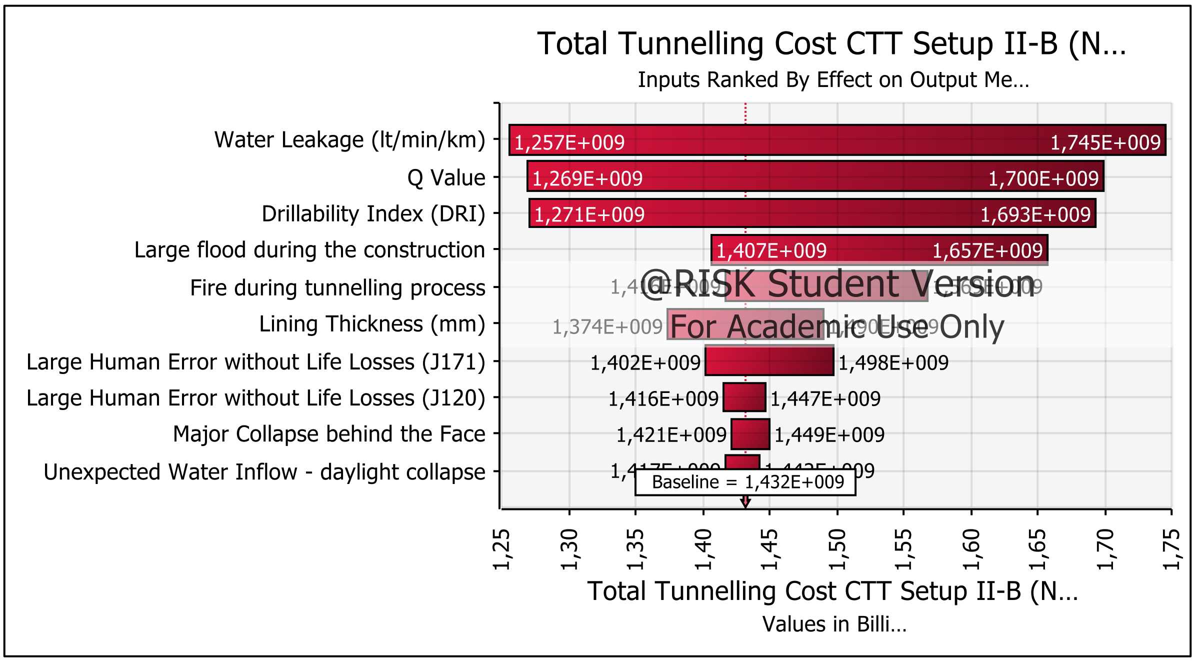

Figure 8.3: Sensitivity Analysis Setup II-B, this output shows the different level of influence that every random input has in the final model output, i.e.: total tunnelling cost (C_{TT}).

When division of the tunnel length is incorporated in the analysis (i.e.: Setup III), the results for the Chacao Tunnel Project remain consistent with both general cost estimation theory and with the results obtained for other researchers.

As highlighted by Isaksson (2002), Min (2003), Oreste (2006), and other researchers, the division of the tunnel length into homogeneous zones allows estimators to better represent the characteristic and uncertainty regard geological aspects, where tunnels are executed. This discretisation of the tunnel length will consequently helps obtaining more precise cost estimation for the normal tunnel cost in the specific zones and therefore for the total tunnel length. According to these authors, the main effect of the discretisation of the tunnel length may be appreciated as a continuous reduction in the range of the final estimation (i.e.: less standard the deviation). This procedure may also be associated with standard and common cost estimation practices, where the most "sensitive" elements that contribute with larger uncertainty (i.e.: greater standard deviation) are divided into sub elements, in order to perform a more detailed analysis and reduce the final range of the cost estimation, see Lichtenberg (2005), PMI (2008) and Samset (2010).

Since the proposed model assumes that geology on the tunnel alignment represents the most sensitive aspect for the normal tunnelling cost (C_{NT}), the identification of homogeneous zones appears as a useful measure to better assess the tunnelling cost and obtain more precise estimations.

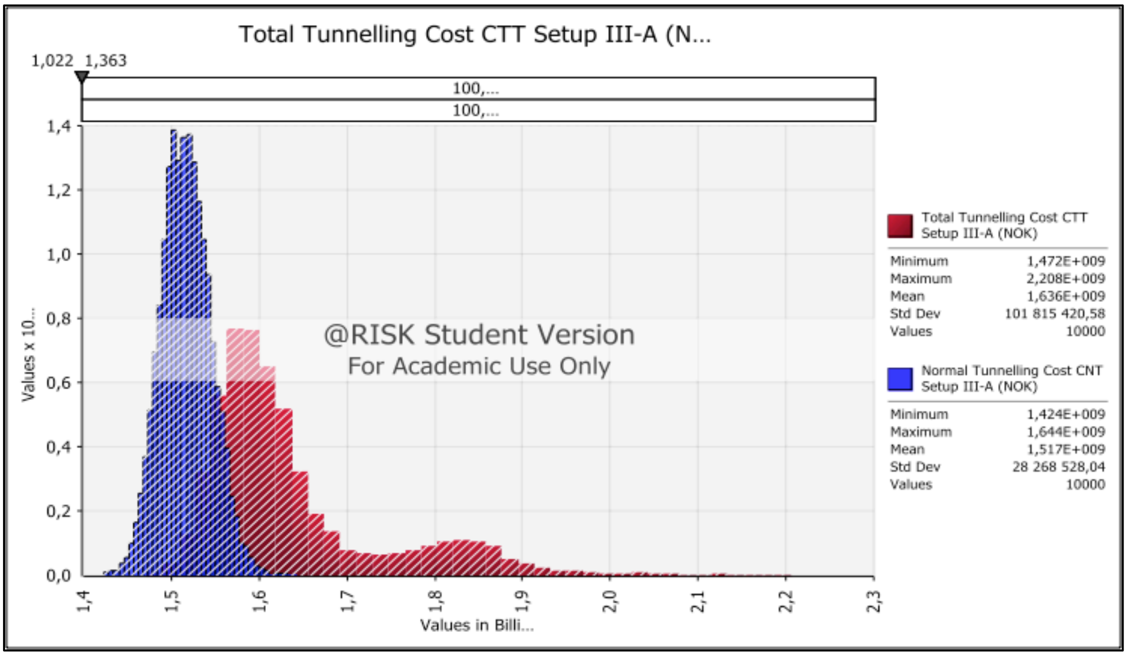

Figure 8.4: Model Outputs Comparison, including Deterministic Base case and Set III-A

The results obtained after the application of Setup III are fully coherent with the objectives behind the practice previously discussed. In the specific case of Setup III-A, the mean value for the total tunnelling cost is set in 1.636 MNOK with a standard deviation of 101,82 MNOK.

This result evidences an increment of the expected value (i.e.: mean value) and a lower standard deviation for the total tunnelling cost, when comparing with results of Setup II. In this specific case the standard deviation decreases from 148,75 MNOK (Setup II-A) to 101, 82 MNOK (Setup III-A). Since this model setup does not determine the correlation among risk events, the major reduction of the standard deviation is due to the more detailed analysis done exclusively in the normal tunnelling cost.

Regarding Setup III-B, which includes the correlation of cost drivers and homogeneous zones (i.e.: geological correlation), the mean value does not experiment changes respect to Setup III-A (i.e.: remains close to 1.636 MNOK), nonetheless the standard deviation increased from 101,82 up to 103,29 MNOK, which is explained due to the incorporation of the correlations among cost drivers and homogeneous zones.

It must be clarified that the low difference in the standard deviation, between Setup III-A (i.e.: non correlated) and III-B (i.e.: full correlated), it must be caused due to the incapacity of the author to assess the correlations among the homogeneous zones (i.e.: geological correlation). Similar difficulties are highlighted by Isaksson (2002), who emphasised that correlation among geotechnical aspects have large effects in the final distribution of the total tunnelling cost.

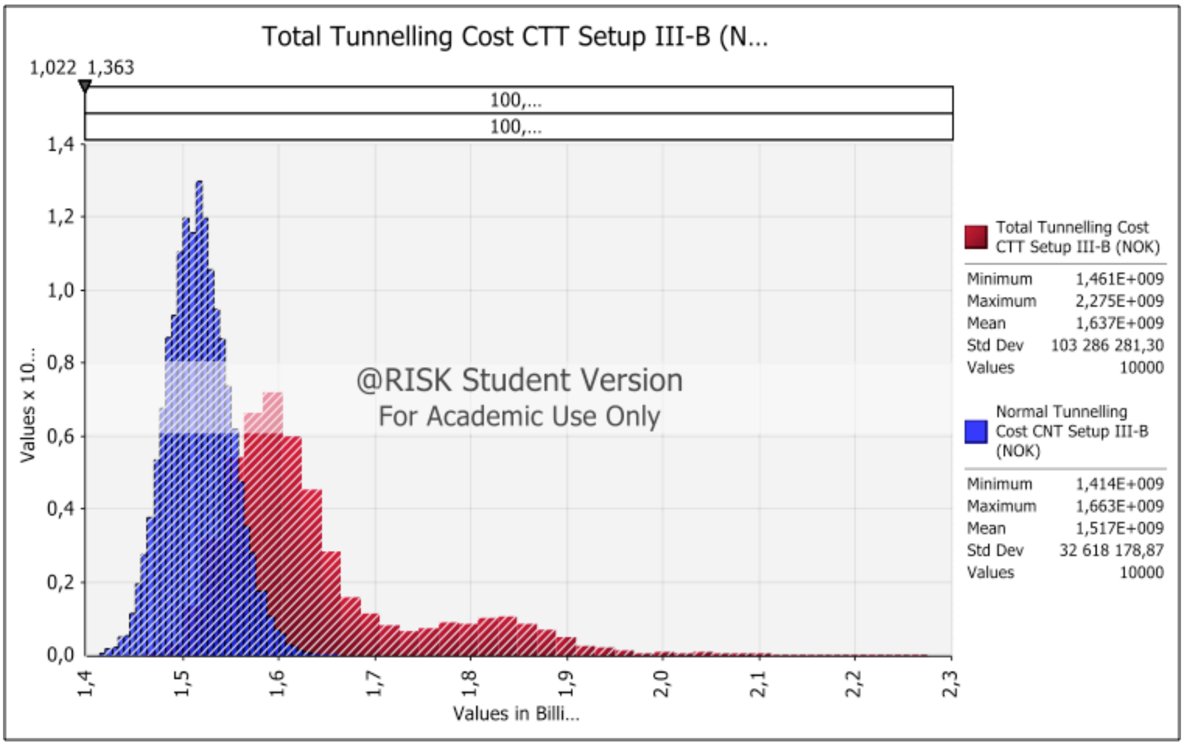

Figure 8.5: Model Outputs Comparison, including Deterministic Base case and Set III-B

As presented in the figures 8.4 and 8.5, the deterministic cost estimation (i.e.: base case) has not chance to be achieved, when considering the distribution obtained for the Setup III-A and III-B. In other words the probability of exceed the deterministic base case obtained, is equal to 100%. This constitutes a sound proof of the lack of reliability of deterministic cost estimations, which is highlighted in several researches that were reviewed as part of this work, see Isaksson (2002), Min (2003), Issakson and Stille (2005), Oreste (2006), and Spackova, Sejnoha et al. (2013 a).

When reviewing the sensitivity analysis of Setup III-B, the results appear to be different regarding those obtained for Setup II-B. When homogeneous zones are identified and assesses in more detailed form, the standard deviation of the normal tunnelling cost (C_{NT}) decrease and the most sensitive inputs are now located in the risk events. This can be appreciated in Figure 8.6, which shows the specific sensitivity analysis after correlation among cost drivers were introduced.

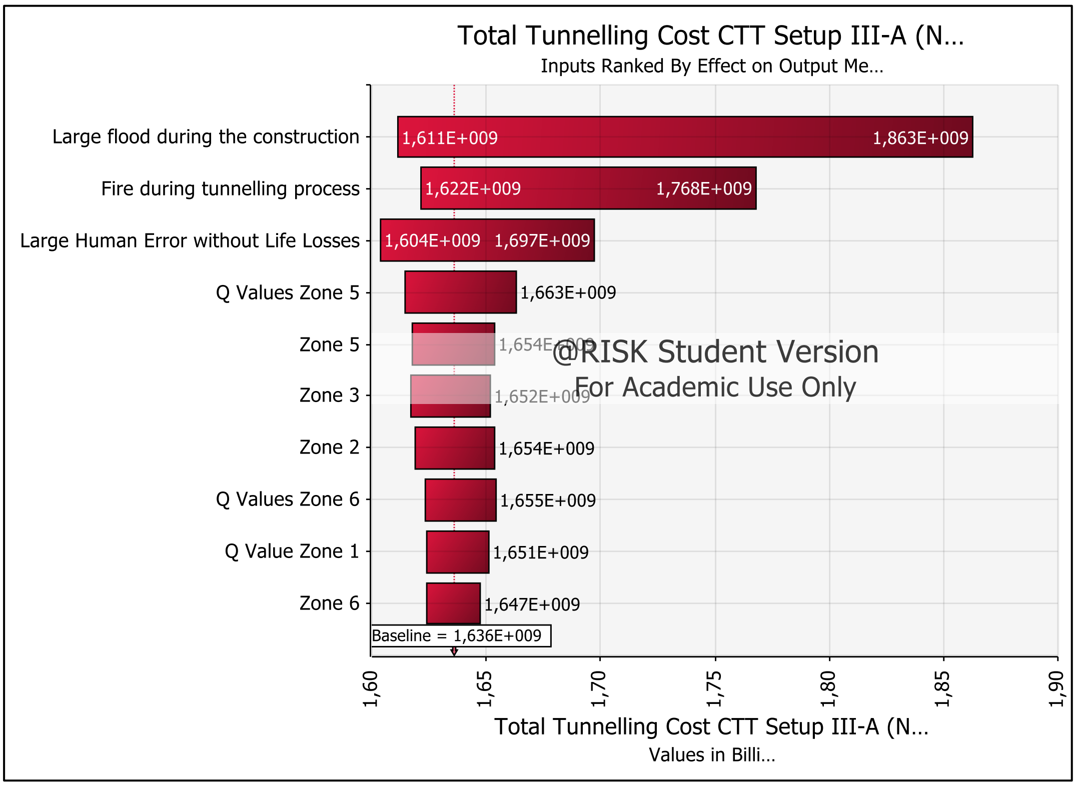

Figure 8.6: Sensitivity Analysis Setup III-B.

Beside of the full consistency of the results with other models developed for the cost estimation of underground projects, the figures (i.e.: cost estimation) also show a complete agreement and consistency with the general theory regarding cost estimation. The steady growth in the expected cost (i.e.: the mean value) for the total tunnelling cost, as well as the continuously reduction of their standard deviation, constitute a full agreement with those concepts regarding the cost estimation maturity emphasised in GAO (2009), PMI (2008), and Samset (2010).

Even though the estimation for the total tunnelling cost (C_{TT}) follows the expected tendency, it is necessary to highlight that this behaviour is basically due to changes introduced in the normal tunnelling cost (C_{NT}). As previously stated, the application of the model in this specific case study did consider a single evaluation of the risk events.

The main effect of this simplification is reflected in the steady behaviour of the extraordinary tunnelling cost (C_{ET}), which remains practically constant in its mean value for all the stochastic assessment (i.e.: Setup II and III). The main effect of this simplification is a null effect in the distribution of extraordinary tunnelling cost (C_{ET}), which controls the extreme values in the total tunnelling cost (C_{TT}).

Table 8.2: Extraordinary Tunnelling Cost for Stochastic Setups (II and III)

Model Setup	***Extraordinary Tunnelling Cost "C_{ET}" (MNOK)***			
	Min	***Mean***	***Max***	***S.Deviation***
Setup II-A	21,01	119,63	686,10	97,73
Setup II-B	23,14	119,53	719,26	97,76
Setup III-A	22,95	119,45	660,00	98,18
Setup III-B	22,54	119,68	745,68	98,57

One of the reasons that sustain the decision to do not modify the analysis of the assessment of the extraordinary tunnelling cost lies in the difficulties to assess probabilities and consequences, as well as the correlations for the risk events. The assessment of undesirable events is extremely difficult to be performed, without the collaboration of tunnelling project experts.

Since the proposed model is fully designed to incorporate and capture these aspects, this should not be considered a shortcoming of the model itself and it should considered as a particular inconvenient faced during the specific assessment process, which was not performed as originally designed.

In the same perspective, another aspect that clearly affects the final estimation of the extraordinary tunnelling cost is the risk event identification. Single assessment does not allow identify a broad perspective of events; while at the same time incorporate a clear bias in the assessment of the consequence and occurrence. The relevance of the risk identification and its effects in the final estimation are emphasised by Isaksson (2002), who states that the is direct correlation among the number of identified events and the final cost estimation.

After reviewing the main results (i.e.: mean value and standard deviation), it is possible to state that the obtained cost estimation show consistency with the general theory of cost estimation, see APM (2006), PMI (2008), GAO (2009), and Samset (2010). In all these text, it is established that the range of the cost estimation should, at least decrease, as more information became available and incorporated in the cost estimation process.

Nonetheless, the results offered by the proposed model go beyond than the former discussed; therefore a brief discussion is introduced respect to the other important findings obtained for the case study.

One of the tools incorporated in @Risk allows finding the most suitable statistical distribution that describes the random behaviour of the different cost assessed in the model. Considering the results obtained for Setup II-B and III-B, the statistical distributions that represent the total tunnelling costs (C_{TT}) are not fully consistent with the results obtained in others models, such as Isaksson (2002), and Oreste (2006). As depicted in Figures 8.1, 8,2, 8.4 and 8.5, the distributions, obtained when applying the proposed model, present a left-bound shape with longer tail, while the other results, obtained by Isaksson (2002), Min (2003) and Oreste (2006), present more symmetrical distributions, close to Gaussian or Normal distribution. Similar left-bound shape distributions are presented in the research of Spackova, Sejnoha et al. (2013 a) and Spackova, Sejnoha et al. (2013 b).

The differences with Min (2003) and Oreste (2006) may be explained in the fact that extraordinary risk are partially or totally neglected, either they are assessed in a different perspective. Other factor than may affect the final shape of the distribution is the number of variables involve in the problem. Distributions trend to be normal, when large number of independent variables are considered (i.e.: Central Limit Theorem). Regardless the difference with the works presented by Isaksson (2002), Min (2003) and Oreste (2006), the author believes that the obtained distributions constitute a suitable representation of the cost behaviour especially for those complex activities with high level of uncertainty and risk.

Another important aspect to be analysed is the consistency of the obtained results with previous undersea tunnel projects executed in Norway. Nonetheless this process was not straightforward. Most of the available information contains the cost regarding the whole construction phase, including tunnel facilities and other indirect and general cost that are not considered as part of the estimation of the total tunnelling cost (C_{TT}). Regardless the difficulties found, the information was used and comparison among tunnelling costs was feasible. The results show consistency; especially in those obtained in the stochastic setups.

According with the revision of 21 subsea tunnel projects, in Norway, the estimated tunnelling costs are as follows:

Table 8.3: Model Results versus Actual Project Cost in Norwegian Undersea Tunnel Projects. The unit costs (i.e.: NOK/m and NOK/m^3) were derived, considering the mean values of the total tunnelling cost. Similarly the actual cost of previous projects also corresponds to the mean value estimated after a statistical analysis introduced in section 7.4.

Model Setup	***Model Result (Mean Values)***			***Previous Projects (Mean Values)***	
	CTT (NOK)	***NOK/m (*)***	***NOK/m3 (**)***	***NOK/m***	***NOK/m3***
Setup II-A (Mean Values)	1.431.740.000	79.541	1.187,18	71.984	1.211
Setup II-B (Mean Values)	1.431.640.000	79.536	1.187,10	71.984	1.211
Setup III-A (Mean Values)	1.636.450.000	90.914	1.356,92	71.984	1.211
Setup III-A (Mean Values)	1.636.680.000	90.927	1.357,11	71.984	1.211

The estimated tunnelling costs of previous undersea tunnel projects were estimated in 71.984 (NOK/m) and 1.211 (NOK/m^3), which are consistent with the results obtained for the model setups II and III. The consistency between the model results and the actual cost of previous projects may be considered, as a suitable support when the numbers are obtained considering the same scope of work, therefore this consistency must be carefully treated and it should not be considered as a definitive proof of the model accuracy.

An additional feature to be discussed about the estimations obtained for the case study is the currency in which the outcomes are given (i.e.: Norwegian crowner). The model has been built considering prices that reflect the technology, conditions and requirements of the tunnel industry in Norway; therefore it can be assumed that the total tunnelling cost is representative of a project to be executed in Norway, given identical conditions than the described in the case study. In order to express the total tunnelling cost in Chilean Pesos (CLP), corrections regarding prices and construction performance must be done. The difficulties regarding this process may be avoided by selecting more appropriate case studies for futures researches, in which the results may be directly applied.

Finally and to sum up the analysis of the results related to the Chacao Channel Project, it may be stated that the total (C_{TT}), normal (C_{NT}) and extraordinary (C_{ET}) tunnelling costs are fully consistent with the theory that support the cost estimation, and they are considered to be valid for the specific case study.

8.2 Assessing the Modelling Process

In the opinion of the author, a relevant aspect to be included in this discussion is the modelling process itself, which goes beyond than the specific results obtained for the selected case study.

The analysis of different aspects involved in the cost modelling (e.g.: assumptions, inputs, processes, and outputs) will provide a suitable source to understand which features may be improved, as well as identify the measures to overcome the actual limitations. Additionally, this will help to identify those aspects where major agreement and differences were found regarding the models presented by other researchers executed in the same area.

Firstly and addressing the most general aspects of the proposed model, it has been proved that integration of uncertainty and risk analysis into the cost estimation process is a key factor that may improve the quality of the outputs (i.e.: the cost estimation), and in this way improve other project management processes, especially during the early project stages.

The need of incorporating the risk and uncertainty into the construction management processes has been extensively pointed out in several studies, standards, and polices, which range from the broader project management perspective to those more related to the specific development of underground projects.

In the first group, researches such as Al-Bahar and Crandall (1990), Mustafa and Al-Bahar (1991), Lessard and Miller (2001), as well as other well-known professional practices such as APM (2006), and PMI (2008) emphasise the necessity of carrying out and integrating the risk and uncertainty analysis with other relevant management processes, such as cost estimation.

In the specific field of underground projects, this need is sustained in the development of several researchers, models and tools, such as the Decision Aids for Tunnelling (DAT), in which uncertainty related to geological and construction aspects are incorporated for assessing tunnelling time and cost, Min (2003). Other researches that claim the systematic incorporation of risk and uncertainty during the entire development of underground projects are the works presented by BTS (2003), Reilly and Brown (2004), Eskesen, Tengborg et al. (2004), Sousa (2010), Pennington (2011), Spackova (2012), and ITIG (2012).

Other relevant examples, where the analysis of geological and construction uncertainty and risk is directly incorporated in the specific cost estimation process are the researches performed by Isaksson (2002), Min (2003), Oreste (2006) Spackova, Sejnoha et al. (2013 a) and Tamparopoulos (2013).

All the models previously mentioned claim that deterministic cost estimation are not capable to deal with the uncertainty that govern underground project, therefore cost estimation base on deterministic approach may be considered not reliable either realistic, Spackova, Sejnoha et al. (2013 b). The results obtained for the specific case study presented in this research, confirm the fact previously highlighted, and it proves the need for designing and implementing stochastic tools in the cost estimation process for underground projects.

Since the determination of the cost is done through specific cost drivers, which are mainly geological or hydrogeological parameters, the model is fully aligned with those that claim for a stochastic approach to the analysis of soil or rock properties. The stochastic nature of geotechnical and geological aspects is extensively treated and emphasised in works such as, Fenton (1997), Nadim (2000), Fenton and Griffiths (2002), and DNV (2007).

All the above-mentioned support the rationale that sustains the proposed model, and it confirms the relevance of integrating risk and uncertainty analysis when modelling generic project management processes, as well as the need to incorporate the stochastic approach to theses processes

In more specific aspects of the cost modelling, the author fully agree with Isaksson (2002) and Spackova, Sejnoha et al. (2013 a) on the need to assess independently the normal and extraordinary cost of the tunnelling process. This specific approach differs respect to other stochastic models; where both normal and extraordinary costs are aggregate in a single estimation that describes the total cost of the tunnel activities. This is the case presented in the models presented by Min, Einstein et al. (2005) and Oreste (2006), where the results are presented as a final estimation, without differentiation among normal and extraordinary cost.

As presented in Chapter 6, the normal tunnelling cost (C_{NT}) is based on the estimation of the construction cost for four different construction activities that conform the tunnelling process. The unit costs are determined by mix of parametric and analytic methods, which implies the use of specific cost drivers and cost functions to determine the specific unit cost for each activity.

The used of driver-based approach for the cost estimation is considered a powerful tool to incorporate and quantify the uncertainty and risk in the cost estimation process. The driver-based approach represents significant advantages; when comparing with classical models based on line-by-line estimations, which are typically obtained from detailed material take off. The advantages of the driver-based estimations is highlighted in the theory by Hollmann (2007), who also emphasises the suitability of this approach (driver-based), when applying Monte Carlo Simulation and correlation among cost elements must be determined. The used of driver based method, during the pre-investment phases, is also supported in general project management standards, such as PMI (2008) and GAO (2009).

Nonetheless, the selection of the variables to be used as cost drivers was an extremely difficult process to perform. The difficulties found, during the execution of this process, arise mainly from two sources, which are as follows:

i. The extreme complexity, interrelations, and random nature of the variables involved in the execution of the tunnelling process in undersea tunnel projects.

ii. Model aspects related to the data collection, processing, and final assessment.

These difficulties are consistent with those highlighted by Tamparopoulos (2013), who developed a cost estimation model for the Brenner Base Tunnel based on risk factors as individual cost elements.

The selection of the parameters, which better represent the tunnelling activities, encompassed the revision of large quantities of technical information, especially those publications provided by the Norwegian Tunnelling Society (see: NFF (2005), NFF (2009), NFF (2010), and NFF (2011)), as well as other empirical prognosis models developed by NTNU, NTNU2B-05 (2006), and NTNU2C-05 (2006).

Eventually, the definition of the variables was done, considering the level of correlation with the tunnelling cost, and the capacity to be treated and assessed as random variable. Three geological parameters (i.e.: Drillability Index, Water Inflow, and Q-Value) and one design parameter (lining thickness) were selected as the cost drivers for estimating the normal tunnelling cost. This cost estimation also implied the design of the specific cost functions that allow obtaining the specific unit costs. A similar approach for the cost estimation of road tunnel is considered by Paraskevopoulou (2012), who assesses the cost of excavation and temporary support, using the GSI values as cost driver and specific cost functions for the unitary cost (i.e.: €/m and €/m^3).

After performing the determination of cost drivers and cost functions, it is possible to state that the most challenging aspects to assess were the water inflow control and rock support activities. For the water inflow control, the primary difficulty was found in linking a specific hydrogeological parameter and the unit cost of the construction activities. Furthermore, when a single parameter was defined (i.e.: water leakage) several difficulties arose to obtain reliable data to determine the specific cost of the construction activities. Reduced quantity of information was found regarding costs and other relevant technical aspects, such as material consumption, unit prices and construction performances.

The difficulties to link hydrogeological parameters and final cost of the water control activities is fully consistent with other works published as part of NFF (2005) and NFF (2011), where is also highlighted the difficulties to assess this process, especially due to the lack of correlation between encountered conditions and the actual level of water tightness achieved after the grouting process.

Similar challenges were found during the assessment of the unit cost for the rock support activities, where the existing prognosis models for bolting and sprayed concrete, NTNU10A-91 (1991) and NTNU10B-91 (1991), were not updated. Additionally these models are not directly linked with the selected cost driver (i.e.: Q-Values) and therefore, it was assumed that these models do not reflect the latest technological and research progress in this particular field. Once again, reduced quantity of information regarding specific construction aspects was found and several assumptions were made in order to obtain the final cost function.

Contrarily the excavation process, which was assessed through the NTNU prognosis model, was the most straightforward activity and it provides the most reliable and valid cost obtained as part of the model. This opinion is sustained in the large quantity of empirical data that is contained in the drill and blast prognosis models, NTNU2C-05 (2006). This also constitutes a firm proof of the relevance, claimed by Rostami, Sepehrmanesh et al. (2013) that systematic data collection and analysis has to enhance the estimation of underground tunnels projects.

