

Tunnel Excavation Material Handling Using Decision Analysis

Master of Science Thesis

by

Stefan Ritter

Bachelor of Science in Natural Resources (2009)
University of Leoben, Austria

Submitted to the Chair of Subsurface Engineering in Partial Fulfillment of the
Requirements for the Degree of Master of Science in Mining and Tunneling

at the

University of Leoben, Austria

Thesis Supervisor: Robert Galler
Professor of Subsurface Engineering
University of Leoben

Research Supervisor: Herbert H. Einstein
Professor of Civil and Environmental Engineering
Massachusetts Institute of Technology

Leoben, May 2011

AFFIDAVIT

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich diese Arbeit selbsständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch somit keiner unerlaubten Hilfsmittel bedient habe.

.....
Stefan Ritter

Leoben, May 2011

PREFACE

Most of the research work described in this thesis was carried out at the Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge. The financial support of this research was provided by the Marshallplan-Jubiliäumsstiftung through the "Marshal Plan Scholarship" and the University of Leoben. The information and data of the Brenner Base Tunnel (BBT) project was provided by the Brenner Basistunnel BBT SE.

Many people have stimulated, supported and assisted this research. It would not have been possible without you; thus, I express my gratitude to all of you. However, I will specially thank:

Professor Herbert H. Einstein, my research supervisor. I am very grateful for all his support, suggestions and guidance. Especially, the weekly meetings stimulated this thesis. His unconditional support enabled me doing this research in collaboration with MIT. It was a honor to work with him.

My thesis supervisor, Professor Robert Galler, for his support and encouragement doing this research in collaboration with MIT. His deep interest in the recycling of excavated materials has been very valuable for this work. Also, I would like to give him special thanks for his advices and guidance during my entire study.

Special thanks go to the Decision Aids for Tunneling (DAT) group. Yvonne Moret, for being such a good DAT teacher and all the discussions and advices which helped me during this research. Claude Indermitte and Sangyoon Min, for the patient explanations about the DAT and fixing bugs always so quickly.

I am very grateful to the Brenner Basistunnel BBT SE for allowing me to use information and data of the BBT project. Especially, Professor Konrad Bergmeister and Daniel Alfreider, for the support of this research and to supply me with data and information.

To all the experts of tunnel excavation material handling who collaborated in this research and were so kind to answer the questionnaire about the uncertainties affecting tunnel excavation material handling.

The Marshallplan-Jubiliäumsstiftung and the University of Leoben for providing financial support for this research.

To all my friends at MIT: My colleagues of the Intelligent Transportation Systems (ITS) lab for being such good office mates. Marty, David, Gonzalez, and Heiko for the (at least for me) too early Monday morning squash games. All the teammates of the MIT graduate soccer team who helped me keeping fit. It was a real pleasure traveling around Boston and playing half a season with you. Ana B., Ana Laura C., André, Christian, Dario, Daniel, Elisabeth, Enrico, Eunice, Frederico, Hegoi, Henrik, Ines, Michael, Nuno, Peter, Sergio, Simone, Swapnil, and Travis for being my friends and making my time at MIT so much fun.

To Heiko, for all his support planning the time at MIT. The numerous discussions about our work, our shared meals, and the huge amounts of coffee. Thanks for sharing this unique experience with me.

I owe my deepest gratitude to my parents who supported me during my entire life. They have always been open for my ideas and inspired me to follow my dreams. Thank you for taking such good care of me and for believing in me!

Finally, I thank my girlfriend Kathrin for her understanding, patience, and love during my entire study. She always helped me to find the right decisions even if such decisions separated us for some months. It would not have been possible without you!

Stefan Ritter
Leoben, May 2011

ABSTRACT

Success in tunneling also depends on a sustainable tunnel design, which jointly considers social, environmental, and economic issues. Planning the handling of excavated materials of a tunnel construction project will possibly avoid waste deposits, save mineral resources as well as energy, and reduce some of the project costs. Hence, planning the handling of excavated materials contributes to a sustainable tunnel design. However, this planning process is affected by many uncertainties and, thus, a challenge.

This research describes how decision analysis can be used to deal with the uncertainties of tunnel excavation material handling (TEMH). Therefore, a brief review of the basic aspects of decision analysis under uncertainty is followed by an overview over TEMH and a determination of the main uncertainties of materials management in tunneling. In particular, this thesis presents a simulation model, which uses the Decision Aids for Tunneling (DAT) and their resource module, to describe and evaluate uncertainties affecting TEMH. The emphasis in this simulation model is placed on representing the individual steps in the material handling process starting with excavation and ending with the reuse or final depositing of the material.

An application to a real tunnel construction project, namely a part of contract section Wolf of the Brenner Base Tunnel (BBT) demonstrates the efficiency of the decision analysis. The results obtained in these materials management simulations can optimize the design of a tunnel construction project.

KURZFASSUNG

Erfolg im Tunnelbau hängt unter anderem von einer nachhaltigen Planung ab, welche die Gesellschaft, Umwelt und Wirtschaft gleichermaßen berücksichtigt. Die Planung des Umgangs mit Tunnelausbruchmaterial kann durch eine mögliche Einsparung von Deponieflächen, mineralischen Rohstoffen, Energie und Projektkosten wesentlich zu einer nachhaltigen Planung von Tunnelbauprojekten beitragen. Jedoch ist diese Planung der Materialbewirtschaftung durch den Einfluss von Unsicherheiten charakterisiert und dadurch eine Herausforderung.

Diese Arbeit beschreibt den Einsatz von Entscheidungsanalysen um Unsicherheiten bei der Planung der Materialbewirtschaftung zu berücksichtigen und folglich zu managen. Zuerst werden die theoretischen Grundlagen von Entscheidungsanalysen unter Einfluss von Unsicherheiten zusammengefasst, ein Überblick über die Materialbewirtschaftung von Tunnelbauprojekten gegeben und anschließend die maßgeblichsten Unsicherheiten bei der Materialbewirtschaftung bestimmt. Vor allem wird ein Simulationsmodell vorgestellt, das auf dem Computerprogramm Entscheidungshilfen für den Tunnelbau (EHT)¹ und dem dazugehörigen Ressourcenmodul basiert. Dieses Simulationsmodell ermöglicht es Unsicherheiten der Materialbewirtschaftung zu beschreiben und zu bewerten. Hauptaugenmerk des Simulationsmodells ist eine ganzheitliche Betrachtung der Materialbewirtschaftung beginnend mit der Gewinnung und endend mit der Wiederverwertung oder Deponierung des Tunnelausbruchmaterials.

Anhand der Anwendung des Simulationsmodells an einem aktuellen Tunnelbauprojekt – ein Teil des Hauptbauloses Wolf des Brenner Basistunnels – wird die Effizienz der Entscheidungsanalyse dargestellt. Die gewonnenen Ergebnisse können zur Optimierung der Planung des Tunnelbauprojekts verwendet werden.

¹Der englische Name dieses Computerprogramms lautet "The Decision Aids for Tunneling (DAT)". Steiger (2009) beschreibt die EHT in Deutsch.

TABLE OF CONTENTS

TABLE OF CONTENTS	xi
1 INTRODUCTION	1
1.1 Problem Description	1
1.2 Research Objectives and Approach	1
1.3 Thesis Outline	2
2 DECISION ANALYSIS	3
2.1 Uncertainty	3
2.1.1 Uncertainty in Tunneling	3
2.1.2 The Nature of Uncertainty	4
2.2 Basics of Decision Analysis	5
2.2.1 Definitions	5
2.2.2 Formal Aspects of Decision Analysis	6
2.2.3 Decision Analysis in Practice	7
2.2.4 Model Sequence	9
3 TUNNEL EXCAVATION MATERIAL HANDLING	11
3.1 Need for Tunnel Excavation Material Handling	11
3.2 Principles of TEMH	12
3.3 Uncertainties Affecting TEMH	14
4 THE DECISION AIDS FOR TUNNELING	17
4.1 Description of the Decision Aids for Tunneling	17
4.1.1 Geologic Module	18
4.1.2 Construction Module	18
4.2 Resources in the Decision Aids for Tunneling	21
4.2.1 Principles of Modeling Resources	21
5 SIMULATION MODEL	23
5.1 The Geologic Module	25

5.2	The Construction Module	26
5.2.1	The Parallel Structure of the Tunnel Network	28
5.2.2	"Reused" Activities	33
5.2.3	Construction Model	35
5.2.4	Transportation Model	36
5.2.5	Recycling Model	36
5.2.6	Resources in the Simulation Model	37
5.3	Modeling Mechanized Tunneling	38
5.3.1	Construction Model Applied to Mechanized Tunneling	38
5.3.2	Transportation Model Applied to Mechanized Tunneling	42
5.3.3	Recycling Model Applied to Mechanized Tunneling	44
5.4	Modeling Conventional Tunneling	49
5.4.1	Construction Model Applied to Conventional Tunneling	49
5.4.2	Transportation Model Applied to Conventional Tunneling	53
5.4.3	Recycling Model Applied to Conventional Tunneling	56
5.5	Comments on the Simulation Model	60
6	BRENNER BASE TUNNEL PROJECT	61
6.1	Tunnel Design (29-02-2008)	61
6.2	Current Project Status (Spring 2010)	65
6.3	Tunnel Geology	65
6.4	Tunnel Excavation Material Handling of the Brenner Base Tunnel	71
6.4.1	Objectives of the Tunnel Excavation Material Handling	72
6.4.2	Excavation Material Classification	72
6.4.3	Final Repositories, Aggregate Plant	74
6.4.4	Transport Logistics	75
6.5	Contract Section Wolf	76
6.5.1	Tunneling of Contract Section Wolf	76
6.5.2	Tunnel Excavation Material Handling of Contract Section Wolf	78
7	APPLICATION OF THE SIMULATION MODEL	81
7.1	Simulation Area	81
7.2	Simulation Inputs	83
7.2.1	Geologic Module Inputs	83
7.2.2	Construction Module Inputs	94
7.3	Specific Simulation Techniques	105
8	SIMULATION RESULTS	109
8.1	Results of Simulation Technique I	109
8.2	Results of Simulation Technique II	123
8.3	Additional Simulation Results	126

9 CONCLUSIONS AND PERSPECTIVES	131
9.1 Conclusions Drawn from the Simulations	131
9.2 Assessment of the Decision Aids for Tunneling	133
9.3 Recommendations for Future Work	134
BIBLIOGRAPHY	137
APPENDIX: END POSITIONS OF THE GROUND CLASSES	141
LIST OF ABBREVIATIONS	145
LIST OF FIGURES	146
LIST OF TABLES	150

Chapter 1

INTRODUCTION

1.1 PROBLEM DESCRIPTION

Growing awareness exists that our world has limited non-renewable natural resources such as mineral raw materials. Otherwise, the construction of underground projects is increasing worldwide and produces vast amounts of excavated materials. There is, therefore, an increasing effort in recent and planned tunnel projects to consider a possible reuse of excavated materials, which possibly saves mineral resources, avoids waste deposits, saves energy due to shortened transport routes, and reduces some of the project costs. However, a successful reuse of excavated materials requires a systematical handling of the excavated materials. This so-called tunnel excavation material handling (TEMH) has to be considered in a sustainable tunnel design to manage underground projects more effectively.

Tunneling, more than other areas of civil engineering, is characterized by high degrees of uncertainties. These uncertainties can be uncertainties about the geology, the construction process, and also the TEMH. Furthermore, the TEMH and especially the reuse of excavated materials depend on the geologic conditions encountered and the applied construction method. One can follow that planning the TEMH is affected by uncertainty and has to consider the geology as well as the construction process. Hence, planning the TEMH is a challenge.

1.2 RESEARCH OBJECTIVES AND APPROACH

The objective of this research is to demonstrate that decision analysis can be used to deal with the complexity of planning TEMH, which is a process of decision making under uncertainty. Therefore, a simulation model, which uses the Decision Aids for Tunneling (DAT) and its resource module, is introduced. The aim of this simulation model is to provide a standard procedure to apply decision analysis to TEMH.

Thereby, the main focus is to simulate the individual steps in the TEMH process starting with the excavation and ending with the reuse or final depositing of the material. Most importantly, uncertainties about geology, the construction process, and the TEMH can be considered in the simulation model. Hence, the simulation model allows one to investigate the planned TEMH of a tunnel construction project under conditions of uncertainty. Results of such materials management simulations can contribute to the design of the TEMH and the entire tunnel construction project.

A further intent of this thesis is to demonstrate the applicability of the simulation model to a real tunnel construction project. Kollarou (2002) was the first who applied a previous version of the resource module of the DAT to the Löttschberg Base Tunnel to investigate its materials management system. At the present some parts of the Brenner Base Tunnel (BBT) is under construction and was selected to apply the simulation model in a case study. Due to the complexity of the BBT the simulation model is applied to a part of contract section Wolf.

1.3 THESIS OUTLINE

This thesis is organized in three parts:

The first part of the thesis summarizes the theoretical background of the conducted research. In Chapter 2, a brief review of the basics of decision analysis is given. The decision analysis cycle and the practical application of the decision analysis process in geotechnical engineering is explained. Chapter 3 provides an overview over TEMH and concentrates on the uncertainties affecting TEMH. An introduction to the DAT is given in Chapter 4.

In the second part a methodology is proposed which allows one to apply decision analysis to TEMH. This methodology is based on the simulation model, which is explained in detail in Chapter 5.

The third part of this thesis presents a case study, which applies the simulation model to a part of the BBT project. In Chapter 6, a general description of the BBT project, including tunnel design, current project status, geology, and TEMH is provided. Emphasis is placed on contract section Wolf and the particular TEMH. In Chapter 7, the simulation model is applied to a part of contract section Wolf. Therefore, Chapter 7 describes the input of the collected information of contract section Wolf. All the necessary assumptions made, the modeled uncertainties, and the main input windows of the DAT are presented. The results of this case study are summarized and analyzed in Chapter 8.

Finally, the conclusions drawn from this research, followed by an assessment of the DAT, and recommendations for future work are provided in Chapter 9.

Chapter 2

DECISION ANALYSIS

Before applying decision analysis to TEMH it is necessary to introduce some basic notions and give a brief overview over decision analysis. Specifically, the decision analysis cycle and the practical application of the decision analysis process in geotechnical engineering are discussed.

2.1 UNCERTAINTY

2.1.1 UNCERTAINTY IN TUNNELING

In underground construction uncertainty is central. Einstein and Baecher (1983), for example, argue that the most characteristic distinction between engineering geology, which is a part of tunneling, and other engineering fields are uncertainties of geologic conditions and geotechnical parameters. Typical parts of tunneling associated with uncertainty are the geology, hydrogeology, construction performance, contract, economic-, and environmental conditions. Consequently, engineers have developed different strategies to deal with uncertainty. An overview of typical techniques used in geotechnical engineering, following Christian (2004), is given below:

1. Ignore it
2. Be conservative
3. Use the observational method
4. Quantify uncertainty

Although, the approaches (1.) and (2.) appear to be unsupportable, they are widespread (Christian, 2004). Various agencies and corporations make their decisions without considering associated uncertainties (Christian, 2004). Being conservative

(2.) is generally expensive and leads to unacceptable construction time estimates (Christian, 2004).

The observational method (3.) is the preferred way to deal with uncertainty in geotechnical engineering and is widely applied to tunneling. Using the observational method deals with uncertainty through a flexible design or construction approach and considers the results of field measurements during construction. Based on the results of the field measurements, the construction process is adjusted to the current conditions. The limitations of the observational approach are that the engineer on the construction site must have access to the decision maker during the entire construction process to change the design or construction approach; also, the probability of undesirable events are not explicitly considered, and field measurements cost a lot of money (Christian, 2004). Christian (2004) argued that the approach of quantifying uncertainty (4.) is a logical extension of the observational approach. Quantifying uncertainty includes developments of probabilistic methods such as reliability-, risk- or decision analysis.

2.1.2 THE NATURE OF UNCERTAINTY

For the purpose of discussing the nature of uncertainty related to decision analysis it is common to interpret and distinguish uncertainty in regard to its type and origin (Faber, 2009). Several attempts have been made to categorize the sources of uncertainty which affect geotechnical engineering, for example, Baecher (1972), Einstein and Baecher (1983), Christian et al. (1994), and Lacasse and Nadim (1996). This report uses the classification proposed by Einstein and Baecher (1983):

- **Type 1:** Innate spatial and temporal variability of geological factors
- **Type 2:** Errors introduced by measuring and estimating engineering properties, including statistical fluctuation
- **Type 3:** Model Uncertainties
- **Type 4:** Load Uncertainties
- **Type 5:** Omissions

Another way of characterizing uncertainties, which has achieved wide circulation and application is to define uncertainty as either aleatory or epistemic (Paté-Cornell, 1996; Christian, 2004; Faber, 2009). The aleatory uncertainty has its origin in the randomness of sampled variables; in contrast, the epistemic uncertainty represents a lack of knowledge and is also known as ambiguity uncertainty (Paté-Cornell, 1996). Further ways of characterizing uncertainty can be found in Christian (2004).

The uncertainties of Type 1, 2, and 3 which usually concern geotechnical engineering such as tunneling are, in general, caused by aleatory- and epistemic uncertainties

(Einstein, 2008). For example, following Einstein (2008), the distribution of joint (fracture) orientation which is an innate spatial variability (Type 1) has an aleatory- and an epistemic component. The aleatory component is the randomness of sampled variables (e.g., joint orientation). On the other hand, the epistemic component represents the lack of knowledge that the same joint (fracture) pattern of the surface exists also at a certain depth.

2.2 BASICS OF DECISION ANALYSIS

Given that uncertainties are so important in tunneling, a formal procedure which incorporates uncertainty such as the process of decision making under uncertainty is desirable. This Section gives a brief overview over decision analysis. In particular, the meaning of some important notions are described, followed by an introduction to decision analysis, the decision analysis cycle and the practical application of decision analysis.

2.2.1 DEFINITIONS

Before explaining the principles of decision analysis, based on Howard (1966; 2010a; 2010b), it is necessary to outline the meaning of the word decision, the distinction between a good decision and a good outcome, and the difference between a decision analyst and a decision maker. The following definitions are referred to Howard (1966).

Throughout this work, a decision means a final allocation of resources, which leads to a situation, in which it is impossible or only with high monetary effort to return to the situation, which existed before this decision. Therefore, a decision is to pursue a course of action, and not a mental commitment to follow a course of action.

A good decision follows a logic framework of information, values, and preferences of the decision maker. In contrast, a good outcome is characterized through a high value of interest (e.g., profit) for the decision maker. Thus, a good outcome is one that is desired. To ensure that good outcomes are produced through good decisions is the purpose of a decision analysis. However, to ensure this is not a straightforward procedure; a good decision can also yield to a bad outcome and a bad decision to a good outcome. To avoid these, decision analysis has to be a logical procedure, which deals with the factors influencing the decision.

A clear distinction between a decision analyst and a decision maker is of importance to perform a successful decision analysis. The decision analyst is the person who performs the decision analysis on behalf of the decision maker. Hence, the decision analyst is an expert in decision analysis theory and its application. By contrast, the decision maker is the person who has substantial knowledge on the decision problem. Consequently, good communication between the decision analyst and the decision maker as well as a clear allocation of tasks is essential. The decision maker expects

as a result of a decision analysis a recommended course of action from the decision analyst. Finally, it is the decision maker's decision to follow this recommendation or to ignore it.

2.2.2 FORMAL ASPECTS OF DECISION ANALYSIS

The description of the formal aspects of a decision analysis follows Howard (2010b; 2010a).

Generally, any decision consists of three elements, represented graphically through the legs of the stool in Figure 2.1. "What you can do" illustrates the alternatives, "what you know" stands for the existing information, and "what you want" reflects the preferences of the decision maker. The three legs jointly explain the decision basis. If there is any leg missing it is not possible to make a logical decision. It is the task of the decision analyst to elicit these three elements of the decision basis from the decision maker or his delegates. The logic procedure of the decision analysis, operating on the decision basis, represents the seat of the stool. Also, to make a decision depends on the environment the decision problem is located in. A different environment can change all elements of the decision basis. The frame in Figure 2.1 represents this environment. To define the environment, which affects the decision making procedure, is a task of the decision maker. Additionally, the decision maker has to outline what decision within the frame is under consideration.

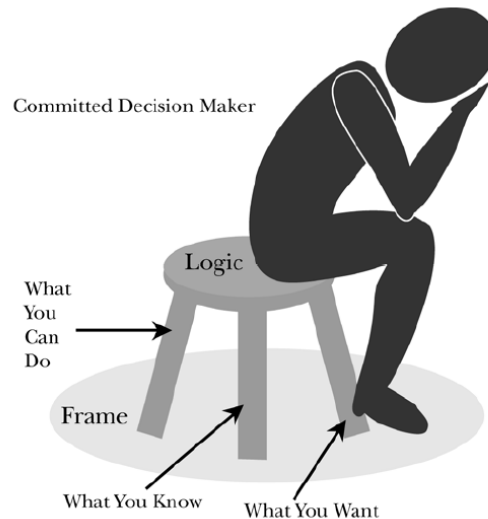


Figure 2.1: Representation of the Formal Aspects of a Decision Analysis (Howard, 2010b)

In conclusion, every element of the decision basis, the frame, and the logic procedure of the decision analysis must be determined by the person on the stool, the decision maker, with advice by the decision analyst. Howard (2010a) states that

decisions are created through the human mind and not a product of nature; hence, the decision maker as well as the decision analyst are of main importance to carry out a successful decision analysis.

2.2.3 DECISION ANALYSIS IN PRACTICE

The application of the decision making process is generally described through a decision analysis cycle. Figure 2.2 graphically represents the decision analysis process similar to that proposed by Raiffa and Schlaifer (1964), but adapted to engineering. In engineering one uses this decision analysis cycle to determine parameters, include them in engineering models, and make decisions based on the results of the model (Karam et al., 2007). This framework can be used to apply decision analysis to TEMH. A brief description of the main elements of this decision analysis cycle, based on Howard (1966, 2010a) and Einstein (2008), is given below. Emphasis of this research is put on the probabilistic model phase.

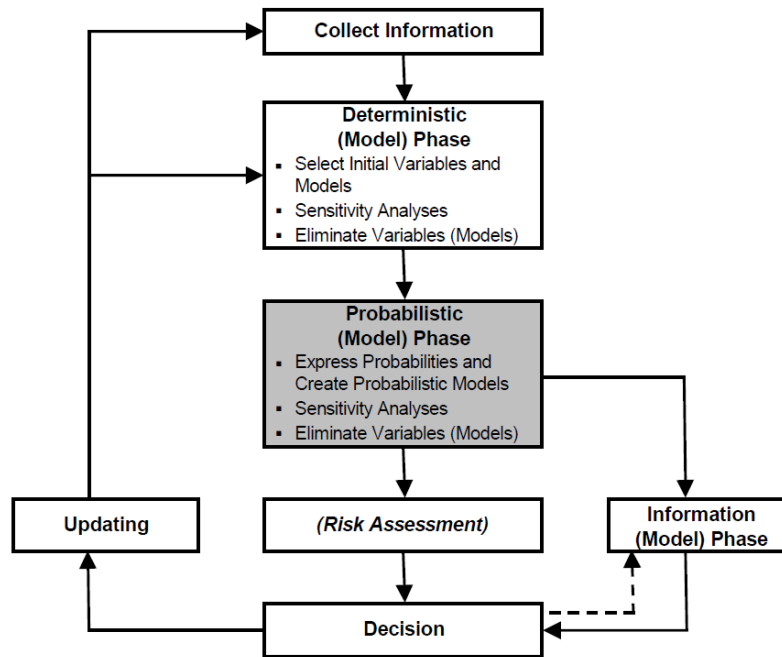


Figure 2.2: Decision Analysis Cycle (Einstein and Sousa (2006) and Einstein (2008))

Information collection in geotechnical engineering is mainly based on the geologic/geotechnical investigations and the construction schedule of the planned construction. The collected information, for example joints in a rock mass has to be described which can be done deterministically, statistically and probabilistically.