Even though the results related to the normal tunnelling cost (C_{NT}) are considered valid, it does not constitute sufficient and necessary conditions to conclude that the selected parameters are the aspects that best represent the uncertainty regarding the geological and construction aspects. Nevertheless, the results obtained for the specific case study should be considered a confirmation that these parameters (i.e.: cost drivers) are able to capture the uncertainty of the geological and hydrogeological aspects related to the tunnelling process.

Another relevant aspect regarding the normal tunnelling cost (C_{NT}) that must be dully managed is the discretisation of the tunnel length into homogeneous zones. Even though this procedure is considered valid and concordant with other models, such as Isaksson (2002), Oreste (2006), and Spackova, Sejnoha et al. (2013 a), the author believes that the discretisation of the tunnel must be coherent with the quantity and quality of the available information. Consequently, exhaustive detailed division of the tunnel must be avoided if information is not sufficient to provide sound basis to assess the cost drivers in each zone and the correlations among homogeneous zones.

When reviewing the modelling of extraordinary tunnelling cost (C_{ET}), most of the difficulties were found in the assessment process, especially when assessing probabilities of occurrence and consequences of undesirable events. Contrarily and since the modelling of extraordinary tunnelling cost (C_{ET}) is based on standard risk management practices, the model design process was straightforward and did not represent a relevant problem during the development of this research. The integration of standard risk management practices and tools for the determination of the extraordinary tunnelling cost (C_{ET}), is also highlighted and implemented in the models developed by Isaksson (2002) and Spackova, Sejnoha et al. (2013 a).

When reviewing the specific assessment of the extraordinary tunnelling cost (C_{ET}), the proposed model presents also differences with other models reviewed in Chapter 5, which are basically related to approach to incorporate the risk in the final cost assessment. The models presented by Min (2003) and Oreste (2006) do not present clear description of which levels of risk are included in the estimations, and the final cost estimation are presented in an aggregate number. Rostami, Sepehrmanesh et al. (2013) do not include the construction risk, and they propose the use of construction contingency factors, which are represented as percentages of the construction cost. A similar approach is recommended in the Drill and Blast Prognosis Model, NTNU2C-05 (2006), were elemental and construction cost are corrected by specific factors related to the occurrence of undesirable events.

Besides of the specific challenges faced in the individual modelling process of normal (C_{NT}) and extraordinary tunnelling cost (C_{ET}), these two process share common challenges, which were experienced throughout the development of this work and are fully consistent with those aspects highlighted by Tamparopoulos (2013), Isaksson (2002) and Spackova, Sejnoha et al. (2013 a). Some examples of the common challenges faced during the design and implementation of stochastic models are as follows:

i. Assessment and selection of the most suitable statistical distributions
ii. Analysis and determination of correlations among variables
iii. Variable assessment and model feeding.

Regarding the assessment and selection of the statistical distribution that better describes the random behaviour of model variables, it is a critical aspect analysed in several researchers, such as Spackova, Novotna et al. (2013), and Tamparopoulos (2013).

Since statistical data was not available to assess the "best fit" distribution for the selected cost drivers, continuous triangular distribution was assumed for each of them. This simplification is clearly not realistic; nonetheless it was considered sufficient and suitable for this specific assessment. A clear disadvantage of triangular distribution is the difficulties found to assess the boundaries (i.e.: the extreme values). Nevertheless, triangular distribution can be easily built by expert opinion, when more specific data is not available.

Due to the discrete behaviour of the risk events, distinct probability density functions were used. Discrete distributions such as binominal, Poisson, and Bernoulli, were found suitable to describe the features of risk events and to achieve the dynamic modelling of the risk.

Another common challenge, when modelling normal and extraordinary cost is the assessment of the correlations that random variables may have. The relevance of setting correlations, among random variables in models based on Monte Carlo Simulation, is a matter highly emphasised by authors such as Hollmann (2007), Isaksson (2002), and Tamparopoulos (2013).

Unfortunately, an accurate determination of correlations demands the statistical analysis of large quantity of data that were not available during the execution of this research; therefore particular simplifications were considered, when assessing the correlations in the specific case study. As previously explained, correlations were only assessed for the cost drivers, while correlations for geological zone were not possible to determine, as well as those correlation among risk events.

Although the difficulties related to the determination of the correlations were confirmed during the execution of this work, the author agrees with Hollmann (2007) on that driver-based approach offers significant advantages to perform the correlation analysis, especially when comparing with other classical detailed estimations, based on single cost element or line-by-line assessment. Regardless the difficulties and simplification made in this aspect, the results obtained for the specific case study allowed the author to identify the effects of correlation, especially in the magnitude of the estimation ranges and consequently in the extreme values of the total cost distribution.

The feeding of the model is also a relevant aspect to be evaluated, which may have a significant influence in the final results. As stated in Chapter 6, the proposed model offers the possibility to be feed by expert opinion, as well as data collected from the field investigations, during the pre-investment phases. The model also offers the possibility to be updated with information obtained from the face mapping performed during the actual construction phase. The relevance of a flexible assessment and update is a model attribute emphasised by Isaksson (2002), Min (2003), Paraskevopoulou and Bernardos (2013), and Spackova, Sejnoha et al. (2013 a).

On the other hand, the flexibility offered by the model in terms of the incorporation of expert opinion must be also understood as potential source of bias in the model results. As highlighted by Tamparopoulos (2013), assessments based on expert opinion are unavoidably affected by ignorance and distorted by bias. Since the model was not assessed as originally planned, and it was eventually done by the single judgment of the author, an important level of arbitrary and bias were included in the evaluation of cost drivers, as well as during the identification and analysis of undesirable risk events.

To sum up this section, it is possible to state that modelling process represents a complex process that demands a combination of theoretical and practical knowledge, during both the design activities and during the assessment of the model variables. In the personal opinion of the author, most of the difficulties, encountered during the development and application of the model, may be better overcome through cooperation between researchers and project organisations interested the execution of undersea tunnel projects. Cooperation may certainly provide a significant improvement in the level of reliability of this model.

8.3 Assessing the Quality of the Model

The quality of the model and its outcomes (i.e.: cost estimation) is a core aspect to be considered, when analysing the capabilities of the proposed model and its potential applicability for assessing the cost of other subsea tunnel projects.

The assessment of the cost estimations quality may be performed using general approaches given in general practices and standards related to project and cost management, which have been incorporated in the theoretical framework of this work, such as PMI (2008), APM (2006), and GAO (2009). All these professional practices agree on the fact that high quality cost estimates must, at least, be well documented, comprehensive, accurate, and credible. Regardless singular definitions used in these practices, it is totally agreed that cost estimations must provide the sufficient quality to support the decisions under analysis and being consistent with the level of information that is available at the evaluation point.

In a broader perspective, and considering the cost modelling as a single experiment designed to assess a specific attribute, the model may be assessed, in terms of its validity and reliability. Both concepts are highly related to the assessment of quantitative research and, as presented in the methodology chapter, they are two relevant aspects to be incorporated as part of the final discussion. It is believe that the evaluation of the validity and reliability will help to assess the applicability and generalisation of the proposed model.

As defined in Chapter 2, the validity is the degree of success in the measure or experiment that is being performed. The validity of the model involves the rigor of the process performed (i.e.: internal validity), as well as the extent on what the model is generalizable (i.e.: external validity). Complementary, the reliability of the model is a measure of the capacity of the model to deliver in a systematic manner the same results; therefore it can be also understood as the model capacity to deliver consistent and accurate results when the experiment is executed.

When assessing these two concepts, the focus must not be exclusively on the results of the cost estimation. The analysis must be also done in the inputs, and the process itself, which certainly controlled the quality of the final results.

Considering the topics discussed in the previous sections, it is believed that the selected model inputs, both cost drivers (i.e.: for the normal tunnelling cost) and risk events (i.e.: for the extraordinary tunnelling cost) are valid elements to estimate the cost of tunnelling activities and they are able to capture and incorporate the effects of geological uncertainty and risk events.

Similarly and regarding the modelling process itself, the use of standard approaches for cost estimation (i.e.: drivers based) and risk analysis (qualitative and quantitative risk assessment), as well as the deployment of well-known tools such as Monte Carlo Simulation (MCS) ensure the validity of the tools deployed in this model.

Even though the inputs and tools deployed in the selected model are considered totally valid for the cost estimation of undersea tunnels, the author recognises the shortcoming that the model may present in the accuracy of the results. In fully agreement with Tamparopoulos (2013), the author is aware on the effects that factors such as uncertainty related to the assessment of model variables, epistemic uncertainty in the model design, ignorance, bias, induction of non-existing information, and simplifications may cause major deviation on the accuracy of the results, and therefore affect the reliability of the final cost estimation.

Considering all the above mentioned, the author believes that the model provides a valid means for the cost estimation of undersea tunnel, nonetheless specific aspects of the model should be improved in order to achieve a higher level of reliability in the final results.

8.4 Addressing the Research Questions

Four research questions were originally established in order to achieve the main objectives of this research work. The most relevant and conclusive remarks regarding these questions are briefly presented in this section.

After performing this research work, it has been proved that the cost estimation process may be improved during the pre investment phases by introducing models based on uncertainty and risk analysis. This remark is consistent with other researches performed in the specific area of cost estimation of underground projects. Some of the researches that emphasised the need of incorporating and deploying more advance tools in the cost estimation for tunnelling project are the works performed by Einstein (1996), Isaksson (2002), Oreste (2006), Spackova, Sejnoha et al. (2013 a), among other authors reviewed in this work.

Even though the first attempts to perform stochastic cost estimation of tunnelling can be found in the earlier 70th, Min (2003), standard practices still rely in the systematic use of deterministic methods for determining the tunnel cost. This fact is highlighted by Spackova, Sejnoha et al. (2013 b) and it is linked as one of the main causes of the systematic underestimation of the tunnel cost.

Continuous overrun detected in the development of underground projects (i.e.: road tunnel), which is highlighted in reports, such as Flyvbjerg, Holm et al. (2002) and Efron and Read (2012), is partially explained by the systematic underestimation of the actual project costs. This constitutes an irrefutable proof of the extensive and recurrent use of deterministic approach, but also it may be observed as the evidence for major improvements in the existing stochastic models.

In the personal experience of the author, cost estimation based on random cost drivers, is an extremely useful mean, in order to incorporate the uncertainty related to construction activities. This idea is consistent with the approach used by Isaksson (2002), who assesses the "production effort" as random variable to determine the expected cost and time in tunnelling activities. The use of cost drivers allows estimators incorporate in a better way the uncertainty of the tunnelling process.

As demonstrated in this work, the normal tunnelling cost may be derived, using a certain group of cost drivers, which in this specific case were selected from geological and design aspects. This is one of the main differences, respect to the models presented and analysed in Chapter 5, where cost estimations are basically performed as a function of the construction time, advance rate or other similar performance measures, see (Isaksson 2002), (Min 2003), (Oreste 2006), and (Spackova, Sejnoha et al. 2013 a).

This work has also proved that a clear differentiation between normal and extraordinary risk may be done. To perform the modelling of undesirable risk events, several models and tools have been designed and incorporated in the project management profession that may help to carry out this activity. In this sense, there is a full agreement with the works presented by Isaksson (2002), Spackova, Sejnoha et al. (2013 a), and Spackova, Novotna et al. (2013), where similar approaches are considered to assess the extraordinary tunnelling cost related to risk events.

The modelling of undesirable risk events is done considering these events as a random process, which is the function of the occurrence and consequences if the risk events happen. As previously mentioned, both occurrence and effects are then modelled as a random variables defined by singular values and probabilistic distribution.

Considering all above mentioned, the author believes that stochastic approaches, based on uncertainty and risk analysis, may bring higher value in the project management process, especially when facing the early phases of complex projects, where higher level of uncertainty and risk should definitely be assessed in order to obtain sound basis for the decision making process.

8.5 Further Studies

Since this research is framed in a relatively reduced period of time (i.e.: about five months) and none agreement for cooperation was subscribed to perform this work, several model's aspects were simplified, which eventually may affect the accuracy of the model results. In order to overcome the shortcomings of the model, more advanced research is required in specific aspects related to the estimation of both the normal and extraordinary tunnelling cost.

Firstly, and specifically related to the normal tunnelling cost (C_{NT}), more advanced research is required in those aspects such as water inflow control and rock mass support. Following the same standard provided for those prognosis models developed by NTNU (e.g.: NTNU2C-05 (2006)), similar models may be developed for the water control and rock support activities, which also considers the latest progresses and advances achieved in the tunnelling industry and in the academic research.

In the same line, statistical analysis of the construction data that supports the prognosis models may be observed as an opportunity to identify other geological parameters, which present higher level of correlation with the cost of tunnelling activities and therefore it can be used for designing more valid and reliable driver-based cost estimation models.

When considering the difficulties faced during the modelling of undesirable risk events, it is clear that systematic collection of data regarding the occurrence and consequences of risk events, in real projects, may help to better assess the extraordinary tunnelling cost. Systematic collection and analysis of such a data will ensure a realistic assessment of risk events during the cost estimation process.

Considering a broader perspective, similar stochastic and driver-based estimation models may be developed for mechanised tunnelling methods (i.e.: TBM). Even though the author recognises that TBM compromises a higher level of complexity regarding geological and performance aspects, the prior development of the prognosis models (i.e.: NTNU1C-98 (1998)) should be considered as a major opportunity for developing new stochastic estimation methods.

Finally, other researches focused on the integration, programming, and automation of both models (i.e.: drill and blast and TBM) may provide a comprehensive and powerful decision-making tool for project organisation related to the development of tunnelling projects.

9. CONCLUSIONS

The cost estimation for tunnelling projects is a challenging and demanding task, especially during the pre-investment phases where level of uncertainty and risk trend to be higher, and key information is restricted by the unique location of this class of projects, Isaksson (2002), and Spackova, Sejnoha et al. (2013 a). All these factors are accentuated in undersea tunnel projects, and therefore more advanced modelling should be undertaken to support the pre-investment decisions, Pennington (2011).

The ill-defined conditions existing during the early project phases of undersea tunnel projects may be better represented by stochastic estimation models, which may help to capture and incorporate the complexity and uniqueness of undersea tunnel projects. Given the complex and unique circumstances where the tunnelling process is performed, the stochastic approach is particularly suitable to estimate the cost related to the tunnelling activities, Spackova, Sejnoha et al. (2013 b).

The stochastic model presented in this work considers that the tunnelling cost is better represented through an independent analysis of normal and extraordinary cost, which can be modelled by the integration of standard project management tools. Throughout this work has been demonstrated that the normal tunnelling cost (C_{NT}) may be assessed using driver-based methods (i.e.: cost drivers), while the extraordinary tunnelling cost (C_{ET}) may be estimated by standard qualitative and quantitative risk management tools. Both costs are modelled as random processes, which are dependent of specific random variables. Through the use of expert assessment and @Risk, which allows performing Monte Carlo Simulation (MCS), the proposed model provides specific probability density functions for both the normal (C_{NT}), extraordinary (C_{ET}) and total tunnelling costs (C_{TT}).

The proposed estimation model was applied in the Chacao Channel Project, which is a non-executed project concept in Chile. The results obtained, after applying the proposed model, are considered valid, realistic and coherent with the level of information existing at the assessment point. Nonetheless, several aspects regarding the model design should be reviewed and improved, in order to increase the model reliability. Due to the non-executed condition of the selected case study, direct comparison between the model results and the actual tunnelling cost was not possible to be performed; yet results are congruent with actual costs obtained from previous undersea tunnel projects developed in Norway.

After performing this work, it is possible to state that more specific research and systematic data collection should be performed in relevant tunnelling aspects, such as rock support and water inflow control. Similar driver-based models may be designed and customised for mechanised excavation method (i.e.: TBM). The integration of both methods (i.e.: drill and blast and mechanised) may provide a comprehensive decision-making tool, during the pre investment phases of undersea and general tunnelling projects.

Modelling is a high complex activity, which tries to provide a representation of real process and its outcomes. It must be understood that there is not perfect model that can predict exactly the project results regarding the cost; nevertheless better modelling, based in the integration of key project management tools, such as risk and uncertainty management, may provide a more realistic perspective about the expected project's outcomes.

It has been proved through the development of this work that the integration of risk management is a key aspect to be considered, when developing cost estimations for undersea tunnel projects. This integration will contribute to optimise the decision-making process and increase the probabilities of project success after the execution.

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APPENDIXES

Appendix A: Concept Map of the Research Project

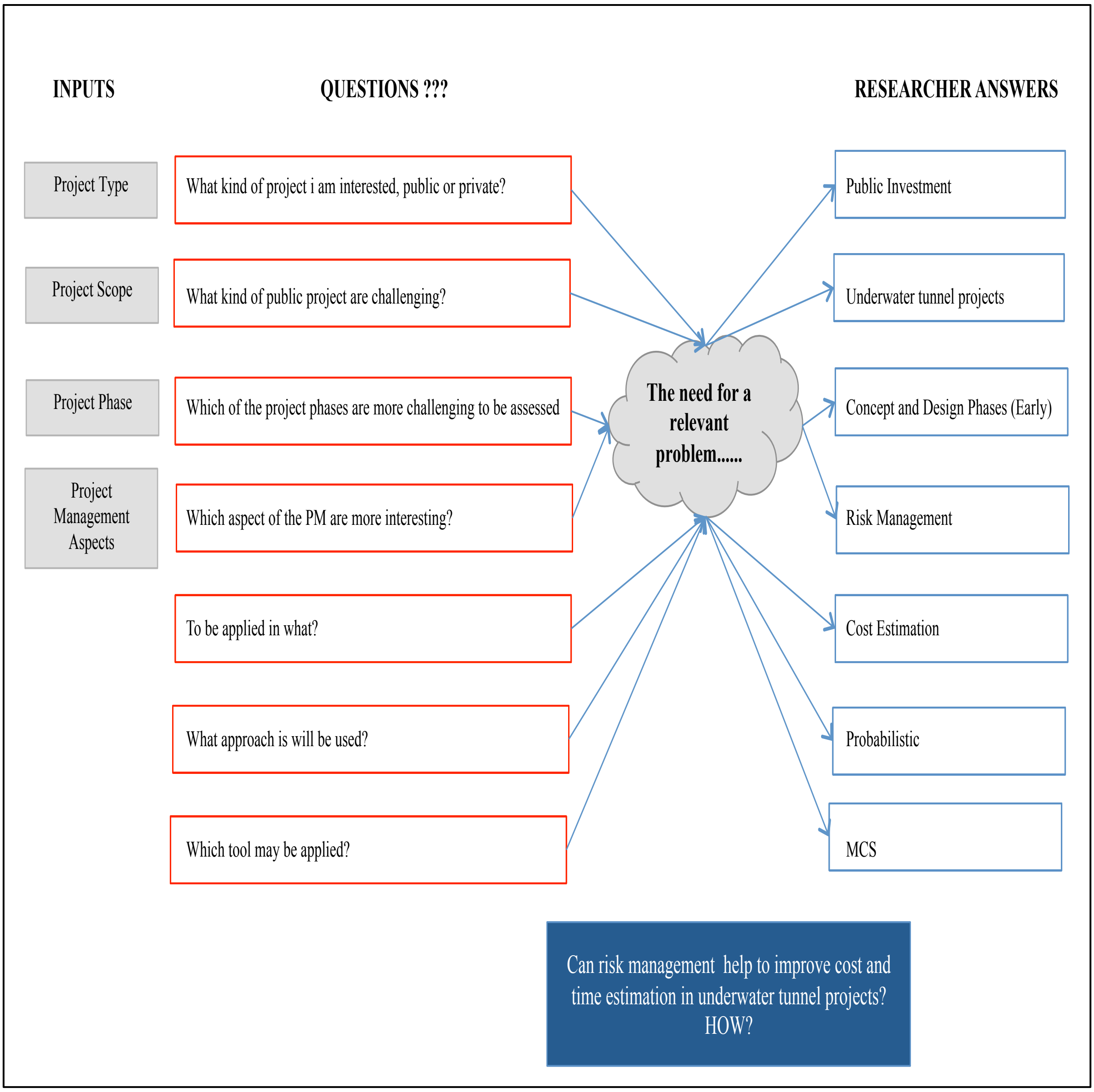


Figure A.1: Concept Map developed to define the research topic. As explained in Chapter 2 "Research Methodology", the research topics was defined by balancing academic and personal interests, as well as the relevance of the topics for integrating different aspects of Project Management.

Appendix B: The Generic Cost Estimation Process (PMI)

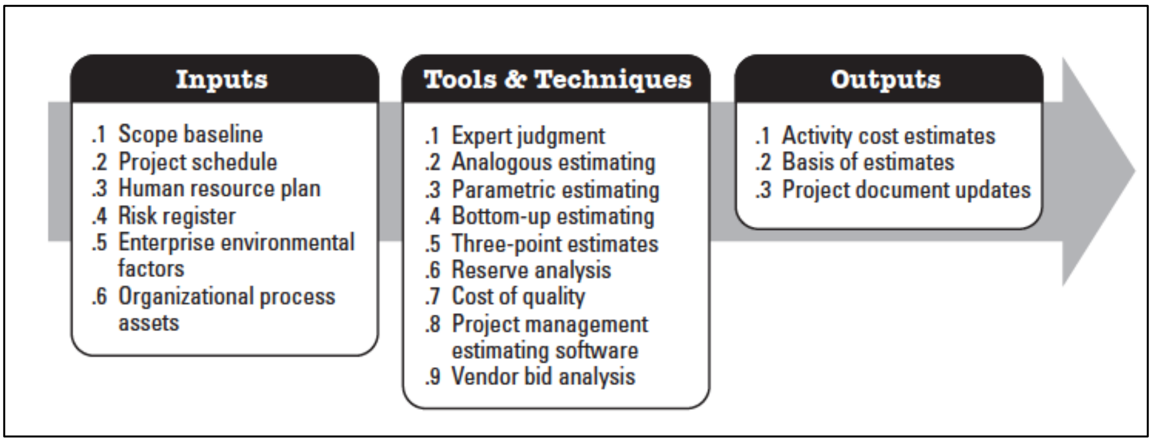


Figure B.1: Project Management Institute, Generic Cost Estimation Process ((PMI 2008)

The elements of this process are further described in the following sections.

B.1 Cost Estimation Process Inputs

i. *Project Requirements*: this constitutes a relevant piece of information to be considered at any phase during the cost estimation process. It will determine the requirements stated for the different interested part (e.g.: project owners, and stakeholders) involved in the project development and its operation. The project requirement statement must not be neglected, and must be always incorporate in the cost estimation process. This deliverable is obtained as part of the Project Scope Management processes.

ii. *Scope of Work*: the project scope is defined by creating a specific Work Breakdown Structure (WBS), which is defined by (PMI 2008) as *"A deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives and create the required deliverables. It organizes and defines the total scope of the project"*. This deliverable is obtained as part of the Project Scope Management processes.

iii. *Project Schedule*: according to (PMI 2008), the project schedule is *"The planned dates for performing schedule activities and the planned dates for meeting schedule milestones"*. This deliverable is obtained as part of the Project Time Management processes.

iv. *Risk Register*: the (PMI 2008) defines the Risk Register as *"The document containing the results of the qualitative risk analysis, quantitative risk analysis, and risk response planning. The risk register details all identified risk, including description, category, cause probability of occurring, impact(s) on objectives, proposed responses, owners, and current status"*. The risk register is obtained as part of the Project Risk Management processes.

B.2 Cost Estimation Methods

Cost estimation may be performed deploying different approaches; methods and tools that will depend of the project phases and the level of accuracy required for the decision makers and project governance. Methods that ranges from analytic to numerical, the following tools and techniques, describes by PMI (2008), may be deployed in the execution of the cost estimation process

i. *Expert Judgement*: since cost estimates are influenced by a large number of variables (e.g.: material cost, labour rates, and risk factors), expert judgement provides a critical and valuable insight about the execution of previous projects.

ii. *Analogous Estimating*: this technique uses the actual cost of previous and similar projects as the basis for estimating the cost of the current project. Analogous estimating provides a gross estimation that may not reflect the real complexity of the current project, nonetheless it is time and cost efficient. Additionally this technique allows project organization to estimate parameters when there is a limited quantity of information about the project conditions, consequently is often used in the early phases of the project. Analogous cost estimating uses historical information and expert judgement.

iii. *Parametric Estimating*: this technique uses statistical relationship (i.e.: statistical correlations) between historical data and other project variables to estimate cost activity parameters. The level of accuracy given by this technique is higher than analogous estimating, and it depends upon the sophistication and data considered into the model. Parametric estimating may be used to estimate the cost of the total project or specific systems or work packages, and it can be used with other estimating methods.

iv. *Bottom-Up Estimating*: this method is uses to estimate the cost of different component of work. Consequently the cost of packages or activities regards a specific component is estimated with a certain level of detailed and then is summarised to higher levels. The accuracy and cost of this method is affected by the size and complexity of individual activities or work packages.

v. *Three Point Estimates*: this technique is based on the original concept of the program evaluation and review technique (PERT), where each activity cost is defined by three values, which represents the most likely, the optimistic and pessimistic values given different scenarios. This technique estimates an expected value and its respective standard deviation.

vi. *Simulation*: this tool represents more advanced software applications and computerised spreadsheet that deploy simulation process and statistical tools for estimating cost. These applications may be found as a clear recognition of the random nature of the project cost.

B.3 Cost Estimation Process Outputs

i. *Activity Cost Estimate*: the activity cost estimate represents a quantitative assessment of the probable cost required to achieve the project deliverable. This includes all the resources required to perform all the activities involved in the project scope, including but not limited to, direct cost such as: labour, material, equipment, services, among others. Indirect cost may be also included in the cost estimate, either at the activity level or at higher levels.

ii. *Basis of Estimate*: this constitutes the supporting documentation for the cost estimation process and it should provide a clear and complete understanding of how the process were performed and project cost estimation was derived. Typical information contained as part of the basis of estimate may be as follows:

- Documentation of all assumptions made,
- Documentation of the basis of the estimates,
- Documentation of known constraints,
- Range value of the estimates,
- Indication of the confidence level of the final estimate.

iii. *Project Document Updates*: all project documents connected with the cost estimation process must be updated after the process has been performed at any of the project phases (i.e.: risk register, project contracts, among others).

Appendix C: Planning and Construction in Undersea Tunnels

C.1 Planning Process

C.1.1 Geotechnical Design

The geotechnical design process is focused on determine the ground and soil characterisation, which is the main basis for the selection of the excavation method and the risk management process to be implemented. This process basically involves different level of geotechnical and geological investigations that must be consistent with the level of project development. In this way, it is possible to recognise the following class of investigations, which are described according to Pennington (2011).

i. *Conceptual Site Investigation and Reconnaissance*: this represents the earliest investigation activities, and it aims to establish the general site and surface conditions along the possible tunnel alignments. Regardless the early nature of these studies, they are expected to be as comprehensive and exhaustive as possible. An early risk assessment of the parameters obtained during these studies must be always considered for awareness of the project team. The information gathered in this stage may be considered to be part of the contract and other commercial documents to be used during construction.

ii. *Preliminary Geotechnical Risk Assessment*: this assessment is performed through a systematic process, where risk events are identified and assessed on terms of their probability and impacts in cost, schedule, safety and environment. The information of this process is registered and tracked by the risk register.

iii. *Initial Surface Characterisation*: these investigations aim to provide more information to the general design process. In general terms these explorations focus on provide information for an efficient selection of the construction method, identify potential problem zones, define stratification on rock structure and its degree of variability. These investigations must be flexible allowing changes in the tunnel alignment or configuration, if required. Considering the data collected, a conceptual model of the surface condition along potential tunnel alignment should be performed, emphasising key geotechnical or geologic risk areas.

iv. *Design Level Site Investigations*: this level of investigations is intended to deliver the greatest resolution to the geologic model. The information provides at this stage should increase the reliability of the model and the critical areas previously identify. At this stage the critical areas, where more detailed investigations are required must be identified. Design level investigation includes: drilling and sampling along tunnel alignment, in situ testing (e.g.: cone penetration test, packer testing, groundwater pump test), laboratory testing, and supplemental geophysical surveys.

v. *Final Risk Assessment*: in this stage all the previous information must be incorporated and updated and it must reflect all the final design decisions. The results of the risk assessment must be integrated in all relevant documentation for execution, such as contract, drawing, and specifications. The final risk assessment should confirm the selected excavation method. Emphasis in potential zones along tunnel alignment should be consistent with the previous risk and geological reports.