After collecting information, the deterministic (model) phase starts. The first step of the deterministic phase is to define the decision problem. Then relevant parameters, which describe the decision problem, are defined. Subsequently, these

parameters, which can be state- or decision variables² are included in a deterministic engineering model which is suitable to model the decision problem. Deterministic models and probabilistic models in geotechnics can be, referring to Einstein (2008):

- **Performance Models**

- Stability (e.g., face stability)
- Deformation (e.g., settlement)
- Flow (e.g., ground water inflow)

- **Economic Models**

- Cost (e.g., construction costs)
- Time (e.g., construction time)
- Resource (e.g., consumption of construction materials)

The performance- and the economic models can be analytical and numerical models, empirical models, or combinations (Einstein, 2008). Sensitivity analyses of the deterministic (model) phase are, in general, performed by holding all but one variable constant. Hence, a sensitivity analysis allows one to evaluate how a change of an uncertain parameter affects the outcomes of the deterministic model. Correlation effects can also be determined if more than one parameter is varied. Parameters which do not influence the results of the decision problem are kept as constants in the subsequent probabilistic (model) phase. Unsuitable models for the decision problem can be eliminated.

The difference between the probabilistic (model) phase and the deterministic (model) phase is that the uncertain parameters (variables) are assigned probabilities. Obtaining these probabilities is called uncertainty- or probability encoding and is discussed by Howard (1966) and Spetzler and Staël Von Holstein (1975). In this encoding process, judgment is generally included. As mentioned before, the used type of model (e.g., performance- or economic model) is the same as described in the deterministic (model) phase. The outcomes of the probabilistic phase are, in general, in the form of distributions which can be, for instance, described with probability density functions (Einstein et al., 1978). A probabilistic model with mostly economic characteristics is, for example, the DAT (Einstein, 2008).

Many attempts have been made to define risk. A widespread definition of risk is

$$Risk = P[U] \cdot Worth\ of\ Loss \quad (2.1)$$

where $P[U]$ denotes the probability of unsatisfactory performance which can be the outcome of the probabilistic (model) phase. It is important to realize that one can

²Spetzler and Staël Von Holstein (1975) discuss the difference between state- and decision variables in detail.

make decisions based on the outcomes of the probabilistic (model) phase and, thus, it is not necessary to assign risk to the decision problem (Einstein, 2008). Other definitions of risk are discussed in Einstein (1996, 2008).

After the probability of unsatisfactory performance (or the risk) is determined one can make a decision. One possible decision is to collect further information to update the decision problem. Updating makes, in general, use of the Bayes theorem which modifies the original probabilities (Einstein, 2008). Moreover, one likes to find out if gathering new information is beneficial which is the task of the information (model) phase (see Figure 2.2). Gathering new information can reduce or even eliminate any or all uncertainties of the decision problem. On the other hand, the disadvantage of gathering new information is that it is associated with costs. Therefore, the information phase compares, for example, the costs of ignorance of the best alternative up to this point with the costs of gathering new information to eliminate the uncertainties, which caused the costs of ignorance. If gathering additional information seems to be beneficial the decision cycle is run again. Accordingly, the decision making process is adaptive and always based on the current state of knowledge.

2.2.4 MODEL SEQUENCE

This section presents the different steps of progress in modeling the decision problem, following Howard (2010b). In general, the model (e.g., performance- or economic model) is developed using computer programs (e.g., the DAT). Figure 2.3 illustrates the model sequence.

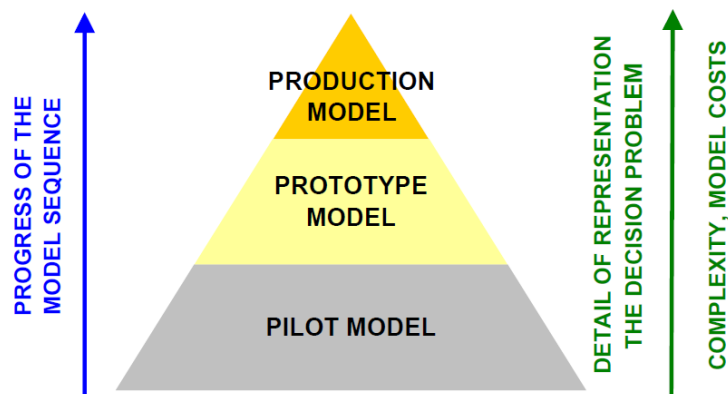


Figure 2.3: Model Sequence of a Decision Analysis (Howard, 2010b)

The pilot model is the first model in the model sequence, in which only the most important relationships between the variables are included. Hence, it is a simplified model of the decision problem.

The prototype model represents the decision problem in detail. However, there are still a few properties excluded, which can be of importance for the decision making

process or properties included which have to be eliminated. The main goal of the prototype model is to identify the most important parts of the production model.

Finally, based on the prototype model, the production model is developed. The production model represents the decision problem in the most realistic way, considering a justifiable effort to perform the decision analysis.

Chapter 3

TUNNEL EXCAVATION MATERIAL HANDLING

The goal of this Chapter is to demonstrate the need for TEMH with emphasis placed on the reuse of tunnel excavation material. In addition, the principles of the TEMH followed by an overview of the main uncertainties affecting the TEMH are described.

3.1 NEED FOR TUNNEL EXCAVATION MATERIAL HANDLING

During the construction of tunnel projects large quantities of excavation material are produced. For instance, it is predicted that during the construction of the BBT, described in Chapter 6, roughly 15.5 million cubic meters of rock (solid volume) will have to be excavated (Bergmeister, 2010). Most of the excavated material of tunnel projects have so far been used to refill an excavated area close to the construction site (backfilling) or have been transferred to repositories (tipping) (Resch et al., 2009). However, growing awareness exists that our world has only limited non-renewable natural resources such as mineral raw materials. For this reason, the Brundtland Commission (1987) came to the conclusion that a sustainable development is a development "*that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987). Thus, a sustainable development jointly considers the society, economy, and environment. Reusing tunnel excavation material, which is a part of the TEMH, is such a sustainable development which saves non-renewable resources, avoids waste deposits, limits nuisance to the population in the vicinity of the construction site, and possibly saves energy due to reduced transportation. Common possibilities to reuse excavated material are to use them as fill material, for instance, for embankments, and as concrete- or shotcrete

aggregate. Resch et al. (2009) quoted additional possibilities to reuse excavated material (see below), which might be considered in future tunnel projects.

- Limestone as raw material for the steel industry, as filler³ and in the feedstuffs industry.
- Clay as raw material for brick production.
- Rock dust for the improvement of agricultural land.
- Mica as a raw material for the painting industry.

Reuse of the excavated material can also have an economic consequence by cutting transportation- and storage costs (Gertsch et al., 2000 and Kruse, 2002). However, extra costs such as, for instance, the set up and operation of the recycling plant of the excavated material have to be considered in these economic considerations (Resch et al., 2009). Hence, muck, which is the term for excavated material which can or cannot be reused, should be considered as a resource from the beginning of tunnel design and not treated like waste (Gertsch et al., 2000).

3.2 PRINCIPLES OF TUNNEL EXCAVATION MATERIAL HANDLING

For the first time on a large scale, the Lötschberg and Gotthard Base Tunnel projects have demonstrated a practicable reuse of tunnel excavation material as concrete- or shotcrete aggregate (Resch et al., 2009). Based on the TEMH of these tunnel projects the material flow in the TEMH process with the corresponding investigations of the excavated material can be described. Figure 3.1 schematically illustrates the general material flow in the TEMH process.

The TEMH starts with the production of the excavated material from tunnel excavation, which is affected by the tunneling method, such as mechanized- or conventional tunneling. Subsequently, geologists visually assess the excavated material at the face of the excavation to evaluate its properties. This evaluation can be called the "*Preliminary Material Classification*" which correlates the results of the geologic exploration and laboratory testing during the exploration- and design phase with the geologist's assessment. Based on this "*Preliminary Material Classification*" the excavated materials are assigned excavation material classes. Examples of such excavation material classes, following the general material flows in the TEMH process (see Figure 3.1), are described below. Several other attempts to define excavation material classes have been made (e.g., Harer and Pichler (2009), Lieb (2009), and

³Fillers are particles added to materials such as, for example, plastics to cheapen end products or enhance the technical properties of the products.

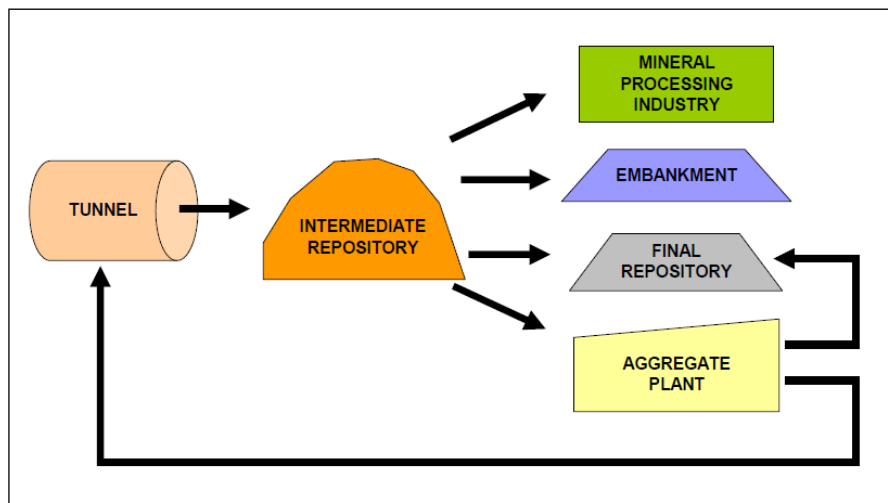


Figure 3.1: Materials Flow Scheme of the Excavated Material in the TEMH Process

Bergmeister (2010)). This attempts consider the main goals of the TEMH in the particular tunnel project and, thus, can change from project to project.

- **Material Class 1:** Excavated material suitable to be recycled for concrete- or shotcrete aggregate.
- **Material Class 2:** Excavated material suitable to be purchased by the mineral processing industry.
- **Material Class 3:** Excavated material suitable to be used as backfilling material or as fill material for embankments.
- **Material Class 4:** Excavated material which has to be tipped at final repositories.

After this "*Preliminary Material Classification*" the excavated material classes are separately transported to the intermediate repository using muck trucks or conveyor belt systems. In general, the intermediate repository is located next to the portal of the tunnel. At the intermediate repository the excavated material is temporarily stored in order to perform additional investigations on the excavated material to define its quality in detail. This "*Final Material Classification*" consists, in general, of a standardized testing plan for the excavated material. As a result of the "*Final Material Classification*" the excavated material can be assigned other excavation material classes than after the previous "*Preliminary Material Classification*". The excavated material class that qualifies for aggregate production is transported from the intermediate repository to the aggregate plant. The remaining excavated materials are transported to their final usage such as reusing as material for backfilling or as fill material for embankments, purchase by the mineral processing industry, and tipping

at a final repository. At the aggregate plant the excavated materials become aggregate of different sizes and will be reused in the shotcrete- or concrete applications on the construction site. Naturally, the processed aggregates can also be purchased.

As mentioned before, the tunneling method affects the production of the excavated material. Specifically, the production of excavated materials with hard rock tunnel boring machines, which are generally outfitted with disc cutters, influences the shape of the excavated material. In general, tunnel boring machine (TBM) excavated material is a poorly graded material containing large, flat, elongated chips with relatively few fines (Gertsch et al., 2000). However, research showed that some TBM muck can become aggregate for high value shotcrete or concrete if the right disc cutter spacing and suitable processing is used (Thalmann, 1996). A disadvantage of crushed rock from conventional- and mechanized tunneling which is used as aggregate for shotcrete or concrete is that the cement consumption of the concrete rises about 15 per cent in contrast to using gravel (Thalmann, 1996).

3.3 UNCERTAINTIES AFFECTING TUNNEL EXCAVATION MATERIAL HANDLING

Following Sousa (2010), two major factors are responsible for the high degree of uncertainties characterizing tunneling. The first factor involves the geologic conditions, which can never be determined exactly. The second factor, which can be uncertain even if the geologic conditions are known, is the construction process itself. Examples of such construction uncertainties influencing the construction process are the performance of the equipment or the skills of the workers.

The TEMH is also characterized by the influence of these geologic- and construction uncertainties. For example, problematic geologic conditions such as mechanical and petrographical properties can strongly influence the suitability of the excavated materials for recycling (Lieb, 2009). Moreover, the time dependency of the processing of qualified excavated materials to concrete aggregate and the consumption of these materials on the construction site is strongly affected by the planned construction schedule (Lieb, 2009). Even if it is assumed that the geologic conditions are known, the construction schedule, which depends strongly on the advance rates of the excavation methods, can be considerably influenced by construction uncertainties. Additionally, the TEMH is associated with uncertainties due to the processing technology of the excavated materials. These processing uncertainties involve, for example, the performance of the processing facilities, which can be independent of the geologic conditions. Taken together, the TEMH is affected by three major types of uncertainties which are the geologic-, construction-, and processing uncertainties.

In order to cope with these uncertainties generous margins can be applied to plan the TEMH at the beginning of a project (Lieb, 2009). Another approach of planning the TEMH is to determine the particular uncertainties affecting the TEMH and to

consider these uncertainties when modeling TEMH. To determine these particular uncertainties a questionnaire had been developed and answered by experts. Table 3.1 represents the results of these investigations by showing the five most important uncertainties affecting the TEMH.

Table 3.1: Main Uncertainties Affecting the TEMH Based on a Questionnaire which Was Answered by Experts

Ranking	Uncertainty Description
(1)	Concept of the Processing Technology of the Excavated Materials (<i>e.g., Array of the Processing Facilities in the Aggregate Plant, etc.</i>)
(2)	Occurrence of Discontinuities in the Geology
(3)	Displacement of Planned Contract Section Boundaries
(4)	Chemical Components of the Excavated Materials
(5)	Grading Size Curves of the Excavated Materials

As mentioned before, the Löttschberg and Gotthard Base Tunnel projects reused excavated materials as concrete- and shotcrete aggregates and therefore obtained useful experience regarding uncertainties influencing TEMH. The following statements can be drawn from the experience gained:

- Proper process technologies exist to process qualified excavated materials to concrete- or shotcrete aggregates (Thalmann, 1996 and Kruse, 2002).
- Alterations in the project development can change the original demand for concrete- and shotcrete aggregates as well as the expected quantity of suitable excavated materials for recycling (Teuscher et al., 2007 and Lieb, 2009).
- Tunnel exploration in the early phases of a project such as excavation of exploration tunnels and recycling tests with excavated materials of these exploration tunnels can reduce the geologic uncertainties influencing the TEMH (Lieb, 2009).

The determination of the main uncertainties affecting the TEMH, which took into account subjective estimates of experts (answering of a questionnaire) and experience gained from recent tunneling projects, shows that the planning of the TEMH is strongly influenced by geologic- and construction uncertainties. Experts determined the concept of the processing technology of the excavated materials (see Table 3.1), which is an uncertainty about processing, as the major uncertainty of TEMH. On the other hand, proper process technologies to process excavated materials to shotcrete- or concrete aggregates were successfully applied in recent tunnel construction projects

(see Thalmann, 1996 and Kruse, 2002). These processing technologies have to be investigated in actual and future tunnel construction projects to obtain more experience regarding uncertainty about processing of tunnel excavation material.

Chapter 4

THE DECISION AIDS FOR TUNNELING

The Decision Aids for Tunneling (DAT), a computer-based tool, are used in this research to model the decision problem. The present Chapter describes the DAT based on Einstein (2001, 2004) and Min (2008). In addition, the resources module of the DAT is introduced.

4.1 DESCRIPTION OF THE DECISION AIDS FOR TUNNELING

In essence, the DAT enable one to determine the tunnel construction cost and time as well as produced resources such as excavated materials and required resources such as construction materials. The DAT work with standard information such as geologic/geotechnical descriptions, tunnel geometries, and construction characteristics, which are used by tunnel designers and contractors. In general, these input parameters are obtained through a combination of objective information from typical geologic explorations as well as geotechnical investigations and subjective estimates of experts. The level of detail of the input, defined by the user, depends on the available information and, thus, on the project phase. Most important, the DAT allow one to consider uncertainties in all the input parameters. Accordingly, results will be distributions of construction cost, time and resources. These results can be the basis of decision- or risk analysis.

The DAT essentially consist of two major components (Figure 4.1):

- Geologic Module (Description of Geology) and
- Construction Module (Construction Simulation and Construction Management).

A somewhat different way of describing the structure of the DAT is to define four components (modules): geologic module, construction module, resource module, and updating module (Moret et al., 2009; Einstein, 2008). The subdivision of the DAT into two components, shown in Figure 4.1, incorporates the resource module and the updating module in the construction module. This build-up into two components depicts the data structure of the DAT; thus, it is used throughout this research.

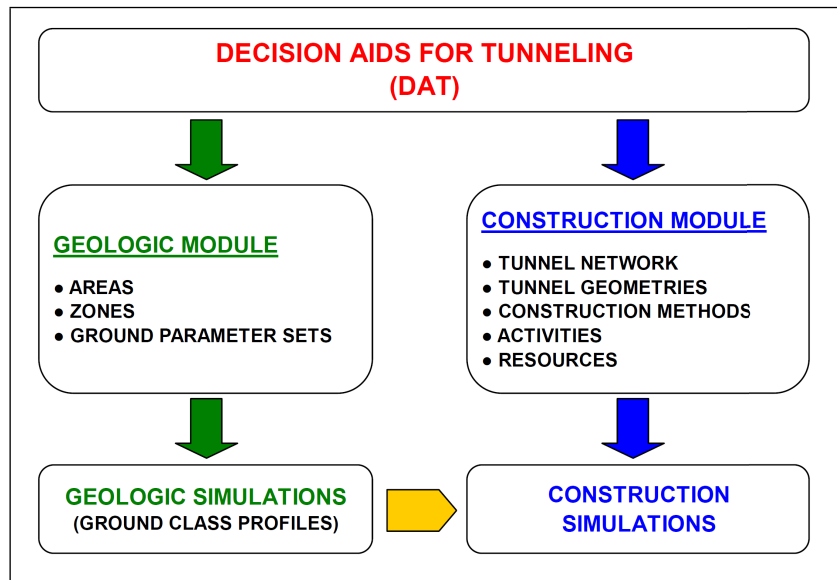


Figure 4.1: Major Components of the DAT (Min, 2008)

4.1.1 GEOLOGIC MODULE

The geologic module uses the geologic/geotechnical parameters such as, for example, lithology, water occurrence, and overburden, to produce probabilistic "Ground Class" profiles. Based on the included uncertainties in the geologic/geotechnical parameters the DAT simulate a possible profile for each parameter. A combination of these parameter profiles results in the ground class profile. Figure 4.2 illustrates parameter profiles of a single simulation with the corresponding ground class profile. A number of simulations results in a distribution of different ground class profiles, which represents the uncertainty in the geology.

4.1.2 CONSTRUCTION MODULE

The construction process through the ground class profile, obtained from the geologic module, is simulated with the construction module. Therefore, "Construction Methods" are assigned to corresponding ground classes. These construction methods determine the tunnel cross section, the support system, and the excavation method, which is best suited for a particular ground class. Again, the level of detail of the

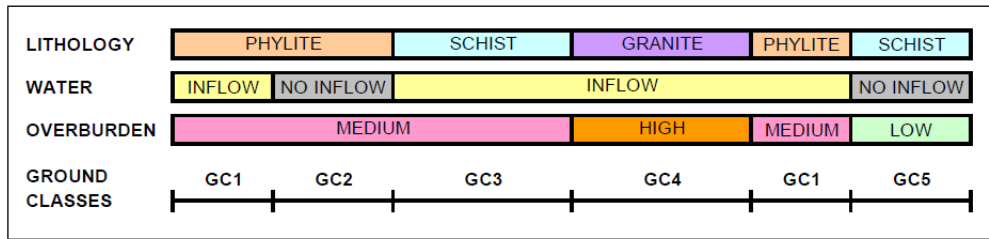


Figure 4.2: Ground Class Profile (Note that the same parameter states lead to the same ground class, for example, "GC1".)

input can be defined by the user and depends on the project phase. The DAT enable the user to define each construction method with associated "Activities". These activities are combined for each construction method in a corresponding "Activity Network". If a low level of detail of the simulation is sufficient the construction method is characterized by one activity. For instance, one activity models the entire construction round of Drill and Blast or the entire construction cycle of a TBM. A more detailed approach, describes a construction method with a series of activities to express all steps (e.g., drilling, loading, blasting, mucking, bolting, etc.) of each round (or cycle) of the construction performance. Hence, one round (or cycle) is simulated with an activity network which consists of one or more activities. Figure 4.3 schematically illustrates the relationship of the different components of the construction module.

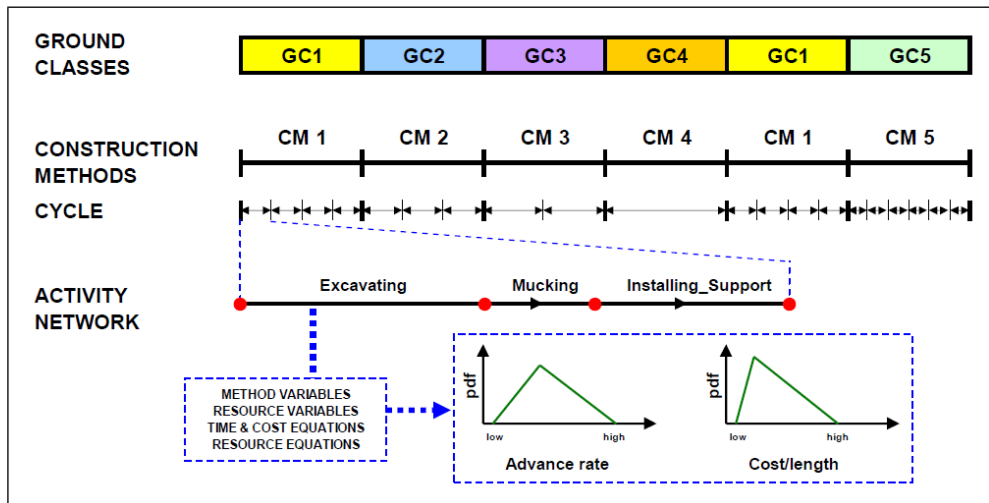


Figure 4.3: Construction Simulation

As mentioned before, the DAT allow to produce construction time and cost. Therefore, the activities are defined with method variables, which are in the simplest case in the form of advance rates and costs per linear meter. These variables are related in time and cost equations. Figure 4.3 illustrates the method variables

in the form of probability density functions (pdf). These probability distributions incorporate the construction uncertainties, which are independent of the geology, in the construction module. Due to the cyclic characteristic of tunnel performance the cost and time to complete each activity is calculated for each cycle (or round). Consequently, the total construction time and cost to construct the entire tunnel is computed by summing up all the times and costs of each cycle (or round).

Further, the construction methods treat the used and produced "*Resources*" during the construction performance. The amount of resources used or produced from a particular activity is computed from resource variables as with the resource equations. These resource variables and resource equations can be defined by the user. Most importantly, the DAT enable one to include uncertainties in the resource variables.

The Monte Carlo procedure is used to simulate the construction process. At the beginning, one of the many probabilistic ground class profiles is computed based on the geologic module. Accordingly, this ground class profile is related to the corresponding construction method profile. Then the construction simulation performs cycle by cycle (or round by round) through the ground class profile. This procedure results, among others, in a total cost and time for each simulation. Repeating this procedure yields another ground class profile as well as method variables and therefore different total costs and total times. Figure 4.4 illustrates a so-called time-cost scattergram. One point in this scattergram represents the total cost and time for a particular simulation. In addition, the DAT provide various other possibilities to represent the simulation results in tables or graphs, such as position-time plots, cost-time plots, and volume-time plots.

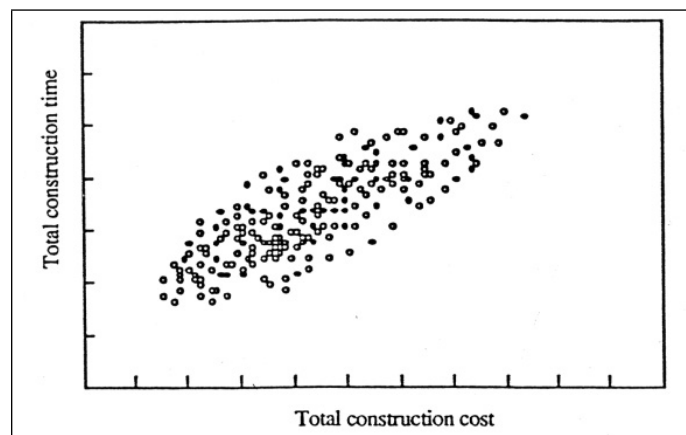


Figure 4.4: Time-Cost Scattergram (Einstein, 2001)

Other factors involved in tunnel construction such as delays caused by construction method changes, learning curves, and other delays due to operational aspects can also be considered in the DAT. Moreover, the DAT enable one to model entire tunnel systems with several tunnels, shafts, and other features. Modeling such a tunnel systems makes use of a "*Tunnel Network*" which depicts the relation and

time order of the parts of the tunnel system in the DAT. Figure 4.5 represents a simple tunnel network. A so called "Dummy" tunnel is an imaginary tunnel which is necessary to model the tunnel construction sequence correctly.

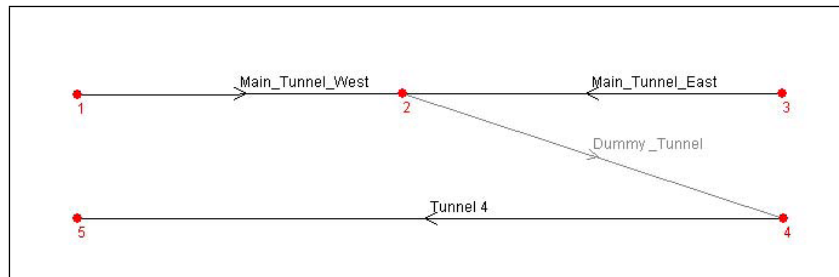


Figure 4.5: Tunnel Network (Min et al., 2009)

4.2 RESOURCES IN THE DECISION AIDS FOR TUNNELING

Currently the fourth resource module is used to model resources in the DAT. The first resource modules were developed by Halabe (1995) and Marzer (2002). Kollarou (2002) applied the resource module with the interface MBK⁴ based on Marzer (2002) to simulate the excavation materials handling in the Löttschberg Base Tunnel. This research is summarized in Einstein (2004). Min (2008) enhanced the previous resource modules.

4.2.1 PRINCIPLES OF MODELING RESOURCES

This Subsection follows the User's Manual of the DAT (Min et al., 2009) to explain the basics of incorporating resources in the simulations. The goal of the resource module is to consider resources such as construction material, excavation material, labor or equipment in the simulation. Thus, the simulation considers how the construction process is influenced due to these resources. For instance, a lack of construction materials, such as rock bolts for initial support works, results in an idle time and, thus, leads to an interruption of the construction process.

The resource module of the DAT enables one to define all resources produced or used during the tunnel construction or only the resources which are of interest for the particular simulation. For each activity one has to define what resources will be used and produced. The amount of these used or produced resources of the particular activity is specified with resource equations. These resource equations are defined by the input of the user. In the next step the "Repositories" are created. A repository is

⁴MBK is the abbreviation of the German word "*Materialbewirtschaftungskonzept*", which means Materials Management Concept.

where the tunnel draws resources from or deposits into. Each resource is allocated to a specific part of the repository, which are denoted by "*Stocks*". Moreover, the initial-, minimum- and maximum level of each resource in the repository can be defined by the user; thus, the capacity of the repository as well as the amount of available resources are incorporated in the simulation. In the last step the user specifies for each "*Tunnel*" in the tunnel network what repository must be used and where the repository is located on the construction site. It is important to note that the DAT allow one to allocate only one repository to a particular tunnel.

Chapter 5

SIMULATION MODEL

As mentioned in Subsection 2.2.3, in engineering one uses the decision analysis cycle (see Figure 2.2) to determine parameters, include them in engineering models, and make decisions based on the results of the model. This Chapter describes such an engineering model which simulates the TEMH and, thus, is called simulation model.

In TEMH, determined parameters are, for example, the geologic information of the investigated tunnel construction project such as the lithology or information regarding the transportation concept of the excavated materials. In general, these parameters depend on the respective tunnel construction project and its actual planning stage. After collecting this information, the determined parameters are included in an engineering model, which simulates the TEMH. In the following Sections, a possible engineering model, which is based on the DAT and their resource module, is explained. This explanation is subdivided corresponding to the main components of the DAT, the geologic module and the construction module (see Section 4.1). Specifically, the construction module treats the material flows in the TEMH process. Figure 5.1 shows the material flows with related actions in the TEMH process. In addition, the general applicability of the model to common tunneling methods such as mechanized- and conventional tunneling is discussed in this Chapter.

The so-called simulation model can be defined as an economic (resource) model (see Subsection 2.2.3) and can be used deterministically and/or probabilistically. As a result, the simulation model can be applied in the deterministic- and/or probabilistic (model) phase of the decision analysis cycle (see Figure 2.2). Due to the intent of this research, managing the uncertainties in TEMH using decision analysis, the focus lies on a probabilistic application of the simulation model.

Referring to the discussed model sequence of Subsection 2.2.4, the simulation model can be classified as a prototype model. This prototype model considers all relevant steps of the tunnel construction as well as the related handling of the excavated materials. An upgrade to a production model would, for instance, consist

of including specific characteristics of a tunnel construction project. Based on the results of the simulation model one can make decisions which may lead to a quite different concept of handling the excavated materials.

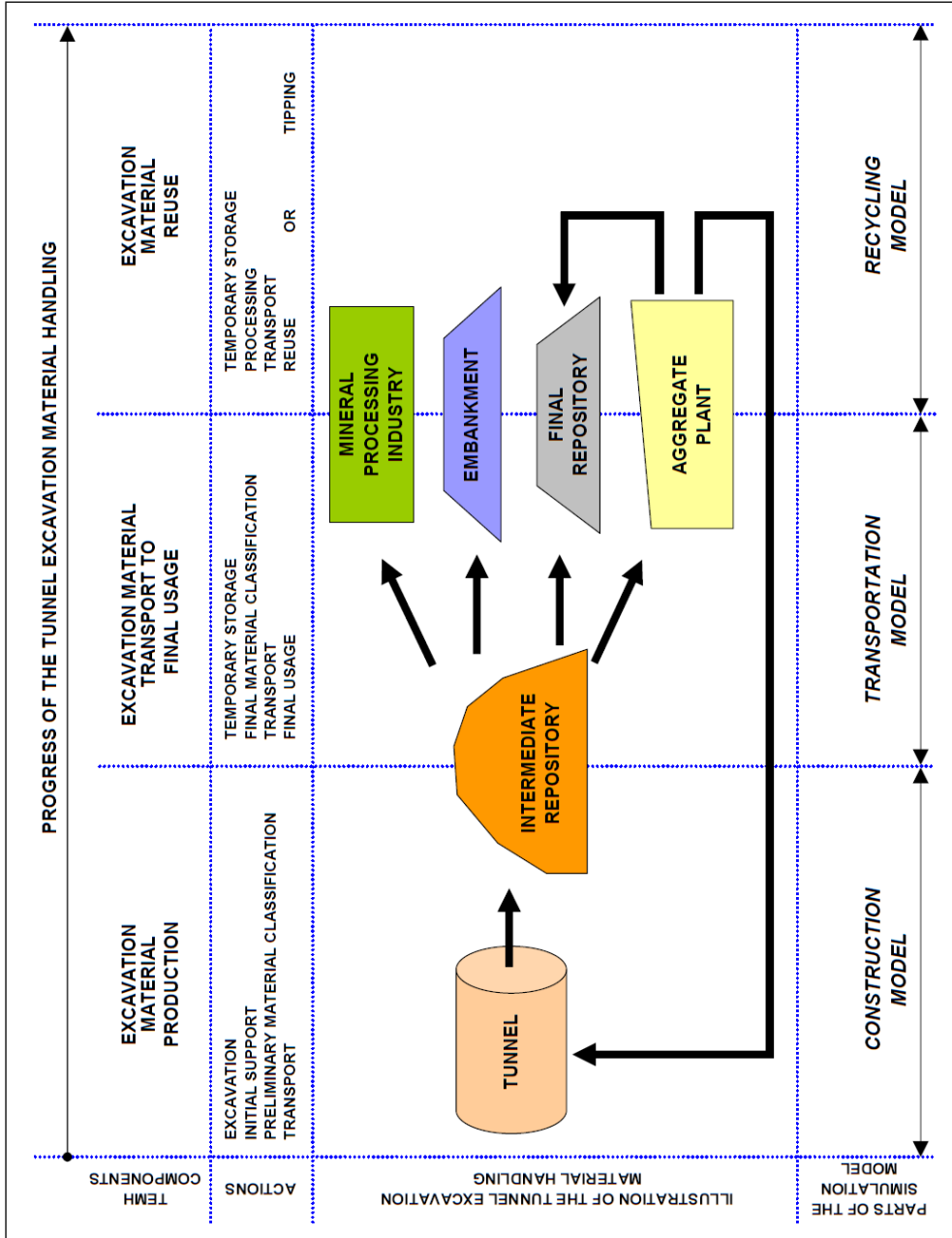


Figure 5.1: Material Flows in the TEMH Process

5.1 THE GEOLOGIC MODULE

Emphasis in this Section is placed on the implementation of the excavation materials classification in the geologic module. Figure 5.2 represents the general schematic of a ground class profile in the simulation model. First, the geologic/geotechnical parameters such as, for example, lithology, water occurrence, and overburden determine the preliminary ground class profile. Further results of exploration and investigation regarding the excavation materials properties are included ("*Excavation Material Classes*"). Therefore, each preliminary ground class, for example "GC1", is extended by the predicted excavation material classes. This procedure ensures that each final ground class, for example "GC1_A", consists of a particular excavation materials class. Hence, the geologic module in the simulation model ensures that each excavated material is related to the corresponding excavation materials class. This procedure simulates the "*Preliminary Material Classification*". The "*Preliminary Material Classification*" is the preliminary allocation of the excavated materials to the specified excavation materials classes. In reality, the "*Preliminary Material Classification*" is based on a correlation of geologic exploration, laboratory testing during the exploration- and design phase, and the engineering geologist's assessment of the excavated materials at the tunnel face.

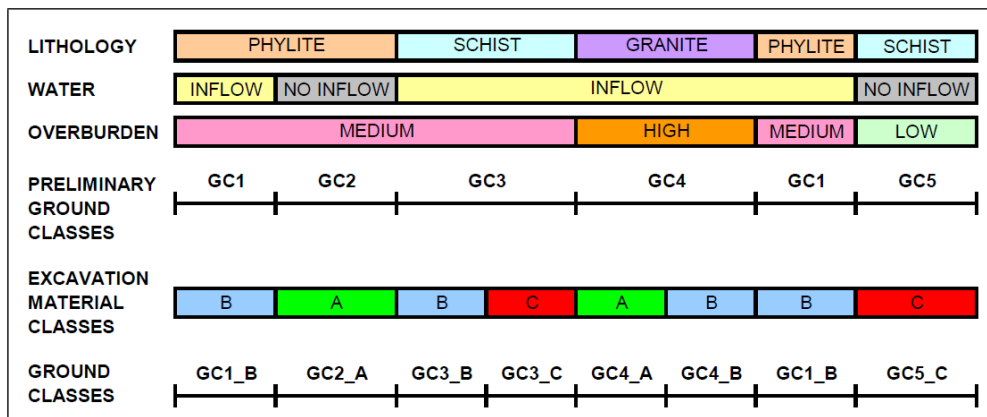


Figure 5.2: Ground Class Profile with Implementation of the "*Preliminary Material Classification*" ("*Excavation Material Classes*")

It is important to remember that the DAT allow one to consider uncertainties in the geologic/geotechnical parameters as well as in the excavation materials classification. Thus, the produced ground class profile indicates the probabilities of the occurrence of particular excavation materials classes at a particular tunnel location. This is an essential aspect in the management of the excavated materials.

5.2 THE CONSTRUCTION MODULE

The construction module of the simulation model relates the construction process through the ground class profile to the particular TEMH. This involves relating the ground classes to corresponding construction methods. Figure 5.3 schematically illustrates this relation. Construction methods and their associated activities, which are combined in an activity network, define the tunnel cross sections, excavation methods, and support measures that are best suitable to the corresponding ground class.

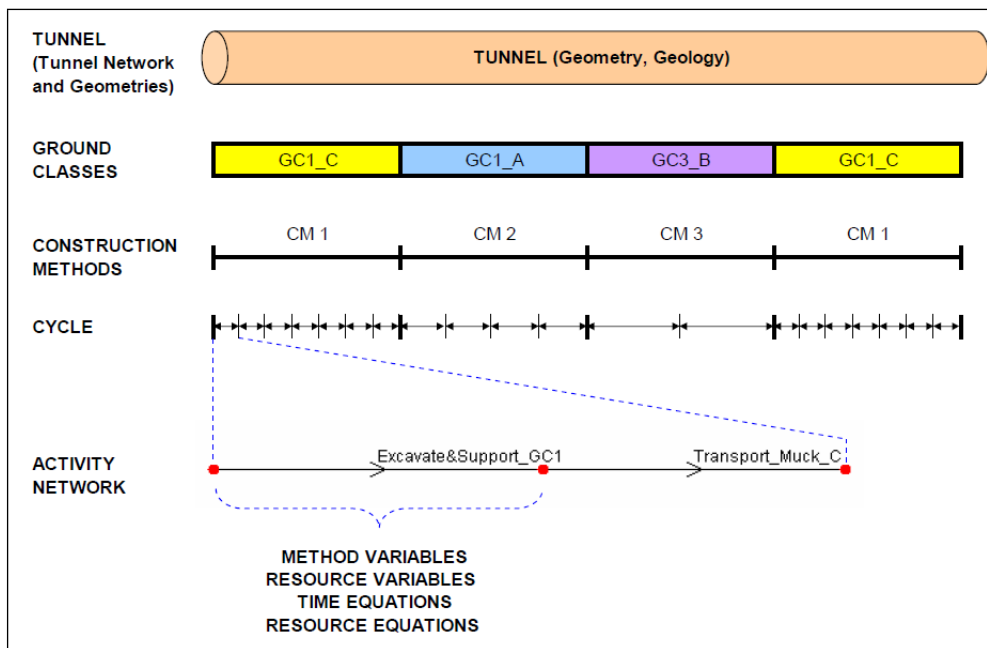


Figure 5.3: Relationship between Tunnel Geometry, Geology (Ground Classes), Construction Methods, Activities, and Time/Resource Equations in the Simulation Model

Figure 5.4 illustrates the structure of the standard tunnel network⁵ of the developed simulation model. This tunnel network models the tunnel construction performance as well as the related TEMH of a particular tunnel. Each part of the tunnel network such as the "Construction Model", "Transportation Model", and "Recycling Model", is related to the same ground class profile of the particular tunnel and is performed for each simulation. Also construction methods are assigned to each part of the simulation model. Figure 5.1 shows which part of the tunnel network of the simulation model treats which component of the TEMH process. The simulation tasks of the parts and subparts of the tunnel network are illustrated in Table 5.1 and are introduced below.

⁵Recall: The tunnel network depicts the relation and time order of "Tunnels" in the DAT. It is important to note that "Tunnels" in the DAT can be physical tunnels or imaginary (so-called "Dummy") tunnels, which are necessary to perform the simulations.

Table 5.1: Simulation Tasks of the Components of the Simulation Model

COMPONENTS OF THE SIMULATION MODEL	SIMULATION TASKS	TREATED RESOURCES
CONSTRUCTION MODEL		
Excavation	Tunnel Construction (Excavation and Initial Support)	No Resources
Excavation with TEMH	Excavation Material Production	Excavation Material Classes – Intermediate Repository
	Preliminary Excavation Material Classification	Recycled Excavation Material
	Excavation Material Transport to Intermediate Repository	
	Reuse of the Recycled Excavation Material – Initial Support	
TRANSPORTATION MODEL		
Muck Transport	Final Excavation Material Classification	Excavation Material Classes – Intermediate Repository
	Excavation Material Transport to Final Usage	Excavation Material Classes – Final Usage
RECYCLING MODEL		
Processing	Excavation Material Recycling	Excavation Material Classes – Final Usage
		Recycled Excavation Material
Inner Liner	Construction of the Inner Liner	Recycled Excavation Material
	Reuse of the Recycled Excavation Material – Inner Liner	

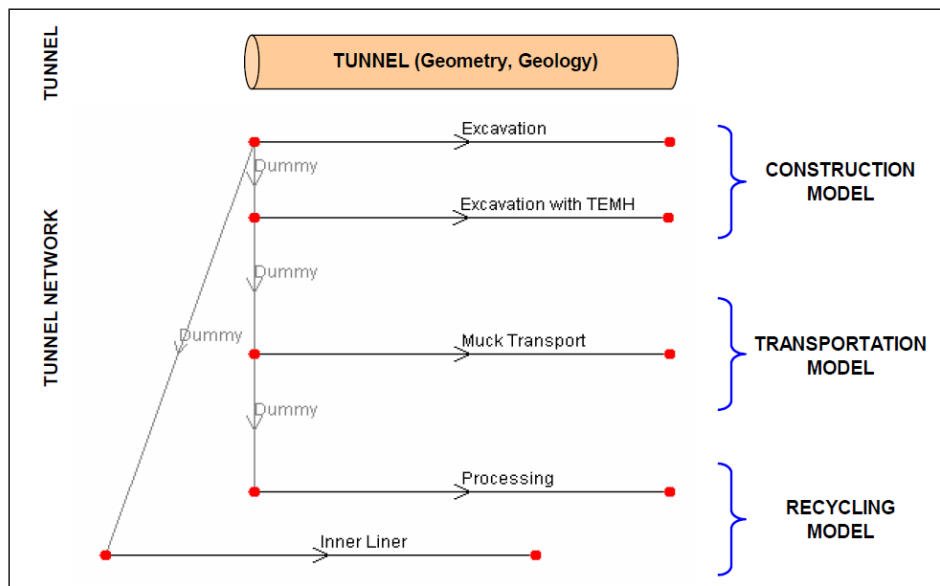


Figure 5.4: Structure of the Tunnel Network of the Simulation Model

The "Construction Model" consists of the "Excavation" and the "Excavation with TEMH" subparts. The "Excavation" subpart simulates the tunnel construction; namely, the excavation and the related initial support without considering the TEMH. To simulate the TEMH between the tunnel face and the intermediate repository is the task of the "Excavation with TEMH" subpart. Specifically, the excavation material production, the "Preliminary Material Classification", the transport of the excavated materials to the intermediate repository, and a possible reuse of recycled excavated materials in the initial support is treated in the "Excavation with TEMH" subpart. The "Muck Transport" subpart of the "Transportation Model" simulates the "Final Material Classification" and the transport of the excavated materials between the intermediate repository and their final usage. Finally, the "Recycling Model" with the "Processing" and "Inner Liner" subparts treats a possible reuse of the excavated materials. The recycling of the excavated materials to concrete- or shotcrete aggregates is modeled with the "Processing" subpart. The reuse of these recycled excavated materials in the inner liner is simulated by the "Inner Liner" subpart. The Subsections 5.2.3 to 5.2.5 summarize the parts of the simulation model in detail.

With this introduction of the parts and subparts of the tunnel network, it is now possible to discuss the structure of the tunnel network.

5.2.1 THE PARALLEL STRUCTURE OF THE TUNNEL NETWORK

The subparts of the tunnel network (see Figure 5.4) such as the "Excavation", "Excavation with TEMH", "Muck Transport", and "Processing" start at the same time. This structure, which uses these subparts in parallel, demands that a subpart of the

tunnel network (e.g., "Muck Transport") includes the time of the preceding subpart (e.g., "Excavation with TEMH") to simulate the progress of the TEMH accurately. In other words, the computed time of the preceding subpart has to be considered in the current subpart (see Figure 5.5). Therefore, the activity network of the current subpart is based on the activity network of the preceding subpart (see Figure 5.6). In particular, the current subpart uses activities which are similar or equal to activities of the preceding subpart to consider the time of the preceding subpart (see Figure 5.5 and 5.6). These similar or equal activities use the same time equations as the corresponding activities of the preceding subpart and are called "reused" activities throughout this research. Subsection 5.2.2 discusses these "reused" activities in detail. The new activities of the current subpart (see Figure 5.5) simulate the components of the TEMH process which correspond to the current subpart.

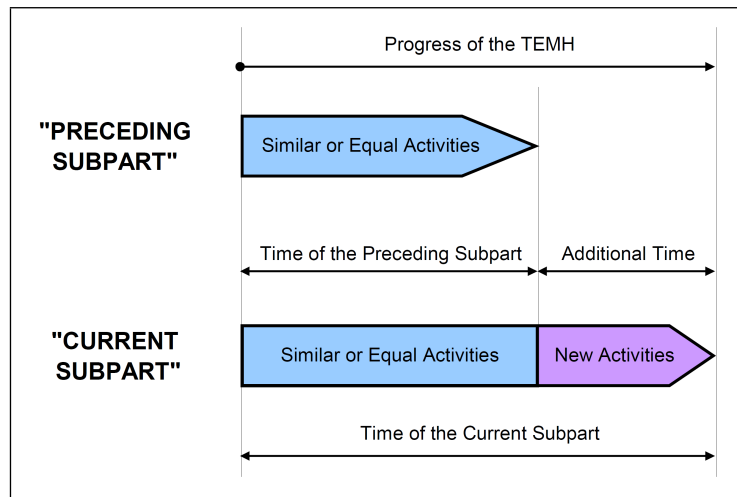


Figure 5.5: Time of the Preceding Subpart Considered in the Current Subpart

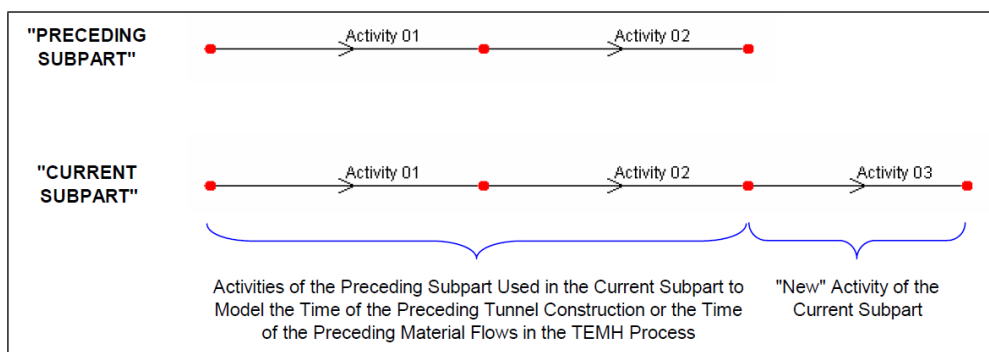


Figure 5.6: Activities of a Preceding Subpart of the Tunnel Network Used in the Activity Network of the Current Subpart of the Tunnel Network (Note that "Activity 01" and "Activity 02" are not assigned resources.)

The reason for using the parallel structure of the tunnel network is that each

subpart produces as a simulation outcome a specific curve in a position-time plot (see Figure 5.7). Thus, such a position-time plot shows the general performance of the tunnel construction without considering the material flows in the TEMH process ("Excavation" curve). More importantly, the performance of the specific components of the TEMH process, which are successively included in the subsequent subparts ("Excavation with TEMH", "Muck Transport", and "Processing") are illustrated. As a result, the time consumption of specific components of the TEMH at a certain position of the tunnel can be investigated. For example, Figure 5.7 presents the time consumption " $\Delta T1$ " of the components of the TEMH at the position "X" of the tunnel, which are modeled with the new activities of the "Excavation with TEMH" subpart (see Figure 5.5). Figure 5.7 also shows that the time of the preceding subpart (e.g., "T1" of the "Excavation" subpart) is considered in the current subpart (e.g., "Excavation with TEMH" subpart).