C.1.2 Design Considerations

Design considerations for underwater tunnel have a substantial impact on project objectives, such as cost, time and safety. Most of the design considerations have effects not only in the execution cost, but also in the tunnel cost operation. Considerations such as water leakage criteria and waterproofing must be duly managed during the design phase, in order to maximise the solutions to be implemented during the execution phase and consequently the total cost of the tunnel project (Total Cost of Ownership - TCO). Risk assessment regards these design considerations must be always included, when performing tunnel design activities. The most relevant design considerations for underwater tunnels are describe in this section, and they are summarised in the following table.

Table C.1: Design Considerations for Underwater Tunnels (source: Pennington (2011))

Underwater Design Consideration	
Watertightness	Permitting
Waterproofing	Alignment Geometry
Gaskets	Shoreline Development
Groundwater Inflow	Third Party Considerations
Flooding	

i. *Watertightness*: Given the location of underwater tunnels, Watertightness may be considered as one of the most important design parameters, and tunnel must be designed to withstand the negative effects of groundwater. The level of Watertightness will depend on the intended function of the tunnel, nevertheless for road or traffic underwater tunnels; it must be always considered a high level of Watertightness.

Groundwater control may be achieved by design measures, such as the use of impermeable membranes, or gaskets, or during the construction phase by using pre-excavation grouting, which will provide groundwater cut-off in the tunnel section. Different levels of watertightness may be found depending on the specified use. Table C.2 shows typical European requirements regard tunnel watertightness.

Table C.2: Watertightness Requirement in Europe (source: Pennington (2011))

Water Tightness Class	Wetness	Typical Use	Daily Leakage (gal/ft2)
1	Completely Dry	Passenger Facilities	0,00002
2	Largely Dry	Subway Tunnel	0,0004
3	Moisture Capillarity	Subway and Tram Tunnel	0,002
4	Slightly Dripping	Railway Tunnel	0,01
5	Dripping	Sewage Tunnel	0,02

ii. Waterproofing: different waterproofing system may be applied during tunnel construction, which ranges from sheet, sprayed, and hybrid system. Groundwater control may be performed in short and long terms. Shotcrete and concrete layers have demonstrated to be an adequate temporary groundwater barrier. Nevertheless, for long terms, these solutions present a low degree of performance due to the tendency of concrete materials to crack. When strict level of water leakage must be achieved, a secondary waterproof system must be considered, which may be performed by crack injection of expansive resin or other polymer.

iii. Gaskets: these elements are installed between segment joints of two precast concrete segment used for tunnel lining. Two main gaskets types are used for precast concrete segments, which are: elastomeric (EPDM) and hydrophilic. Elastomeric gaskets have demonstrated to be highly efficient water proofing system, not requiring secondary measures. Hydrophilic gaskets are commonly used as secondary system or in combination with elastomeric gaskets. The factors that influence the selection of gaskets includes: hydrostatic pressure, required factor of safety, tunnel lining, tunnel function, groundwater chemistry, among others.

iv. Groundwater Inflow: this parameter must be analysed during the design process, especially in terms of predicted quantity and frequency of groundwater inflow. As previously presented, the groundwater inflow will highly affect the construction and operation performances; therefore this parameter must duly treated and managed during the design process.

Groundwater inflow is controlled by the hydrogeological conditions where the tunnel is built, especially upon permeability of the rock or soil and the permeability of the discontinuities in permeable rock mass. The estimation of groundwater inflow is a hard job to be done by engineers, nevertheless some models may be applied to obtain reliable estimations. Darcy model is recommended for tunnel excavated in soft ground, while the model proposed by Raymer (2001) may be applied in hard rock tunnel.

Groundwater inflow, especially under high pressure, may severely affect the tunnel excavation by reducing advance rates, reducing stability of the rock, and making difficult the installation of rock support and tunnel lining.

v. *Flooding*: the tunnel flooding must be properly assessed for both construction and operation phases. Nevertheless this risk trends to be more likely during the construction phases, when stability problem are more likely to occur. An effective mitigation strategy is to install permanent or temporary floodgates, which must be designed to resist full hydrostatic pressure, as well as hydrodynamic forces.

vi. *Permitting*: this consideration is highly relevant, and it may have large effects in the tunnel time and cost. Permits for tunnelling will depend of the location and regulation where the project is executed.

vii. *Alignment Geometry*: the tunnel alignment may be optimised, minimizing the thickness of the overburden, this will directly affect the tunnel length and reduce ground load on the tunnel section. Nonetheless the tunnel alignment is also affect by other issues that must be considered, during the design phase. The vertical and horizontal alignment is driven by the minimum distance, between the bottom and the top of the tunnel and geological conditions existing underneath, such as fault zones, weakness zones or water bearing features. Depending on the selected excavation method (i.e.: Drill and Blast or Boring Machines) specific restrictions may be established, especially respect to maximum vertical and horizontal curvatures.

viii. *Shoreline Development*: the location of underwater development may influence potential developments across to the shoreline (e.g.: industrial and sport facilities); therefore it must be duly discussed and agreed with the pertinent authorities. In the same way new developments near to existing underwater tunnels may also affect its operation and safety, consequently the tunnel lay out must be agreed by considering existing and futures development in the area.

ix. *Third Party Considerations*: Some of the aspect to be evaluated as part of third party design considerations are for example: forces and load product of vessel anchors, which may affect the tunnel construction process and its operation. This is especially relevant in tunnel planned in soft soil, where anchor penetration may cause significant undesirable effects.

C.2 The Tunnelling Process (Construction Process)

C.2.1 Excavation

i. *Conventional Method or Drill and Blast*: this method considers the use of drilling equipment (e.g.: jumbo) and explosives to excavate the tunnel face. The material is removed by different means that may consider: trucks, overland belt conveyors or mixes of both systems.

The DB method is a repetitive method, which is generally performed in cycles so-called "rounds". A typical DB round is composed by the activities:

- Equipment and Machinery Relocation
- Drilling
- Charging
- Blasting
- Ventilation
- Scaling
- Mucking

ii. *Mechanised Methods - Tunnel Boring Machines (TBM)*: the mechanised methods excavate the rock or ground by a combination of mechanical means (e.g.: cutting disc), rotation and thrust force. Depending of the soil or rock characteristic and site conditions Tunnel Boring Machines may have different configurations, such as

The main activities performed when excavating by mechanised methods are:

- TBM placement (steering and alignment)
- Boring and Thrusting
- Mucking

C.2.2 Ground Water Inflow Control

The water inflow control may be considered as part of the excavation process, or as part of the preliminary support, nevertheless it has been considered relevant to be described separately, given its high preponderance for both construction and operation of underwater tunnels.

According to NFF (2011), the control of water inflow may be performed throughout rock pre grouting, and post grouting, which are described bellow.

i. *Pre grouting (grouting)*: this process aims to reduce the permeability of the rock mass by pre excavation grouting, this is performed as part of the construction process at the tunnel face. The primary objective of pre-grouting is to make the tunnel section tight enough for its operational purposes and facilitate the excavation activities.

Computerised machines perform the pre grouting activities, which allow injecting several holes at the same time. The most well known materials to perform grouting are cement-based grout, such as: standard cements, micro cements, and ultrafine cements. Pre grouting activities are initiated when the water inflow parameter established in the contract are exceeded.

ii. *Post grouting*: this process has the same objective than pre grouting, and it is performed when strict level of water inflow exists. This is a difficult and time-consuming activity; therefore the water inflow restrictions should be achieved during the pre grouting activities.

iii. *Drainage and Water Pump*: this system must be always considered, and it is basically conformed by drainage pipes located in side trenches, and a pump system with enough capacity to keep the water inflow controlled, as part of the whole system.

C.2.3 Rock Support

Rock support is the process where the rock mass is stabilised by different means that eventually contribute to achieve a new equilibrium condition in the modified rock or soil mass.

Rock support may include both preliminary and permanent measures. Preliminary support must be carried out in order to perform the excavation process safely, therefore it can be also included as part of the excavation process. It is carried out as part of every single round at the tunnel phase. According to (NFF 2010), the most relevant methods for rock support at the working face are:

i. *Bolting*: the main objective is to maintain the theoretical cross section until the permanent support is carried out. This is performed through ordinary reinforcement steel and grout, having no requirement of corrosion protection. The standard length of bolts is 6 meters and its density will primarily depends on the quality of the rock mass.

ii. *Spiling*: this method use steel pipes to provide support is loose material or weakness zones. This method may be also implemented in hard rock tunnelling, when facing weakness or fault zones. Normal diameter of steel pipes is from 75 mm to 120 mm, and steel thickness is 5-7 mm. This system is especially suitable when normal bolting is not possible or difficult to carry out.

iii. *Injection*: this method aims to stabilise highly cracked and weathered rock mass before excavating the same section. This is carried out through injection that fills cracks and pores in the rock mass, helping to the water control (i.e.: leakage) and blasted profile.

iv. Jet Grouting: this method helps improving the mechanical properties of loose material by using cement based mortar, which is flushed with high pressure (400 bars). This method is especially suitable for clay, silt and sand with low or moderate degree of consolidation.

v. Freezing: this method may be used in zones of loose material and stability problems. This method may be combined with cement injections to stabilise the material and facilitate the drilling process. Content of salt in the water leakage presents in underwater tunnel must be taken in consideration.

The categorisation for permanent rock support, according to (NFF 2010), is as follows:

i. Support for Rock Spalling Situations: in rock spalling (i.e.: rock burst) areas, sprayed concrete may be applied as soon as possible after each blast, considering a thickness of 5-6 cm and before bolting takes place. The bolts used in this situation are end-anchor type with thread. Triangular steel plates are screwed against the concrete, without bolt pre-tensioning. A secondary layer of concrete may be applied to ensure the combined effect of bolts and concrete.

ii. Deformable Support Systems at High Rock Tensions: these support systems must absorb deformation without collapsing, when high rock stress and deformation exist. These deformations are usually developed into slow squeezing of tunnel control and strong spelling of rock. The support system consists in circular steel girder elements that allow rock deformations. It also requires the application of concrete with a normal thickness larger than 40 cm

iii. Sprayed Concrete Ribs with Lattice Girders: this system consists on prefabricated rebar girders, which are built through lattice with triangular cross section. These lattice girders are fully embedded in sprayed concrete and they are considered non-deformable elements so there are not suitable in rock when high level of deformation is expected.

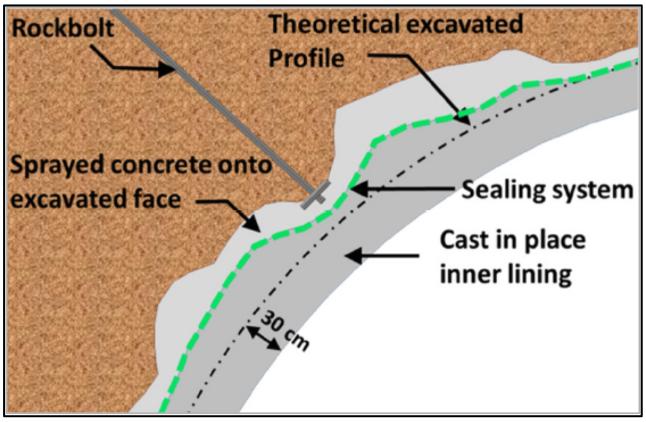
iv. Sprayed Concrete Arch: this must be considered an option to in situ cast concrete arches. This consists basically in a continuous layer of thick fibre reinforced concrete, which is sprayed in layers of 30-50 cm.

v. Support of Rock with Swelling Clay: this system must be carried out when the risk of load induced by swelling clay exists. This is performed by a combination of bolts, reinforced sprayed concrete or concreted invert.

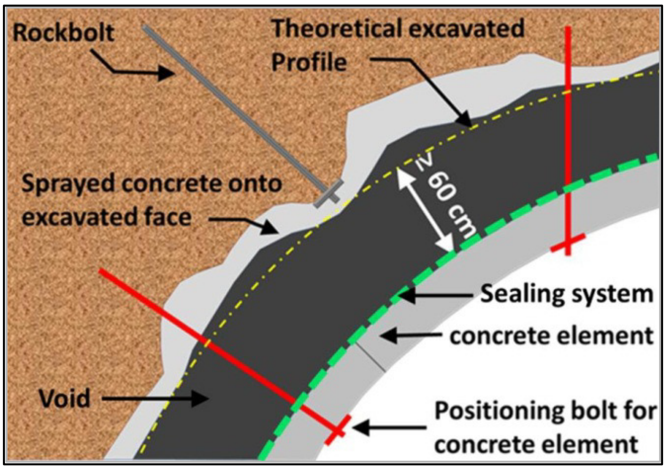
C.2.3 Tunnel Lining

Tunnel lining is required when the tunnel section passes across weak zones with heavy rock fall, massive swelling zones, highly crushed rock, and zones with water leakage problems (i.e.: it may also be considered as part of water inflow control measures). Tunnel lining may be also required as part of the operational requirements in specific road projects. Tunnel geometry and soil/rock loads are two relevant parameters to define the final lining design in tunnels.

i. <u>*In situ Concreting*</u>: this system is basically performed in drill and blast excavation process, according to the encountered rock conditions. This is basically performed; using work forms, reinforce steel and concrete. This method may be used as part of the rock support.



ii. <u>*Pre-casted Concrete Lining*</u>: this system is used when excavating by mechanised means, such us TBM. After the excavation and rock support is performed the pre-casted concrete units are placed. This method cannot be considered as part of the definitive rock support.



According to NFF (2005), the tunnel lining system may also includes, depending on conditions, the use of impermeable sheets of polyethylene foam (covered by sprayed concrete and mesh for fire protection) and located in the tunnel wall and roof.

Appendix D: Cost Estimation Models for Underground Projects

D.1 The Application of the "Decision Aids for Tunneling to the Sucheon Tunnel in Korea"

Min (2003) applied the Decision Aid for Tunnelling (DAT) to assess cost and time of a specific tunnel project in Korea (Sucheon Tunnel Project). DAT developed in 1979 at the Massachusetts Institute of Technology (MIT) by Einstein, it is a tool that allows engineer to simulate the tunnel construction, considering two main sources of uncertainty, which are namely: *i) geology conditions* and *ii) construction process*.

This model is based on a stochastic approach that use a simulation process (i.e.: Monte Carlo Simulation) in order to estimate the expected values for cost and time, for a given tunnel configuration. The main inputs of DAT are parameters regard geological conditions and construction process. The results of this simulation process are distributions of the total construction cost and duration. Min (2003) applied DAT in the Sucheon Tunnel Project in Korea, and the research was developed in three distinct phases, which represent different level of maturity in the final project estimation. These phases were as follows:

i. Phase 1: Original estimation based on preliminary data available
ii. Phase 2: Second estimation based on update data
iii. Phase 3: Final simulation considering the client feedback

Each phase is performed in similar manner (i.e.: by simulations), but they are characterised by different level of uncertainty regards geological and constructions aspects. This means that early estimations are based on several assumptions; whilst information became available these assumptions may be updated for actual data (e.g.: rock mass quality, construction prices, construction quantities). The basic logic of DAT is presented in figure X. As shown in this figure, geological input (i.e.: ground classes) are introduced first, followed by constructions inputs (i.e.: construction cost and time), which eventually allow obtaining the cost and time estimations.

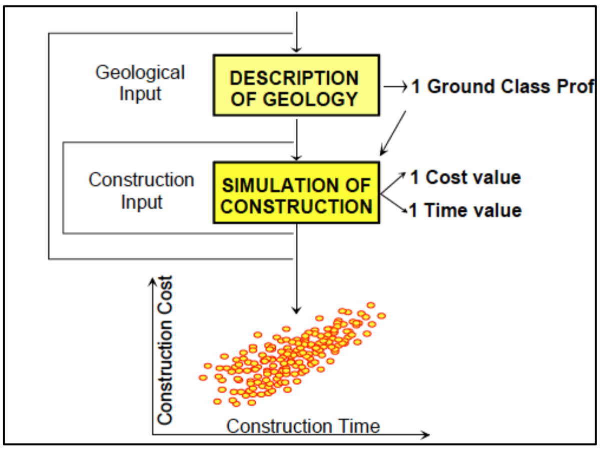


Figure D.1: DAT Generic Process. First are required the geological inputs and afterward the construction aspect are assessed to obtain cost and time scatter plot.

Firstly, the geological inputs are obtained considering different ground class profiles along the tunnel alignment. Ground classes are determined by combining different ground parameters, which are: rock classification and overburden. The rock classification is performed considering values regard RMR, Resistivity and Q-value and assigning values from I (very good) to V (very poor). The overburden is determined by the respective measure on the rock and soil over the tunnel profile and it is classified in low (<200), medium (200-250) and high (>250). By combining these ground parameters, 15 different ground classes are obtained, which will serve as the basic geological input for defining the construction methods to be used in each zone. These ground class profiles aim to represent the uncertainty and complexity of the geological conditions along the tunnel alignment and they can be assessed using Markov chain.

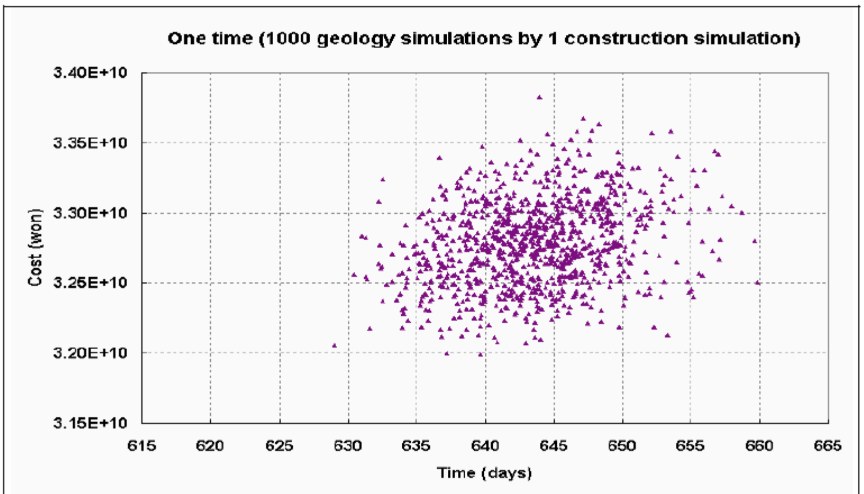
The construction methods are selected according to the ground classes and the geometry of the specific tunnel sections (e.g.: main or secondary tunnels). According to this, 12 “construction patterns” are defined, which cover the whole construction of the tunnel under analysis. For each construction pattern, the mean advance rate (m/day) and unit cost (cost/meter) are assumed or determined (depending on the phase). Additionally (Min 2003) also analyse the cost related to tunnel lining process and the construction of cross over tunnel required by the project scope.

(Min 2003) emphasises the relevance to analyse the variation in the construction inputs (i.e.: variation in advance rate and unit cost), as well as the correlation between these two parameters. These two analyses and the study of daily simulation have a critical influence in the accuracy of the results. Once both inputs (i.e.: geological and construction) and their respective correlation have been incorporated in the model, DAT is able to perform the simulations, which will give the distribution of tunnel cost and duration.

As previously explained, different simulations were performed, using distinctive levels of data regards geological and construction inputs. During the phase 3, (Min 2003) configured different settings respect of the uncertainty to be incorporated in the simulation (i.e.: geological and construction), generating 4 different setting which are depicted in table X. This helps to understand what is the contribution of each source in the overall project uncertainty.

An example of the results obtained for the setting A is shown in Figure G.2. The scattergram shows the joint probabilities for the total project cost, expressed in Korean currency (1 NOK = 178 Won approximately) and duration (days).

As demonstrated in the difference phases performed, DAT allows estimators to incorporate new information (i.e.: update process), when this became available (i.e.: geological conditions, and construction cost, advance). This is relevant because the results of the model will better represent the “actual” conditions of the project development.



One time	Min	Mean	Max	Stdev	COV
Time	629	644	660	5.06	0.79%
Cost	31996722191	32786673442	33826274239	303826309	0.93%

Figure D.2: Final output of DAT. The scatter plot shows different probabilities of the tunnel cost and time.

One the other hand, one disadvantages observed in DAT, lies in its impossibility to differentiate between normal and extraordinary risk events, therefore the final results (e.g.: project cost and time) are expressed as aggregate number.

Min (2003) concludes that tunnel cost is more sensitive to variation in the geological conditions; this is mainly because the difference between cost of different methods is higher than the differences between their respective advance rate. On the other hand, time is more dependent of construction uncertainty, which is explained because the range of advance rate (m/day) (distribution) is greater than the range for unit cost per length ($/m). In more general terms Min (2003) highlights that DAT is a highly valuable tool during the early projects phases, where several simulations may be performed in order to estimate the project out put for different tunnels alignment, and in this way support in sound basis the decision making process.

D.2 Assessing the Construction Cost of Greek Transportation Tunnel Projects

Paraskevopoulou and Bernardos (2013) present a research which is basically based no the statistical analysis of 9 tunnel project executed in Greece, focusing in the cost of excavation and temporary support and its dependency respect to the geological conditions encountered. Paraskevopoulou and Bernardos (2013) emphasise that by using past data valuable lessons may be obtained by understanding the effect of the ground conditions on the construction cost.

According to the opinion of these authors, the key cost drivers for the tunnelling cost are the geological conditions that surround the project location, the excavation method, and the end-use of the tunnel facility. In the perspective of (Paraskevopoulou and Bernardos 2013), the geological conditions govern the excavation and support methods, consequently geology is the most relevant aspect that affect the final project cost.

The authors present and consider the total cost as the summation of excavation and temporary support. The model proposed by (Paraskevopoulou and Bernardos 2013) is based on analogical method, which is implemented on the principles of the case base reasoning (CBR) methodology. The CBR basically generates assumptions or proposes solutions to new situations (cases) based on the experience and knowledge gained for previous experiences (i.e.: previous projects). It is also highlighted that generalisation of average construction cost and other relevant assumptions based on past data must be accepted only when a deep analysis of the project conditions has been performed and when general conclusions are required.

The CBR methodology helps to obtain realistic estimators or assumptions (i.e.: tunnel construction cost), in which is considered the current engineering practices and the experience gained from the previous tunnels developed in Greece. The estimator is obtained through the analysis of overall cost of comparable projects and the analysis of cost composition. Considering the data previously mentioned, the authors link geological conditions and the respective construction cost. Regression analysis (RA) is also performed as part of this research, in order to understand the correlation between geological conditions and tunnel construction cost.

The geological modelling was performed through the identification of different geotechnical categories, which range from very good to very poor quality rock masses (A, B, C, D, and E). These categories are determined considering GSI value of the rock mass. For each particular geological category, excavation and temporary support characteristics are analysed and determined. The construction cost of each section is assessed considering a unit pricing approach, which was performed considering available prices from October 2011.

As previously presented the examined sample of this research corresponds to 9 transportation tunnel projects executed in Greece, which are considered representative the current tunnelling practices in this country and covering a wide spectrum of geological conditions. The tunnels considered as part of the dataset have median length of 1270 m and cross section of 140 m2.

From the analysis of the data set, the cost range estimation is presented for each geotechnical category (A, B, C and D), which is expressed in cost per cubic meter (€/m3) and cost per tunnel meter (€/m) and include the cost of excavation and temporary support. In the same line of its assumption, the variability of the rock mass property has a clear effect in the average cost (excavation and temporary support), which ranges from 4.665 €/m for the best geological category (A) to 17.986 €/m for category D. In order to provide a more detailed estimation of the tunnel cost based on the geological conditions, a more detail analysis was performed considering GSI values and total cost (avoiding the use of categories). The estimator is given in €/m3 and it is directly assessed for the GSI values obtained at any tunnel point. The Figure D.3 shows the best-fit curve obtained for tunnel cost (€/m3), and the respective lower and upper boundary of cost dispersion. Similar plots were obtained for lineal cost of tunnel (€/m), Figure D.4.

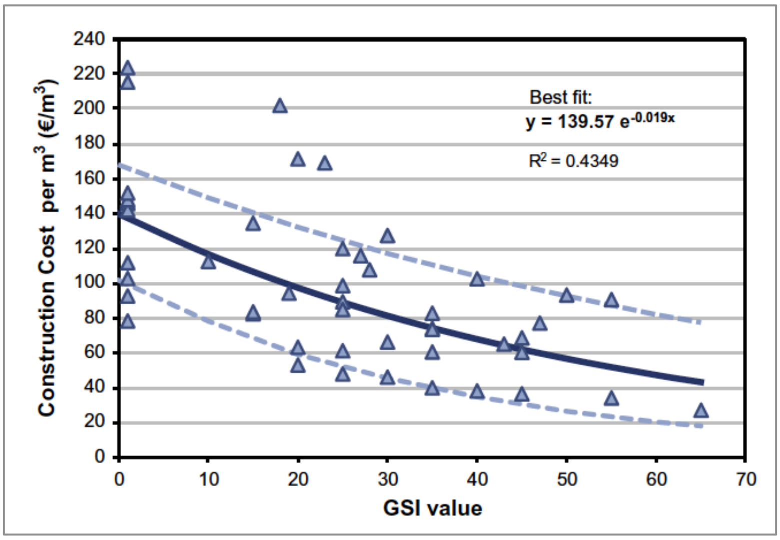


Figure D.3: Scatter plot, obtained as an input of this model, which relates GSI Values (rock mass quality index) and construction cost per m3, expressed in (€/m3).

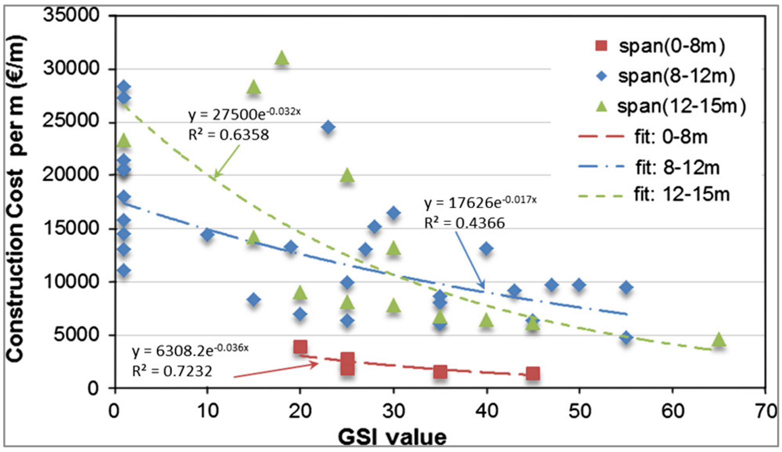


Figure D.4: Scatter plot, obtained as an input of this model, which relates GSI Values (rock mass quality index) and construction cost per metre, expressed in (€/m).

As part of the conclusion of this research, the authors emphasises that even though tunnel cost is a multivariate problem, geological conditions is the most relevant parameter that influence project cost. Therefore databases that compile information that relate geology and construction performance, are key elements for improving the cost estimation process in tunnelling and help project organisations to maximise their decisions, especially in the early project stages.

D.3 Planning Level Tunnel Cost Estimation based on Statistical Analysis of Historical Data

Rostami, Sepehrmanesh et al. (2013) present a model for cost estimation during planning stages, based on statistical analysis of historical data. The authors recognise the multivariable nature of the cost estimation process and the difficulty to perform this process during the early phases, due to the limited information available.

The proposed model is based on the analysis of 270 tunnelling projects, where several class of tunnel were analysed. This analysis is based on commonly available cost indices (CCI and BCI), which help to adjust the estimated cost according to the time and location of the specific projects.

According to Rostami, Sepehrmanesh et al. (2013) the cost of a tunnel project is a function of the tunnel length and size, geological conditions, support system, mucking and haulage, fit outs, and the rate of advance. Additionally, the authors highlight that many non-technical and organisational factors influence the final cost in tunnelling projects. Unfortunately most of these variables and their correlation are totally or partially unknown during the early stages of tunnel projects.

The model proposed by Rostami, Sepehrmanesh et al. (2013) is developed by setting a database that contains data from 272 tunnel projects executed in North America, considering different tunnel applications, sizes, locations and geological conditions. Data regards cost was collected primarily by direct interviews and questionnaire with the specific project managers and these only included the direct cost regards the project execution. The collected data was subject to statistical analyses, considering a specific categorization that includes five different project classes.

The categories reviewed, as part of this study, are namely: i) conventional tunnelling, ii) mechanised hard rock, iii) mechanised soft ground, iv) mixed mechanised, and v) micro-tunnelling. Rostami, Sepehrmanesh et al. (2013) highlights that by considering this differentiation based on tunnel methods, aspects regard geology and tunnel dimensions are inherently incorporate, this is because tunnel methods in a function of these two tunnel aspects. Additionally the authors state a secondary categorization based on tunnel uses that considers the following tunnel applications: i) highway, ii) water, iii) waste water, iv) subway tunnels.