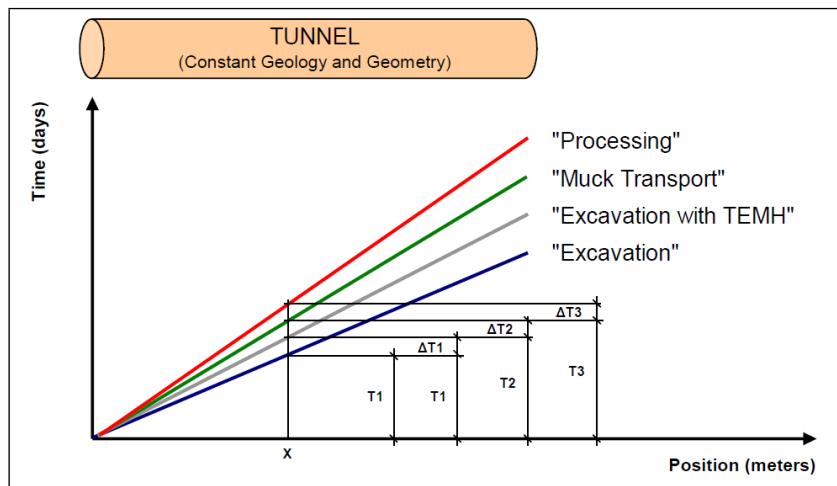


Figure 5.7: Subparts in a Schematic Position-Time Plot

If components of the TEMH process can be performed simultaneously with the tunnel construction (excavation and initial support) or other material flows in the TEMH process the curves will overlap. For instance, Figure 5.8 schematically illustrates an overlapping of the "Excavation" and "Excavation with TEMH" curves. This is so because in this example it is anticipated that the transport of the excavated materials between the tunnel face and the intermediate repository is performed simultaneously with the initial support of the same cycle (or round). Figure 5.9 schematically illustrates how a simultaneous performance of activities is modeled. The similar or equal activities simulate, for example, the tunnel construction with the initial support. Otherwise, the new activities treat the transport of the excavated materials, which can be performed simultaneously with the initial support. As a result, the current subpart (e.g., "Excavation with TEMH") consumes the same time as the preceding subpart (e.g., "Excavation") and, thus, the curves overlap (see

Figure 5.8). Such position-time plots, which present a specific curve for the subparts "Excavation", "Excavation with TEMH", "Muck Transport", and "Processing", exist only due the parallel structure of the tunnel network and can be useful for decision making.

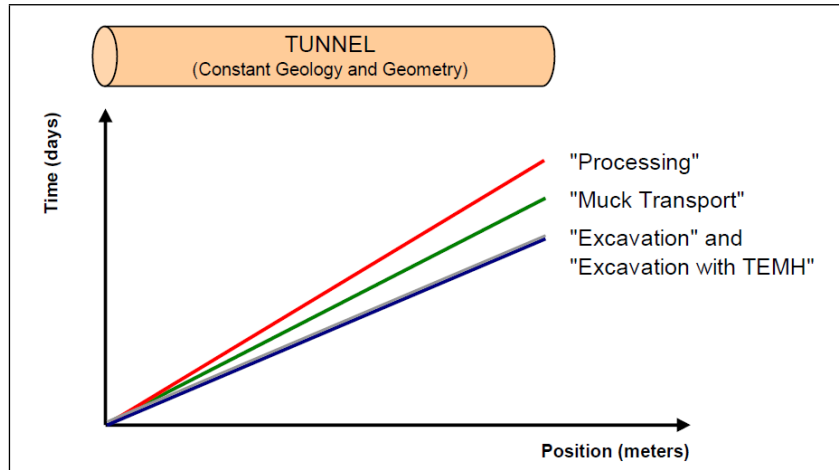


Figure 5.8: Overlap of two Subparts in a Schematic Position-Time Plot

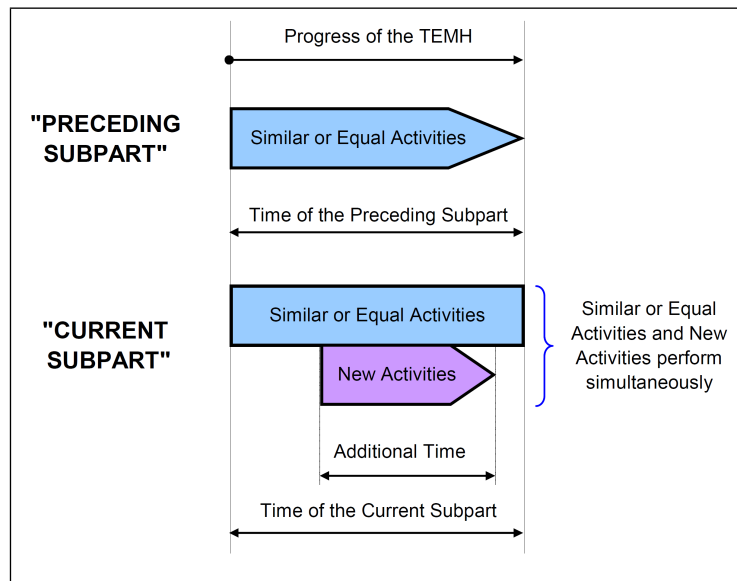


Figure 5.9: Modeling of a Simultaneous Performance in the Simulation Model

It is important to note that due to the parallel structure of the tunnel network each subpart of the tunnel network treats only the resources, which are related to the simulation tasks of this particular subpart (see Table 5.1). If all the parallel subparts, which start at the same time and model the material flows in the TEMH process ("Excavation with TEMH", "Muck Transport", and "Processing"), would model,

for instance, the excavation material production due to the tunnel excavation the computed quantity of the excavated materials would be three times higher than the real quantity. As a result, only the "Excavation with TEMH" subpart, which treats the excavation material production as a simulation task (see Table 5.1), models the resources of the excavation material production in the simulation model. The "Muck Transport" subpart and the "Processing" subpart do not treat the resources of this preceding material flow in their activity networks. However, as mentioned before, the time of the activities of the preceding subparts have to be considered in the activity networks of the current subpart to simulate the progress of the TEMH correctly. Figure 5.10 schematically illustrates how preceding material flows and simulation tasks are modeled in the parallel structure of the simulation model.

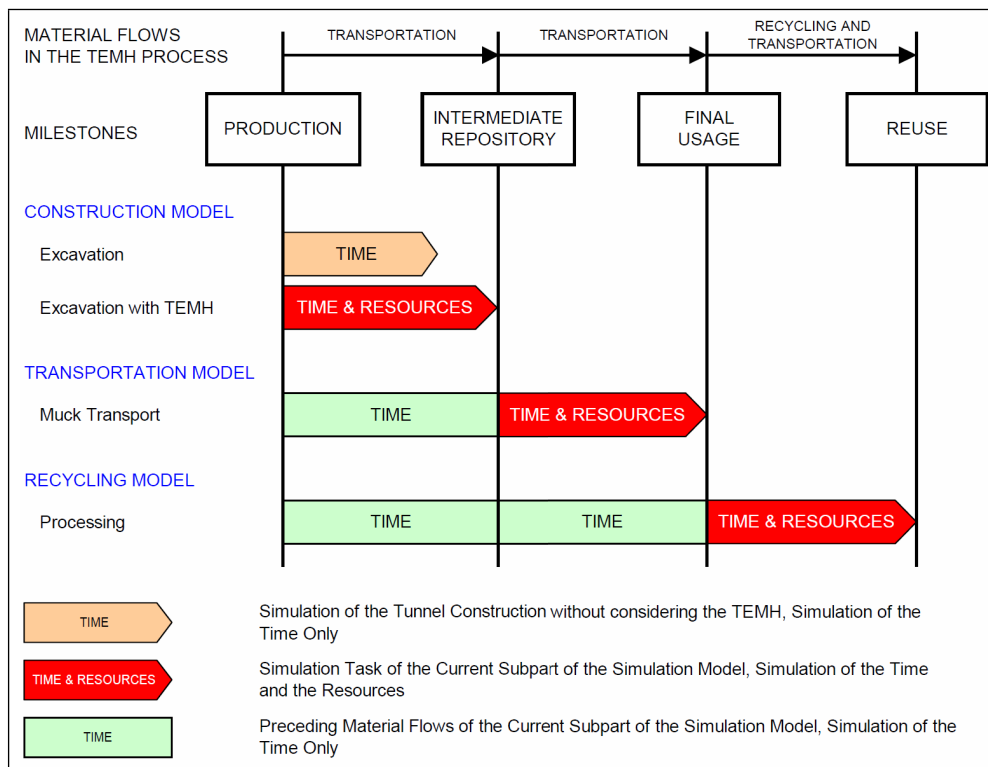


Figure 5.10: Preceding Material Flows and Simulation Tasks of the Subparts of the Tunnel Network (Note that the "Inner Liner" subpart starts a certain time after the other subparts and, thus, is neglected in this Figure.)

The construction of the inner liner ("Inner Liner" subpart, see Figure 5.4) starts a certain time after the starting of the tunnel construction ("Excavation" subpart). Therefore, in the tunnel network the "Inner Liner" subpart is connected by a "Dummy Tunnel" to the "Start Node" of the "Excavation" subpart (see Figure 5.4). To model the duration between the start of the "Excavation" and the start of "Inner Liner" the

DAT allow the user to define a "Time Delay"⁶ between the start of the "Excavation" and the "Inner Liner". The other subparts are also connected with "Dummy Tunnels" but no "Time Delays" are defined; thus, they start at the same time (see Figure 5.7).

5.2.2 "REUSED" ACTIVITIES

As mentioned before, in the activity network of the current subpart of the tunnel network similar or equal activities of the preceding subpart are used. These "reused" activities consider the time of the preceding subpart in the current subpart of the tunnel network, which is necessary due to the parallel structure of the tunnel network (see Subsection 5.2.1). Therefore, a "reused" activity uses the same time equation as the related activity of the preceding subpart. Moreover, "reused" activities also treat resources if they model a simulation task of the specific subpart of the tunnel network. The advantage of this concept of reusing activities is that the input of the simulation model is significantly reduced because activities of the preceding subpart can be equally "reused" in the activity networks of the current subpart or copied, modified, and subsequently "reused" in the activity networks of the current subpart. Modifications occur because "reused" activities have to consider that a subpart of the tunnel network treats only resources, which are related to the simulation tasks of this particular subpart (see Subsection 5.2.1). Due to these modifications, three types of "reused" activities (see Table 5.2) are distinguished in the simulation model:

- **Type A:** In the preceding- and current subpart an activity of type A does not simulate a simulation task and, thus, an activity of type A does not treat resources. The same time equation is used to compute the time of the activity in the preceding and current subpart. Hence, the same activity (e.g., "A") is used for the preceding- and current subpart.

An example of a "reused" activity of type A is the activity "Maintenance", which simulates the maintenance on the TBM (see Subsection 5.3.1). The activity "Maintenance" does not treat resources in the preceding- (e.g., "Excavation") and current (e.g., "Excavation with TEMH") subpart. Hence, the activity "Maintenance" is used in both subparts to compute the time of the maintenance on the TBM.

- **Type B:** In the preceding subpart an activity of type B (e.g., "B") uses a particular time equation to compute its time but does not treat resources. However, in the current subpart an activity of type B treats resources because it models a simulation task of the current subpart. For this reason, the activity "B" of the preceding subpart is copied and assigned resources. This copied and modified activity is "reused" in the current subpart and called "B.Res". Both activities (e.g., "B" and "B.Res") use the same time equation, which expresses their

⁶The "Time Delay" is discussed on page 62 of the SIMJAVA User's Manual (Min et al., 2009).

similarity.

A "reused" activity of type B is, for example, the activity "*Excavate&Support_Res*" of the "*Excavation with TEMH*" subpart (see Subsection 5.3.1). In the preceding subpart (i.e., "*Excavation*" subpart) the similar activity "*Excavate&Support*" does not treat resources because the "*Excavation*" subpart neglects the material flows in the TEMH process. However, the current subpart (i.e., "*Excavation with TEMH*" subpart) considers the TEMH and, thus, treats resources. Therefore, the activity "*Excavate&Support*" is copied and assigned resources to model a simulation task of the "*Excavation with TEMH*" subpart. The copied and modified activity is called "*Excavate&Support_Res*" and uses the same time equation as the activity "*Excavate&Support*" of the preceding subpart.

- **Type C:** An activity of type C of the preceding subpart (e.g., "*C*") treats resources because it models a simulation task of the preceding subpart. However, in the current subpart an activity of type C does not treat resources because the activity does not model a simulation task. Therefore, the activity "*C*" is copied and the assigned resources are deleted. Subsequently, the copied and modified activity is "reused" in the current subpart and called "*C_noRes*". Again, both activities (e.g., "*C*" and "*C_noRes*") use the same time equation.

The activity "*Transport_Final_Usage_noRes*" of the "*Recycling Model*" of conventional tunneling (see Subsection 5.4.3) is an example of a "reused" activity of type C. In the preceding subpart (i.e., "*Muck Transport*" subpart) the similar activity "*Transport_Final_Usage*" simulates a simulation task (i.e., excavation material transport to final usage, see Table 5.1) and, thus, is assigned resources. In the current subpart (i.e., "*Processing*" subpart) the transport of the excavated materials from the intermediate repository to their final usage is not a simulation task (see Table 5.1). Therefore, only the time of the transport of the excavated materials to their final usage is considered in the current "*Processing*" subpart. To do this, the activity "*Transport_Final_Usage*" is copied and the assigned resources are deleted. This copied and modified activity is called "*Transport_Final_Usage_noRes*" and "reused" in the "*Processing*" subpart to consider the time of the preceding "*Muck Transport*" subpart.

Table 5.2 summarizes these three types of "reused" activities and shows how they are specified in the current subpart of the tunnel network. The checkboxes of Table 5.2 illustrate if the particular activity is used to treat resources and/or to compute its time.

The Subsections 5.2.3 to 5.2.5 discuss the parts of the tunnel network of the simulation model (see Figure 5.4), followed by an explanation of simulating resources in the simulation model (Subsection 5.2.6).

Table 5.2: Types of "Reused" Activities in the Simulation Model (Note that activities of one type always use the same time equation to calculate their time.)

	Preceding Subpart		Current Subpart
Type A	<div style="border: 1px solid black; padding: 5px; width: fit-content;"> <p style="text-align: center;">Activity "A"</p> <p>Resources <input type="checkbox"/></p> <p>Time <input checked="" type="checkbox"/></p> </div>	→	<div style="border: 1px solid black; padding: 5px; width: fit-content;"> <p style="text-align: center;">"Reused" Activity "A"</p> <p>Resources <input type="checkbox"/></p> <p>Time <input checked="" type="checkbox"/></p> </div>
Type B	<div style="border: 1px solid black; padding: 5px; width: fit-content;"> <p style="text-align: center;">Activity "B"</p> <p>Resources <input type="checkbox"/></p> <p>Time <input checked="" type="checkbox"/></p> </div>	→	<div style="border: 1px solid black; padding: 5px; width: fit-content;"> <p style="text-align: center;">"Reused" Activity "B_Res"</p> <p>Resources <input checked="" type="checkbox"/></p> <p>Time <input checked="" type="checkbox"/></p> </div>
Type C	<div style="border: 1px solid black; padding: 5px; width: fit-content;"> <p style="text-align: center;">Activity "C"</p> <p>Resources <input checked="" type="checkbox"/></p> <p>Time <input checked="" type="checkbox"/></p> </div>	→	<div style="border: 1px solid black; padding: 5px; width: fit-content;"> <p style="text-align: center;">"Reused" Activity "C_noRes"</p> <p>Resources <input type="checkbox"/></p> <p>Time <input checked="" type="checkbox"/></p> </div>

5.2.3 CONSTRUCTION MODEL

The "Construction Model" consists of two subparts, namely, the "Excavation" and the "Excavation with TEMH" subpart. Both subparts are performed in each simulation. The "Excavation" subpart treats the tunnel construction such as, for example, excavating and initial support without considering any corresponding resources such as the handling of the excavated materials. On the other hand, the "Excavation with TEMH" subpart simulates, due to the parallel structure of the tunnel network (see Subsection 5.2.1), the tunnel construction of the particular tunnel in the same way as the preceding "Excavation" subpart. Additionally, the "Excavation with TEMH" subpart includes the handling of the excavated materials such as the "Preliminary Material Classification", the transport of the excavated materials to the intermediate repository, and a possible reuse of the recycled excavation materials (concrete- or shotcrete aggregate) in the initial support. Hence, the output of the two subparts of the "Construction Model", for instance, the construction time, can be different if the TEMH affects the tunnel construction performance. The reuse of excavated materials in the initial support is always simulated by the "Excavation with TEMH" subpart because the aggregate need of the initial support exists after the excavation of the current tunnel round (or cycle) is finished and not after the excavated materials are processed to concrete aggregates. Thus, the reuse of excavated materials in the initial support works is a simulation task of the "Excavation with TEMH" subpart (see Table 5.1).

5.2.4 TRANSPORTATION MODEL

The transportation of the excavated materials from the intermediate repository to their final usage such as, for example, reuse as fill materials, purchase by the mineral processing industry, recycling at the aggregate plant, and tipping at the final repository is simulated with the "*Transportation Model*". Hence, the "*Transportation Model*", with the related subpart "*Muck Transport*", simulates the removal of the excavated materials from the intermediate repository as well as their transport to their final usage. In addition, the "*Transportation Model*" incorporates the "*Final Material Classification*" of the excavated materials which consists, in general, of a testing plan with standardized methods of investigation to determine the properties of the excavated materials. The observed information of this testing plan can be used to update the predictions for the as yet unexcavated part which can lead to a further reduction of the uncertainty of the unexcavated tunnel and, thus, of the TEMH. Therefore, the updating of the DAT based on research by Haas (Haas, 2000; Haas and Einstein, 2002) can be incorporated in the simulation model. As mentioned before, the "*Transportation Model*" has to consider the time of the preceding tunnel construction as well as the time of the preceding material flows of the excavated materials. However, the "*Transportation Model*" does not include the resource equations, which compute the production of the excavated materials, their transport to the intermediate repository and the reuse of recycled excavation materials in the initial support because these are the simulation tasks of the "*Construction Model*" (see Subsection 5.2.1).

5.2.5 RECYCLING MODEL

The "*Recycling Model*" consists of two subparts, namely, the "*Processing*" and the "*Inner Liner*" subpart that are performed in each simulation. Processing of qualified excavated material to, for instance, shotcrete- or concrete aggregate for the initial- or final support is simulated with the "*Processing*" subpart. Again, the "*Processing*" subpart considers the time of the preceding tunnel construction as well as the time of the preceding material flows of the excavated material. The resource equations of the preceding material flows are not considered because these are simulation tasks of the preceding subparts (see Subsection 5.2.1).

Reusing the recycled excavation materials in the final support is modeled with the "*Inner Liner*" subpart, which simulates the reuse of recycled excavation materials in the concrete of the inner liner. As explained before, the "*Inner Liner*" subpart starts a certain time after the other subparts of the tunnel network of the simulation model; thus, the "*Inner Liner*" does not explicitly consider the time of the preceding tunnel construction or the time of the preceding material flows.

5.2.6 RESOURCES IN THE SIMULATION MODEL

The resource module of the DAT (see Subsection 4.2.1) is extensively used in the simulation model to simulate the material flows in the TEMH process. In the resources module one has to define what resources are treated throughout the simulation. These resources are the different classes of the excavated materials at the intermediate repository or the final usage as well as the recycled excavation materials. The classification of the excavated materials is, in general, based on their reuse properties. Furthermore, for each activity one has to define the associated resources, which can be used or produced in the particular activity. Resource equations are used to specify the amount of these used or produced resources. Time equations compute the required time of this activity. Subsequently, a *"Repository"* for the entire simulation model is created from which the *"Tunnels"* draw resources from or deposit into. This *"Repository"* covers the entire TEMH process (see Figure 5.1) because the DAT allow one to assign only one specific *"Repository"* to a particular *"Tunnel"*. However, it is possible to subdivide this *"Repository"* into arbitrary sections denoted by *"Stocks"*. Each stock expresses in the simulation model a part of a particular *"real"* repository within the TEMH process and treats a particular excavation materials class. For instance, *"Int_Rep_Muck_A"* specifies the part of the intermediate repository which temporarily stores the excavation materials usage class A; in contrast, *"Final_Rep_Muck_C"* denotes the part of the final repository where the excavation materials usage class C is tipped. This procedure allows one to incorporate the location of the particular repository within the TEMH process. Figure 5.11 shows a possible subdivision of the intermediate repository into as many stocks as excavation materials classes are defined.

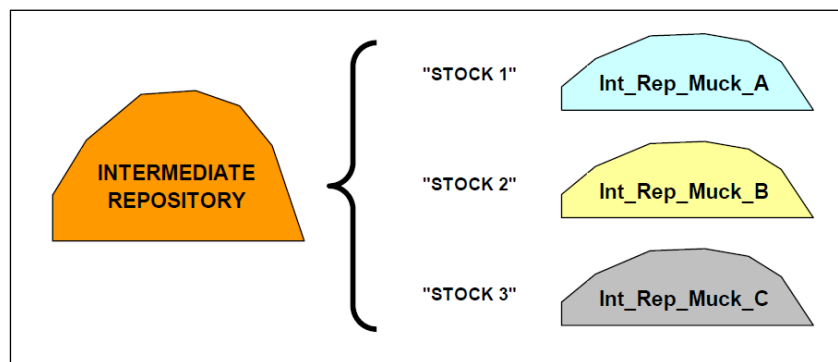


Figure 5.11: Intermediate Repository Subdivided into Stocks

Furthermore, the user has to define the initial-, minimum-, and maximum level of each stock of the *"Repository"*. Limited surface areas of the tunnel construction site often determine the capacity of the intermediate repositories and as a result can affect the construction performance. Thus, the determination of these levels is an important feature of the resource module because they enable one to incorporate the

specific capacity of each repository of the TEMH process in the simulation model.

As mentioned in the geologic module (Section 5.1), the DAT enable one to consider geologic uncertainties in the simulations. In addition, the construction module of the DAT allows one to incorporate construction uncertainties which are independent of the geology. These uncertainties are, for example, modeled as probability distributions and assigned variables of the time equations and resource equations.

At this point the structure of the developed simulation model has been explained. However, the TEMH is affected by the tunneling method. Specifically, the cyclic operation of tunneling has to be considered (Min, 2008). This cyclic operation yields a cyclic production and a cyclic transportation of the excavated materials. For example, a muck truck is repetitively used to transport the excavated materials from the tunnel face to the intermediate repository at the tunnel portal. Hence, Section 5.3 and 5.4 apply the simulation model to common tunneling methods such as mechanized- and conventional tunneling. Emphasis is placed on the activity networks of the subparts of the tunnel network of the simulation model (see Figure 5.4). It is important to note that in the following explanations the activities of the activity networks use general names. Thus, the relation to a corresponding ground class is not defined. The aim of this simplification is to enhance the clarity of the explanation of the simulation model. In contrast, Figure 5.3 shows one example of how activities are labeled if they are related to their corresponding ground class.

Furthermore, the time- and resource equations of the activities in the simulation model are described in the following Sections. The time equations are used to compute the activity time. The resource equations compute the used and/or produced resources of an activity. It is important to mention, that these equations with the related variables can be defined by the user. Moreover, internal functions (e.g., *round.length()*, see Equation (5.1)) of the DAT can be included in the equations. These internal functions return different states of a tunnel (e.g., the actual round length, position, water flow, etc.) during the simulation (Min et al., 2009).

5.3 MODELING MECHANIZED TUNNELING

To model the TEMH process of mechanized tunneling, each part and subpart of the tunnel network of the simulation model (see Figure 5.4) has to be performed. The following Subsections explain each part for mechanized tunneling.

5.3.1 CONSTRUCTION MODEL APPLIED TO MECHANIZED TUNNELING

As mentioned before, the *Excavation* subpart of the *Construction Model* simulates the tunnel construction (excavation and initial support) without the TEMH. Figure 5.12 illustrates the general activity network of the *Excavation* subpart of the *Construction Model* for mechanized tunneling, which is repeated for each cycle

of the construction process. The activity "*Excavate&Support*" represents the excavation of the tunnel as well as the initial support. The maintenance on the TBM is simulated through the activity "*Maintenance*".



Figure 5.12: Activity Network Modeling the "*Excavation*" Subpart of the "*Construction Model*" for Mechanized Tunneling

Time equations are assigned to each activity to calculate its time. Equations (5.1) and (5.2) specify the activities "*Excavate&Support*" and "*Maintenance*" for each type of ground class. The variable "*round_length()*" is an internal function of the DAT and returns the length (e.g., meters) of the actually performed cycle of the tunnel. The variable "*excavate&support_advance_rate*" describes the advance rate (e.g., meters per day) of the tunnel construction. In general, the advance rate varies from ground class to ground class. The variable "*maintaining_time*" expresses the time per cycle (e.g., days) to perform the maintenance on the TBM.

$$\text{Excavate\&Support Time} = \frac{\text{round_length}()}{\text{excavate\&support_advance_rate}} \quad (5.1)$$

$$\text{Maintenance Time} = \text{maintaining_time} \quad (5.2)$$

Figure 5.13 shows the activity network of the "*Excavation with TEMH*" subpart of the "*Construction Model*", which uses due to the parallel structure of the tunnel network (see Subsection 5.2.1) similar or equal activities ("*Excavate&Support_Res*" and "*Maintenance*") of the "*Excavation*" subpart. In addition to the "*Excavation*" subpart the material flows in the TEMH process are considered. Therefore, the activity "*Transport_Muck*" is introduced, which deals with the transport of the excavated materials from the cutter head of the tunnel boring machine to the intermediate repository using a conveyor. Reuse of recycled excavation materials as concrete aggregate⁷ for the initial support such as, for example, prefabricated segments is considered in the activity "*Excavate&Support_Res*", which is a "reused" activity of type B of the preceding "*Excavation*" subpart (see Subsection 5.2.2). The activity "*Maintenance*" of the "*Excavation with TEMH*" subpart is a "reused" activity of type A (see Subsection 5.2.2). The activities "*Dummy*" are not real activities but they are necessary to model the activity sequence correctly.

A specific characteristic of the activity network of "*Excavation with TEMH*" is its structure which takes the concurrent operation of a tunnel boring machine into account. In particular, the simultaneous muck production ("*Excavate&Support_Res*")

⁷The recycling of excavated materials of mechanized tunneling to concrete aggregate is explained in Subsection 5.3.3.

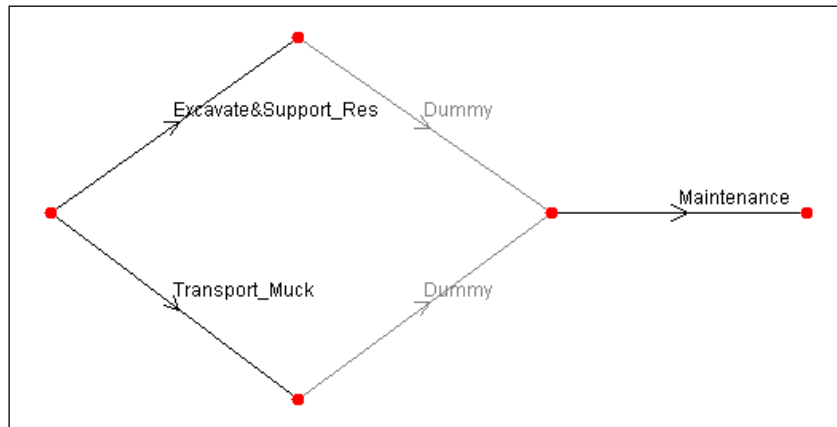


Figure 5.13: Activity Network Modeling the "Excavation with TEMH" Subpart of the "Construction Model" for Mechanized Tunneling

and muck transportation with a conveyor to the intermediate repository ("Transport_Muck") is considered. Additionally, this activity network expresses the interdependence of the muck production and the muck transportation. For example, transportation occurs only if muck is produced. In contrast, the excavation and, thus, the muck production will stop if the muck transportation stops due to an obstacle in the conveyor system. Hence, the tunnel advance depends on both the activity "Excavate&Support_Res" and the activity "Transport_Muck". This interdependence has to be considered in the calculation of the construction time. Due to the structure of the activity network either the time to perform the excavation ("Excavate&Support_Res") or the time to deal with the excavated materials ("Transport_Muck") is included in the construction time; the longer lasting one (critical path) is the one that is used. For example, if "Excavate&Support_Res" consumes more time than the simultaneous "Transport_Muck" the time of the entire activity network is the sum of the time of "Excavate&Support_Res" and "Maintenance". It is important to realize that the "critical path concept" does not work if, for instance, the activity "Excavate&Support_Res" produces a resource and "Transport_Muck" uses this particular resource. In this case, the activity "Transport_Muck" waits until the resource is produced due to the activity "Excavate&Support_Res" and then performs. Accordingly, the time of both activities ("Excavate&Support_Res" and "Transport_Muck") are summed up to compute the time of the activity network and as a result the simultaneous muck transport and tunnel excavation is not considered in the activity network.⁸ To consider the simultaneous muck transport and tunnel excavation in the activity network of the "Excavation with TEMH" subpart, only the activity "Transport_Muck" treats resources which model the excavation material

⁸The paragraph "Activity Status" on page 86 of the SIMJAVA User's Manual (Min et al., 2009) explains why both activities directly affect the time of the activity network if one activity uses the particular resource which is produced from the other activity.

production and the transport to the intermediate repository.

The time of the activities "*Excavate&Support_Res*" and "*Maintenance*" of the "*Excavation with TEMH*" subpart are computed with the Equations (5.3) and (5.4). Note that Equations (5.3) and (5.4) are the same as Equations (5.1) and (5.2) because, as mentioned before, the activities "*Excavate&Support_Res*" and "*Maintenance*" are "reused" activities of the "*Excavation*" subpart and therefore use the same time equations as the corresponding activities of the "*Excavation*" subpart (see Subsection 5.2.2).

$$\text{Excavate\&Support_Res Time} = \frac{\text{round_length}()}{\text{excavate\&support_advance_rate}} \quad (5.3)$$

$$\text{Maintenance Time} = \text{maintaining_time} \quad (5.4)$$

Equation (5.5) expresses the transportation time of the excavated materials between the cutter head of the tunnel boring machine and the respective intermediate repository using a conveyor. This transport is computed with the activity "*Transport_Muck*". The variable "*cross_section*" represents the cross sectional area (e.g., square meters) of the particular tunnel, the "*loosening_factor*", for example, the loosening of the excavated materials after the excavation, and the "*conveyor_capacity*", for example, the capacity (e.g., cubic meters per day) of the conveyor.

$$\text{Transport_Muck Time} = \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.5)$$

As discussed in Section 5.1, the produced excavation materials class depends on the currently encountered geology. This relation of an excavation materials class to a specific type of geology (ground class) simulates the "*Preliminary Material Classification*". The produced amount of each class of excavated material is calculated through the resource equations of the DAT. Equation (5.6) shows the resource equation for the activity "*Transport_Muck*" and calculates the amount of excavated material which is excavated by TBM tunneling ("*Muck Produced TBM*") and subsequently transported to the intermediate repository. The produced amounts of the different classes of excavated materials are related to the corresponding stocks of the "*Repository*", which model the intermediate repository.

$$\text{Muck Produced TBM} = \text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor} \quad (5.6)$$

The activity "*Excavate&Support_Res*" considers, in contrast to the activity "*Excavate&Support*" of the "*Excavation*" subpart, the reuse of recycled concrete aggregate in the initial support (e.g., prefabricated segments). Simulating this reuse

is a simulation task of the "Excavation with TEMH" subpart (see Table 5.1). The concrete aggregate consumption of the initial support is computed as

$$\begin{aligned} \text{Initial Support Aggregate TBM} = \text{concrete_volume} \cdot \text{round_length}() \cdot \\ \text{aggregate_factor} \end{aligned} \quad (5.7)$$

where the variable "concrete_volume" expresses the volume of shotcrete or prefabricated segments per length of the particular cycle (e.g., cubic meters per meter), and the variable "aggregate_factor" expresses the portion of concrete aggregates within the concrete volume.

At this point of the simulation model the excavated material classes have reached the intermediate repository. The simulation of the subsequent material flows in the TEMH process need further discussion as presented below.

5.3.2 TRANSPORTATION MODEL APPLIED TO MECHANIZED TUNNELING

The "Transportation Model" simulates the removal of the excavated materials from the intermediate repository and the subsequent transport to their final usage. Additionally, the temporary storage time at the intermediate repository due to the "Final Material Classification" has to be included in the "Transportation Model" for mechanized tunneling. Figure 5.14 shows the activity network of the "Transportation Model" if mechanized tunneling is used. This activity network is due to the parallel structure of the tunnel network (see Subsection 5.2.1) based on the activity network of the preceding "Excavation with TEMH" subpart (see Figure 5.13) to model the time of the preceding tunnel construction and the time of the preceding material flows in the TEMH process correctly. The activities "Excavate&Support_noRes" and "Transport_Muck_noRes" are "reused" activities of type C of the "Excavation with TEMH" subpart (see Subsection 5.2.2). The activity "Maintenance" is a "reused" activity of type A. On the other hand, the activities "Temporary_Storage" and "Transport_Final_Usage" are newly introduced activities of the "Muck Transport" subpart and model the simulation tasks of the "Transportation Model" (see Table 5.1).

Equations (5.8), (5.9), and (5.10) compute the time of the activities "Excavate&Support_noRes", "Maintenance", and "Transport_Muck_noRes". These activities are, as mentioned before, "reused" activities of the "Excavation with TEMH" subpart (see Subsection 5.2.2). For this reason, the Equations (5.8), (5.9), and (5.10) are equal to the Equations (5.3), (5.4), and (5.5).

$$\text{Excavate\&Support_noRes Time} = \frac{\text{round_length}()}{\text{excavate\&support_advance_rate}} \quad (5.8)$$

$$\text{Maintenance Time} = \text{maintaining_time} \quad (5.9)$$

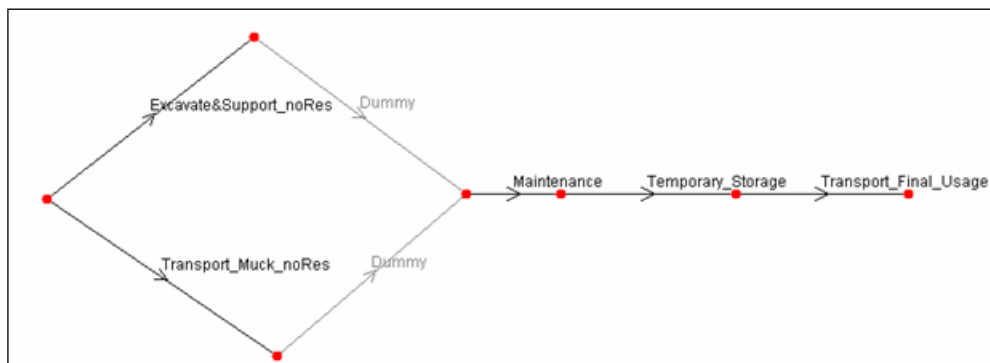


Figure 5.14: Activity Network Modeling the "Muck Transport" Subpart of the "Transportation Model" for Mechanized Tunneling

Transport_Muck_noRes Time =

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.10)$$

The temporary storage time of the excavated materials at the intermediate repository due to the "Final Material Classification" is computed with Equation (5.11). The additional variable "temporary_storage_time" expresses the time (e.g., days) to perform the "Final Material Classification" on the excavated material volume of one cycle.

$$\text{Temporary_Storage Time} = \text{temporary_storage_time} \quad (5.11)$$

The activity "Transport_Final_Usage" deals with the removal of the excavated materials from the intermediate repository and the transport to its final usage. Conveyors or muck trucks are generally used to transport the muck. The transportation time using a conveyor can, for example, be expressed as

Transport_Final_Usage Time =

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.12)$$

Furthermore, the activity "Transport_Final_Usage" simulates the handling of the excavated material classes between the intermediate repository and the final usage. This material handling is modeled in two tasks (see Figure 5.15). Equation (5.13) calculates the amount of the excavated material, which is removed from the intermediate repository (task 1). The same amount is subsequently transferred to its final usage (task 2) and calculated with Equation (5.14).

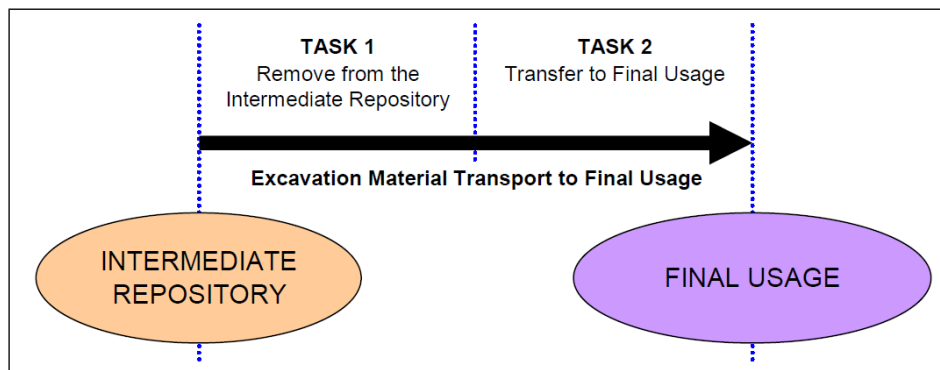


Figure 5.15: Simulation of the Excavation Material Handling between the Intermediate Repository and the Final Usage in Two Tasks

$$Muck\ Used\ TBM = round_length() \cdot cross_section \cdot loosening_factor \quad (5.13)$$

$$Produced\ Muck\ Final\ Usage\ TBM = round_length() \cdot cross_section \cdot loosening_factor \quad (5.14)$$

The amounts of the excavated material classes, which are transported to the different final usages are related to corresponding stocks in the "Repository". Thus, at the end of the "Transportation Model" the excavated material classes which are reused as fill materials, purchased by the mineral processing industry or tipped at the final repository have reached their final destination within the TEMH process. Excavated materials, which can be used for recycling are intermediately stored at a respective final usage stock of the "Repository" and subsequently undergo additional processes as discussed below.

5.3.3 RECYCLING MODEL APPLIED TO MECHANIZED TUNNELING

In tunneling the most common recycling of excavated materials is the processing to concrete- or shotcrete aggregate. This processing is performed, in general, within an aggregate plant. Figure 5.16 shows the relation between input flow and output flows of an aggregate plant. The input flow is the excavated materials class with suitable properties to be reused as concrete- or shotcrete aggregates. In general, two types of outputs exist which are the "valuable" product and the "non valuable"

product. The sum of the quantities of the accruing outputs has to be equal to the quantity of the input. If, for example, the input is the excavated materials class, which is recycled to concrete aggregates, the output are the aggregates for concrete ("valuable" product) and the processing losses ("non valuable" product). The processing losses are unsuitable aggregates for concrete. A typical example of processing losses are fines produced due to crushing. In the following, the "Recycling Model" is explained, which treats the processing of qualified excavated materials to concrete- or shotcrete aggregates as well as their reuse in concrete applications.

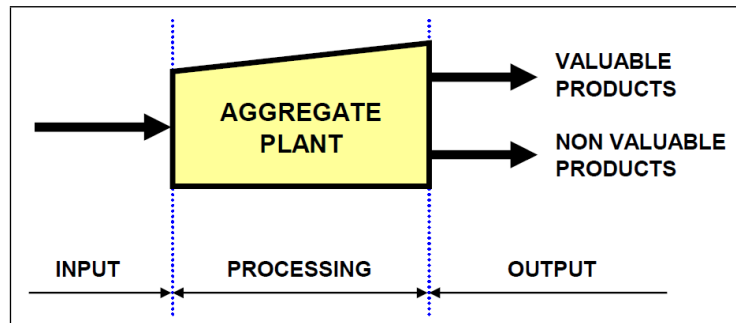


Figure 5.16: Material Flows Related to Processing

The "Recycling Model" (see Figure 5.4) consists of two subparts which are the "Processing" subpart and the "Inner Liner" subpart. Figure 5.17 represents the activity network modeling the "Processing" subpart of the "Recycling Model" if mechanized tunneling is used. Again, this activity network incorporates the activity network of the preceding "Muck Transport" subpart due to the parallel structure of the tunnel network (see Subsection 5.2.1). Therefore, activities of the preceding "Muck Transport" subpart are "reused" (see Subsection 5.2.2). The time of these "reused" activities such as "Excavate&Support_noRes", "Transport_Muck_noRes", "Maintenance", "Temporary_Storage", and "Transport_Final_Usage_noRes" are computed with the Equations (5.15) to (5.19). These Equations are equal to the Equations (5.8) to (5.12) of the "Muck Transport" subpart.

$$\text{Excavate\&Support_noRes Time} = \frac{\text{round_length}()}{\text{excavate\&support_advance_rate}} \quad (5.15)$$

$$\text{Transport_Muck_noRes Time} =$$

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.16)$$

$$\text{Maintenance Time} = \text{maintaining_time} \quad (5.17)$$

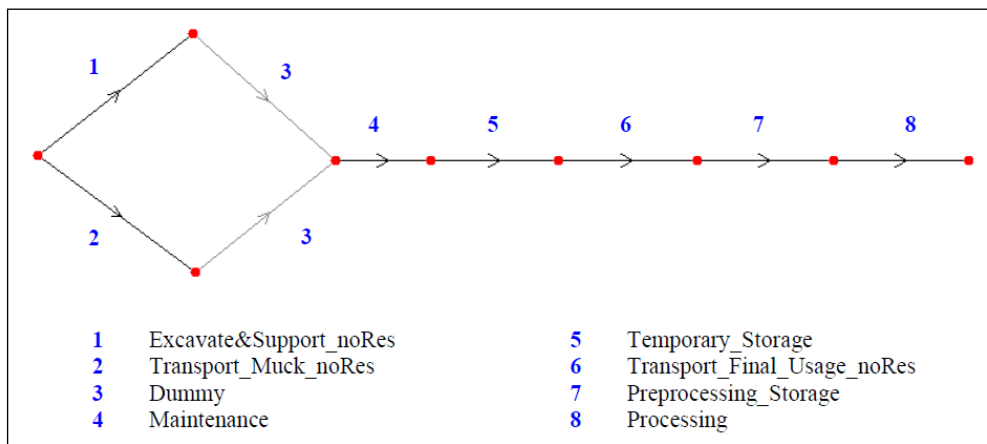


Figure 5.17: Activity Network Modeling the "Processing" Subpart of the "Recycling Model" of Mechanized Tunneling

$$\text{Temporary_Storage Time} = \text{temporary_storage_time} \quad (5.18)$$

$$\text{Transport_Final_Usage_noRes Time} =$$

$$\frac{\text{round.length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.19)$$

The activities "Preprocessing_Storage" and "Processing" model the simulation tasks (see Table 5.1) of the "Processing" subpart. "Preprocessing_Storage" simulates the temporary storage time of the excavated materials before the processing begins. This temporary storage time can be expressed as

$$\text{Preprocessing_Storage Time TBM} = \text{preprocessing_storage_time} \quad (5.20)$$

where the variable "preprocessing_storage_time" expresses the preprocessing storage time (e.g., days) per cycle. The value of "preprocessing_storage_time" is generally obtained from processing experts.

The activity "Processing" simulates the processing. Therefore, Equation (5.21) calculates the processing time. The variable "processing_rate" expresses the volume of excavated material, which is processed during a certain time (e.g., cubic meters per day) and is generally obtained from processing experts. Furthermore, "processing_rate" has to consider the time for additional investigations on the recycled aggregates which is related to the recycling process. These additional investigations are, for instance, laboratory testing to determine the properties of the excavated materials

after the processing.

Processing Time TBM =

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{processing_rate}} \quad (5.21)$$

The handling of the excavated material during the processing is simulated with the activity "Processing" in two tasks (see Figure 5.18). Task 1 of the activity "Processing" is to remove the qualified excavated materials from the respective final usage stock of the "Repository" where the excavated materials are intermediately stored before the processing starts. The amount of this material is subsequently the input of the aggregate plant and calculated with Equation (5.22). The simulation of the processing outputs is task 2 of the activity "Processing". Equation (5.23) and Equation (5.24) are the resource equations for the processing outputs. Each of these two resource equations treats one of the products ("valuable" product and "non valuable" product) of the processing. The "valuable" product is the amount of produced concrete- or shotcrete aggregates of mechanized tunneling and calculated with Equation (5.23). The variable "processing_success_factor" characterizes the processing success and depends on the properties of the excavation materials and the used processing aggregates. The value of this variable is, again, obtained from processing experts. Equation (5.24) computes the amount of the "non valuable" product.

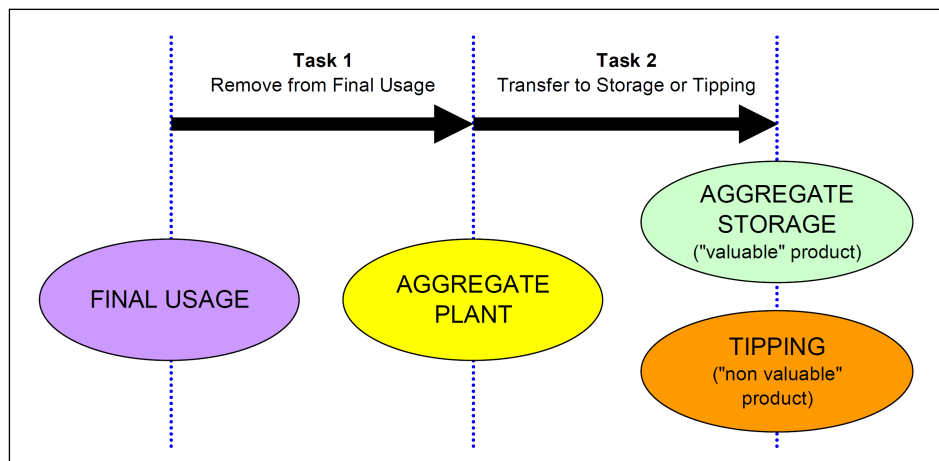


Figure 5.18: Simulation of the Handling of the Excavated Materials during the Processing by the Activity "Processing"

$$\begin{aligned}
 \textit{Used Muck Final Usage TBM} &= \textit{round_length}() \cdot \textit{cross_section} \cdot \\
 &\quad \textit{loosening_factor} \quad (5.22)
 \end{aligned}$$

$$\begin{aligned}
 \textit{Produced Concrete Aggregates TBM} &= \textit{round_length}() \cdot \textit{cross_section} \cdot \\
 &\quad \textit{loosening_factor} \cdot \\
 &\quad \textit{processing_success_factor} \quad (5.23)
 \end{aligned}$$

$$\begin{aligned}
 \textit{Non Valuable Product} &= \textit{round_length}() \cdot \textit{cross_section} \cdot \\
 &\quad \textit{loosening_factor} \cdot \\
 &\quad (1 - \textit{processing_success_factor}) \quad (5.24)
 \end{aligned}$$

After the processing the amount of the produced concrete aggregates is temporarily stored near the aggregate plant. Therefore, in the simulation model the produced concrete aggregates are allocated to a corresponding stock, for example, "Aggregate Storage", of the "Repository" (see Figure 5.18). Subsequently, the concrete aggregates are removed from this stock and reused in different concrete applications on the construction site. Examples of such concrete applications are the initial support or the inner liner. During the investigations of the "valuable" product which is considered in the "processing_time" (see Equation (5.21)), the "non valuable" product is tipped at the final repository.

Recycling of excavated materials to concrete aggregates and reusing them to construct the inner liner has been recently done in tunneling (Teuscher et al., 2007 and Lieb, 2009). The activity "Inner Liner" incorporates this reuse in the simulation model. Figure 5.19 represents the activity network of the "Inner Liner" subpart. As mentioned before, the "Inner Liner" subpart starts a certain time after the "Excavation" subpart. Therefore, the "Inner Liner" subpart disregards the time of the preceding tunnel excavation or the time of the preceding material flows in the TEMH process and, thus, "reused" activities of preceding subparts are not used (see Subsection 5.2.1 and 5.2.2). However, if the concrete aggregate consumption of the inner liner exceeds the production of recycled concrete aggregates, and further concrete aggregates from regional suppliers are not provided, the performance of the inner liner

is affected. Idle times may occur which can interrupt the inner liner construction and, thus, exceed the time of the tunnel construction.