Statistical analysis performed by the authors, considers unit cost analysis (kU$/m) and multi-variable regression. These analyses were performed for all the combinations of methods and tunnel applications, and the results are duly analysed for each combination (e.g.: method – application). Several considerations were taken for performing the statistical analysis, where are highlighted the followings.

BCI and CCI index were required to bring all the data (i.e.: project cost) to a specific reference time (i.e.: December 2008). The tunnel diameter used in the database corresponds to the external (i.e.: previous lining is executed). The scatter plots provide information about the relation between unit price and diameters. A best-fit curve and correlation coefficients are also obtained.

The results of this work are shown through the following output reports for each combination of "method – application":

i. Scattered plots (diameter – unit cost), which contain the best-fitted curve that allow predicting unit cost (KU$/m) and total cost (MU$)
ii. Predicted – actual cost plots and equations that allow estimating cost for new project given a specific predicted cost (MU$).

Figure D.5 and D.6 present the results obtained for the specific case of conventional highway tunnels. Unfortunately the data available for highway tunnel was not sufficient for subsequent analysis. As depicted in Figure D.5 the correlation coefficient for this specific tunnel configuration was low (14%) and the authors stress the need of multivariable analysis for better accuracy. Figure Y shows the comparison between predicted and actual cost, which shows a reasonable accuracy for this type of tunnel configuration (i.e.: highway conventional).

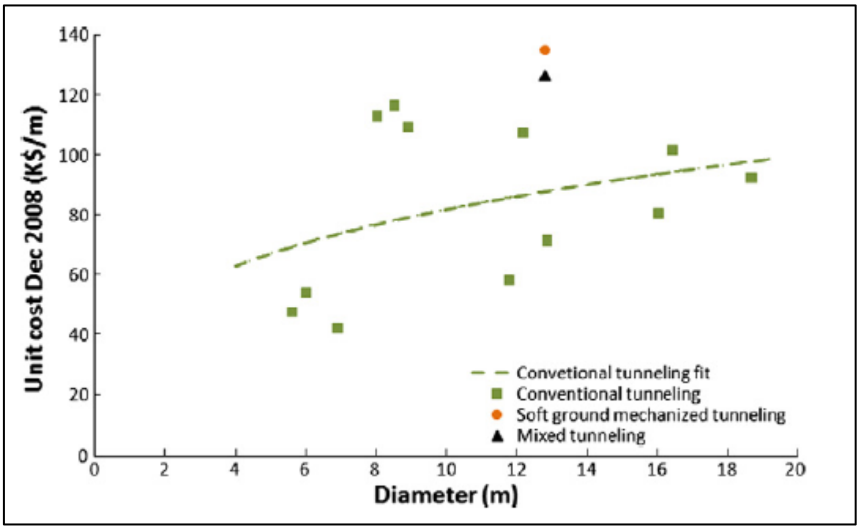


Figure D.5: Results for the tunnel cost of road (highway) tunnels as a function of the tunnel diameter (m), considering three different construction methods.

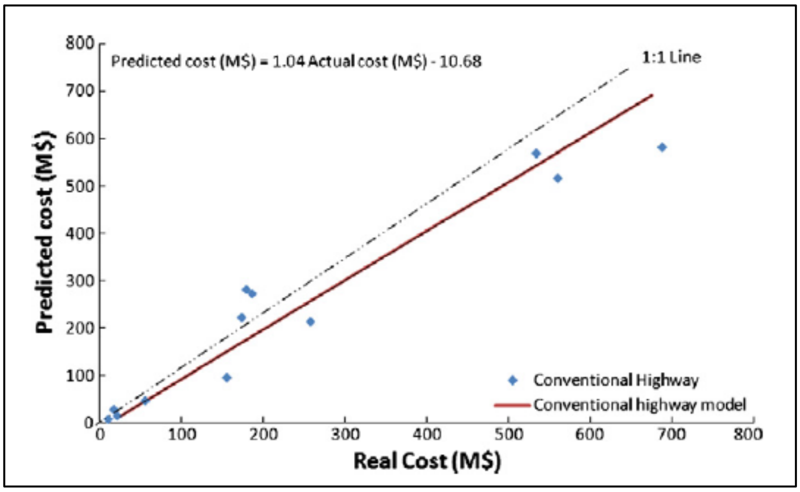


Figure D.6: Predicted equation cost proposed by the authors.

The authors recognise that the proposed equation do not consider any risk analysis, therefore a contingency factor is recommended to be incorporated. The authors recommend a "design" contingency about 30%, which will help to cover any potential change that may occurs between the early design phase and actual execution of the project. Additionally they propose a "construction" contingency of 10-15% of the estimated construction cost. Finally they emphasise that cost related to financing, bonds, engineering and construction management services are not included in the suggested contingencies, therefore they must be duly estimated in the perspective of the owner estimation. The authors propose a tunnel cost estimator (TCE), which is built-up in Matlab and allows estimators to obtain total project cost and average unit cost, based on the equations stated in their analysis. The inputs for this model are tunnel length (L) and diameter (D).

The conclusion of this work highlights that early cost estimation is an essential process during the project development and for the selection of the construction method. Regardless the lack of relevant information during the early phases, there is still a need to provide reasonably accurate cost estimations to perform the trade off studies among different project alternatives and tunnel methods. In order to mitigate potential inaccuracies during the early estimation, the authors recommend the use of high contingency factors. The results obtained by the proposed equations have been compared with other estimation techniques and they have proven to be reasonable. Finally they highlights that futures works must include the risk management analysis, which allow engineers to make better decisions under uncertainty.

D.4 Early Cost Estimating of Road Tunnel Construction Using Neural Networks

Petroutsatou, Georgopoulos et al. (2012) highlights the difficulties regard cost estimation during the early phases, due to the underground uncertainties and risk and it criticality for the initial decision making process. In order to help project organisations to obtain more reliable early cost estimating the authors propose a model based on nearest neighbour (NN) patterns. According to the author, the capability to work with large number of non-parametric statistical estimators makes NN especially suitable for the cost estimation process in underground projects. On the other hands, they also emphasise that the main drawback lies in the difficulty to explain the rationale behind the results obtained.

The development of this model involves three main phases, which are namely: i) the selection of the variables, ii) data collection and analysis, and iii) NN model development and validation. The first stage aims to determine the dependent and independent cost variables for underground projects through literature review and interviews. Data collection and analysis was performed considering quantitative data regards geological and construction parameters collected in several projects executed from 1998 to 2004 in Greece.

Finally NN model were developed for quantities and cost estimates by testing multilayer feed-forward network (MFFN) and general regression neural network (GRNN). After the execution of the first stage, the authors defined the independent and dependent variables of the cost estimation problem, which are summarised in the following table.

Underground Cost Estimation	
Independent Variables	**Dependent Variables**
Geology (Type of Rock / Soil)	Steel Sets
Geological Strength Index (GSI)	Shotcret
Strain	Rock Bolts
Depth of Overburden	Concrete Permanent Support
Excavated Area	Steel of Permanent Support

Table D.1: Cost estimation variables for underground projects. The left hand column shows the independent variables, while the right hand column shows the variables that must be considered dependent during the cost estimation process.

The independent variables are essentially geotechnical parameters that affect the tunnel support and thus also affect the final execution cost, while the depend variables are basically material quantities regards the execution of primary and permanent support.

As previously mentioned, the second phase (e.g.: Data Collection and Analysis) was performed using quantitative data from 149 different tunnel sections (total length 46 km) executed by Drill & Blast between 1998 and 2004 as part of the Egnatia Motorway Project. The geological conditions of this project, were governed by highly heterogeneous and intensely tectonized rock formations. Data collection was executed using questionnaire survey, which was originally completed by site engineers and validate for site visits of researchers. Project cost were normalised, in the range of 0 to 1, for both confidentially and more effective model training.

The final phase, neural network model development, training and validation, was performed in order to provide the final estimation model and assess its accuracy. In this phase 6 NNs are introduced for each dependent variable and for the total construction cost. In order to assess the best approach for the cost modelling, MLFM and GRNN were applied and its results in term of R2, average estimated error rate (AEER) and weighted estimated error rate (WEER) were assessed for this. The main output of this phase is the selection of the most suitable neural architecture (MLFM or GRNN), which delivers the best level of accuracy for the estimation of material quantities (dependent variables) and for the final cost. Once these phase are performed, the model is validate by using the collected data and the results are presented as actual / predicted plots (Figure D.7), which may help estimators to asses projects in term of construction quantities and final cost.

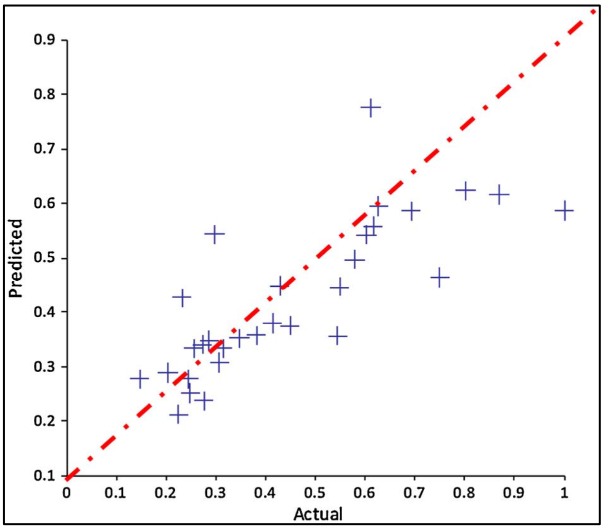


Figure D.7: Model Output shows the actual and predicted cost for data collected from previous project. The dotted red line shows the 1:1 line, where predicted costs are equal to the actual cost.

The results of this research shown that NN models have higher overall accuracy than models based on multivariable regression analysis (MRA). The authors finally conclude that this model provides robust early cost estimate for tunnel construction, which enable project organisations to maximise its decisions during the early project stages.

Appendix E: NTNU Prognosis Model

Drill and Blast Prognoses Model (Cost)

The NTNU prognoses model considers the following cost

i. Elemental Cost and Standard Cost
ii. Total Construction Cost

The cost obtained for this model is representative for the most technically and economically favourable equipment combinations. Elemental Costs are given for 48 mm drill hole diameter and it is also considered the following assumptions.

i. Medium Blastability
ii. Medium Drillability
iii. Drill Hole Length 5 m
iv. Tunnel Length 3 m

The elemental cost considers the following items:

i. Drilling, Charging and Scaling
ii. Loading
iii. Hauling
iv. Additional Work (at the tunnel)
v. Labour Niches

Total Construction cost considers:

i. Worksite, Move-in and Move-out
ii. Worksite Upkeep
iii. Construction Work (included elemental cost)
iv. Unforeseen Events
v. General Cost
vi. Interest During Construction

The figure below represents one of the typical plots presented to the NTNU prognoses model. Given a determined input (i.e.: tunnel section), it is possible to derive the unit price for the basic cost of the tunnel. Similar plot can be found throughout this model to assess the specific unit price of each of the activities previously mentioned. Additionally several correction factors are also included, in order to expand the use of this plot to different tunnel conditions.

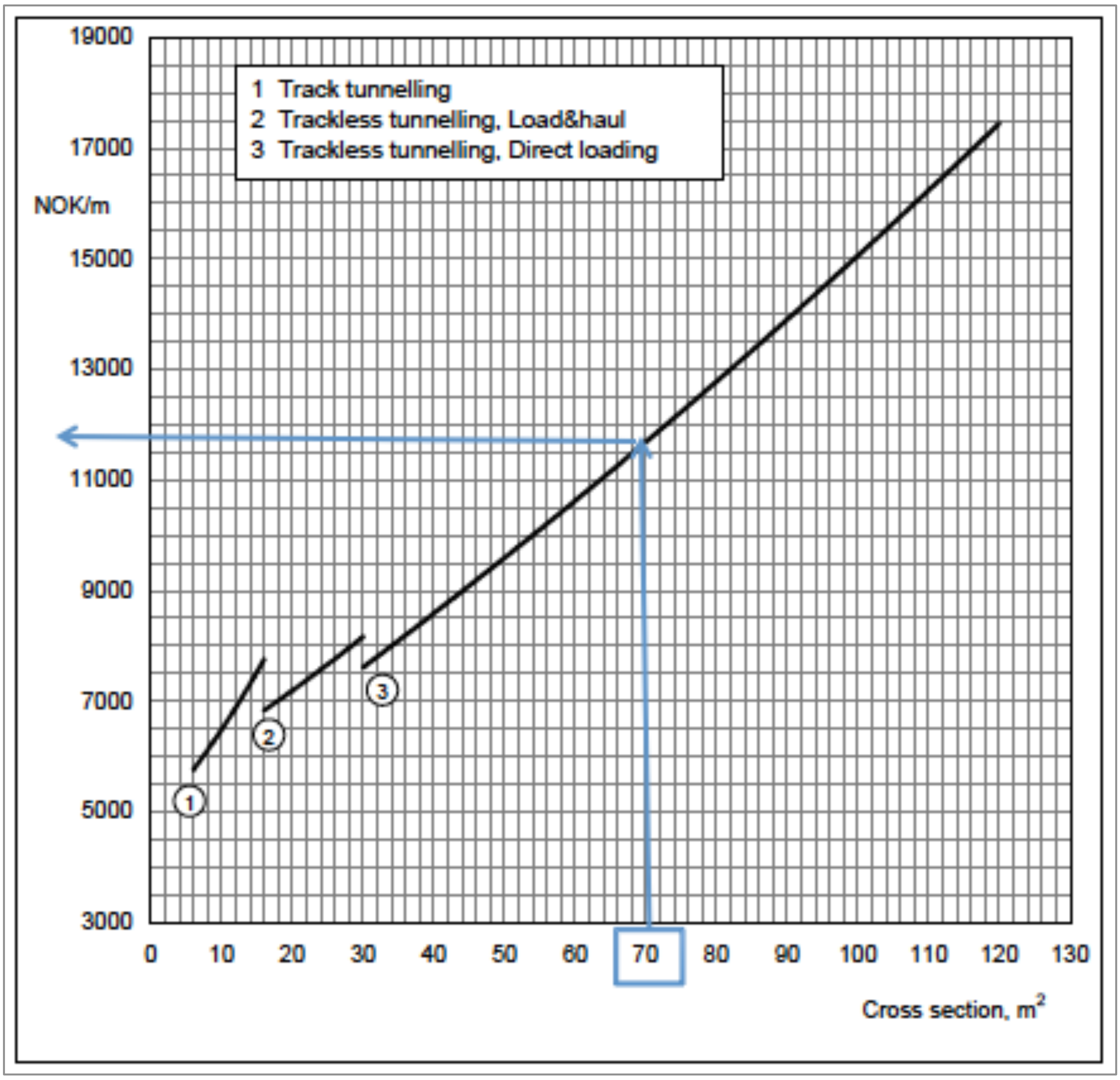


Figure E.1: NTNU Drill and Blast Prognosis Model (Cost). The graph shows the basic cost as a function of the cross section area of the tunnel. The cost is given in NOK/m at 2007 (price level).

The NTNU model presents different level of details. The first section is focused on the cost summary (Figure E.1), where several activities are aggregate and summarised as a total cost for the excavation activities. Section 2 presents a detail for each of the costs (i.e.: elemental costs) that compose the total cost presented in section 1. Finally section present a total construction cost, where other indirect cost related to the tunnel construction are considered.

Appendix F: Cost Drivers for Tunnelling Process

This appendix contains the main features regarding the selected cost drivers for each of the tunnelling activities (i.e.: excavation, water control, rock support, and lining). As previously discuss in Chapter 6, the selected cost drivers must fulfil certain conditions and the following sections provide the support for the selection of these variables.

F.1 Cost Driver for Drill and Blast Excavation

The selected cost driver for excavation (conventional method) is Drillability Index (DRI). The reason that justify the selection of this parameter are as follows:

i. It has been considered in previous models for cost estimation (NTNU Prognosis Model)
ii. There is an extensive register of drillability index in Norway, which allows estimating values of DRI, in a rather simple way, for different types of rock.
iii. It represents the effects of geological uncertainty over construction process and performance (i.e.: drillability, drill bit wear and lifetime, among other)
iv. It is estimated considering two important geological parameter of the rock (i.e.: Brittleness and Sievers J-Value)

According to NTNU2B-05 (2006) the drillability of a rock may be classified according to the scale depicted in Table F.1:

Good drillability	DRI = 65	For example mica schist
Medium drillability	DRI = 49	For example granite
Poor drillability	DRI = 37	For example gneiss

Table F.1: Drillability Index (DRI) categories and examples of type of rock that presents similar values.

Typical DRI values for different type of rock are summarised in the following figure:

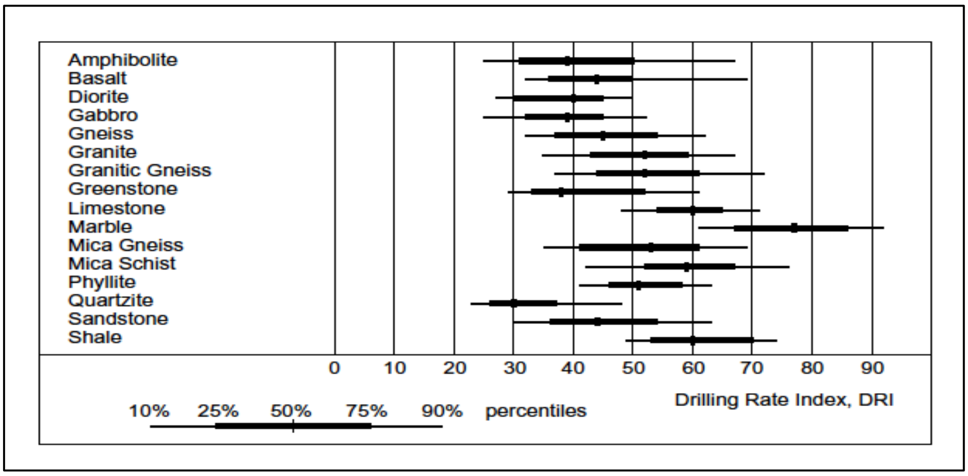


Figure F.1: Specific distribution of DRI values in different type of rocks

Event though Dahls, Bruland et al. (2012) emphasise that determination of drillability properties only based on the rock type is not recommended, the author of this work assumes that this can be overcome by assessing values with larger spread (larger standard deviation).

Another parameter, which is indirectly, used as cost drivers in the proposed model are Blastability Index (SPR) and Q-Values. The Rock Blastability Index (SPR) controls the blast activities, and it can be categorised into the following categories.

Good blastability SPR = 0.38.	Coarse-grained homogeneous granites, syenites and quartz diorites. E.g. "Swedish granite".
Medium blastability SPR = 0.47.	Rock types with blastability between good and poor. For example gneiss.
Poor blastability SPR = 0.56.	Metamorphic rock types with slated structure, often with high content of mica, and a low compressive strength. Characteristic for these rock types are a high level of anisotropy. For instance mica schist in the Rana region in Norway.

Table F.2: Rock Blastability Index (SPR) and examples in different type of rock.

The following figure depicts SPR values for distinct type of rock obtained at NTNU rock lab.

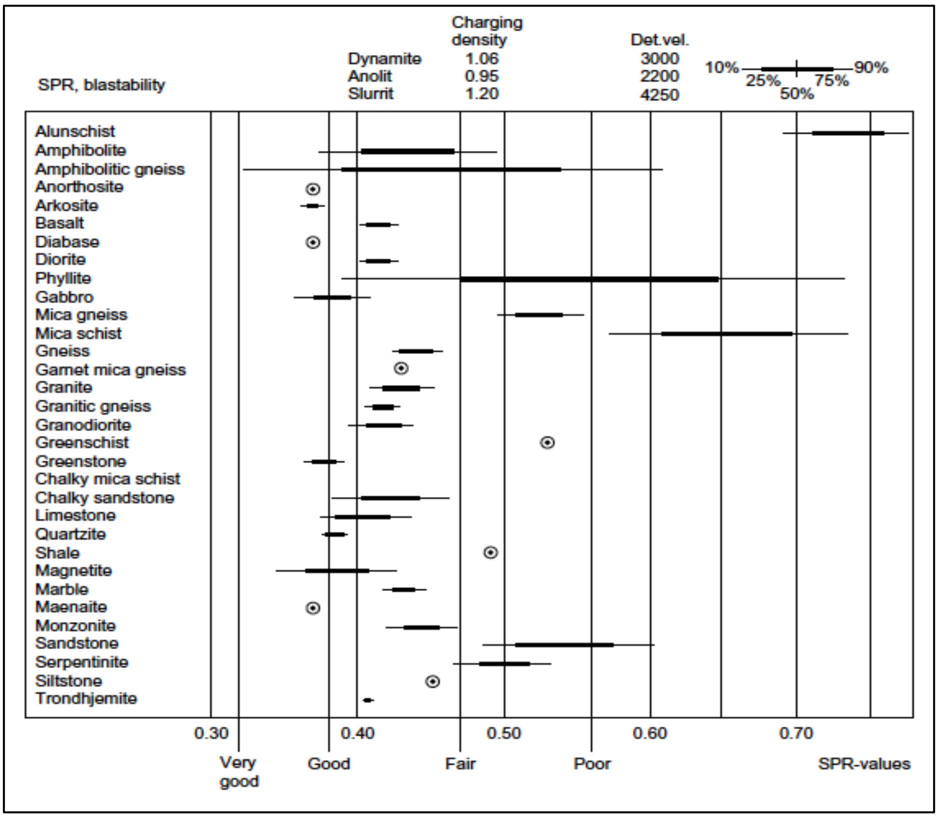


Figure F.2: SPR Distributions in different rock types

F.2 Cost Driver for Water Control

The water inflow in underground structures is basically controlled by the permeability of the rock mass, which is composed by the rock and the existing discontinuities and joints. As presented in the main report of this work the water inflow of a rock mass is controlled by the hydraulic conductivity (K). Nevertheless, this parameter is difficult to estimate, given the low values in which is represented.

Considering the above the selected cost driver to determine the water control cost is the expected water leakage "q" (lt/min/km), which may be derive from given values of K. This value may be assessed in a better way for experts and it can also be obtained from previous experiences. According to the author, this value also represents the uncertainty regard this specific process, and it is representative of the resources and efforts that are required to achieve the objective of the water control activities. Consequently the selected parameter (i.e.: q) fulfils the conditions established for the selection of cost drivers.

Water Inflow Before Performing Water Control					
Base	Scale	Percentil	K (m/s)	Log10(K)	Q (lt/min/km)
1	Very Low	K10	1,00E-09	-9,00	20,32
1	Low	K20	1,00E-08	-8,00	203,19
3	Moderate	K50	3,00E-08	-7,52	609,56
5	High	K80	5,00E-08	-7,30	1015,94
8	Very High	K90	8,00E-08	-7,10	1625,50

Table F.3: Categorisation of the rock hydraulic conductivity and its equivalent expected water leakage, expressed in lt/min/km.

The table above was derived using information provided by NFF (2005) and using the formula given below (Karlsrud / NFF):

$$q = \frac{2\pi * K * h}{ln\left[\frac{2h}{r} - 1\right]}$$

Where:

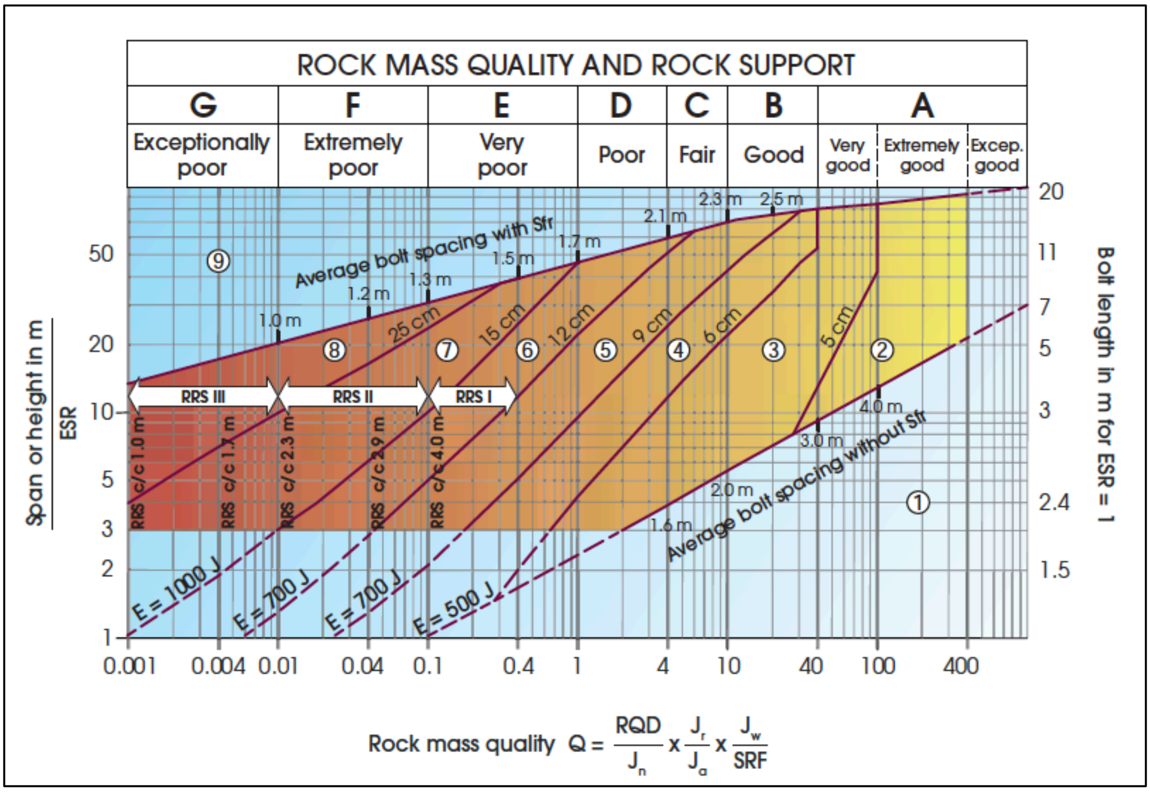
q: water leakage (m3/m/s)
K: hydraulic conductivity around the tunnel (m/s)
h: distance from the tunnel to equipotential (m)
r: tunnel radius (m)

The variables involved in the equation were replaced with specific values related to the case study.

F.3 Cost Driver for Rock Support

According to NFF (2010), rock support may be assessed by the use of rock mass classification systems (e.g.: Q-system), which must be always used as a guideline and supported by competent engineering judgment.

Since Q-System allows representing different rock mass condition, and they represent a easy way to assess different rock support categories, it is considered that the Q-Value fulfil all the requirement to be considered as cost driver.



Support categories

1. Unsupported or spot bolting
2. Spot bolting, **SB**
3. Systematic bolting, fibre reinforced sprayed concrete, 5-6 cm, **B+Sfr**
4. Fibre reinforced sprayed concrete and bolting, 6-9 cm, **Sfr (E500)+B**
5. Fibre reinforced sprayed concrete and bolting, 9-12 cm, **Sfr (E700)+B**
6. Fibre reinforced sprayed concrete and bolting, 12-15 cm + reinforced ribs of sprayed concrete and bolting, **Sfr (E700)+RRS I +B**
7. Fibre reinforced sprayed concrete >15 cm + reinforced ribs of sprayed concrete and bolting, **Sfr (E1000)+RRS II+B**
8. Cast concrete lining, **CCA** or **Sfr (E1000)+RRS III+B**
9. Special evaluation

Bolts spacing is mainly based on Ø20 mm

E = Energy absorbtion in fibre reinforced sprayed concrete

ESR = Excavation Support Ratio

Areas with dashed lines have no empirical data

RRS - spacing related to Q-value

I: **Si30/6 Ø16 - Ø20 (span 10m)**
D40/6+2 Ø16-20 (span 20m)

II: Si35/6 Ø16-20 (span 5m)
D45/6+2 Ø16-20 (span 10m)
D55/6+4 Ø20 (span 20m)

III: D40/6+4 Ø16-20 (span 5 m)
D55/6+4 Ø20 (span 10 m)
D70/6+6 Ø20 (span 20 m)

Si30/6 = Single layer of 6 rebars, 30 cm thickness of sprayed concrete
D = Double layer of rebars
Ø16 = Rebar diameter is 16 mm
c/c = RSS spacing, centre - centre

Appendix G: Cost Functions

This appendix contains the most relevant assumption considered for the determination of the specific cost functions used in the proposed model. Additionally, this appendix contains part of the deliverables obtained during the process of determining the specific functions.