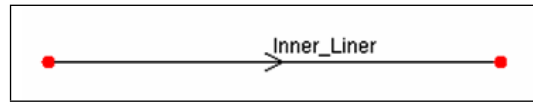


Figure 5.19: Activity Network Modeling the Reuse of Recycled Excavated Materials of Mechanized Tunneling in the Inner Liner

The activity "*Inner_Liner*" simulates the entire construction of the inner liner. Equation (5.25) computes the time to construct the inner liner. The additional variable "*inner_liner_advance_rate*" expresses the advance rate of the entire construction process of the inner liner. In general, this advance rate is expressed in meters per day.

$$Inner_Liner\ Time\ TBM = \frac{round_length()}{inner_liner_advance_rate} \quad (5.25)$$

Equation (5.26) is used to simulate the concrete aggregate consumption of the inner liner. If the amount of recycled concrete aggregate does not satisfy the concrete aggregate demand of the inner liner additional concrete aggregates have to be supplied. In general, these additional concrete aggregates are purchased from regional suppliers.

$$Inner\ Liner\ Aggregate\ TBM = concrete_volume \cdot round_length() \cdot aggregate_factor \quad (5.26)$$

At this point, the entire material flows in the TEMH process for mechanized tunneling, beginning with the excavation materials production and ending with the reuse or tipping of the material, are simulated.

5.4 MODELING CONVENTIONAL TUNNELING

This Section discusses the simulation of the TEMH process of conventional (Drill and Blast) tunneling. Therefore, each part of the tunnel network of the simulation model (see Figure 5.4) has to be implemented. In the following Subsections, similar to Section 5.3, each part and subpart of the developed simulation model are explained.

5.4.1 CONSTRUCTION MODEL APPLIED TO CONVENTIONAL TUNNELING

As mentioned before, the "*Construction Model*" is structured in two subparts which are the "*Excavation*" and the "*Excavation with TEMH*" subparts. The activity network of the "*Excavation*" subpart for conventional tunneling is represented in Figure

5.20. This activity network considers all activities involved in the tunnel construction; namely, "Excavate", "Load", and "Initial Support". The activity "Load" affects the tunnel construction performance because the activity "Initial_Support" can only be performed if the excavated materials are removed from the tunnel face. In contrast to modeling mechanized tunneling (Subsection 5.3) the tunnel excavation and the initial support is simulated with two activities ("Excavate" and "Initial_Support") because the initial support performs in conventional tunneling after the excavation has finished. Hence, this subdivision depicts the characteristic of conventional tunneling. The activity "Initial_Support" of the "Excavation" subpart does not consider the reuse of recycled aggregates in, for example, shotcrete applications.



Figure 5.20: Activity Network Modeling the "Excavation" Subpart of the "Construction Model" for Conventional Tunneling

Equations (5.27), (5.28), and (5.29) are the time equations of the activities "Excavate", "Load", and "Initial_Support". The variables in these equations are "excavate_advance_rate", which expresses the advance rate (e.g., meters per day) of the tunnel excavation, "loading_time", which specifies the time (e.g., days) to load the excavated materials of one round of tunnel construction, and "supporting_time", which expresses the time (e.g., days) to initially support the excavated tunnel length of one round.

$$\text{Excavate Time} = \frac{\text{round_length}()}{\text{excavate_advance_rate}} \quad (5.27)$$

$$\text{Load Time} = \text{loading_time} \quad (5.28)$$

$$\text{Initial_Support Time} = \text{supporting_time} \quad (5.29)$$

Figure 5.21 illustrates the activity network of the "Excavation with TEMH" subpart of the "Construction Model" for conventional tunneling, which considers the tunnel construction and the related TEMH. As a result of the parallel structure of the tunnel network (see Subsection 5.2.1), the "Excavation with TEMH" subpart repeats similar or equal activities of the preceding "Excavation" subpart to model the progress of the TEMH correctly. Such "reused" activities are the activities "Excavate", "Load" (both type A, see Subsection 5.2.2), and "Initial_Support_Res" (type B, see Subsection 5.2.2). The activity "Initial_Support_Res" incorporates the reuse of recycled concrete aggregates in the initial support. The time of the activities "Excavate", "Load", and "Initial_Support_Res" are computed with the Equations (5.30), (5.31), and (5.32). These activities are, as mentioned before, "reused" activities of

the "Excavation" subpart; thus, the Equations (5.30), (5.31), and (5.32) are equal to the Equations (5.27), (5.28), and (5.29).

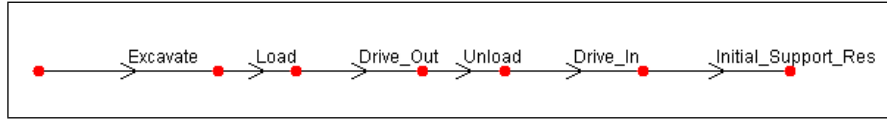


Figure 5.21: Activity Network Modeling the "Excavation with TEMH" Subpart of the "Construction Model" for Conventional Tunneling

$$Excavate\ Time = \frac{round_length()}{excavate_advance_rate} \quad (5.30)$$

$$Load\ Time = loading_time \quad (5.31)$$

$$Initial_Support_Res\ Time = supporting_time \quad (5.32)$$

The newly introduced activities of the "Excavation with TEMH" subpart such as "Drive_Out", "Unload", and "Drive_In" treat the simulation tasks of the "Excavation with TEMH" subpart (see Table 5.1). In contrast to the mechanized tunneling simulation it is assumed that muck trucks are used to transport the excavated materials to the intermediate repository. Furthermore, one can see in Figure 5.21 that the activities of a particular round are following each other, which depicts the cyclic characteristic of conventional tunneling. Specifically, it is assumed that the initial support starts after the entire mucking process ("Load", "Drive_Out", "Unload", and "Drive_In") is finished. In mechanized tunneling, as discussed in Subsection 5.3, specific activities of a cycle can be performed simultaneously (see Figure 5.13). In the following, the time equations of the newly introduced activities are explained. The time of the activity "Unload" can be expressed as

$$Unload\ Time = unloading_time \quad (5.33)$$

where the variable "unloading_time" specifies the time (e.g., days) to unload the excavated materials of the current round. The term unload describes the transfer of the excavated materials from the muck trucks to the intermediate repository.

Equation (5.34) simulates the time of the excavation material transport from the tunnel face to the corresponding intermediate repository using muck trucks. This transport is simulated with the activities "Drive_Out" and "Drive_In". Equation (5.34) is structured in three lines. Line 1 expresses the transportation time of one muck truck between the tunnel face and the intermediate repository ("round_start_position()") is explained below). Line 2 calculates the number of transports needed to remove the entire amount of excavated materials of the current round. Line 3 considers the number of muck trucks simultaneously used in the mucking process.

The variables of Equation (5.34) express the average velocity (e.g., meters per day) of the muck trucks ("*muck_truck_velocity_drive_out*"), the number of the used muck trucks ("*number_muck_trucks*"), and the average capacity (e.g., cubic meters) of one muck truck ("*capacity_muck_truck*"). Note that the time equation for "*Drive_In*" is equal to Equation (5.34); however, the average transport velocity of the muck trucks can change between "*Drive_In*" and "*Drive_Out*" because only the muck trucks of "*Drive_Out*" are fully loaded with excavated materials, which can reduce the average transport velocity compared to "*Drive_In*".

$$\begin{aligned}
 \text{Drive_Out Time} = & \frac{\text{round_start_position}()}{\text{muck_truck_velocity_drive_out}} \cdot \\
 & \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{capacity_muck_truck}} \cdot \\
 & \frac{1}{\text{number_muck_trucks}} \quad (5.34)
 \end{aligned}$$

The special feature of Equation (5.34) is the internal function "*round_start_position()*". This function is used to consider the progress of the tunnel in the "*Travel distance*" (see Figure 5.22) of the excavated materials. The DAT compute at the beginning of each round the position (e.g., meters) of the tunnel face ("*Location of the Current Tunnel Face*") and assigns this value to "*round_start_position()*". If the starting position of the tunnel ("*Tunnel Portal*") is assigned the null position (zero meters) the internal function "*round_start_position()*" returns the "*Travel distance*" of the excavated materials, which moves forward from one round to the next round. Min (2008) discusses the distance-based capability in detail.

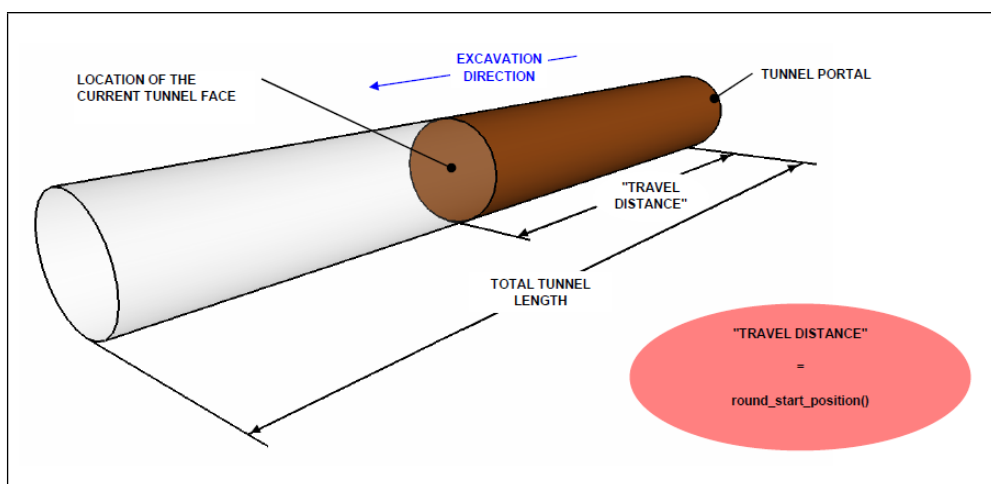


Figure 5.22: The "Travel Distance" of the Excavated Materials

The activity "*Unload*" simulates the production of the excavated materials and their transport to the intermediate repository because it is the last activity in the chain of the mucking process which has direct contact with the excavated materials ("*Load*", "*Drive_Out*", and "*Unload*"). In contrast, the activity "*Drive_In*" models the return of the empty muck trucks to the current tunnel face and, thus, has no direct contact with the excavated materials. Equation (5.35) expresses the resource equation which calculates the amount of excavated materials of each excavation materials class. These produced amounts of muck are assigned to the respective stocks of the "*Repository*" which model the intermediate repository (see Figure 5.11).

$$\begin{aligned} \text{Muck Produced } D\&B = \text{round_length}() \cdot \text{cross_section} \cdot \\ \text{loosening_factor} \end{aligned} \quad (5.35)$$

Reuse of recycled excavation materials as shotcrete aggregate⁹ for the initial support such as shotcrete is considered in the activity "*Initial_Support_Res*". Equation (5.36) is assigned to the activity "*Initial_Support*" to calculate the consumption of recycled excavation materials due to initial support applications. The variable "*concrete_volume*" expresses for modeling conventional tunneling also the volume of concrete or shotcrete of the actual round, and the variable "*aggregate_factor*" the portion of aggregates within the shotcrete- or concrete volume.

$$\begin{aligned} \text{Initial_Support Aggregate } D\&B = \text{concrete_volume} \cdot \text{round_length}() \cdot \\ \text{aggregate_factor} \end{aligned} \quad (5.36)$$

At this point, the excavated materials are produced, assigned to the specified excavation material classes, and transported to the intermediate repository. The simulation of the subsequent material flows in the TEMH process are described in the following.

5.4.2 TRANSPORTATION MODEL APPLIED TO CONVENTIONAL TUNNELING

The "*Transportation Model*" simulates the excavation material transport between the intermediate repository and the final usage of the excavated materials. In addition, the "*Final Material Classification*" during the temporary storage at the intermediate repository is considered.

Figure 5.23 represents the activity network of the "*Transportation Model*" which simulates conventional tunneling. This activity network is based on the parallel

⁹The recycling of excavated materials of conventional tunneling to concrete aggregates is discussed in Subsection 5.4.3.

structure of the tunnel network (see Subsection 5.2.1) using the activity network of the preceding "Excavation with TEMH" subpart (see Figure 5.21). Thus, the activity network of the "Muck Transport" subpart incorporates "reused" activities of the preceding "Excavation with TEMH" subpart to model the progress of the TEMH accurately (see Subsection 5.2.2). "Reused" activities of type A are "Excavate", "Load", "Drive_Out", and "Drive_In". The activities "Unload_noRes" and "Initial_Support_noRes" are "reused" activities of type C.

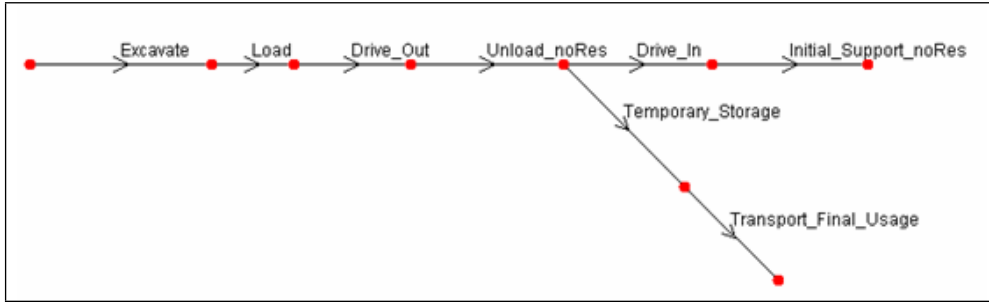


Figure 5.23: Activity Network Modeling the "Transportation Model" of Conventional Tunneling

The Equations (5.37) to (5.41) calculate the time of the "reused" activities "Excavate", "Load", "Drive_Out" (or "Drive_In"), "Unload_noRes", and "Initial_Support_noRes". Hence, these Equations are equal to the corresponding Equations (5.30) to (5.34) of the preceding "Excavation with TEMH" subpart.

$$\text{Excavate Time} = \frac{\text{round_length}()}{\text{excavate_advance_rate}} \quad (5.37)$$

$$\text{Load Time} = \text{loading_time} \quad (5.38)$$

$$\begin{aligned} \text{Drive_out Time} &= \frac{\text{round_start_position}()}{\text{muck_truck_velocity_drive_out}} \cdot \\ &\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{capacity_muck_truck}} \cdot \\ &\frac{1}{\text{number_muck_trucks}} \end{aligned} \quad (5.39)$$

$$\text{Unload_noRes Time} = \text{unloading_time} \quad (5.40)$$

$$\text{Initial_Support_noRes Time} = \text{supporting_time} \quad (5.41)$$

The new activities of the "Muck Transport" subpart ("Temporary_Storage" and "Transport_Final_Usage") deal with the "Final Material Classification" as well as the transport of the excavated materials from the intermediate repository to their final usage. Thus, the activities "Temporary_Storage" and "Transport_Final_Usage" model the simulation tasks of the "Muck Transport" subpart (see Table 5.1). The "Transportation Model" of conventional tunneling simulates the transport of the excavated materials from the intermediate repository to their final usage in the same way, using the activities "Temporary_Storage" and "Transport_Final_Usage", as the "Transportation Model" of mechanized tunneling (see Subsection 5.3.2). The temporary storage time of the excavated materials at the intermediate repository due to the "Final Material Classification" is expressed with

$$\text{Temporary_Storage Time} = \text{temporary_storage_time} \quad (5.42)$$

where the variable "temporary_storage_time" specifies the temporary storage time (e.g., days) of the excavated materials of one tunnel construction round.

Equation (5.43) calculates the time of the excavation material transport between the intermediate repository and their final usage ("Transport_Final_Usage") if a conveyor is used.

$$\text{Transport_Final_Usage Time} =$$

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.43)$$

Figure 5.24 subdivides the activity network of the "Muck Transport" subpart of the "Transportation Model" into three parts. After the activity "Unload_noRes" a branch with the activities "Temporary_Storage" and "Transport_Final_Usage" is appended. This branch considers that right after the excavated materials have reached the intermediate repository investigations on the excavated materials ("Final Material Classification") and the subsequent transport of the investigated muck can proceed. Simultaneously, a part of the mucking process ("Drive_In") as well as the installing of the initial support ("Initial_Support_noRes") can be performed. Hence, the activity network of the "Transportation Model" considers a simultaneous performance of the tunnel construction ("Drive_In" and "Initial_Support_noRes") and the TEMH process ("Temporary_Storage" and "Transport_Final_Usage"). The calculated time of the entire activity network of the "Transportation Model" for conventional tunneling is the sum of "Part 1" and the more time consuming part of "Part 2" or "Part 3". The DAT automatically considers the more time consuming branch ("Part 2" or "Part 3").

The activity "Transport_Final_Usage" simulates the excavation material transport from the intermediate repository to the final usage in two tasks (see Figure 5.15). Equation (5.44) calculates the amount of the excavated materials which is removed

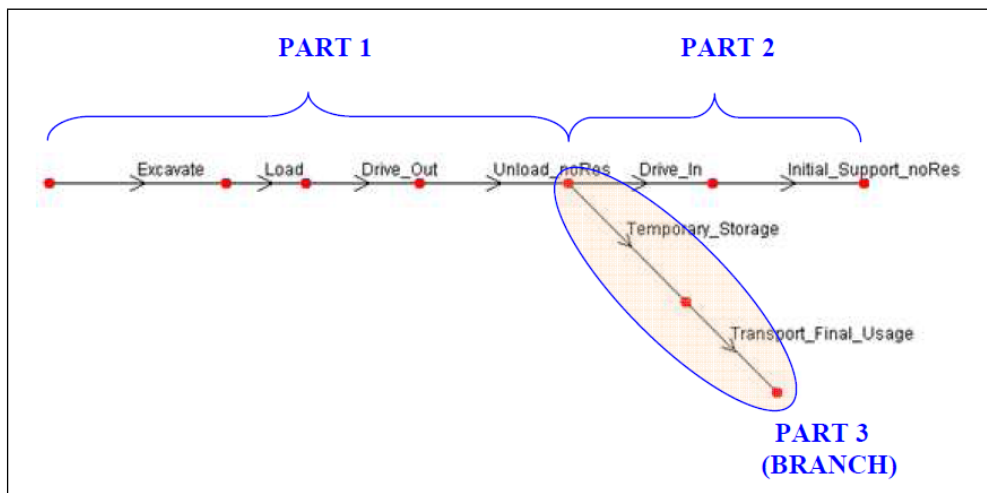


Figure 5.24: Parts of the Activity Network Modeling the "Transportation Model" of Conventional Tunneling

from the intermediate repository (task 1). Subsequently, the same amount of the excavated materials is transferred to its final usage (task 2) and calculated by Equation (5.45).

$$Muck\ Used\ D\&B = round.length() \cdot cross_section \cdot loosening_factor \quad (5.44)$$

$$Produced\ Muck\ Final\ Usage\ D\&B = round.length() \cdot cross_section \cdot loosening_factor \quad (5.45)$$

At the end of the "Transportation Model" excavation material classes, which are tipped at the final repository, used as fill materials or purchased by the mineral processing industry have reached their final destination in the TEMH process. Simulating the recycling of suitable excavated material is described below.

5.4.3 RECYCLING MODEL APPLIED TO CONVENTIONAL TUNNELING

This Subsection models the recycling of excavated material of conventional tunneling to shotcrete- or concrete aggregate and its reuse in the inner liner construction. Subsection 5.3.3 discussed the processing of the qualified excavated materials of mechanized tunneling with an aggregate plant. The relations between the input and

output of the processing, shown in Figure 5.16, are also valid for the excavated materials in conventional tunneling. Moreover, the reuse of recycled concrete aggregates in the inner liner is simulated in the same way as in mechanized tunneling. Hence, the same activities, which simulate the processing and the subsequent reuse of the recycled aggregates in mechanized tunneling (see Subsection 5.3.3), are used.

The "Recycling Model" of the simulation model consists of the "Processing" and the "Inner Liner" subpart. Recycling of the suitable excavation materials class is simulated with the "Processing" subpart. Figure 5.25 represents the activity network of the "Processing" subpart of conventional tunneling, which is based on the parallel structure of the tunnel network (see Subsection 5.2.1) using the activity network of the preceding "Muck Transport" subpart (see Figure 5.23). For this reason, the activity network of the "Processing" subpart partially consists of "reused" activities (see Subsection 5.2.2) of the "Muck Transport" subpart. "Reused" activities of type A are "Excavate", "Load", "Drive_Out", "Unload_noRes", "Drive_In", "Initial_Support_noRes", and "Temporary_Storage". The activity "Transport_Final_Usage_noRes" is a "reused" activity of type C. Equations (5.46) to (5.52) calculate the time of these "reused" activities and are equal to the Equations (5.37) to (5.43).

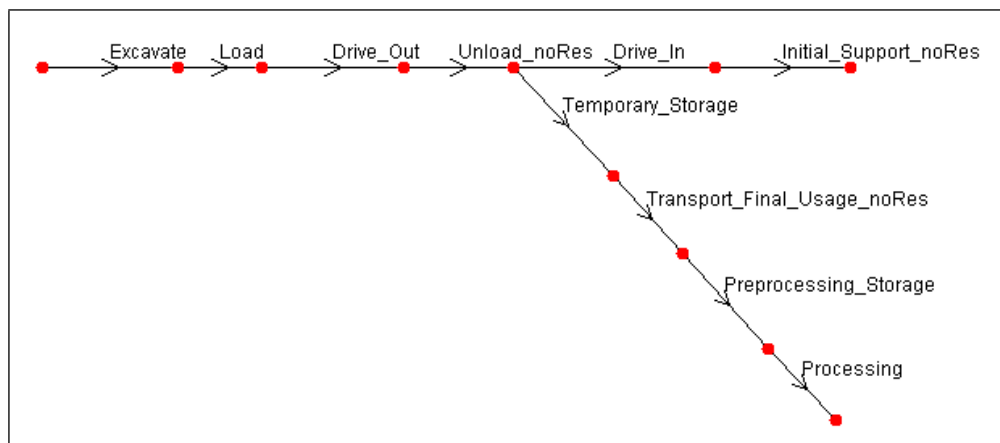


Figure 5.25: Activity Network Modeling the "Processing" Subpart of Conventional Tunneling

$$Excavate\ Time = \frac{round_length()}{excavate_advance_rate} \quad (5.46)$$

$$Load\ Time = loading_time \quad (5.47)$$

$$\begin{aligned}
 \text{Drive_Out Time} = & \frac{\text{round_start_position}()}{\text{muck_truck_velocity_drive_out}} \cdot \\
 & \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{capacity_muck_truck}} \cdot \\
 & \frac{1}{\text{number_muck_trucks}} \quad (5.48)
 \end{aligned}$$

$$\text{Unload_noRes Time} = \text{unloading_time} \quad (5.49)$$

$$\text{Initial_Support_noRes Time} = \text{supporting_time} \quad (5.50)$$

$$\text{Temporary_Storage Time} = \text{temporary_storage_time} \quad (5.51)$$

$$\text{Transport_Final_Usage_noRes Time} =$$

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (5.52)$$

As discussed in Subsection 5.3.3 for mechanized tunneling, the processing is simulated with the activities "Preprocessing_Storage" and "Processing". "Preprocessing_Storage" treats the temporary storage of the excavated materials before the processing starts. Equation (5.53) is used to calculate the time of this temporary storage.

$$\text{Preprocessing_Storage Time D\&B} = \text{preprocessing_storage_time} \quad (5.53)$$

The activity "Processing" simulates the processing of excavated materials to concrete aggregates within an aggregate plant. The processing time can be expressed as

$$\text{Processing Time D\&B} =$$

$$\frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{processing_rate}} \quad (5.54)$$

Furthermore, the activity "Processing" treats the handling of the qualified excavated materials during the processing. Figure 5.18 shows that the activity "Processing" simulates this handling in two tasks. Equation (5.55) calculates the amount of

the qualified excavated materials which is removed from the respective final usage stock of the "Repository" (task 1) where the excavated materials are intermediately stored before the processing starts. This amount of excavated materials is subsequently used as the input of the aggregate plant. The corresponding amounts of the output of the aggregate plant (task 2) which are the "valuable" product (concrete aggregate) and the "non valuable" product are computed with the Equations (5.56) and (5.57).

$$\begin{aligned} \text{Used Muck Final Usage D\&B} = & \text{round_length}() \cdot \text{cross_section} \cdot \\ & \text{loosening_factor} \end{aligned} \quad (5.55)$$

$$\begin{aligned} \text{Produced Concrete Aggregates D\&B} = & \text{round_length}() \cdot \text{cross_section} \cdot \\ & \text{loosening_factor} \cdot \\ & \text{processing_success_factor} \end{aligned} \quad (5.56)$$

$$\begin{aligned} \text{Non Valuable Product} = & \text{round_length}() \cdot \text{cross_section} \cdot \\ & \text{loosening_factor} \cdot \\ & (1 - \text{processing_success_factor}) \end{aligned} \quad (5.57)$$

The "non valuable" product is tipped at the final repository. In contrast, the produced concrete- or shotcrete aggregates are assigned to the corresponding stock of the "Repository" which models the temporary storage of the aggregates after the processing. These aggregates are subsequently reused in concrete applications on the construction site, which is, for example, simulated with the "Inner Liner" subpart of the "Recycling Model".