G.1 Excavation Process (F1 (DRI))

The following assumptions has been considered:

i. Drill hole length 5 m (k_{ls} = 1,00)
ii. Drill hole diameter 48 mm (k_{je} = 1,00)
iii. Number of Hammers 3 (in each tunnel face)
iv. Emulsion Explosives with 5% dynamite portion (k_{de} = 1,00)
v. Nonel Detonators
vi. The cost assessed by this equation corresponds to the Normal Excavation Unit Cost (NOK/m), which is equivalent to the standard excavation cost of NTNU Prognoses Model, therefore no additional costs related to other construction activities are included (e.g.: cost of facilities, general cost, among other).
vii. Other assumptions non-specified in this document are in agreement to the NTNU Prognoses Model.

The process to obtain the function shown below may be summarised as follows:

i. Estimating unit price for all the activities related to tunnelling, using NTNU prognosis model, and for all different combination of SPR and DRI
ii. Correcting Elemental Cost and Obtaining Standard Cost
iii. Correcting Standard Cost by Rock Mass Quality Influence (Q-Value)
iv. Defining Excavation Classes as combination of SPR and Q-Values
v. Plotting and Fitting Equations for each Excavation Class

Excavation Unit Cost				DRILLABILITY								
Ct	Ct = Cdt + Cl + Cht + Ca + Cla + Cn		NOK/m	13.215	13.038	12.860	12.715	12.538	12.340	12.165	11.988	11.810
				37	37	37	50	50	50	65	65	65
kp	2014 K1 = 145,9 and 2007 Kaverage = 115,678			1,26	1,26	1,26	1,26	1,26	1,26	1,26	1,26	1,26
				BLASTABILITY								
		Q effect		Poor	Medium	Good	Poor	Medium	Good	Poor	Medium	Good
Cst = Ct * kp	FOR ROCK A, B, C (Q>4)	1,00	NOK/m	16.668	16.444	16.220	16.037	15.813	15.564	15.343	15.119	14.895
Cst = Ct * kp	FOR ROCK D (4>Q>1)	1,25	NOK/m	20.834	20.555	20.275	20.046	19.766	19.455	19.179	18.899	18.619
Cst = Ct * kp	FOR ROCK E (1>Q>0,1)	1,60	NOK/m	26.597	26.240	25.883	25.591	25.234	24.836	24.484	24.127	23.769
Cst = Ct * kp	FOR ROCK F(0,1>Q>0,01)	2,14	NOK/m	35.716	35.236	34.757	34.365	33.885	33.351	32.878	32.399	31.919
Cst = Ct * kp	FOR ROCK G (0,01>Q>0,001)	3,57	NOK/m	59.525	58.725	57.926	57.273	56.473	55.583	54.795	53.996	53.196

Table G.1: Shows the Unit Cost for the excavation process (standard cost for the excavation, according to the NTNU Model). The unit prices (NOK/m) were corrected by the effect of rock mass quality. This correction was done considering the results obtained (Kim and Bruland 2009). The correction factors for the unit cost are considered to be inversely proportional with the factor related to the advanced rate (m/week).

FROM Y.KIM AND A. BRULAND (2009)					
STANDARD ADVANCE RATE AND Q VALUE (T9)					
		standard	standard		
		m/week	week/m	NOK/m	%
	Q	A.RATE	Inverse		Increment
G	0,001	21	0,048		257%
F	0,010	35	0,029		114%
E	0,100	47	0,021		60%
D	1,000	60	0,017		25%
A,B,C	10,000	75	0,013	base case	0%

Table G.2: Corrected Factor proposed by the author and derived form (Kim and Bruland 2009)

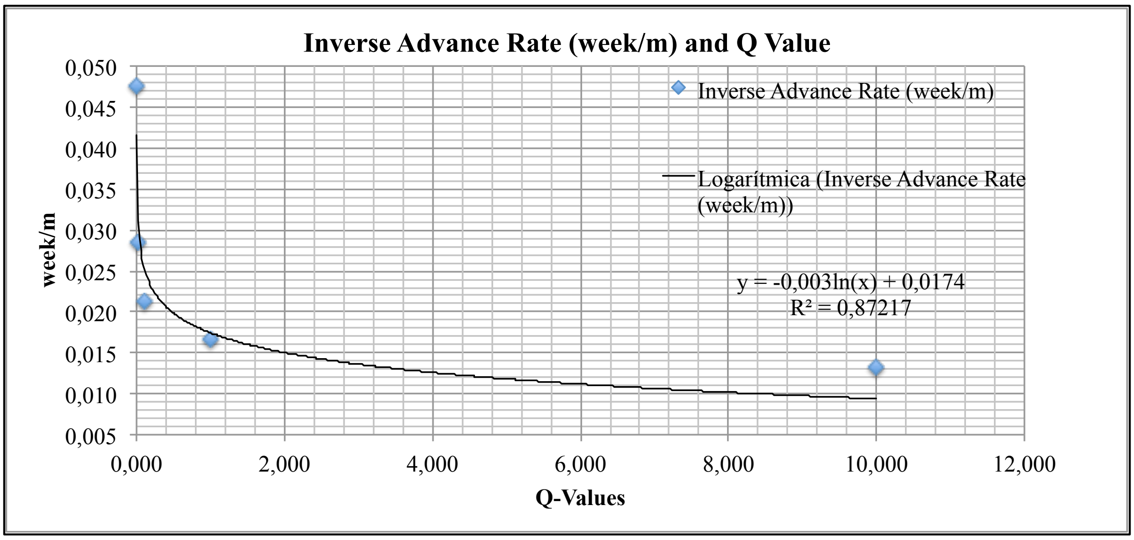


Figure G.1: Correlation Analysis between Inverse Advance Rate (week/m) and Q-Values. The plot shows an important level of correlation between these two variables. The lower Q-Values the more time is required to perform a single meter of excavation (week/m).

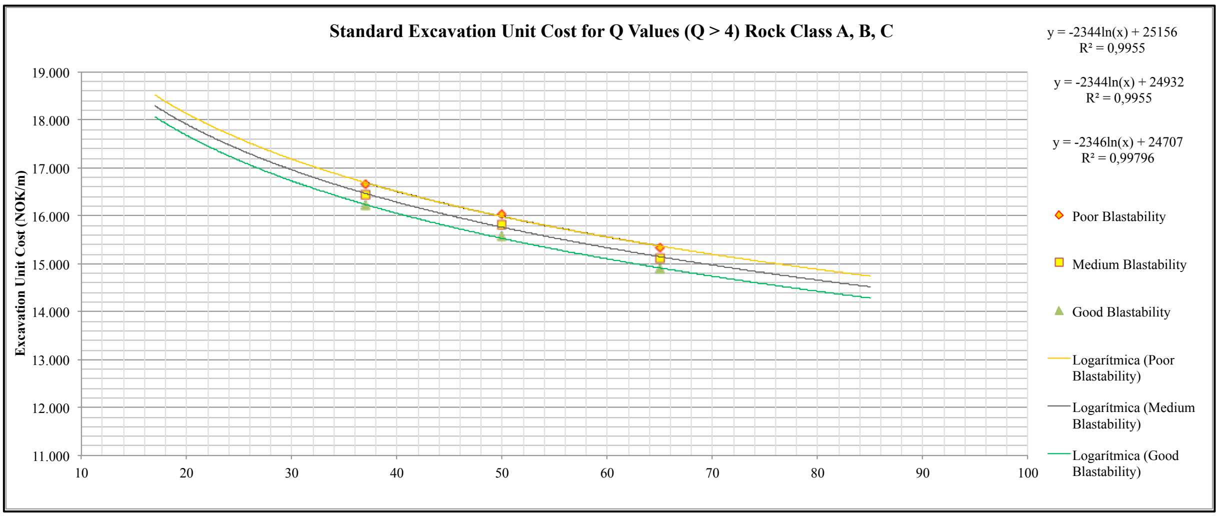


Figure G.2: Unit Excavation Cost for different level of Blastability and Rock Class A, B, C

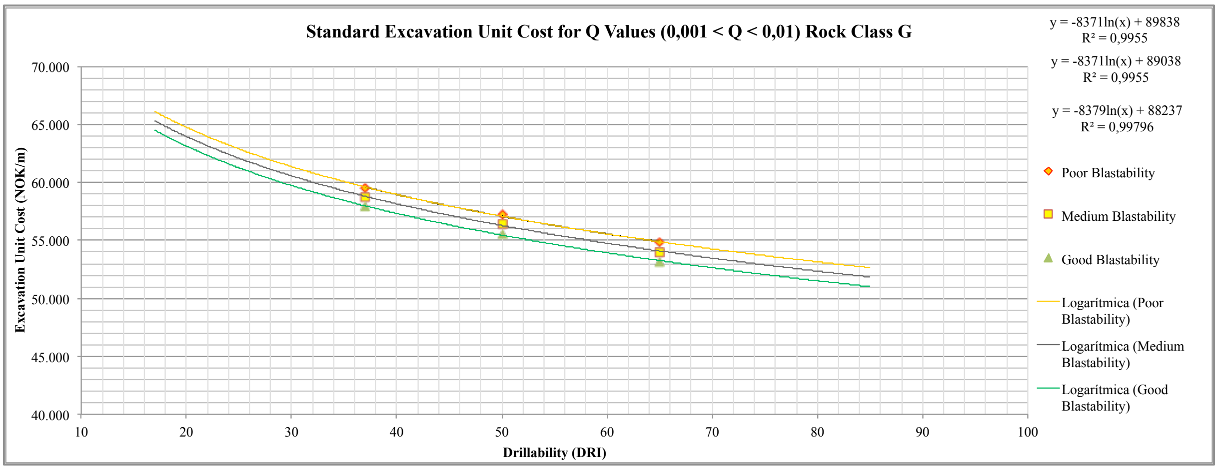


Figure G.3: Unit Excavation Cost for different levels of Blastability and Rock Class

G.2 Water Control Process (F2 (q))

The following assumptions must be considered for water control cost function.

i. The water control process is achieved by through pre-grouting and froze protection; consequently post grouting is not required.

ii. The achieved Rock Mass Hydraulic Conductivity (K) after the grout process is around to $3*10^{-9}$, which fulfils the water tightness required by the project.

iii. The unit price for water control considers all the equipment, material, consumable and all direct resources required to perform the activities of water control, but other indirect construction costs are not included (i.e.: the same scope than excavation cost).

iv. The main items considered for performing water control are: probe drilling, grouting, packages, and frost control. Post grouting may be incorporated if required (new equation).

v. More detailed assumptions regarding construction aspects may be found in the Excel model delivered as an integral part of this work.

A summary of the process performed in order to obtain this specific cost function is as follows:

i. Hydraulic Conductivity of the Rock Mass was classified in 5 categories

ii. Equivalent Water Leakage "q" was estimated (lt/min/km) for specific conditions of hydrostatic pressure and tunnel geometry (T9.5)

iii. Different material usages (quantities) were defined for each category of leakage, using data from previous undersea tunnels, and considering specific pre grout strategy (i.e.: pre grout round length = 25 m and overlap = 10 m)

iv. Specific unit prices were determined for each material.

v. Total Unit Price for Water Control was estimated as the summation of all the items previously mentioned

vi. The scatter plot Water Leakage / Unit Price was obtained

vii. The best fit equation was selected as cost function

Water Inflow Before Performing Water Control					
Base	Scale	Percentil	K (m/s)	Log10(K)	Q (lt/min/km)
1	Very Low	K10	1,00E-09	-9,00	20,32
1	Low	K20	1,00E-08	-8,00	203,19
3	Moderate	K50	3,00E-08	-7,52	609,56
5	High	K80	5,00E-08	-7,30	1015,94
8	Very High	K90	8,00E-08	-7,10	1625,50

Table G.3: Rock Mass Hydraulic Conductivity (m/s) and Water Leakage Categorisation (lt/min/km of tunnel). These categories correspond to the conditions expected at the tunnel face and before performing the water control activities

Water Inflow Before Performing Water Control					1) Pre Grout Drilling				
					Usage	Price	Price	Length (m)	U.P1
Base	Scale	Percentil	K (m/s)	Q (lt/min/km)	holes/round	NOK/m	NOK/holes	Grout Round	NOK/m
1	Very Low	K10	1,00E-09	20,32	10	70	1750	15	1.167
1	Low	K20	1,00E-08	203,19	15	70	1750	15	1.750
3	Moderate	K50	3,00E-08	609,56	20	70	1750	15	2.333
5	High	K80	5,00E-08	1015,94	30	70	1750	10	5.250
8	Very High	K90	8,00E-08	1625,50	60	70	1750	10	10.500

Table G.4: Example of the estimation of the unit price for the pre grout drilling, the same approach was applied for the other activities, in order to get the final unit price.

Water Inflow Before Performing Water Control					Total
					U.Pwc
Base	Scale	Percentil	K (m/s)	Q (lt/min/km)	NOK/m
1	Very Low	K10	1,00E-09	20,32	3.862
1	Low	K20	1,00E-08	203,19	6.095
3	Moderate	K50	3,00E-08	609,56	9.348
5	High	K80	5,00E-08	1015,94	19.420
8	Very High	K90	8,00E-08	1625,50	31.345

Table G.5: Final Unit Price for the water control activities and different water leakage levels

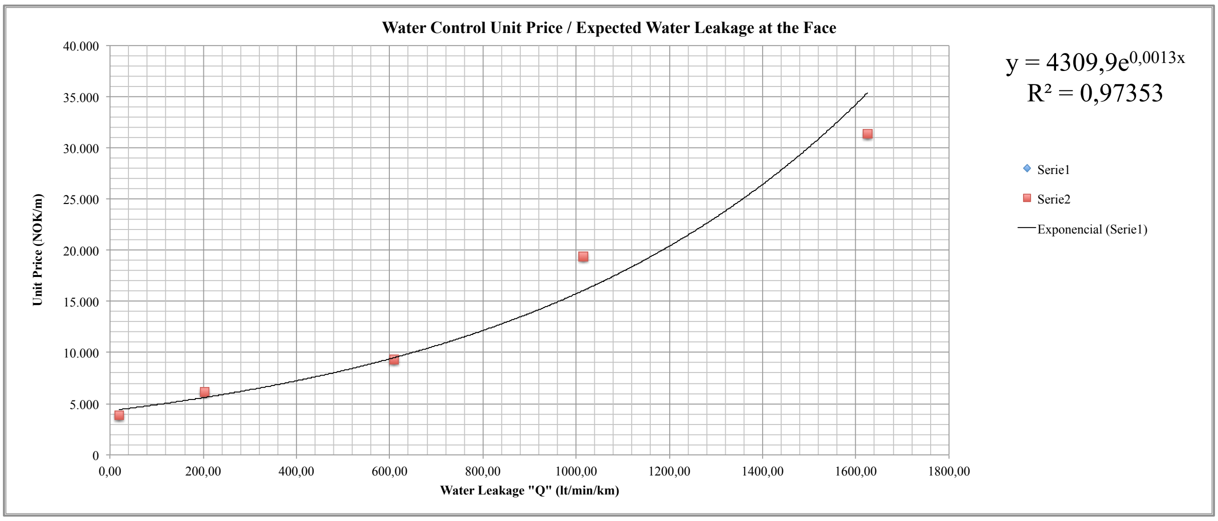


Figure G.4: Water Leakage (lt/min/km) and Unit Price of Water Control Activities (NOK/m).

G.3 Rock Support Process (F3 (Q-Values))

The following assumptions must be considered for the rock support cost function.

i. The rock support is executed considering the classification given in Q-system
ii. The cost function was obtained for a certain level of security (ESR = 1) and specific tunnel geometry (T9.5)
iii. The unit price for rock support considers all the material, equipment and direct resource to execute this activity. Other indirect costs are not included.
iv. The unit price of rock support considers bolting, reinforced shotcrete and reinforced ribs of sprayed concrete (RRS), when required. Therefore the unit price is considered as the summation of all the activities required.
v. The base price for bolting considers bolt length of 3 metres and a basic average bolt spacing of 2,5 metres (with Sfr). A specific correction factor for average spacing was introduced when required.
vi. The base unit cost for shotcrete is determined considering a fibre reinforced sprayed concrete with E=500J and thickness S=6cm. Specific correction factors for energy absorption (E) and shotcrete thickness (S) were introduce when required
vii. Prices were derived from NTNU prognoses model and corrected, according to the construction index

The cost function for the cost support activities was derived through the following activities.

i. Defining tunnel geometry (T9.5)
ii. Defining the required ESR (Excavation Support Ratio)
iii. Defining the required support category according to Q-system
iv. Setting the unit price for each activity (i.e.: bolting, shotcrete and reinforced ribs)
v. Correcting activity prices according to requirements
vi. Estimating Unit Price for each category (from 1 to 8)
vii. Obtaining scatter plot unit price / Q-Value
viii. Obtaining the best fit equation

Support	Bolt Corrections		Shotcrete Correction		Price	Bolts	Shotcrete	RRSX	Total
Category (Q)	Spacing	Length	thickness	E	RRS	NOK/m	NOK/m	NOK/m	NOK/m
1	1	1	1	1	0	2.964	0	0	2.964
2	1	1	1	1	0	6.384	0	0	6.384
3	1	1	1	1	0	6.384	7.296	0	13.680
4	1,47	1	1,29	1	0	9.384	9.412	0	18.796
5	1,67	1	1,71	1,1	0	10.661	13.724	0	24.385
6	1,92	1	2,14	1,1	4.725	12.257	17.175	473	29.905
7	2,27	1	2,43	1,5	7.088	14.492	26.594	1.418	42.503
8	2,50	1	4,29	1,5	9.450	15.960	46.950	1.890	64.800

Table G.6: Rock Support Categories and Proposed Unit Price (NOK/m)

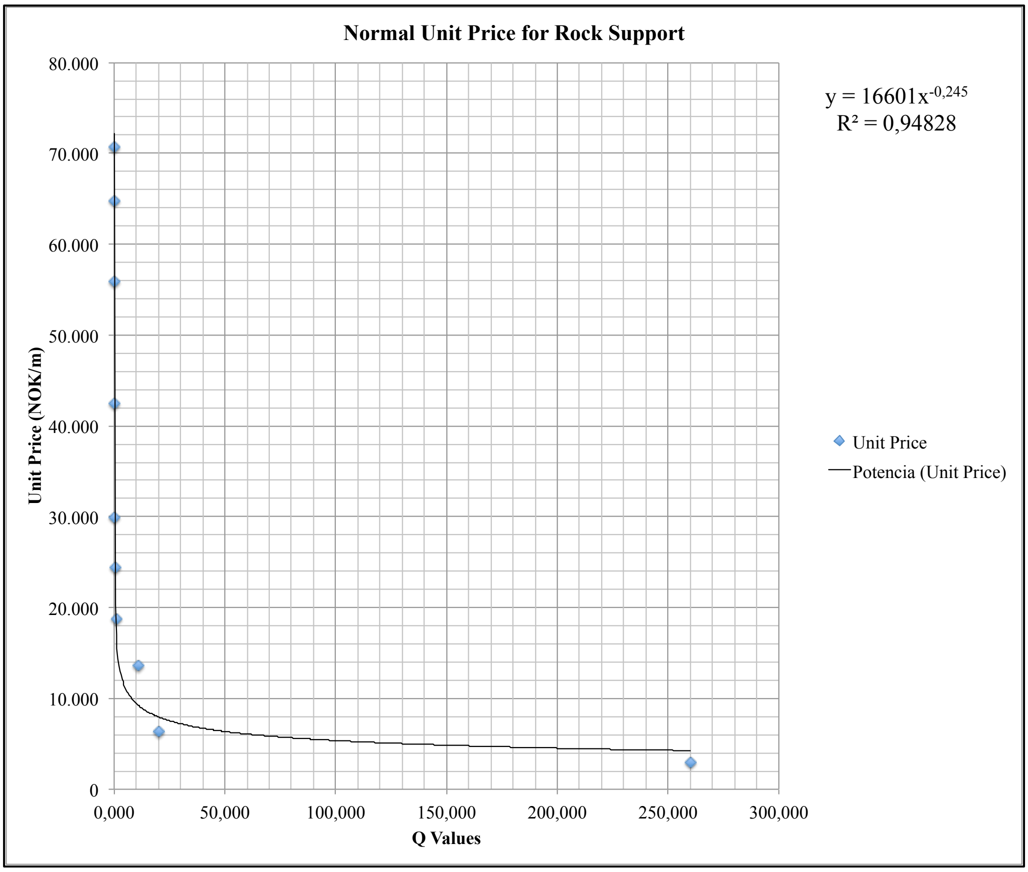


Figure G.5: Unit Price for Rock Mass Support as a function of Q-Values.

G.4 Tunnel Lining Process (F4 (S))

The following assumptions were considered to obtain the tunnel lining cost functions.

i. The equations are given for four (04) different combinations of lining strategies, and considering a specific cross-area (i.e.: T9.5).
ii. The tunnel lining may be performed by precast concrete elements (with or without reinforcement) or by unreinforced concrete lining cast in place (at or behind the face).
iii. The precast lining solution is considered drained solution, while cast in place is considered undrained solution, but its contribution to the water control is neglected.
iv. The contribution of the cast in place lining to the rock support is also neglected.
v. The prices for inner lining cast in place were derived from NTNU Prognosis Model (Report "C-05 Drill and Blast) and corrected by the specific construction index. The correction considered 2/3 of the total correction factor, due to the improvements in the construction process.
vi. The prices for unreinforced precast lining were derived considering 40% more expensive than prices for cast in place behind the face. Prices for reinforced precast segment were considered as 20% more expensive than the solution without reinforcement.
vii. The reinforced precast segments considers a reinforcement based on steel fibres (SFRC), and steel bars are not considered as part of this solution

viii. Precast segments considers gadgets and join systems

ix. The concrete used consider additives for salt-water protection (i.e.: carbonatation)

x. The unit cost for tunnel lining considers all the resources, material, equipment and direct cost related to the execution of this specific activity. Unit cost does not include another indirect and general cost.

Element Thickness		UP (NOK/m)	
S		Behind	At the Face
300	S=300	27.926	35.336
350	S=350	32.550	41.225
400	S=400	37.235	47.114
450	S=450	41.889	53.003
500	S=500	46.543	58.893
550	S=550	51.198	64.782

Table G.7: Estimated Unit Cost for cast in place elements without reinforcement behind and at the tunnel face. The line highlighted in blue corresponds to the base prices obtained from NTNU Model

Element Thickness		UP (NOK/m)	
S		Non Reinforced	Reinforced (SFRC)
300	S=300	39.096	46.916
350	S=350	45.570	54.684
400	S=400	52.129	62.554
450	S=450	58.645	70.374
500	S=500	65.161	78.193
550	S=550	71.677	86.012

Table G.8: Estimated Unit Cost for precast concrete elements/ segment without and with steel fibre reinforcement (SFRC). Prices for non-reinforced elements were derived as 40% more expensive than behind the face solution.

Lining Class	Type	Strategy	Cost Function
L1	Cast in Place	Behind	93,14*S - 27,156
L2	Cast in Place	At the Face	117,78*S + 0,9143
L3	Precast	Unreinforced	130,39*S - 38,018
L4	Precast	Reinforced	156.47*S - 45,621

Table G.9: Cost function for different alternatives of tunnel lining

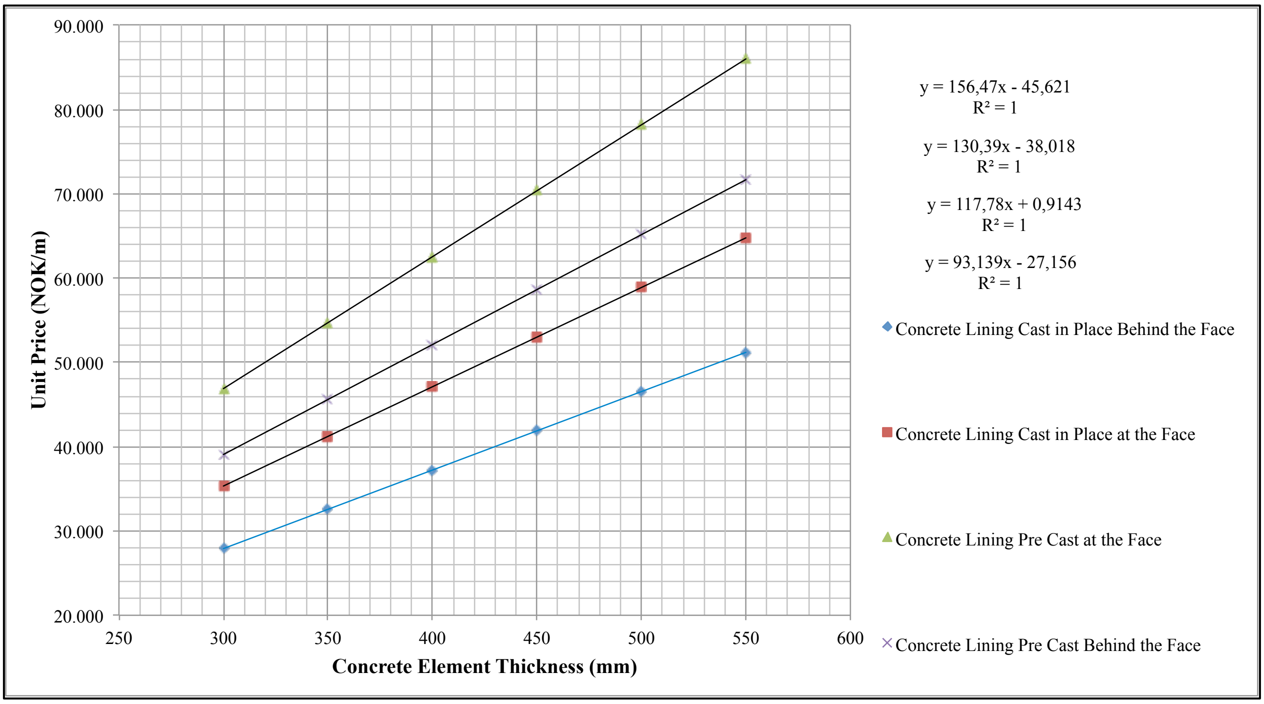


Figure G.6: Unit Cost of Lining Activities as function of the concrete thickness (S)

Appendix H: Overall Project Cost Estimation – Project Budget

In order to model the total cost of underwater tunnel projects (i.e.: project budget), the author designed a project budget model, based on the project Work Breakdown Structure (WBS).

The main reason that sustains this decision is that WBS allows estimators to obtain a well-structured level of detail about the deliverables, system and activities required to obtain the final project deliverable (e.g.: underwater tunnel ready to operate). Considering the WBS defined for undersea tunnel project, the Cost Breakdown Structure (CBS) is determined according to the following figure.

Table H.1: Undersea Tunnel Project Cost Breakdown Structure (CBS)

W.B.S	PROJECT PHASE (DELIVERABLES)				Cost Driver	2 9.000
D.1	**FEASIBILITY PHASE**					**188.681.846**
D.1.1	01.000	**Engineering**			2%	75.472.738
D.1.2	02.000	**Project Management**			3%	113.209.107
D.2	**PLANNING & DESIGN PHASE**					**943.409.228**
D.2.1	01.000	**Engineering**			10%	377.363.691
D.2.2	02.000	**Project Management**			15%	566.045.537
D.3	**EXECUTION PHASE**					**3.773.636.910**
D.3.1	01.000	**Engineering**			5%	139.764.330
D.3.2	02.000	**Project Management**			20%	559.057.320
D.3.3	03.000	**Overhead Project Cost (Owner)**			10%	279.528.660
D.3.4	04.000	**Construction Activities**				
D.3.4	04.001		**Tunnelling**			**2.446.836.600**
D.3.4	04.001			*Normal Tunnelling Cost (Excavation, W. Control, Rock Support, and Lining)*		1.517.000.000
D.3.4	04.001			*Extraordinary Tunnelling Cost (Deterministic Approach)*		119.680.000
D.3.4	04.001			*Additional Construction Cost (Mobilisation, Worksite, Portals, Others)*	30%	491.004.000
D.3.4	04.001			*Overhead Tunnelling Cost (Contractor Interest Profit)*	15%	319.152.600
D.3.4	04.002		**Tunnel Facilities**			**279.450.000**
D.3.4	04.002			*Road Facilities (NOK/m)*	6.000	108.000.000
D.3.4	04.002			*Systems (NOK/m)*	7.500	135.000.000
D.3.4	04.002			*Overhead Construction Cost*	15%	36.450.000
D.3.4	04.003		**Access Project**			**69.000.000**
D.3.4	04.003			*Cut & Cover Tunnel Access*	30.000	0
D.3.4	04.003			*High Way By Pass & Other (Both Sides)*	10.000	60.000.000
D.3.4	04.003			*Overhead Construction Cost*	15%	9.000.000
D.4	**COMMISSIONING PHASE**					**264.245.160**
D.4.1	01.000	**Commissioning (NOK/m)**			7%	19.561.500
D.4.2	02.000	**Project Management**			10%	244.683.660

TOTAL TUNNEL COST (TTC)		
OVERALL PROJECT COST ESTIMATION	**NOK**	**5.169.973.143**
OVERALL PROJECT COST PER METER OF TUNNEL		
OVERALL PROJECT COST ESTIMATION	NOK/m	287.221
OVERAL PROJECT COST PER CUBIC METER OF TUNNEL		
OVERALL PROJECT COST ESTIMATION	NOK/m3	4.287

As shown in Table H.1, each project phase (i.e.: project deliverable) involves different activities or work packages, which represent the cost elements for each specific deliverable.

The determination of the total tunnel cost (T.T.C) is performed by MCS; therefore the dependencies among cost elements should be duly determined previously.

The total tunnel cost (T.T.C) is determined by the following expression, which has been set in the simulation model (MCS):

$$T.T.C = \sum_{i=1}^{n} T.C.D_n \ (MCS)$$

Where
T.T.C: Total Tunnel Cost (NOK)
T.C.D: Total Cost Deliverable "n" (NOK)

H.1 Cost Estimation Deliverable 1, Feasibility
The cost of this phase is determined as a function of the execution phase (e.g.: deliverable 3). The respective cost of the engineering and project management activities is estimated according to the following values:

- Engineering: 2%
- Project Management: 3%

$T.C.D_1 = f_1(T.C.D_3)$

Both percentages were determined according to the information processed as part of this research work and they can be modified in the model. These values are not treated directly as random variables, nonetheless is more information is available these values may be assessed as random variable.

H.2 Cost Estimation Deliverable 2, Planning and Design Phase
The total cost of this deliverable is obtained by applying the procedures explained for Deliverable 1. Nonetheless, percentages used in this phase are increased due to the different level of activities performed as part of this phase. The values and proposed formula are as follows:

- Engineering: 10%
- Project Management: 15%

$T.C.D_2 = f_2(T.C.D_3)$

H.3 Cost Estimation Deliverable 3, Execution or Implementation Phase
The execution or implementation phase has been divided in four main work packages, which are as follows:

- Field Engineering ($T.C_{eng}$)

- Project Management ($T.C_{PM}$)
- Overhead Project Cost ($T.C_o$)
- Total Cost of Construction Activities (T.C.C)

The two first concepts (e.g.: field engineering and project management) are obtained as a function of the cost of the construction activities (T.C.C), and the percentages for engineering and project management are updated according to the level of the activities performed during the execution phase.

The total construction cost (T.C.C) is also broken down in two main groups, which correspond to the tunnel construction and the facilities required. The main reason for splitting these two activities is that are affected by different source of risk, therefore they require a differentiate treatment. Consequently, the T.C.C is conformed by the following elements

- Tunnelling (C_{TT})
  - *Normal Tunnelling Cost (C_{NT})*
  - *Extraordinary Tunnelling Cost (C_{ET})*
  - *Additional Construction Cost*
  - *Overhead Tunnelling Cost*

- Tunnel Facilities (C_F)
  - *Road Structure*
  - *Systems*
  - *Overhead Construction$_1$ Cost*

- Access Projects (C_A)
  - *Cut and Cover Tunnel (Access)*
  - *Highway By Pass and Other*
  - *Overhead Construction$_2$ Cost*

The following expression are used in order to determine the cost of the deliverable and work packages:

$$T.C.D_3 = T.C.C + T.C_{Eng} + T.C_{PM} + T.C_{OH}$$
$$T.C_{Eng} = f_4(T.C.C)$$
$$T.C_{PM} = f_5(T.C.C)$$
$$T.C_{OH} = f_6(T.C.C)$$
$$T.C.C = C_{TT} + C_F + C_A$$

The Total Tunnelling Cost (C_{TT}) includes the Normal Tunnelling Cost (C_{NT}) and the Extraordinary Tunnelling Cost (C_{ET}), and it defined by the following expression.

$C_{TT} = C_{NT} + C_{ET}$

H.4 Cost Estimation Deliverable 4, Commissioning or Close Out Phase

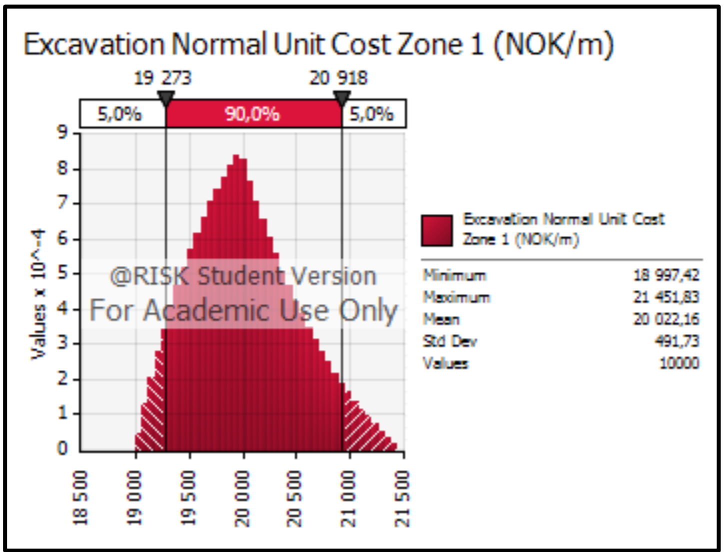
This deliverable is built up by two main work packages, which are project management and commissioning activities.

- Commissioning (C_C)
- Project Management (C_{PM})

$T.C.D_4 = C_C + C_{PM}$

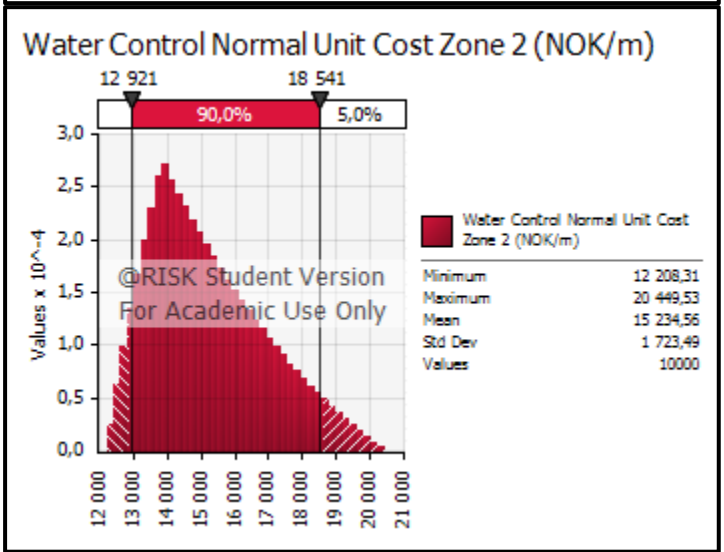
Appendix I: Generic Model Outputs and Reports

The proposed model offers a wide set of reports that are briefly detailed



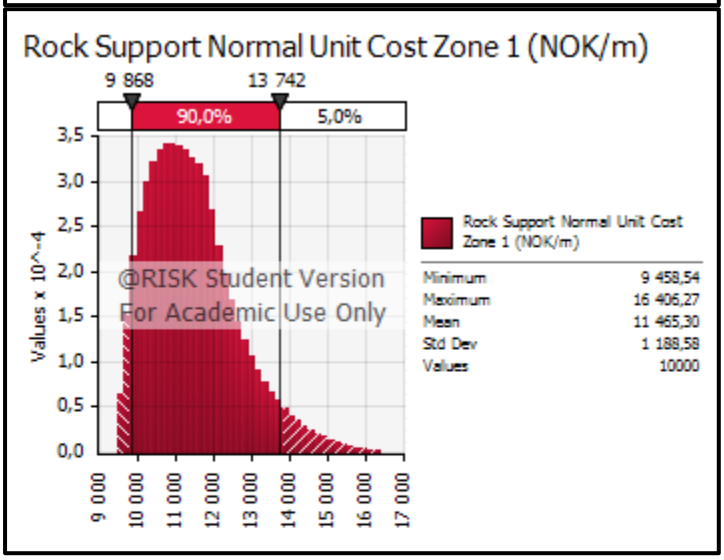
Excavation Unit Cost:
This is one of the basic outputs, which is obtained after a single simulation process. The final distribution shows the expected behaviour for this specific tunnelling activity in a given zone.

The cost driver used in this process is DRI, which is assessed by triple point estimation and a given distribution.



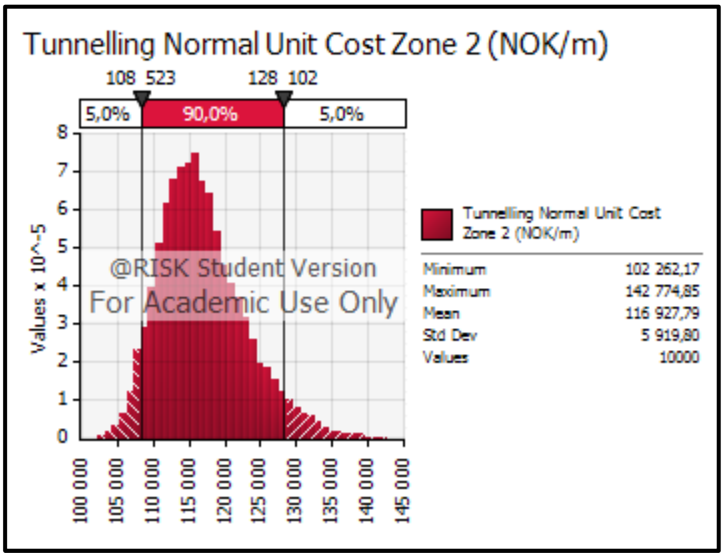
Water Control Unit Cost:
This is one of the basic outputs, which is obtained after a single simulation process. The final distribution shows the expected behaviour for this specific tunnelling activity in a given zone.

The cost driver used in this process is "q", which is assessed by triple point estimation and a given distribution.



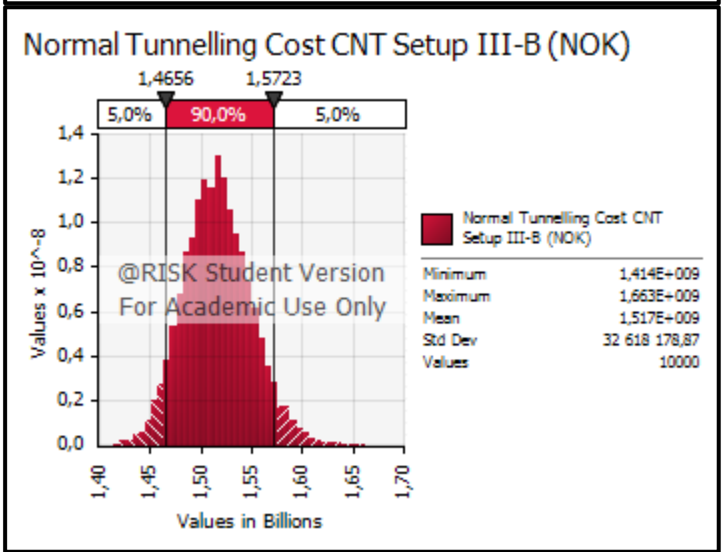
Rock Support Unit Cost:
This is one of the basic outputs, which is obtained after a single simulation process. The final distribution shows the expected behaviour for this specific tunnelling activity in a given zone.

The cost driver used in this process is "Q-Values", which is assessed by triple point estimation and a given distribution.



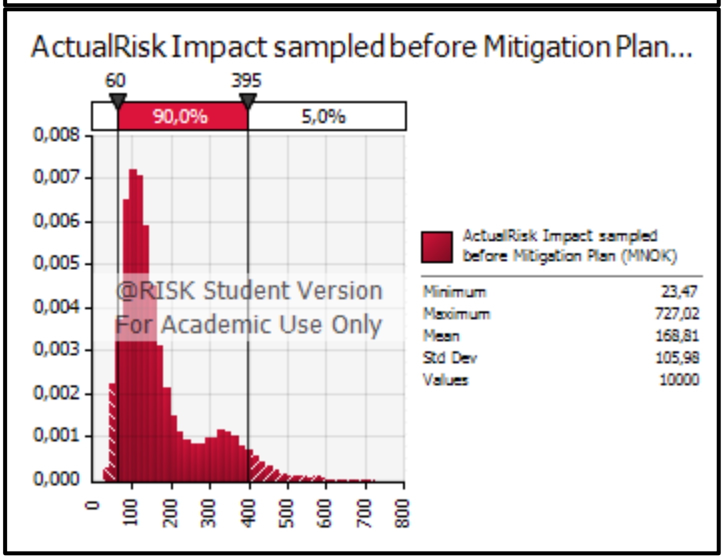
Unit Tunnelling Cost by Zone:

This corresponds to the estimated cost for each specific homogeneous zones and it is estimated as the summation of the unit cost of the specific tunnelling activities.



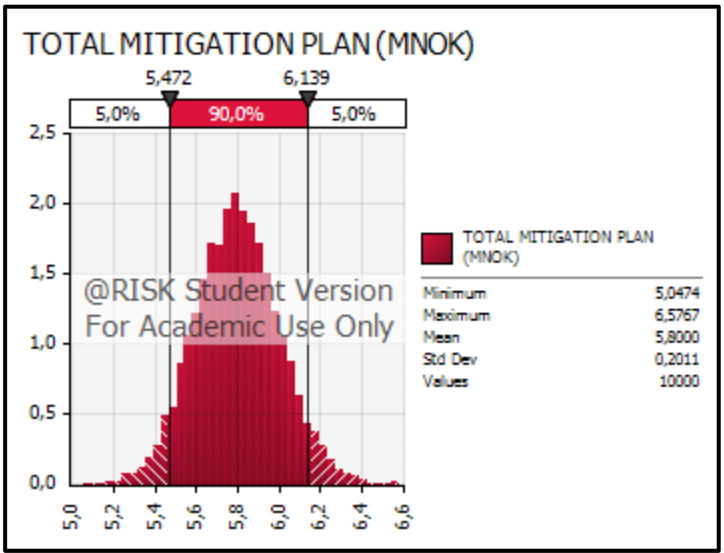
Normal Tunnelling Cost:

This corresponds to the estimated normal cost for the total length of the tunnel. It is given in (NOK)

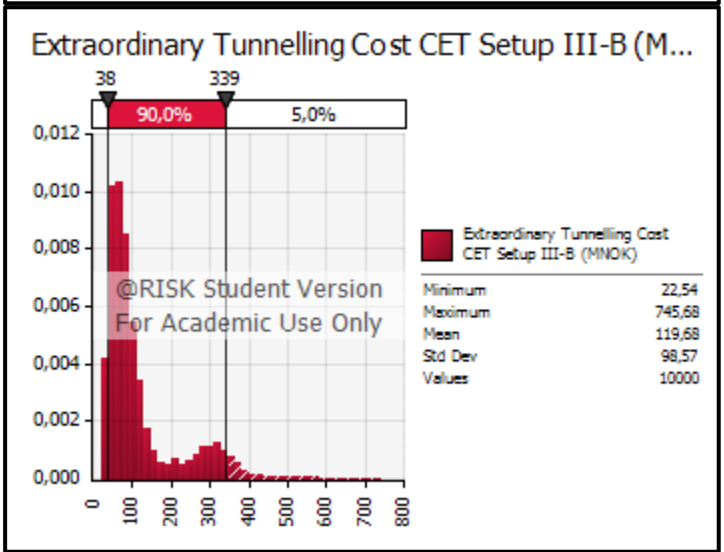


Extraordinary Tunnelling Cost (before mitigation plan):

This corresponds to the sampled extraordinary cost due to the occurrence of undesirable risk events, without considering the execution of a mitigation plan. The values is given in MNOK or NOK

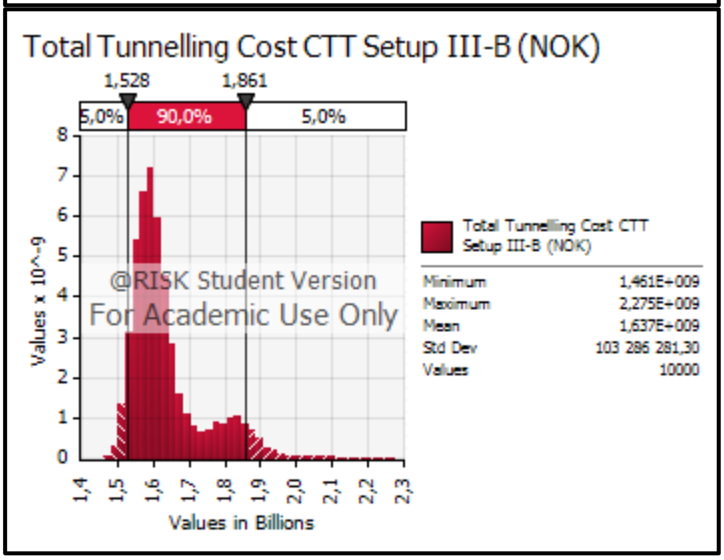


Total Mitigation Plan:
This corresponds to the sampled cost for the measures considered in the mitigation plan. The values are given in MNOK.



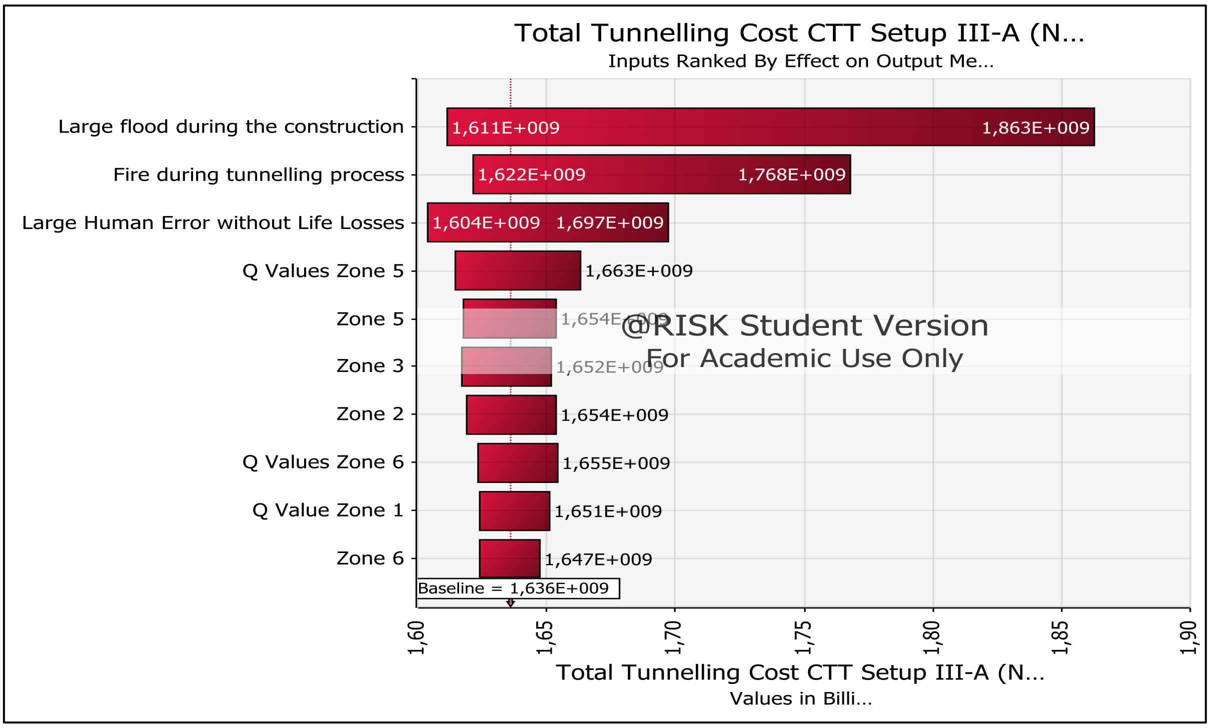
Extraordinary Tunnelling Cost (after mitigation plan):

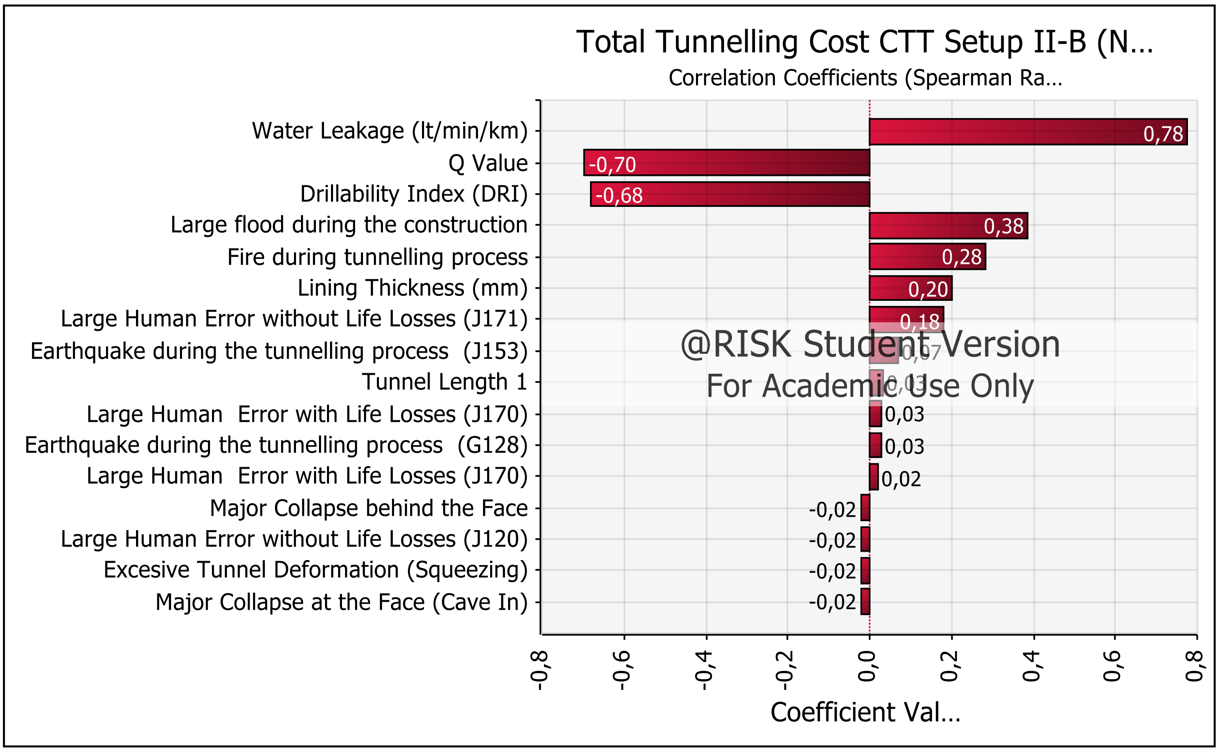
This corresponds to the sampled extraordinary cost due to the occurrence of undesirable risk events, considering the execution of a mitigation plan and including the cost of mitigation. The values is given in MNOK or NOK



Total Tunnelling Cost (before mitigation plan):

This corresponds to the total tunnelling cost, considering the normal and extraordinary costs. The value is given in NOK.


Total Tunnelling Cost CTT Setup III-A (N...
Inputs Ranked By Effect on Output Me...
Large flood during the construction
Fire during tunnelling process
Large Human Error without Life Losses
Q Values Zone 5
Zone 5
Zone 3
Zone 2
Q Values Zone 6
Q Value Zone 1
Zone 6
1,611E+009
1,863E+009
1,622E+009
1,768E+009
1,604E+009
1,697E+009
1,663E+009
1,654E+009
1,652E+009
1,654E+009
1,655E+009
1,651E+009
1,647E+009
Baseline = 1,636E+009
@RISK Student Version
For Academic Use Only
1,60
1,65
1,70
1,75
1,80
1,85
1,90
Total Tunnelling Cost CTT Setup III-A (N...
Values in Billi...


Total Tunnelling Cost CTT Setup II-B (N...
Correlation Coefficients (Spearman Ra...
Water Leakage (lt/min/km)
Q Value
Drillability Index (DRI)
Large flood during the construction
Fire during tunnelling process
Lining Thickness (mm)
Large Human Error without Life Losses (J171)
Earthquake during the tunnelling process (J153)
Tunnel Length 1
Large Human Error with Life Losses (J170)
Earthquake during the tunnelling process (G128)
Large Human Error with Life Losses (J170)
Major Collapse behind the Face
Large Human Error without Life Losses (J120)
Excesive Tunnel Deformation (Squeezing)
Major Collapse at the Face (Cave In)
0,78
-0,70
-0,68
0,38
0,28
0,20
0,18
0,03
0,03
0,02
-0,02
-0,02
-0,02
-0,02
@RISK Student Version
For Academic Use Only
-0,8
-0,6
-0,4
-0,2
0,0
0,2
0,4
0,6
0,8
Coefficient Val...

Appendix J: Case Study, The Chacao Channel Tunnel Project

This appendix introduces specific information about the case study that may be relevant to understand the features of the project location. Most of this information has been taken from public reports performed by the Public Ministry of Public Work of Chile (MOP).

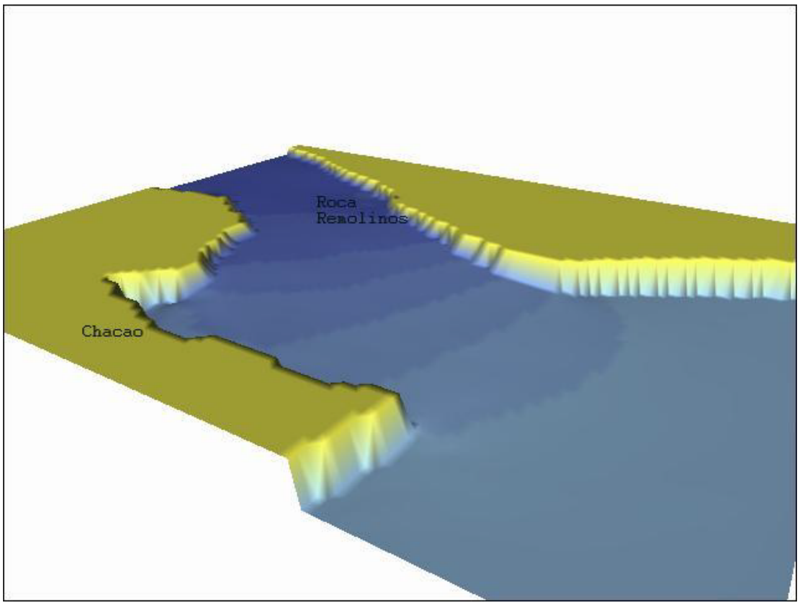


Figure J.1: 3D Profile of the Chacao Channel. This profile shows the shortest distance to be crosses for the projected tunnel (approximately 2.000 metres). The estimated deep of the channel is about 120 metres, and the rock mass is expected to be found at 200 metres (source: Chilean Ministry of Public Works).

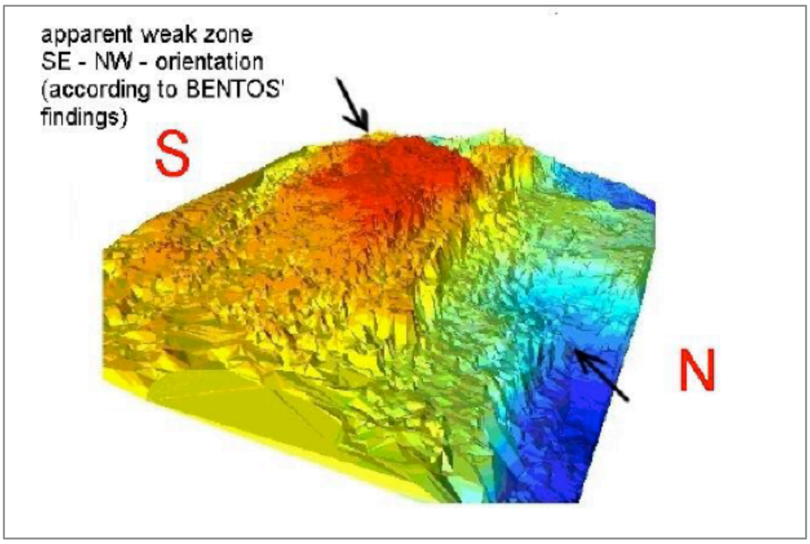


Figure J.2: Soil Analysis performed at Chacao Channel. The red area shows a potential weakness zone (remolinos rock) detected during the investigations of Bentos Consultant (source: Chilean Ministry of Public Works).