Figure 5.26 shows the activity network of the "Inner Liner" subpart. This activity network does not explicitly consider the preceding time of the tunnel construction or the preceding time of the material flows of the excavated materials.

Equation (5.58) computes the time of the activity "Inner Liner".

$$\text{Inner Liner Time D\&B} = \frac{\text{round_length}()}{\text{inner_liner_advance_rate}} \quad (5.58)$$

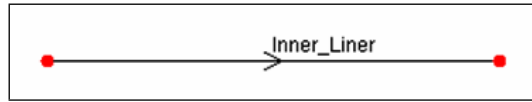


Figure 5.26: Activity Network Modeling the Reuse of Recycled Excavated Materials of Conventional Tunneling in the Inner Liner

The required concrete aggregates of the inner liner are removed from the stock of the "Repository", which models the temporary storage of the recycled concrete aggregates after processing. The quantity of concrete aggregates, which are consumed due to the inner liner construction can be expressed as

$$\begin{aligned} \text{Inner Liner Aggregate D\&B} = \text{concrete_volume} \cdot \text{round_length}() \cdot \\ \text{aggregate_factor} \end{aligned} \quad (5.59)$$

5.5 COMMENTS ON THE SIMULATION MODEL

The objective of the developed simulation model is to provide a model that allows one to simulate the TEMH process with the associated uncertainties. In particular, the entire TEMH process, beginning with excavation materials production and ending with the reuse of the excavated materials on the construction site or tipping, has to be considered. Therefore, various activity networks, described in the Sections 5.3 and 5.4, are used. These activity networks show one way of modeling the TEMH process. The structure and complexity of an activity network depends on the respective tunneling method and on the level of detail of breaking down the work structure of the tunnel construction with the related TEMH. In general, the level of detail of an activity network is affected by a combination of various factors such as, for example, the availability of data, the level of detail of information, which depends on the stage of the project, and the intended objective of the simulation (Min, 2008). Here, emphasis is placed on simulating the main material flows in the TEMH and considering the simultaneous tunnel construction. Hence, this simulation model enables one to show effects of the TEMH on the construction performance.

Similar to the activity networks, the described time- and resource equations are only one way to model the tunnel construction and the related TEMH. Other expressions for the time- and resource equations may be used.

In essence, the developed simulation model shows one way to simulate the tunnel construction and the related TEMH process with associated uncertainties in the DAT.

Chapter 6

BRENNER BASE TUNNEL PROJECT

The intent of this thesis is to apply the TEMH simulation model to a real tunnel project, namely the BBT. For this reason, this Chapter will provide a brief overview over the BBT project. This Chapter's sources of information are project documents of the Brenner Basistunnel BBT SE such as, for example, Technical Report D0154-00044, Technical Report D0118-02916-10, Technical Report D0118-04340, and Technical Report D0118-02369 as well as the web page of the Brenner Basistunnel BBT SE (www.bbt-se.com). Supplementary literature is also provided and referenced. The collected information of the BBT and the particular TEMH is the basis of the decision analysis and, thus, defines the input of the application of the simulation model to the BBT.

6.1 TUNNEL DESIGN (29-02-2008)

The BBT (see Figure 6.1) with a total length of 55 km is the core element of the rail corridor Munich – Verona. It is designed as a tunnel system (see Figure 6.2) with two single-track tubes, a service gallery, three multifunction stations (MFS), and several lateral adits. The average overburden along the alignment of the main tunnel tubes is about 800 m and reaches a maximum of about 1 600 m.

The two single-track tubes (East and West tunnel), generally at a distance of 70 m, have an internal diameter of roughly 8 m and are linked every 333 m by cross passages (see Figure 6.3). The service gallery, with an inner diameter of 5 m, is situated underneath the main tunnel tubes (see Figure 6.3). At an early stage of the project, the service gallery is driven as exploratory tunnel to provide geologic information along the selected route. Other purposes of the service gallery are dewatering and maintenance, which are performed at a later stage of the project. Furthermore, the



Figure 6.1: Project Overview (Bergmeister, 2007a)

tunnel system of the BBT consists of three MFSs (MFS Innsbruck, MFS St. Jodok, and MFS Trens, see Figure 6.2) at distances of about 20 km. The MFSs include emergency stations to rescue passengers of trains, which are involved in an incident, installations for operations and maintenance, and a track crossover. Additionally, the MFS St. Jodok includes two passing tracks. A lateral adit for every MFS will be built and used to start the MFSs. North of the MFS Innsbruck two single-track tunnels connect the BBT to the existing two-track Innsbruck bypass tunnel. The lateral adits Ampass, Ahrental, Wolf and Mauls (see Figure 6.2) provide various working faces and shorten construction time. Contract sections are set up on the basis of these lateral adits. The Austrian part of the BBT is subdivided into the following contract sections (see Figure 6.4):

- contract section Ampass
- contract section Innsbruck
- contract section Ahrental
- contract section Wolf

The Italian part is subdivided into the contract sections Pfitsch, Mauls, and Aicha. Based on the current knowledge of the geology (see Section 6.3) along the alignment of the BBT it is predicted that about 2/3 of the main tunnel and the service gallery will be driven by mechanized means using tunnel boring machines. The remaining 1/3 will be constructed conventionally using the Drill and Blast method (*"conventional"* method). Other parts of the tunnel system such as, for example, the MFSs, the crossover tunnels, and the lateral adits will be constructed conventionally.

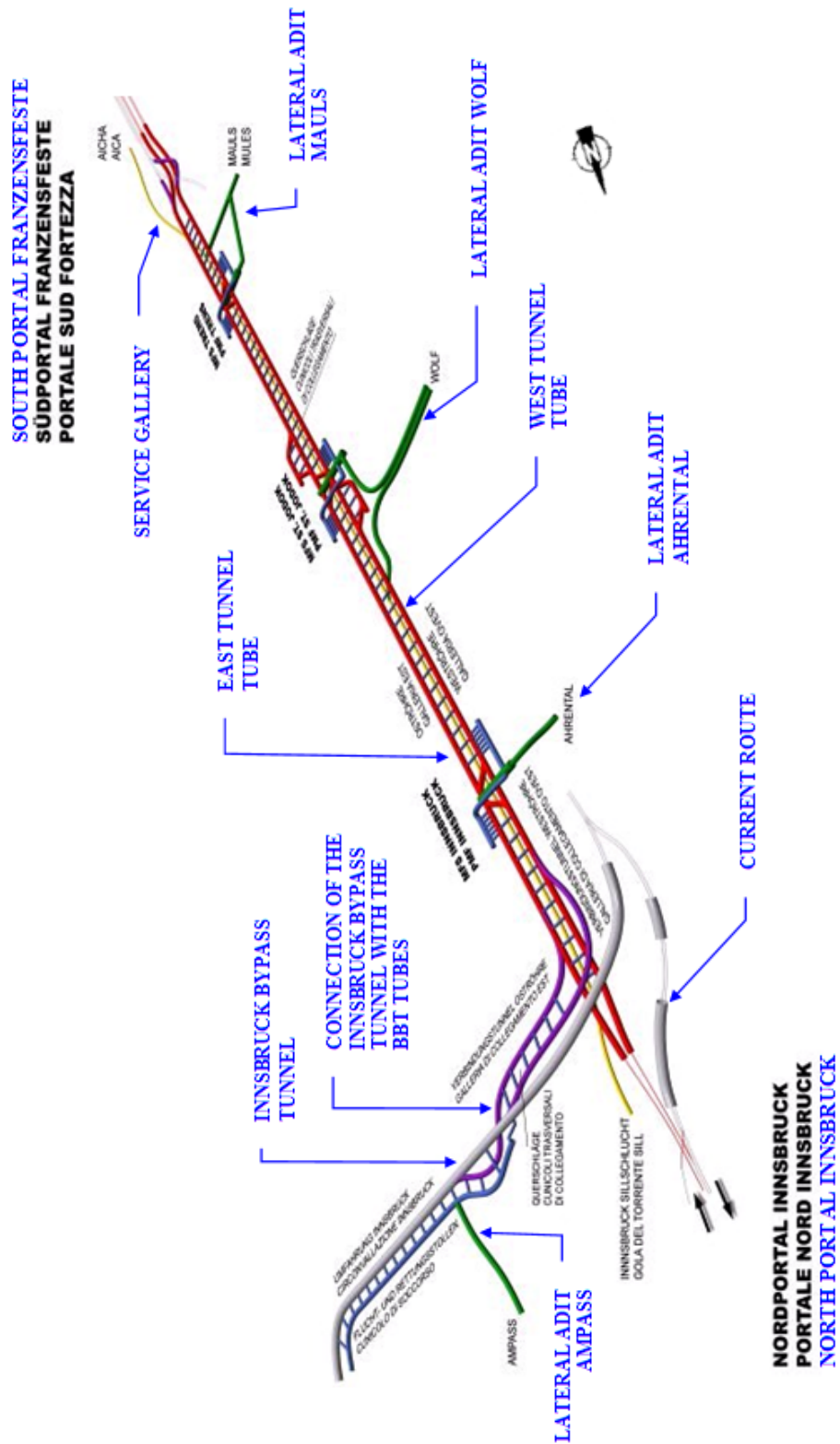


Figure 6.2: BBT's Tunnelsystem (Note that the design of the lateral adit Wolf has changed. Figure 6.6 represents the current design.) (www.bbt-se.com)

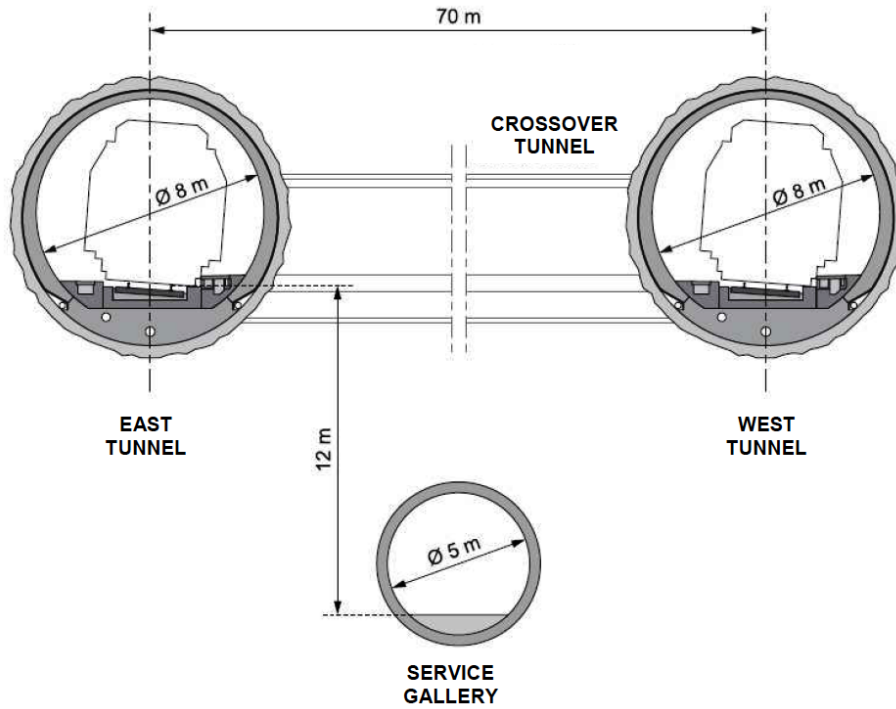


Figure 6.3: Main Tunnel Tubes' and Service Gallery's Standard Cross Sections (www.bbt-se.com)

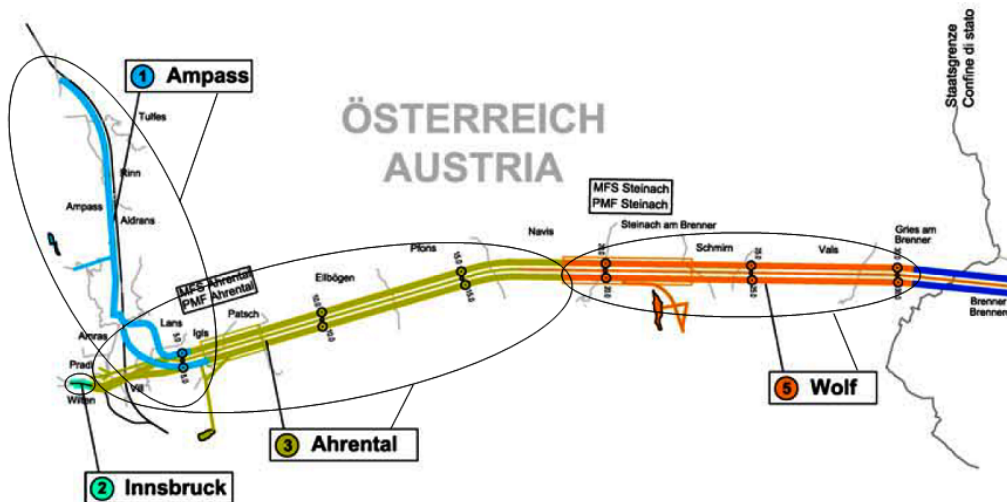


Figure 6.4: Contract Sections of the Austrian Part of the BBT (Note: MFS Ahrental = MFS Innsbruck, MFS Steinach = MFS St. Jodok) (Technical Report D0118-02369)

6.2 CURRENT PROJECT STATUS (Spring 2010)

The current project status of the BBT, referring to Bergmeister (2010), has the goal to achieve the approvals of Italy and Austria to start with the construction of the main tunnel drives. Currently, an extensive geological and hydrogeological exploration drilling program (approximately 25 000 m total borehole length) has been realized as well as 6.5 km of the 10.5 km long Aicha-Mauls exploratory tunnel (see Figure 6.5), which is a part of the service gallery and bored through Brixner Granite using a double shield machine with a diameter of 6.3 m and segmental support. The 1.8 km long lateral adit tunnel at Mauls (see Figure 6.5) has already been completed using Drilling and Blasting. Work on the Innsbruck-Ahrental exploratory tunnel (5.69 km), which is a part of the service gallery (see Figure 6.5) and is excavated conventionally, started at the beginning of December, 2009. The lateral adit Ahrental (see Figure 6.5) with a length of 2.42 km will be constructed also by means of Drilling and Blasting. Additional exploratory features are related to the contract section Wolf and include the construction of the Saxen Tunnel, which will enable one the access to the portal Wolf, the lateral adit Wolf, and the mucking tunnel Padastertal, which will be the access to the final repository Padastertal (see Figure 6.6). The final repository Padastertal is located in the contract section Wolf.

6.3 TUNNEL GEOLOGY

As described in Section 6.2, the exploratory facilities are reasonably advanced. Figure 6.7 to Figure 6.9 show the main geological sections along the alignment of the Austrian part of the BBT. A brief overview of the current knowledge of the geology, following Bergmeister (2010), is given below. Emphasis is placed on the Austrian part of the BBT. Furthermore, predictions about the reusability of the excavated materials based on the Technical Report D0154-00044 are also included.

- **km 0 to km 14: Innsbruck Quartz Phyllite / Unterostalpin (see Figure 6.7)**

Generally friable rock behavior is expected, which can lead to shear failure and squeezing phenomena. In addition, the rock behavior in this zone is strongly influenced by fault zones ("Störung" in German, see Figure 6.7). There is no significant groundwater flow system mapped in the Innsbruck Quartz Phyllite section. However, in the fault zones some groundwater flow can occur. It is predicted that less than 10 percent of the excavated materials can be reused as fill material. The residual amount of the excavated materials are tipped at the final repositories.

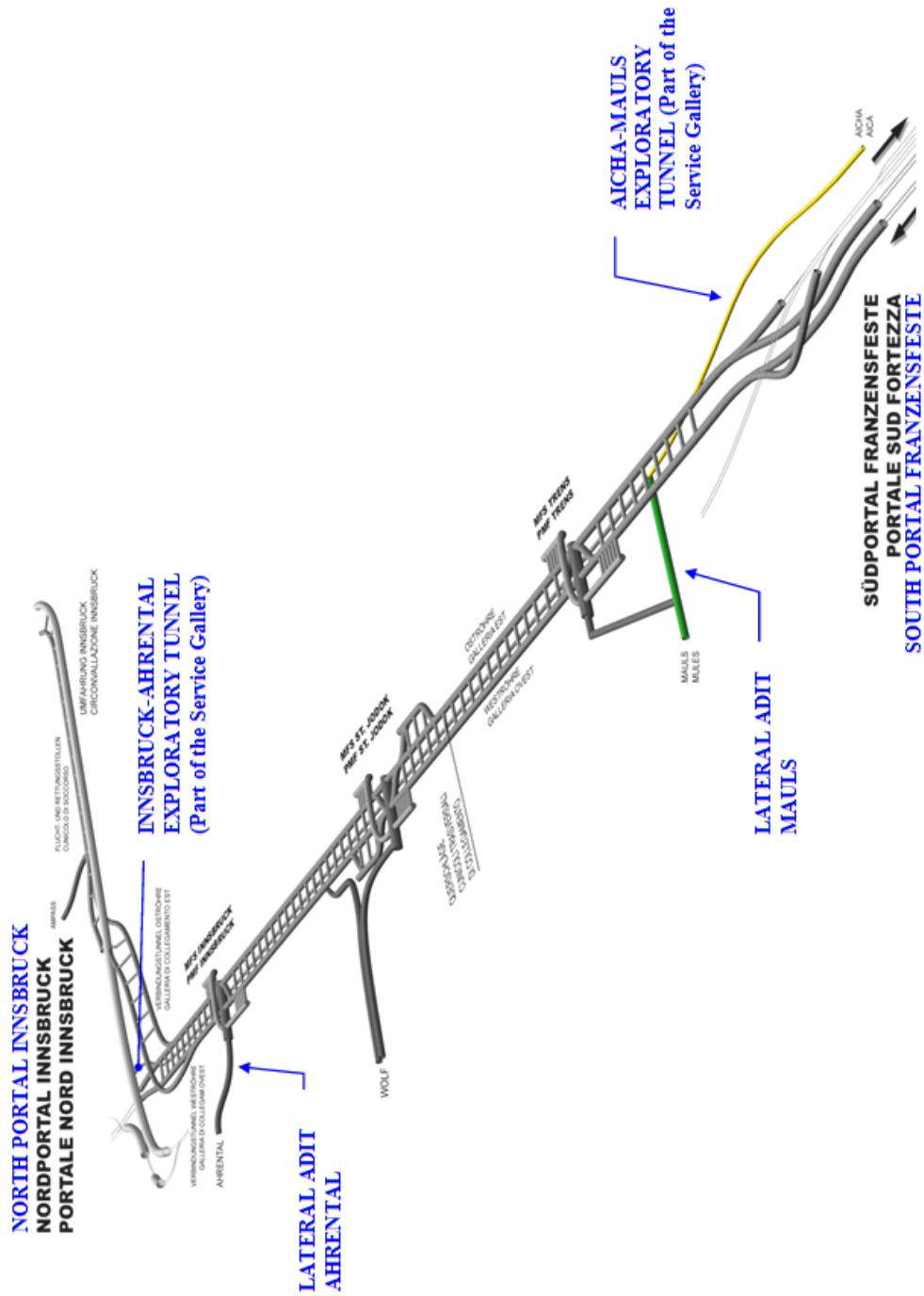


Figure 6.5: Current and Finished Tunnel Drives (Note that the design of the lateral adit Wolf has changed. Figure 6.6 represents the current design.) (www.bbt-se.com)

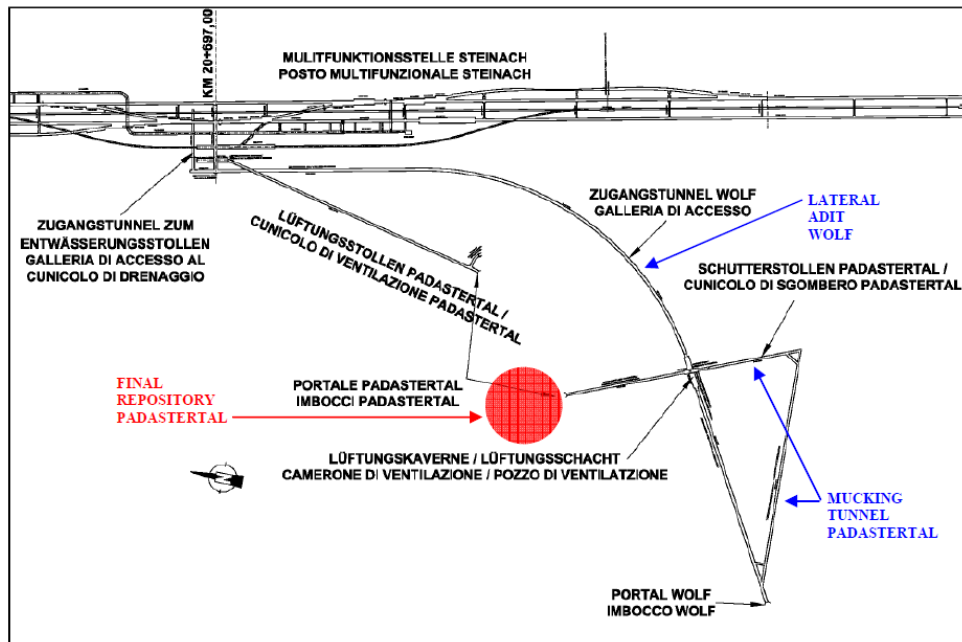


Figure 6.6: Lateral Adit Wolf, Mucking Tunnel Padastertal, Final Repository Padastertal (Technical Report D0118-02916-10)

- **km 14 to km 19: North Marginal Zone of the Tauern Window (see Figures 6.7 and 6.8)**

The main characteristic of this zone is that the conditions vary considerably. Friable behavior which can produce shear failure is to be expected. The appearance of blocks of Anhydrite (also Anhydrite layers restricted to a few centimeters), Dolomite, etc. is subsidiary, but possible. A 50 m thick marginal fault zone (Miskopf Tauern fault, "Tauernnordrand-Störungssystem" in German, see Figure 6.8) is anticipated. Apart from that fault zone, the acute-angled secondary faults of the north-south running normal faults result in squeezing phenomena. Again, less than 10 percent of the excavated materials are predicted to be reusable as fill materials. The rest has to be dumped at the final repositories.