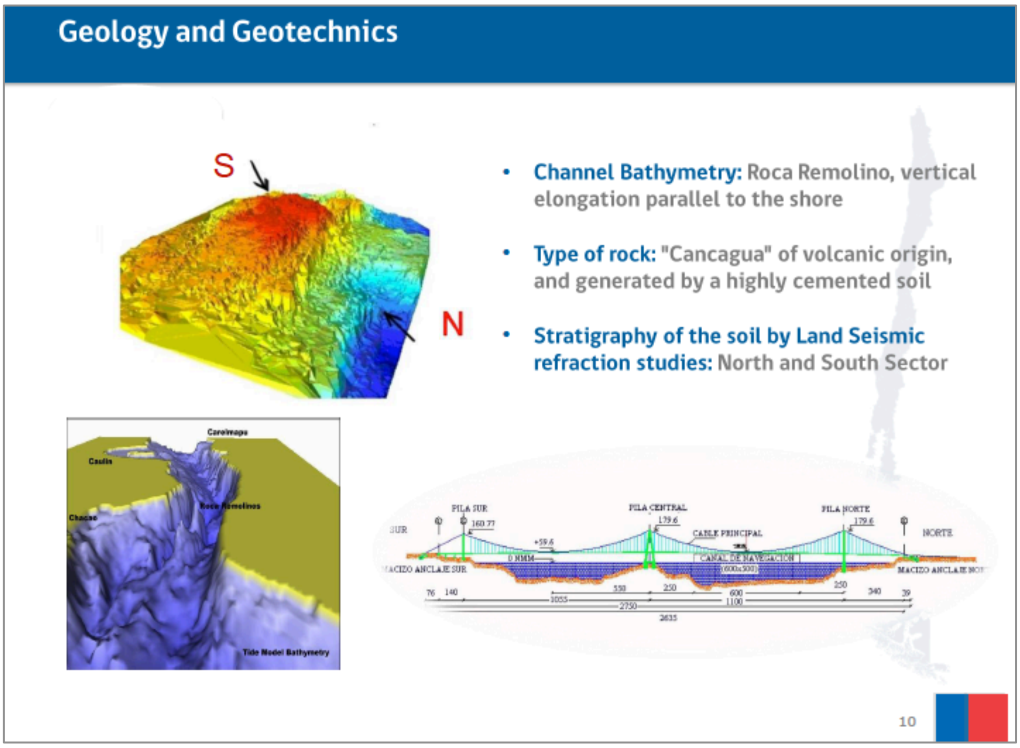


Figure J.3: Geology and Geotechnical Information (source: Chilean Ministry of Public Works)

According to the geological reports prepared for the Chilean Ministry of Public Works and shown in the figure above, the main geological formation in the location of the proposed tunnel is compose by a sedimentary rock, so called "Cancagua", which presents low foliation, high porosity, and low deformation. The mineralogy of this class of rock is basically based on quart and feldespato. A failure zone, designated, as "Ancud Bay Failure" is located in the middle section of the Chacao Chanel, therefore the tunnel alignment must cross this failure zone.

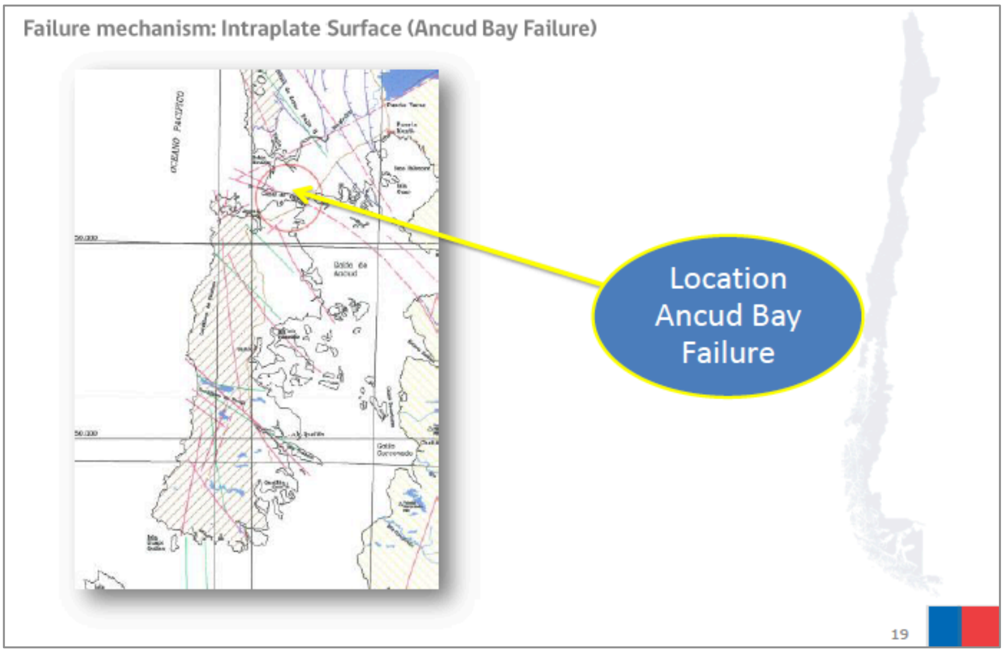
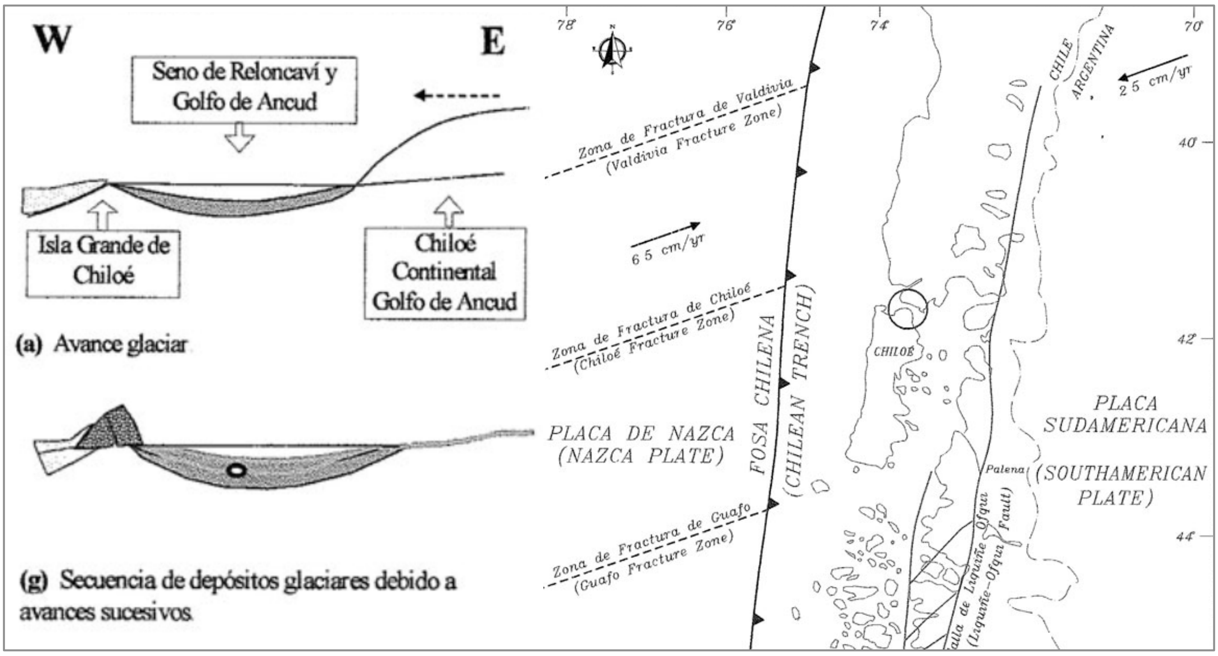


Figure J.4: Ancud Bay Failure at Chacao Channel (source: Chilean Ministry of Public Works)



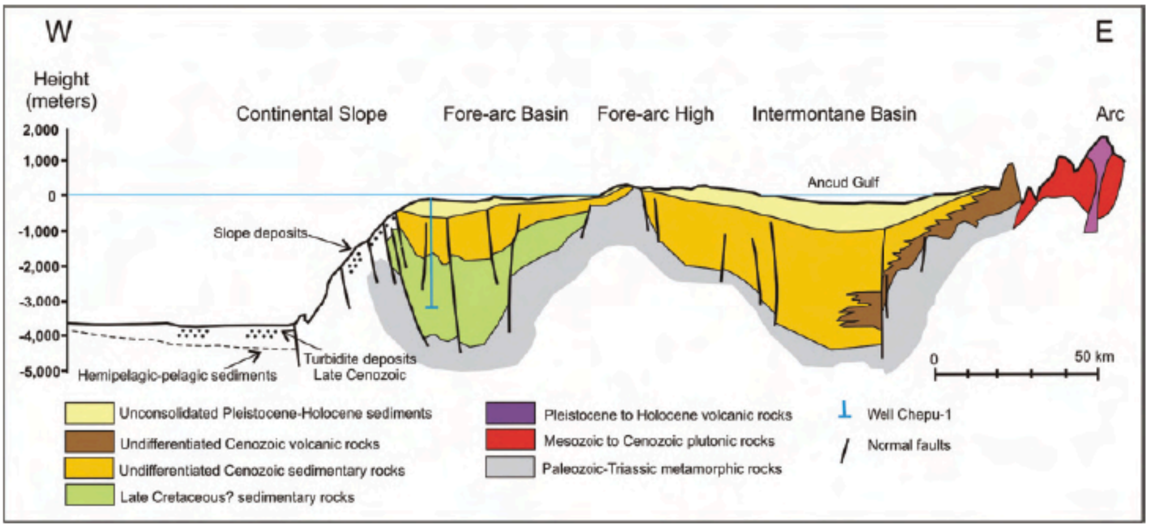


FIG. 3. Geologic profile across the Chilean forearc at latitude 42°S (adapted from González, 1989). At the left, a borehole cuts through fine-grained sandstone and claystone of presumed later Late Cretaceous age (light green), Eocene?-Pliocene sedimentary rocks (dark yellow) and Pleistocene-Holocene sediments (yellow).

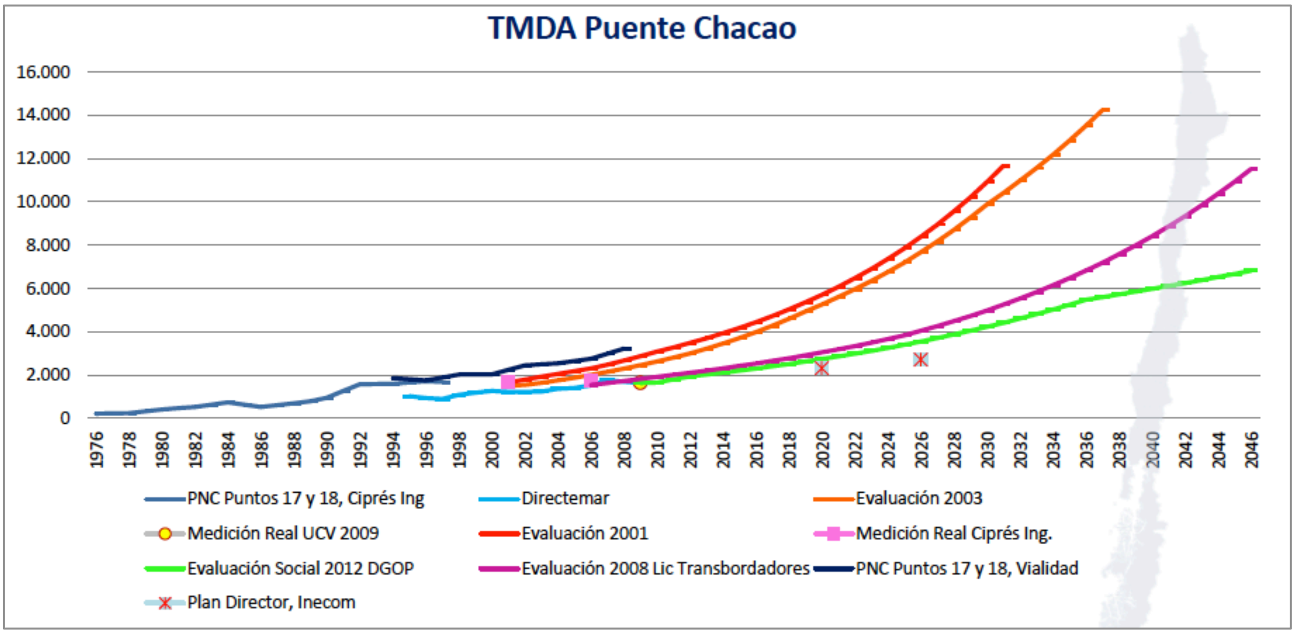


Figure J.6: Traffic Demands regarding the fixed link project. The tunnel design analysed in this work considers the highest demands, which is represented by the orange line (study performed in 2003). Other studies have been performed and they show different results, which establish a lower demand than expected in previous studies.

Considering the information previously introduced, the project analysed in this work considers a double T9.5 section, which presents the following vertical profile.

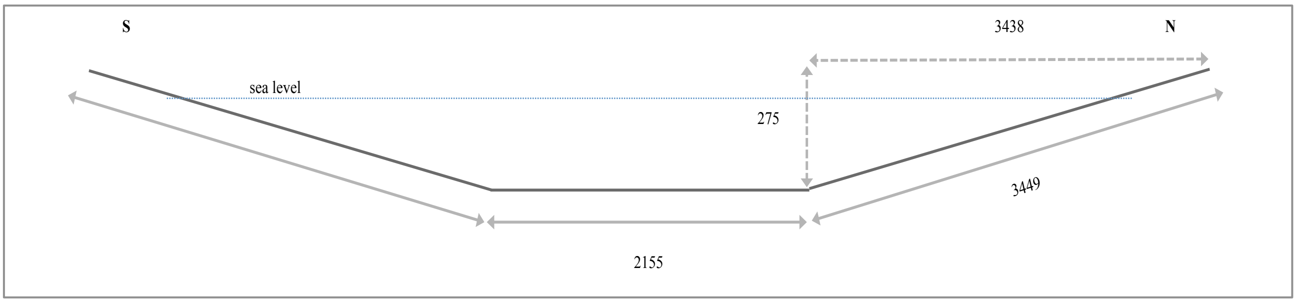


Figure J.7: Vertical Profile of the Proposed Tunnel, which is approximately 9.000 meters (one section)

Appendix K: Case Study, Expert Assessment and Model Inputs

Since the full model is available in the digital version this appendix includes only a specific sample (Setup III-B) of the assessment performed for the specific case study.

K.1 Assessment Normal Tunnelling Cost (C_{NT})

K.1.1 General Model Inputs

ZONE 1 (South)		
T9.5		
67		
3 100	3 200	3 300
Triangular	E(L1) =	3 196,84
Triangular	E(L2) =	3 196,84
LOW	SPR	
D	Q-Value	
E6	Excavation Class (SPR + Q-Value)	
Cast in Place	Behind the Face	L1
Conglomerates (Sedimentary)		

ZONE 2		
T9.5		
67		
700	800	900
Triangular	E(L1) =	798,29
Triangular	E(L2) =	798,29
LOW	SPR	
F	Q-Value	
E12	Excavation Class (SPR + Q-Value)	
Cast in Place	Behind the Face	L1
Sandstone - Cancagua		

ZONE 3		
FAULT		
T9.5		
67		
100	150	200
Triangular	E(L1) =	170,03
Triangular	E(L2) =	170,03
LOW	SPR	
G	Q-Value	
E15	Excavation Class (SPR + Q-Value)	
Cast in Place	Behind the Face	L1
Fracture Conglomerate (Sedimentary)		

ZONE 4		
T9.5		
67		
300	350	400
Triangular	E(L1) =	323,87
Triangular	E(L2) =	323,87
LOW	SPR	
E	Q-Value	
E9	Excavation Class (SPR + Q-Value)	
Cast in Place	Behind the Face	L1
Conglomerate (Sedimentary)		

ZONE 5		
T9.5		
67		
900	1 000	1 100
Triangular	E(L1) =	950,01
Triangular	E(L2) =	950,01
LOW	SPR	
F	Q-Value	
E12	Excavation Class (SPR + Q-Value)	
Cast in Place	Behind the Face	L1
Sandstone - Cancagua		

ZONE 6 (North)		
T9.5		
67		
3 400	3 500	3 600
Triangular	E(L1) =	3 403,06
Triangular	E(L2) =	3 403,06
LOW	SPR	
D	Q-Value	
E6	Excavation Class (SPR + Q-Value)	
Cast in Place	Behind the Face	L1
Conglomerate (Sedimentary)		

K.1.2 Cost Driver Assessment

ZONE 1 (South)		
L	**M**	**H**
30,00	50,00	70,00
Triangular	E(DRI) =	44,79
L	**M**	**H**
500,00	600,00	700,00
Triangular	E(q) =	578,15
L	**M**	**H**
1,00000	4,00000	10,00000
Triangular	E(Q) =	3,98
L	**M**	**H**
300,00	300,00	300,00
Triangular	E(S) =	300,00

ZONE 2		
L	**M**	**H**
15	50,00	90,00
Triangular	E(DRI) =	61,53
L	**M**	**H**
800,00	900,00	1 200,00
Triangular	E(q) =	967,98
L	**M**	**H**
0,01000	0,05000	0,10000
Triangular	E(Q) =	0,07
L	**M**	**H**
300,00	350,00	400,00
Triangular	E(S) =	358,33

ZONE 3		
L	**M**	**H**
20,00	30,00	40,00
Triangular	E(DRI) =	32,94
L	**M**	**H**
1200,00	1 500,00	1 600,00
Triangular	E(q) =	1 424,26
L	**M**	**H**
0,0010	0,0015	0,0020
Triangular	E(Q) =	0,00147
L	**M**	**H**
350,00	400,00	450,00
Triangular	E(S) =	402,54

ZONE 4		
L	**M**	**H**
30,00	50,00	70,00
Triangular	E(DRI) =	55,91
L	**M**	**H**
600,00	800,00	1 000,00
Triangular	E(q) =	871,63
L	**M**	**H**
1,0000	3,0000	4,0000
Triangular	E(Q) =	1,74228
L	**M**	**H**
300,00	350,00	400,00
Triangular	E(S) =	332,95

ZONE 5		
L	**M**	**H**
15	50,00	90,00
Triangular	E(DRI) =	35,09
L	**M**	**H**
800,00	900,00	1 200,00
Triangular	E(q) =	906,61
L	**M**	**H**
0,00100	0,00500	0,01000
Triangular	E(Q) =	0,01
L	**M**	**H**
300,00	350,00	400,00
Triangular	E(S) =	348,80

ZONE 6 (North)		
L	**M**	**H**
30	50,00	70,00
Triangular	E(DRI) =	59,64
L	**M**	**H**
500,00	600,00	700,00
Triangular	E(q) =	624,53
L	**M**	**H**
1,00000	4,00000	10,00000
Triangular	E(Q) =	4,02
L	**M**	**H**
300,00	300,00	300,00
Triangular	E(S) =	300,00

K.1.3 Cost Drivers Correlation Matrix

@RISK Correlations	Drillability Zone 1 in Q24	Water Leakage Zone 1 in Q27	Q Value Zone 1 in Q30	Lining Thickness Zone 1 in Q33
Drillability Zone 1 in Q24	1,000			
Water Leakage Zone 1 in Q27	-0,500	1,000		
Q Value Zone 1 in Q30	0,500	-0,500	1,000	
Lining Thickness Zone 1 in Q33	0,000	0,000	0,000	1,000
@RISK Correlations	Drillability Zone 2 in U24	Water Leakage Zone 2 in U27	Q-Value Zone 2 in U30	Lining Thickness Zone 2 in U33
Drillability Zone 2 in U24	1,000			
Water Leakage Zone 2 in U27	-0,500	1,000		
Q-Value Zone 2 in U30	0,500	-0,500	1,000	
Lining Thickness Zone 2 in U33	0,000	0,000	0,000	1,000
@RISK Correlations	Drillability Zone 3 in Y24	Water Leakage Zone 3 in Y27	Q Value Zone 3 in Y30	Lining Thickness Zone 3 in Y33
Drillability Zone 3 in Y24	1,000			
Water Leakage Zone 3 in Y27	-0,500	1,000		
Q Value Zone 3 in Y30	0,500	-0,500	1,000	
Lining Thickness Zone 3 in Y33	0,000	0,000	0,000	1,000
@RISK Correlations	Drillability Zone 4 in AC24	Water Leakage Zone 4 in AC27	Q Values Zone 4 in AC30	Lining Thickness Zone 4 in AC33
Drillability Zone 4 in AC24	1,000			
Water Leakage Zone 4 in AC27	-0,500	1,000		
Q Values Zone 4 in AC30	0,500	-0,500	1,000	
Lining Thickness Zone 4 in AC33	0,000	0,000	0,000	1,000
@RISK Correlations	Drillability Zone 5 in AG24	Water Leakage Zone 5 in AG27	Q Values Zone 5 in AG30	Lining Thickness Zone 5 in AG33
Drillability Zone 5 in AG24	1,000			
Water Leakage Zone 5 in AG27	-0,500	1,000		
Q Values Zone 5 in AG30	0,500	-0,500	1,000	
Lining Thickness Zone 5 in AG33	0,000	0,000	0,000	1,000
@RISK Correlations	Drillability Zone 6 in AK24	Water Leakage Zone 6 in AK27	Q Values Zone 6 in AK30	Lining Thickness Zone 6 in AK33
Drillability Zone 6 in AK24	1,000			
Water Leakage Zone 6 in AK27	-0,500	1,000		
Q Values Zone 6 in AK30	0,500	-0,500	1,000	
Lining Thickness Zone 6 in AK33	0,000	0,000	0,000	1,000

K.2 Assessment Risk Event (C_{ET})

K.2.1 Risk Register and Qualitative Risk Analysis

6.0 RISK IDENTIFICATION AND QUALITIATIVE RISK ANALYSIS FOR THE TUNNELLING PROCESS								
Risk Identification / Description		**Qualitative Risk Analysis**						**Mitigation**
Risk ID	**Extraordinary Risk Event**	**Likelihood**	**Impacts**	**Risk Level**	**Cost**	**Time**	**Safety**	
R.1.0	**Natural Events**							
R.1.1	Earthquake during the tunnelling process	Very Low	High	Risk Class 2	Yes	Yes	Yes	ALARP
R.1.2	Large flood during the construction	Medium	Very High	Risk Class 1	Yes	Yes	Yes	YES
R.1.3	Fire during tunnelling process	Medium	Very High	Risk Class 1	Yes	Yes	Yes	YES
R.2.0	**Machine Failures**							
R.2.1	Failure of Excavation Rig	Medium	Very High	Risk Class 1	Yes	Yes	No	YES
R.2.2	Failure of the Grouting Rig	Medium	Very High	Risk Class 1	Yes	Yes	No	YES
R.2.3	Failure of the Rock Support Equipment	Medium	Very High	Risk Class 1	Yes	Yes	No	YES
R.2.4	Failure in the Lining Erection Equipment	Medium	Medium	Risk Class 2	Yes	No	No	ALARP
R.3.0	**Geological Events**							
R.3.1	Major Rock Fall at the Face	High	High	Risk Class 1	Yes	Yes	Yes	YES
R.3.2	Major Collapse at the Face (Cave In)	High	High	Risk Class 1	Yes	Yes	Yes	YES
R.3.3	Major Rock Fall behind the Face	Medium	Medium	Risk Class 2	Yes	Not	Yes	ALARP
R.3.4	Major Collapse behind the Face	Medium	Medium	Risk Class 2	Yes	Not	Yes	ALARP
R.3.5	Excesive Tunnel Deformation (Squeezing)	High	High	Risk Class 1	Yes	Yes	Yes	YES
R.3.6	Rock Burst / Spalling	High	High	Risk Class 1	Yes	Yes	Yes	YES
R.3.7	Unexpected Water Inflow - daylight collapse	Very High	Very High	Risk Class 1	Yes	Yes	Yes	YES
R.4.0	**Human Errors**							
R.4.1	Large Human Error with Life Losses	Medium	Very High	Risk Class 1	Yes	Yes	Yes	YES
R.4.2	Large Human Error without Life Losses	Medium	High	Risk Class 2	Yes	Yes	Yes	ALARP

K.2.2 Preliminary Quantitative Risk Analysis

7.0 PRELIMINARY QUANTITATIVE RISK ANALYSIS (BEFORE RISK MITIGATION)							
RISK DESCRIPTION		**OCCURRENCE**		**IMPACT (MNOK)**			
Risk ID	**Extraordinary Risk Event**	**Probability or Failure Rate**	**Occurs?**	**Low**	**Medium**	**High**	**Risk Severity**
R.1.0	**Natural Events**						
R.1.1	Earthquake during the tunnelling process	0,01	0,00	100,00	150,00	200,00	175,81
R.1.2	Large flood during the construction	0,10	0,00	200,00	250,00	300,00	209,72
R.1.3	Fire during tunnelling process	0,10	0,00	100,00	150,00	300,00	249,84
R.2.0	**Machine Failures**	**λ**					
R.2.1	Failure of Excavation Rig	5,00	5,00	1,00	1,50	2,00	1,94
R.2.2	Failure of the Grouting Rig	5,00	3,00	1,00	1,50	2,00	1,34
R.2.3	Failure of the Rock Support Equipment	5,00	4,00	1,00	1,50	2,00	1,50
R.2.4	Failure in the Lining Erection Equipment	3,00	6,00	0,50	0,60	1,00	0,66
R.3.0	**Geological Events**						
R.3.1	Major Rock Fall at the Face	3,00	2,00	1,00	1,20	2,00	1,19
R.3.2	Major Collapse at the Face (Cave In)	2,00	1,00	2,00	3,00	4,00	2,44
R.3.3	Major Rock Fall behind the Face	1,00	1,00	0,50	0,60	1,00	0,62
R.3.4	Major Collapse behind the Face	1,00	0,00	1,00	1,50	2,00	1,19
R.3.5	Excesive Tunnel Deformation (Squeezing)	5,00	2,00	1,00	1,50	2,00	1,62
R.3.6	Rock Burst / Spalling	5,00	9,00	1,00	1,50	2,00	1,44
R.3.7	Unexpected Water Inflow - daylight collapse	3,00	3,00	1,00	1,50	2,00	1,54
R.4.0	**Human Errors**						
R.4.1	Large Human Error with Life Losses	0,50	0,00	10,00	15,00	20,00	18,47
R.4.2	Large Human Error without Life Losses	2,00	1,00	20,00	30,00	40,00	21,61

K.2.3 Risk Mitigation Plan

8.0 RISK MITIGATION PLAN (when required)						
Risk ID	**Risk Events**	**Applicable (Y/N)**	**Estimated Cost of Mitigation Measures (MNOK)**			
			L	**M**	**H**	**Expected**
R.1.0	**Natural Events**					
R.1.1	Earthquake during the tunnelling process	ALARP	0,20	0,30	0,40	0,32
R.1.2	Large flood during the construction	YES	0,50	0,60	0,80	0,68
R.1.3	Fire during tunnelling process	YES	0,60	0,70	0,90	0,70
R.2.0	**Machine Failures**					
R.2.1	Failure of Excavation Rig	YES	0,40	0,50	0,70	0,50
R.2.2	Failure of the Grouting Rig	YES	0,40	0,50	0,70	0,54
R.2.3	Failure of the Rock Support Equipment	YES	0,40	0,50	0,70	0,46
R.2.4	Failure in the Lining Erection Equipment	ALARP	0,40	0,50	0,70	0,56
R.3.0	**Geological Events**					
R.3.1	Major Rock Fall at the Face	YES	0,10	0,20	0,30	0,20
R.3.2	Major Collapse at the Face (Cave In)	YES	0,10	0,20	0,30	0,16
R.3.3	Major Rock Fall behind the Face	ALARP	0,10	0,20	0,30	0,23
R.3.4	Major Collapse behind the Face	ALARP	0,10	0,20	0,30	0,20
R.3.5	Excesive Tunnel Deformation (Squeezing)	YES	0,10	0,20	0,30	0,16
R.3.6	Rock Burst / Spalling	YES	0,10	0,20	0,30	0,22
R.3.7	Unexpected Water Inflow - daylight collapse	YES	0,10	0,20	0,30	0,18
R.4.0	**Human Errors**					
R.4.1	Large Human Error with Life Losses	YES	0,20	0,30	0,40	0,32
R.4.2	Large Human Error without Life Losses	ALARP	0,20	0,30	0,40	0,26

K.2.4 Final Quantitative Risk Analysis

8.0 FINAL RISK ANALYSIS (AFTER RISK MITIGATION)							
RISK DESCRIPTION		**OCCURRENCE**		**IMPACT (MNOK)**			
Risk ID	**Extraordinary Risk Event**	**Probability or Failure Rate**	**Occurs?**	**Low**	**Medium**	**High**	**Risk Severity**
R.1.0	**Natural Events**						
R.1.1	Earthquake during the tunnelling process	0,01	0,00	100,00	150,00	200,00	141,15
R.1.2	Large flood during the construction	0,10	0,00	200,00	250,00	300,00	212,19
R.1.3	Fire during tunnelling process	0,08	0,00	100,00	150,00	300,00	288,79
R.2.0	**Machine Failures**						
R.2.1	Failure of Excavation Rig	3,00	1,00	1,00	1,50	2,00	1,73
R.2.2	Failure of the Grouting Rig	3,00	2,00	1,00	1,50	2,00	1,78
R.2.3	Failure of the Rock Support Equipment	3,00	2,00	1,00	1,50	2,00	1,74
R.2.4	Failure in the Lining Erection Equipment	2,00	3,00	0,50	0,60	1,00	0,65
R.3.0	**Geological Events**						
R.3.1	Major Rock Fall at the Face	3,00	0,00	0,75	0,90	1,50	1,04
R.3.2	Major Collapse at the Face (Cave In)	2,00	1,00	1,50	2,25	3,00	1,84
R.3.3	Major Rock Fall behind the Face	1,00	1,00	0,38	0,45	0,75	0,47
R.3.4	Major Collapse behind the Face	1,00	0,00	0,75	1,13	1,50	1,20
R.3.5	Excesive Tunnel Deformation (Squeezing)	5,00	7,00	0,75	1,13	1,50	1,17
R.3.6	Rock Burst / Spalling	5,00	7,00	0,75	1,13	1,50	1,27
R.3.7	Unexpected Water Inflow - daylight collapse	3,00	3,00	0,75	1,13	1,50	1,20
R.4.0	**Human Errors**						
R.4.1	Large Human Error with Life Losses	0,25	0,00	10,00	15,00	20,00	15,75
R.4.2	Large Human Error without Life Losses	1,00	1,00	20,00	30,00	40,00	32,93

Appendix L: Case Study, Model Results

L.1 Normal Tunnelling Zone for a Specific Zone

Simulation Summary Information	
Workbook Name	03B. Model T9.5 Setup III-B.xls.xlsx
Number of Simulations	1
Number of Iterations	10000
Number of Inputs	147
Number of Outputs	52
Sampling Type	Latin Hypercube
Simulation Start Time	6.2.14 9:39:30
Simulation Duration	00:02:15
Random # Generator	Mersenne Twister
Random Seed	523698283

Summary Statistics for Tunnelling Normal Cost - CNT Zone 3 (NOK)

Statistics		Percentile	
Minimum	40 316 147	**5 %**	48 089 045
Maximum	86 953 727	**10 %**	50 779 364
Mean	62 553 150	**15 %**	52 975 747
Std Dev	8 710 277	**20 %**	54 721 342
Variance	7,58689E+13	**25 %**	56 319 879
Skewness	0,02779173	**30 %**	57 782 587
Kurtosis	2,447904865	**35 %**	59 014 318
Median	62 527 047	**40 %**	60 196 483
Mode	65 404 765	**45 %**	61 329 222
Left X	48 089 045	**50 %**	62 527 047
Left P	5 %	**55 %**	63 649 581
Right X	77 025 917	**60 %**	64 859 545
Right P	95 %	**65 %**	65 979 010
Diff X	28 936 872	**70 %**	67 328 583
Diff P	90 %	**75 %**	68 767 042
#Errors	0	**80 %**	70 299 314
Filter Min	Off	**85 %**	72 098 842
Filter Max	Off	**90 %**	74 367 942
#Filtered	0	**95 %**	77 025 917

Change in Output Statistic for Tunnelling Normal Cost - CNT Zone 3 (NOK)

Rank	Name	Lower	Upper
1	Zone 3	47 879 636	77 163 825
2	Water Leakage Zone 3	59 473 703	64 831 699
3	Q Value Zone 3	60 164 707	65 316 043
4	Drillability Zone 3	60 358 431	64 011 584
5	Lining Thickness Zone 3	61 332 389	63 707 601
6	Major Collapse at the Face (Cave In)	61 945 880	63 176 283
7	Major Rock Fall at the Face	61 940 385	63 164 824
8	R.2.4	61 767 128	62 950 099
9	Zone 4	62 083 969	63 260 208
10	Failure of the Grouting Rig	62 147 680	63 300 848
11	Water Leakage Zone 1	61 813 881	62 956 009
12	Major Collapse behind the Face	62 144 081	63 266 870
13	Extraordinary Tunnelling Cost CET Setup III-B (NOK)	61 932 496	63 028 824
14	Q Values Zone 6	62 024 389	63 077 015

L.2 Normal Tunnelling Cost (Total Tunnel Length: 18.000 m)

Simulation Summary Information	
Workbook Name	03B. Model T9.5 Setup III-B.xls.xlsx
Number of Simulations	1
Number of Iterations	10000
Number of Inputs	147
Number of Outputs	52
Sampling Type	Latin Hypercube
Simulation Start Time	6.2.14 9:39:30
Simulation Duration	00:02:15
Random # Generator	Mersenne Twister
Random Seed	523698283

Summary Statistics for Normal Tunnelling Cost CNT Setup III-B (NOK)			
Statistics		**Percentile**	
Minimum	1 413 926 273	**5 %**	1 465 618 605
Maximum	1 663 115 879	**10 %**	1 475 973 401
Mean	1 516 861 085	**15 %**	1 483 312 915
Std Dev	32 618 179	**20 %**	1 488 931 221
Variance	1,06395E+15	**25 %**	1 494 107 497
Skewness	0,215884392	**30 %**	1 498 782 506
Kurtosis	3,048966457	**35 %**	1 503 468 568
Median	1 515 600 092	**40 %**	1 507 435 450
Mode	1 514 527 471	**45 %**	1 511 748 399
Left X	1 465 618 605	**50 %**	1 515 600 092
Left P	5 %	**55 %**	1 519 681 236
Right X	1 572 289 664	**60 %**	1 523 796 205
Right P	95 %	**65 %**	1 528 453 604
Diff X	106 671 059	**70 %**	1 532 870 845
Diff P	90 %	**75 %**	1 538 293 251
#Errors	0	**80 %**	1 544 132 003
Filter Min	Off	**85 %**	1 550 732 254
Filter Max	Off	**90 %**	1 559 308 543
#Filtered	0	**95 %**	1 572 289 664

Change in Output Statistic for Normal Tunnelling Cost CNT Setup III-B (NOK)			
Rank	**Name**	**Lower**	**Upper**
1	Q Values Zone 5	1 495 140 102	1 549 189 839
2	Q Values Zone 6	1 498 318 134	1 540 154 926
3	Zone 5	1 496 008 468	1 536 569 470
4	Q Value Zone 1	1 499 753 755	1 539 407 855
5	Water Leakage Zone 5	1 499 951 693	1 536 847 616
6	Water Leakage Zone 6	1 498 715 959	1 535 005 399
7	Drillability Zone 5	1 500 044 258	1 535 257 146
8	Zone 2	1 499 493 624	1 533 977 405
9	Drillability Zone 6	1 502 256 041	1 534 897 628
10	Water Leakage Zone 1	1 502 782 970	1 533 297 966
11	Zone 3	1 502 416 421	1 532 331 864
12	Drillability Zone 1	1 503 806 868	1 533 409 930
13	Q-Value Zone 2	1 506 512 378	1 534 700 731
14	Drillability Zone 2	1 507 672 186	1 529 516 467

L.3 Extraordinary Tunnelling Cost

Simulation Summary Information	
Workbook Name	03B. Model T9.5 Setup III-B.xls.xlsx
Number of Simulations	1
Number of Iterations	10000
Number of Inputs	147
Number of Outputs	52
Sampling Type	Latin Hypercube
Simulation Start Time	6.2.14 9:39:30
Simulation Duration	00:02:15
Random # Generator	Mersenne Twister
Random Seed	523698283

Summary Statistics for Extraordinary Tunnelling Cost CET Setup III-B (MNOK)			
Statistics		**Percentile**	
Minimum	22,54	**5 %**	38,47
Maximum	745,68	**10 %**	42,64
Mean	119,68	**15 %**	46,44
Std Dev	98,57	**20 %**	50,76
Variance	9715,116904	**25 %**	57,29
Skewness	1,833807282	**30 %**	63,85
Kurtosis	6,021269279	**35 %**	68,83
Median	81,47	**40 %**	73,13
Mode	43,82	**45 %**	76,99
Left X	38,47	**50 %**	81,47
Left P	5 %	**55 %**	87,48
Right X	339,47	**60 %**	94,71
Right P	95 %	**65 %**	103,47
Diff X	301,01	**70 %**	113,16
Diff P	90 %	**75 %**	126,77
#Errors	0	**80 %**	155,21
Filter Min	Off	**85 %**	234,89
Filter Max	Off	**90 %**	294,96
#Filtered	0	**95 %**	339,47

Change in Output Statistic for Extraordinary Tunnelling Cost CET Setup III-B (MNOK)			
Rank	**Name**	**Lower**	**Upper**
1	Large flood during the construction	94,31	347,99
2	Fire during tunnelling process	105,10	250,95
3	Large Human Error without Life Losses	90,56	181,95
4	Large Human Error with Life Losses	116,24	136,06
5	Rock Burst / Spalling	113,05	129,80
6	Zone 5	111,92	128,41
7	Failure of the Grouting Rig	111,01	126,80
8	Q Values Zone 6	112,84	128,26
9	Drillability Zone 1	111,16	124,90
10	Excesive Tunnel Deformation (Squeezing)	113,42	126,80
11	Failure of Excavation Rig	112,97	126,10
12	Normal Tunnelling Cost CNT Setup III-B (NOK)	113,80	126,55
13	Drillability Zone 2	114,90	127,49
14	R.3.5	113,02	125,37

L.4 Total Tunnelling Cost

Simulation Summary Information	
Workbook Name	03B. Model T9.5 Setup III-B.xls.xlsx
Number of Simulations	1
Number of Iterations	10000
Number of Inputs	147
Number of Outputs	52
Sampling Type	Latin Hypercube
Simulation Start Time	6.2.14 9:39:30
Simulation Duration	00:02:15
Random # Generator	Mersenne Twister
Random Seed	523698283

Summary Statistics for Total Tunnelling Cost CTT Setup III-B (NOK)			
Statistics		**Percentile**	
Minimum	1 461 266 695	**5 %**	1 528 191 376
Maximum	2 275 415 364	**10 %**	1 543 096 754
Mean	1 636 541 571	**15 %**	1 553 377 579
Std Dev	103 286 281	**20 %**	1 561 463 558
Variance	1,06681E+16	**25 %**	1 569 563 471
Skewness	1,553166481	**30 %**	1 577 234 991
Kurtosis	5,334983057	**35 %**	1 584 337 214
Median	1 605 289 935	**40 %**	1 590 621 982
Mode	1 590 107 625	**45 %**	1 597 957 472
Left X	1 528 191 376	**50 %**	1 605 289 935
Left P	5 %	**55 %**	1 613 426 087
Right X	1 861 021 958	**60 %**	1 621 849 363
Right P	95 %	**65 %**	1 631 064 339
Diff X	332 830 582	**70 %**	1 643 392 044
Diff P	90 %	**75 %**	1 660 180 044
#Errors	0	**80 %**	1 690 148 358
Filter Min	Off	**85 %**	1 751 907 330
Filter Max	Off	**90 %**	1 810 527 704
#Filtered	0	**95 %**	1 861 021 958

Change in Output Statistic for Total Tunnelling Cost CTT Setup III-B (NOK)			
Rank	**Name**	**Lower**	**Upper**
1	Large flood during the construction	1 611 318 617	1 863 548 161
2	Fire during tunnelling process	1 622 047 259	1 766 990 375
3	Large Human Error without Life Losses	1 607 325 887	1 698 519 347
4	Q Values Zone 5	1 615 896 666	1 668 305 487
5	Q Values Zone 6	1 614 777 555	1 662 194 348
6	Zone 5	1 618 070 663	1 659 783 155
7	Q Value Zone 1	1 617 538 902	1 654 934 104
8	Water Leakage Zone 6	1 617 971 400	1 654 670 991
9	Drillability Zone 6	1 621 702 936	1 656 837 747
10	Drillability Zone 2	1 624 838 978	1 657 004 795
11	Water Leakage Zone 5	1 620 198 245	1 651 351 857
12	Drillability Zone 5	1 620 315 152	1 650 838 272
13	Zone 3	1 621 421 514	1 651 109 007
14	Q-Value Zone 2	1 626 570 576	1 655 679 791

Appendix M: Probability Theory, Fundamentals

M.1 Statistical Tools for Managing Uncertainty in Geological and Geotechnical Aspects

The material related to uncertainty management applied in geological and geotechnical aspects was taken from the following sources Fenton (1997), Nadim (2000), Fenton and Griffiths (2002), DNV (2007).

M.2 Statistical Distribution

This section is based on the definitions provided by Vatn (2013) in his compendium "Project Risk Analysis". This was the guide textbook used for the course in "Risk Project Management" at NTNU, which is also teach by professor Jørn Vatn.

Triangular Distribution (Continuous Distribution)

The triangular distribution is defined by three points, which are namely the lowest value (L), the most probable value (M), and the highest value (H). The probability density function (PDF) is given by the following expression:

$$f_X(x) = \begin{cases} \frac{2(x-L)}{(M-L)(H-L)} & \text{if } L \leq x \leq M \\ \frac{2(H-x)}{(H-M)(H-L)} & \text{if } M \leq x \leq H \end{cases}$$

Similarly the cumulative density function (CDF) is defined by:

$$F_X(x) = \begin{cases} \frac{(x-L)^2}{(M-L)(H-L)} & \text{if } L \leq x \leq M \\ 1 - \frac{(H-x)^2}{(H-M)(H-L)} & \text{if } M \leq x \leq H \end{cases}$$

The expected value (E(x)) and Variance (Var(x)) related to a specific random variable (x) is defined by the following expressions:

$$\mathrm{E}(X) = \frac{L + M + H}{3}$$

$$\mathrm{Var}(X) = \frac{L^2 + M^2 + H^2 - LM - LH - MH}{18}$$

This particular distribution is useful when assessing values from expert opinion, and it also provide a good choice when extreme values are relevant, due to it gives larger probabilities to these values.

PERT Distribution (Continuous Distribution)

As well as the Triangular distribution PERT distribution can be obtained by the assessment of low, medium, and high values. Nevertheless and in order to obtain the respective distributions, it is required to obtain the following values:

$$\alpha_1 = \frac{4M + H - 5L}{H - L}$$
$$\alpha_2 = \frac{5H - 4M - L}{H - L}$$
$$z = \frac{x - L}{H - L}$$

Then the PDF and CDF are given as a function of the complete and incomplete beta function, according to the following expressions:

$$f_X(x) = \frac{(x - L)^{\alpha_1 - 1}(H - x)^{\alpha_2 - 1}}{B(\alpha_1, \alpha_2)(H - L)^{\alpha_1 + \alpha_2 - 1}}$$

$$F_X(x) = \frac{B_z(\alpha_1, \alpha_2)}{B(\alpha_1, \alpha_2)}$$

Finally the expected value and variance for a given random variable (X) is given by the following expressions:

$$\mathrm{E}(X) = \frac{L + 4M + H}{6}$$
$$\mathrm{Var}(X) = \frac{(\mathrm{E}(X) - L)(H - \mathrm{E}(X))}{7}$$

Binominal Distribution (Discrete Distribution)
In order to define the Binomial distribution, it is necessary to define the binomial trials. Let A be an event, and assume that the following holds:

i. N trials are performed, and in each trial we record whether A occurs or not
ii. The trials are stochastic independent to each other
iii. For each trial Pr (A) = p

Now let X be the number of times event that A occurs in such a binomial trial. X is then a stochastic variable with a binomial distribution, with a probability mass function (PMF) equal to:

$$\Pr(X = x) = \binom{n}{x} p^x (1 - p)^{n-x} \text{ for } x = 1, 2, .., n$$

The cumulative density function P(X<x) is given in statistical tables. The expected value and variance of the random variable X are given as follows.

$$E(X) = np$$
$$\mathrm{Var}(X) = np(1-p)$$

Poisson Distribution (Discrete Distribution)

The Poisson distribution is appropriate where the stochastic variable may take discrete values (i.e.: 0, 1, 2, 3, n), and where the expected number of occurrences is proportional to an exposure measure such as time or space. The probability mass function (PMF) are given for the following expression:

$$p(x) = \Pr(X = x) = \frac{\lambda^x}{x!}e^{-\lambda}$$

While expected value and variance are given by:

$$E(X) = \lambda$$
$$\mathrm{Var}(X) = \lambda$$

The λ is defined as the failure rate related to the random event (X).

Bernoulli Distribution (Discrete Distribution)

This distribution is based on Bernoulli trials that represent experiments whit only two possible outcomes (i.e.: success "1" or failure "0"). Then if a sequence of trials are mutually independent and with constant probability of occurrence "p", then the sequence is defined as a Bernoulli Process.

The probability mass function (PMF), for success and none success, are given for the following expression:

$$P[X_j = 1] = p$$
$$P[X_j = 0] = 1 - p = q$$

The expected value and variance for a Bernoulli process are obtained by:

$$\begin{aligned} \mathrm{E}\left[\hat{P}\right] &= \mathrm{E}\left[\frac{1}{n}\sum_{i=1}^{n} X_i\right] \\ &= \frac{1}{n}\sum_{i=1}^{n} \mathrm{E}\left[X_i\right] = \frac{1}{n}(np) \\ &= p \end{aligned}$$

$$\begin{aligned} \mathrm{Var}\left[\hat{P}\right] &= \mathrm{Var}\left[\frac{1}{n}\sum_{i=1}^{n} X_i\right] \\ &= \frac{1}{n^2}\sum_{i=1}^{n} \mathrm{Var}\left[X_i\right] = \frac{1}{n^2}(npq) \\ &= \frac{pq}{n} \end{aligned}$$

Appendix N: Expert Assessment, Basic Concepts

This appendix contains relevant information related to the elicitation of expert judgment and calibration process (when required). This appendix is based on Vatn (2013).

N.1 Expert Judgment

According to (Vatn 2013), expert judgment is relevant when statistical information is not available. Nevertheless, the process must be handled in a structured and systematic way, in order to ensure the validity of the results.

The expert judgement may be considered as a process that is carried out in three phases, which are as follows:

- Preparation Phase
- Elicitation Phase
- Calculation Phase

Expert judgement differs to engineering aspects and some of them are highlighted in the following table:

Factors	Formal expert judgment	Engineering judgment
Structure	Systematic and structured method/process.	Unsystematic and unstructured process. "Discussion across the table".
Specification of information	Well specified. Only information given as answers of well defined questions.	Imprecise. Assumptions are not specified.
Documentation	All steps of the procedure are well documented.	Poor or no documentation.
Extent of collected information	Limited. Only that obtained through predefined questions.	Wide. May cover many aspects of the subject, also through follow-up questions.
Evaluation of experts	"Objective" rules for evaluation and possible weighting of the experts.	The confidence in a specific expert is judged subjectively by the analyst.
Simplicity	Extensive and expensive.	Very simple. Performed without preparations.

According to this author, the expert must have the following qualifications:

- Experience in performing judgment and making decisions
- More than 10 years of experience within the current subject
- Inherent qualities like self-confidence and adaptability

The Expert Judgment is based on the following basic requirements:

i. Documentation
ii. Objectivity
iii. Empirical Control
iv. Completeness
v. Simplicity

Some features must be continuously controlled, when performing elicitation of expert judgment are as follows:

i. Unbiasedness
ii. Calibration
iii. Over and Underestimation
iv. Informativeness
v. Subjective Informativeness
vi. Over and Under confidence
vii. Dependence
viii. Resolution
ix. Consistency
x. Coherence
xi. Reproducibility or Inter Expert Reproducibility

N.2 Calibration

Calibration is usually performed as part of the calculation phase, when distinct indications of one or more expert are systematically over or underestimating the correct value. Calibration requires the use of control questions and it should be performed when:

(1) For $n \geqslant 5$, a calibration is done when
$Z < n/2 - \sqrt{n}$ or $Z > n/2 + \sqrt{n}$
Example: For $n = 5$ we calibrate if Z = 0, or Z = 5
For $n = 10$ we calibrate if Z = 0, 1, 9, 10
(2) For $2 \leqslant n \leqslant 4$ and $Z = 0$ or $Z = n$, a calibration is done if, in addition, Y_i/x_i generally are "large" (»1) or "small" («1). That is:
(i) $Z = 0$ and $1/n \sum_i (Y_i/x_i) < 1/(6-n)$, or
(ii) $Z = n$ and $1/n \sum_i (Y_i/x_i) > (6-n)$

Where:

n = The number of control questions
x_i = the correct value (control question no. i), known by analys
Y_i = the expert's estimate
Z = The number of $Y_i - x_i$ (control question no. i) that are >0

The calibration process is performed according to a specific method, where it is assumed that there is a linear relation between the true values (x) and the original estimates (Y).

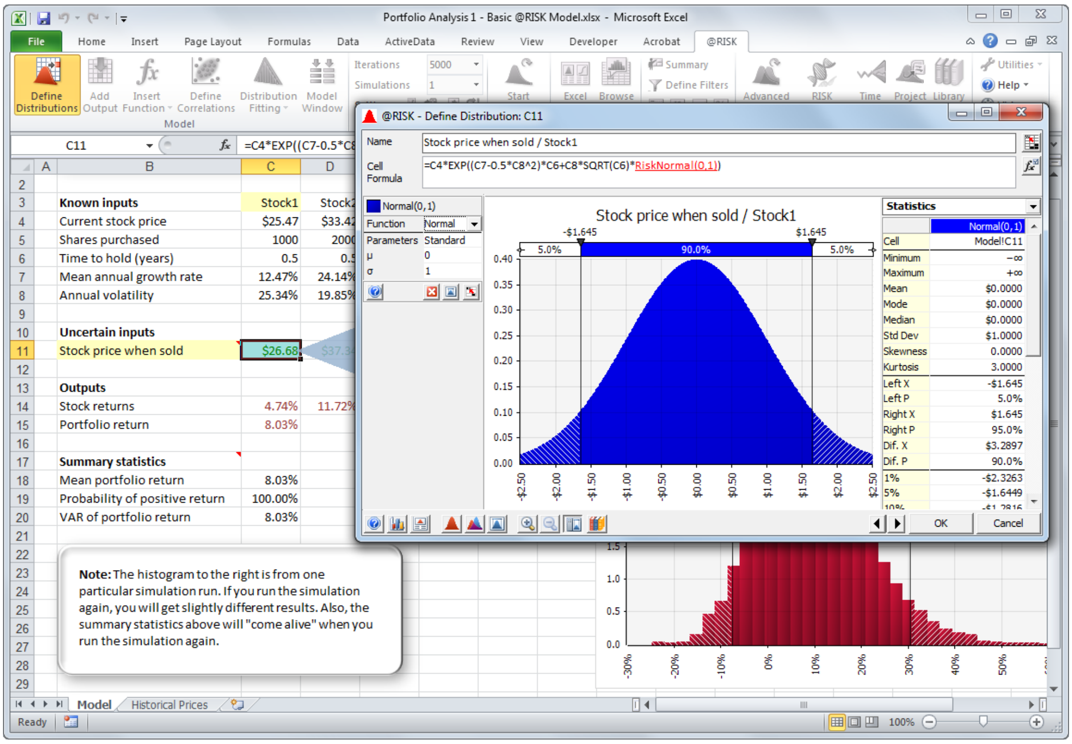
$$x_i = \beta_0 + \beta_1 Y_i + \text{error term}$$

$$\hat{\beta}_1 = \frac{\sum_i (Y_i - \bar{Y}) x_i}{\sum_i \left(Y_i - \bar{Y}\right)^2}$$

$$\hat{\beta}_0 = \bar{x} - \hat{\beta}_1 \bar{Y}$$

Appendix O: @ Risk

@ Risk is an add-in to Microsoft Excel, which is integrated to standard excel spreadsheet. The software use standards excel formulas and it also incorporates more formulas that are specially designed to perform risk analysis process, such as simulation, event tree, and neuronal analysis. The figure bellow shows a classical @risk display.



A specific academic licence that belongs to the author of this work was used during the development of this work.

This add-in represents a very simple way to perform calculations where uncertainty and risk must be integrated for obtaining better and more accurate results. The main @risk operation performed to create the proposed model were as follows:

- Defining uncertain model inputs (i.e.: cost drivers)
- Defining model inputs distributions (e.g.: normal, PERT, triangular, binominal)
- Defining operation (i.e.: cost functions)
- Defining uncertain model outputs (i.e.: unit cost, normal and total tunnelling cost)
- Monte Carlo Simulation (MCS)
- Sensitivity Analysis
- Correlation Analysis
- Fitting Suitable Distributions
- Managing Reports

The software has more than 30 years in the market and it is used for large companies and educational institutions, more information about the software may be found in the corporate website (www.palisade.com).

Appendix P: Definitions

- Risk: it is an uncertain event or condition that, if it occurs, has an effect on at least one project objective. A risk may have one or more causes and, if it occurs, it may have one or more impacts, PMBoK (2008).

- Uncertainty: it is broadly defined as the lack of information regarding a specific variable or the outcome of a given process. According to Nadim (2002), uncertainty may be divided in two categories: aleatory and epistemic. Aleatory uncertainty represents the natural randomness of a variable and it cannot be reduced or eliminated. Epistemic uncertainty represents the lack of knowledge on a specific variable and it includes measurement uncertainty, statistical uncertainty (limited information) and model uncertainty. This class of uncertainty may be reduced.

- Consequence: A measure of the damage caused by a specific risk. It can be defined as time, money or other measurements.

- Risk Acceptance Criteria: qualitative or quantitative expression defining the maximum risk level that is acceptable or tolerable for a given system or organization, The Engineering Council (1993)

- Project Management: application of knowledge, skills, tools, and techniques to project activities to meet the project requirements, PMBoK (2008).

- Project Risk Management: the processes of conducting risk management planning, identification, analysis, response planning, and monitoring and control on a project.

- Project: temporary endeavour undertaken to create a unique product, service, or result, PMBoK (2008).

- Project Objectives: it may include, but not limited to scope, schedule, cost, and quality, PMBoK (2008).

- Underground Projects: any project that is developed or build using the ground as main structure (e.g.: tunnels, water plants, industrial facilities, etc.)

- Project Life Cycle: a collection of generally sequential project phases whose name and number are determined by the control needs of the organizations involved in the project, PMBoK (2008).

- Project Phase: A collection of logically related project activities, usually culminating in the completion of a major deliverable, PMBoK (2008).

- Budget: the approved estimate for the project or any work breakdown structure component or any schedule activity, PMBoK (2008).

Appendix Q: Digital Appendix

Q.1 Cost Estimation Functions

- 01. Model T9.5 Final Cost Functions.xls

Q.2 Cost Models and Inputs

- Model T9.5 Setup I.xls
- 02A. Model T9.5 Setup II-A.xls
- 02B. Model T9.5 Setup II-B.xls
- 03A. Model T9.5 Setup III-A.xls
- 03B. Model T9.5 Setup III-B.xls

Q.3 Cost Models and Outputs

- 01. Full Report II-A 02.06.14.xls
- 02. Full Report II-B 02.06.14.xls
- 03. Full Report III-A 02.06.14.xls
- 04. Full Report III-B 02.06.14.xls

Q.4 @Risk Trial

- The Decision Tools Suit 6 Trial Version (to be installed)