- **km 19 to km 28.5: Glockner Nappe (see Figures 6.8 and 6.9)**

In the southern zone an increasing extent of black Phyllites is expected, which can lead to slightly squeezing effects. However, no large swelling will occur in the Anhydrites (see later). The main lithology of this zone is Bündner Schist, which contains varying amounts of Limestone. Subsidiary contents of Dolomites, Quartzites, Anhydrites, Graywackes and Sericites are to be found within the Schist. Permeability can considerably increase but only in the main fault zones. Such fault zones can contain damaged Limestone-rich Bündner Schist affected by chemical solution. At the tunnel level, even in the fault areas,

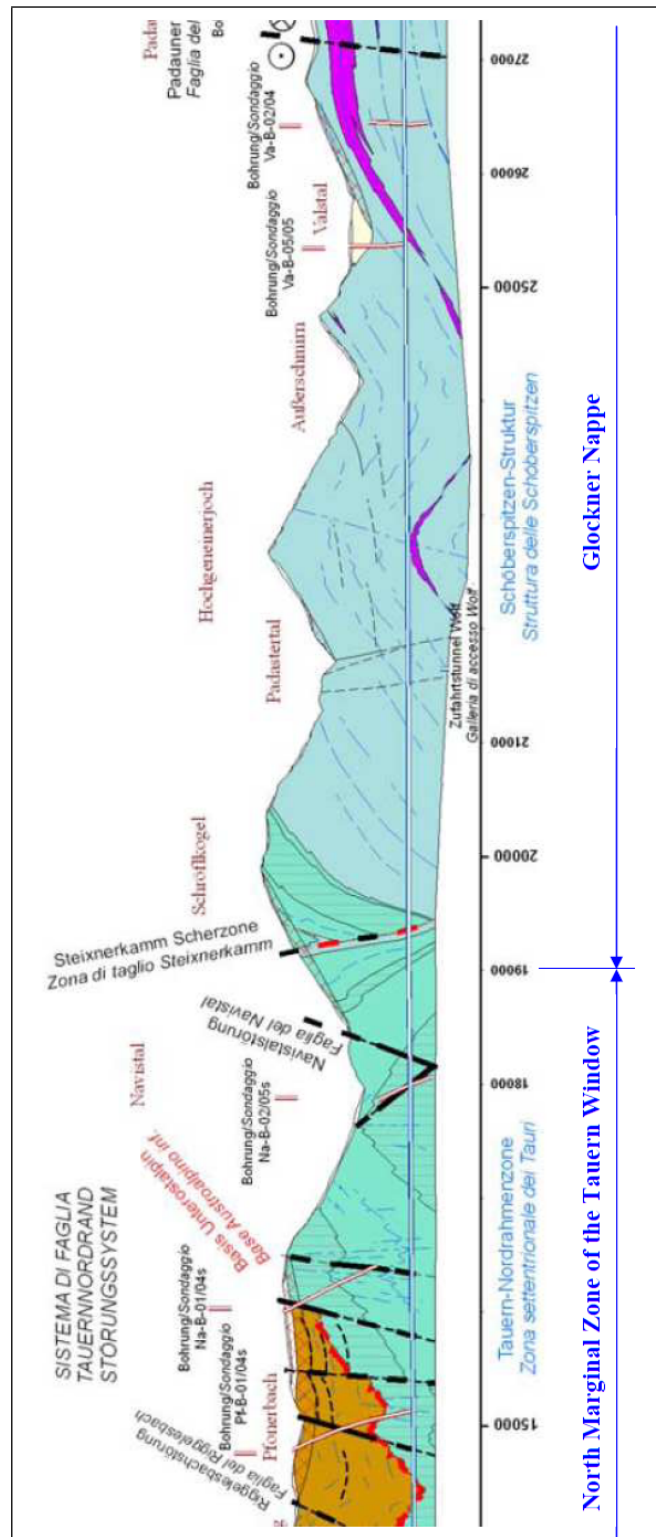


Figure 6.8: Geological Longitudinal Section 02 of the Austrian Part of the East Tube of the BBT (Technical Report D0154-00031)

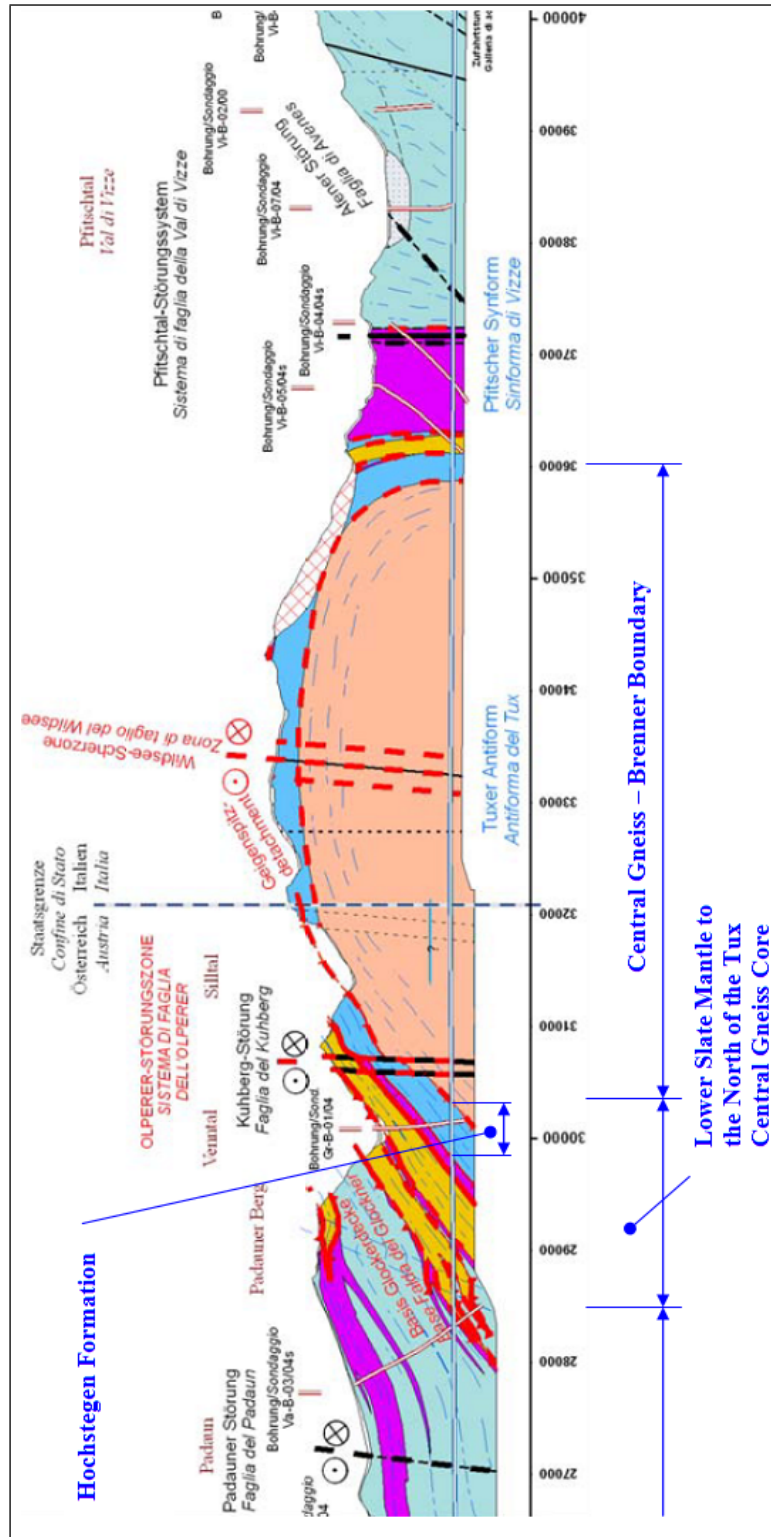


Figure 6.9: Geological Longitudinal Section 03 of the Austrian Part of the East Tube of the BBT (Technical Report D0154-00031)

no significant groundwater flow is expected. Along this section the excavation material properties vary considerably. An estimate of the average amount of excavated materials that can be reused as fill materials is about 20 percent. The remainder of the excavated materials has to be tipped at designated final repositories.

- **km 28.5 to km 30.3: Lower Slate Mantle to the North of the Tux Central Gneiss Core (see Figure 6.9)**

In this section alternating rock conditions, such as shear features, deep-lying deconsolidation, and pronounced ground water ingress dominate. Anhydrite leaching and material erosion can result in friable rock. In this section, excavation materials which can be recycled to concrete aggregates are predicted. A geologic subsection (Hochstegen formation, see Figure 6.9) of a length of about 470 meters is predicted to be 70 percent reusable as concrete aggregate, 20 percent as fill materials, and 10 percent tipped at final repositories. The remaining geologic subsections are at about 30 percent reusable as fill materials and at 70 percent tipped at final repositories.

- **km 30.3 to km 36.0: Central Gneiss - Brenner Boundary (see Figure 6.9)**

Generally, the Central Gneiss has stable rock conditions; however, joint plane solutions have to be considered. In addition, the Olper Faults zone ("*Olperer Störungszone*" in German, see Figure 6.9) is anticipated, in which squeezing phenomena are expected. Otherwise the fault zones will not greatly influence the rock behavior. In the Central Gneiss no groundwater flow is predicted. However, it is anticipated that the permeability can increase in the fault zones. A high percentage, 70 – 80 percent, of the excavated materials is predicted to be reusable as concrete aggregate. In addition, about 20 percent of the excavated material is assumed to be used as fill materials. The remaining excavated materials are tipped at the final repositories.

6.4 TUNNEL EXCAVATION MATERIAL HANDLING OF THE BRENNER BASE TUNNEL

In the following, the current stage of planning the TEMH of the BBT is presented. At the present (Spring 2010) the framework of the TEMH such as the objectives of the excavation material management, the excavation material classification, the repository concept, and the transportation logistics exists and can be summarized below. It is important to mention that the current stage of planning does not yet consider the development of a testing plan of the excavated materials or the description of the processing steps when recycling the excavated materials.

6.4.1 OBJECTIVES OF THE TUNNEL EXCAVATION MATERIAL HANDLING

During the construction of the BBT roughly 15.5 million cubic meters materials (in the solid state) will be excavated (Bergmeister, 2010). The Brenner Basistunnel BBT SE (client) formulated three main goals to handle these materials:

- Greatest possible reuse of excavation materials to achieve a maximum self-supply of concrete aggregates.
- Optimization of the materials management by keeping costs of transport, storage and purchase of concrete aggregates as low as possible.
- Minimum environmental effects from traffic, noise and dust due to excavation materials handling as well as the conservation of natural resources.

6.4.2 EXCAVATION MATERIAL CLASSIFICATION

During the exploratory phase of the BBT project investigations to describe the properties of the excavation materials are performed through the Brenner Basistunnel BBT SE and contractors. These investigations are based on geological mapping, the information on lithology collected throughout the drilling program and laboratory tests on core samples. Based on the results of these investigations, a classification of the excavation materials is performed. The objective of this classification is to examine their possible reuse as concrete aggregate or fill materials (Bergmeister, 2007b).

The first step of the classification is to forecast the lithologies of the excavated materials and to associate them with four lithology classes. Table 6.1 shows the four lithology classes with two representative lithologies in each lithology class. The entire lithology classification is presented in Technical Report D0118-04340.

Table 6.1: Classification of the Predicted Lithologies in Four Lithology Classes (Technical Report D0118-04340)

Lithology Class	Representative Lithology
Class 1	Quarternary Unconsolidated Segments Brixner Granite
Class 2	Innsbrucker Quartz Phyllite Upper and Lower Bündner Slates
Class 3	Paragneiss Amphibolite
Class 4	Central Gneiss Marble

In the second step, each of the four lithology classes is subdivided into the defined usage classes of the BBT¹⁰:

- **Usage Class A:** high quality materials, suitable for aggregates in concrete
- **Usage Class B:** materials suitable as fill materials for embankments or backfills
- **Usage Class C:** materials with non-reusable properties, material has to be tipped at final repositories

The third step combines the first two steps and, thus, forecasts the percentage of each usage class within a lithology class. Table 6.2 represents this prediction.

Table 6.2: Percentage of the Usage Classes within each Lithology Class (Technical Report D0118-04340)

	Class 1	Class 2	Class 3	Class 4
Usage Class A	70 %	0 %	0 %	50 %
Usage Class B	20 %	20 %	50 %	30 %
Usage Class C	10 %	80 %	50 %	20 %

As a result of the investigations, it is predicted that roughly 6 percent of the excavated materials (953 000 m³ in the solid state) can be usable as shotcrete- or concrete aggregates. About 15 percent (2 325 000 m³ in the solid state) can be used for embankments or other backfilling purposes. The remaining of the excavated materials (roughly 79 percent, 12 245 000 m³ in the solid state) appears to be useless for construction purposes without further treatment and, thus, has to be transported to final repositories. However, it is stated in a project document of the BBT (Technical Report D0154-00044) that about 20 percent of usage class C materials can potentially be upgraded to usage class B if additional processing such as, for example, the separation of fines or if a longer period of intermediate storage is applied. The concrete aggregate need for the initial- and final support of the entire BBT is anticipated to be about 4.2 million cubic meters in the solid state. Table 6.3 summarizes these predictions.

Based on the classification, Granite, Granite-Gneiss, and chalky Marble (Hochsteigen Formation, see Figure 6.9) can produce excavation materials that are suitable as concrete aggregate. Furthermore, it is assumed that processing losses between 15 and 20 percent will occur when using suitable excavated materials (usage class A) of conventional tunneling. Typical processing losses are fines produced due to the different processing steps in an aggregate plant. A significantly higher processing loss

¹⁰In contrast to the general attempt of Section 3.2, the Brenner Basistunnel BBT SE does not consider a possible reuse of excavated materials due to the mineral industry in their defined usage classes.

Table 6.3: Volumes of Excavation Material Usage Classes Compared to Concrete Aggregate Need (Note that usage class A is suitable for aggregates in concrete.)

	Solid State Volume
Usage Class A	953 000 m ³
Usage Class B	2 325 000 m ³
Usage Class C	12 245 000 m ³
Concrete Aggregate Need	4 200 000 m ³

is expected when processing suitable excavated materials of mechanized tunneling because these materials are poorly graded (see Section 3.2). The processing losses are classified as usage class C and are generally tipped at the final repositories.

6.4.3 FINAL REPOSITORIES, AGGREGATE PLANT

This Subsection briefly summarizes the locations of the final repositories along the Austrian part of the BBT as well as the forecast quantities of the excavated materials that will be tipped in each final repository. In addition, the location of the aggregate plant is discussed.

Figure 6.10 shows a schematic overview of the final repositories of the Austrian part along the alignment of the BBT and represents the forecast of the excavated material quantities, which will be tipped in each final repository. Although, excavated materials of usage class B are suitable as fill materials for embankments or backfills, the Brenner Basistunnel BBT SE considers the quantity of this material class in the determination of the storage size of the final repositories. Excavation materials of usage class A will be processed at an aggregate plant and used as concrete aggregate. Therefore, one aggregate plant for the entire Austrian part of the BBT is located at the final repository Padastertal, which is a part of the contract section Wolf, because only excavated materials of the contract section Wolf (see Figure 6.10 and 6.11) are predicted to be classified as usage class A materials. After the processing of these excavated materials to shotcrete- or concrete aggregates, the recycled materials will be reused within the contract section Wolf to shorten the transport distances. Reuse possibilities of these excavated materials are, for example, concrete applications of the initial- or final support.

If excavated materials of the other contract sections (i.e., Ampass, Innsbruck, and Ahrental; Figure 6.4) will be classified as usage class A, which is not predicted, the excavated materials will temporarily be stored at the intermediate repositories which are, in general, located near the adit portals of the particular contract sections. Subsequently, these materials will be transported to the aggregate plant of the final repository Padastertal.

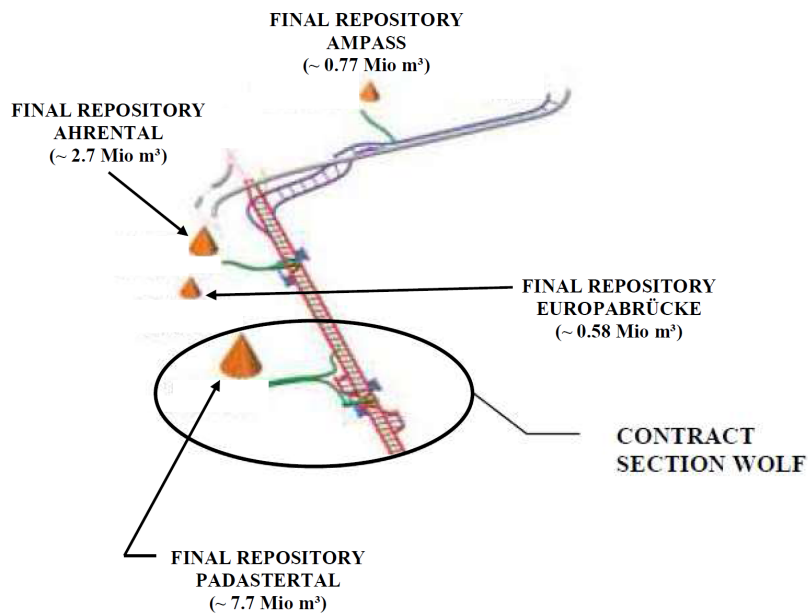


Figure 6.10: Final Repositories Along the Austrian Part of the BBT (Bergmeister, 2010)

6.4.4 TRANSPORT LOGISTICS

To consider the different local conditions along the alignment of the BBT the transport logistic of each contract section has to fulfill other conditions. The main goal of the transport logistic concept is to ensure that the environment, landscape, and the stakeholders will be affected as little as possible. To fulfill this goal, the final repositories will be set up near the portals at the lateral adits minimizing lengthy transportation via public roads (see Figure 6.10). Accordingly, in contract section Wolf a specific mucking tunnel is planned to transport the excavated materials of contract section Wolf to the final repository Padastertal (see Figure 6.11). The transportation of the excavated materials is generally assumed to be done with conveyor belt systems or muck trucks. In addition to the final repositories, intermediate repositories are located next to the portal to handle the excavation materials coming from the tunnel. Muck trucks or conveyor belt systems subsequently transport the excavated materials to their further usage (see Section 3.2). However, as stated above, the mucking tunnel Padastertal directly connects the tunnelsystem of the BBT with the final repository Padastertal. Therefore, the final repository Padastertal also incorporates the tasks of an intermediate repository such as the "Final Material Classification" (see Section 3.2).

6.5 CONTRACT SECTION WOLF

The following discussion summarizes why contract section Wolf is the core of the TEMH of the Austrian part of the BBT:

- Excavation materials of usage class A are only predicted in contract section Wolf.
- The aggregate plant of the Austrian part of the BBT is located in contract section Wolf.
- Recycled excavated materials (shotcrete- and concrete aggregates) are only reused within contract section Wolf.

Hence, the simulation model (Chapter 5) is applied to a part of contract section Wolf (Chapter 7) to simulate parts of the TEMH process of the BBT. Figure 6.11 shows the main part of contract section Wolf. In particular, the mucking tunnel Padastertal, the lateral adit Wolf and the final repository Padastertal are important for the TEMH. In the following a brief overview of the construction schedule of contract section Wolf and the particular TEMH is given.

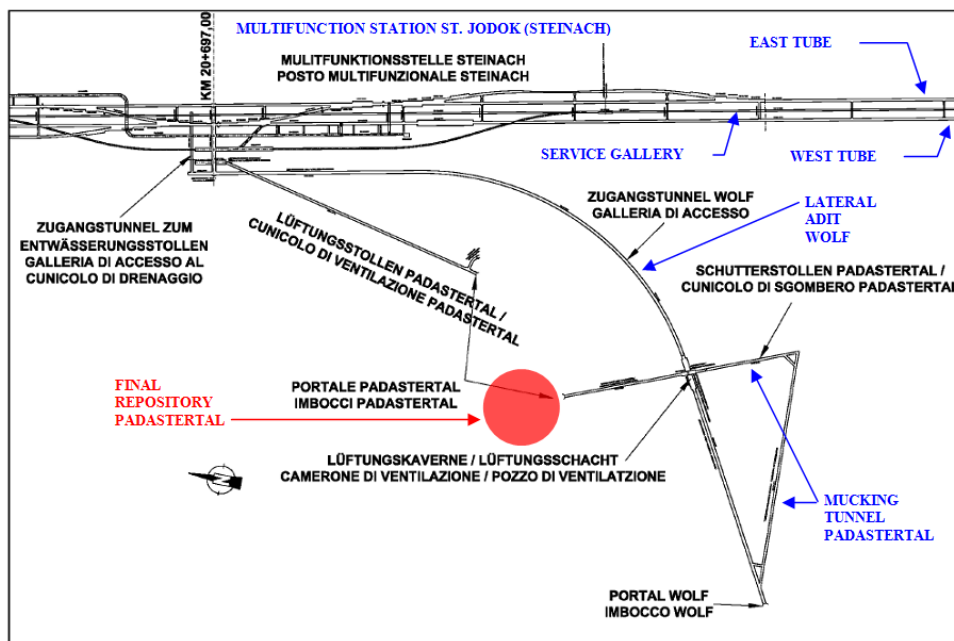


Figure 6.11: Contract Section Wolf (Technical Report D0118-02916-10)

6.5.1 TUNNELING OF CONTRACT SECTION WOLF

The tunnel construction of contract section Wolf is subdivided into construction phases, which are discussed below. Figure 6.12 illustrates which tunneling method is

used for which tunnel section and shows which tunnel drifts of the main tunnel tubes and the service gallery are related to the contract section Wolf. The tunnel drifts which are represented with arrowheads that point away from the lateral adit Wolf are tunnel drifts of the contract section Wolf.

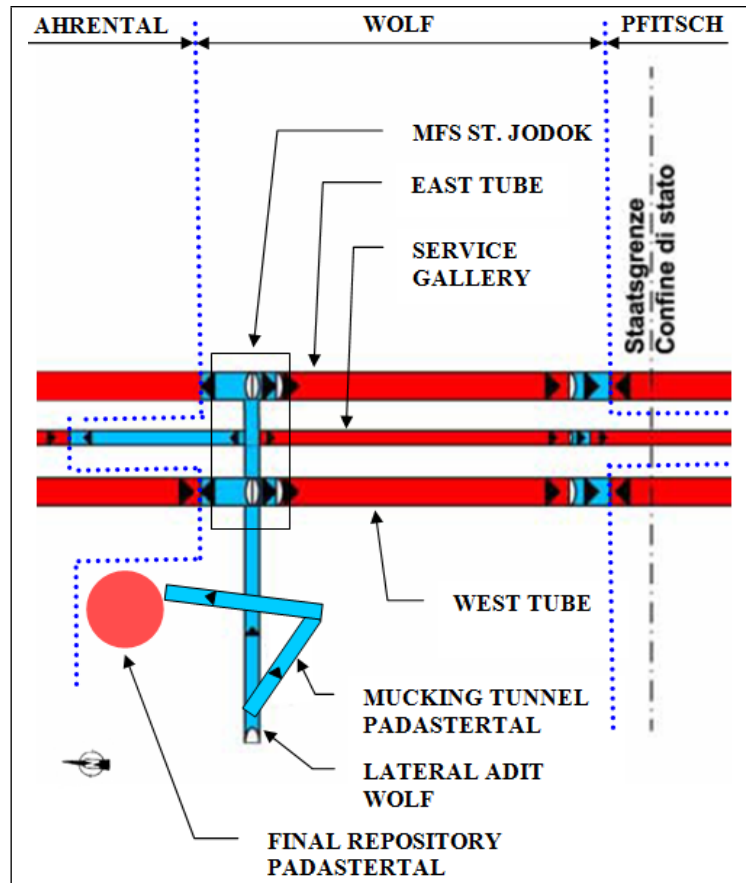


Figure 6.12: Tunneling Methods of Contract Section Wolf: Red Tunnels Are Constructed by Mechanized Means, Blue Tunnels Are Constructed Conventionally, Arrowheads Show the Direction of the Tunnel Advance (Technical Report D0118-02369)

- **"Construction Site Installation Phase"**

The first meters of the lateral adit Wolf and the entire mucking tunnel Padasteral will be excavated within the installation phase of the construction site Wolf.

- **"Exploration Phase"**

During the exploration phase the tunnel drift of the lateral adit Wolf will continue. Furthermore, the installation caverns, which start from the lateral adit Wolf and are parts of the MFS St. Jodok, will be excavated. Parts of the South- (mechanized tunneling) and the North drift (conventional tunneling) of the service gallery are also excavated.

- **"Construction Phase"**

In the construction phase the East and West tunnel tubes will be excavated, the excavation of the service gallery will continue, and the MFS St. Jodok will be constructed simultaneously.

Figure 6.12 shows that the main parts of the East and West tunnel tubes as well as the service gallery will be constructed by mechanized means. It is anticipated to perform the mechanized tunneling sections with single shield TBMs with prefabricated segments as initial support. The tunnel sections, which will be constructed conventionally will use the New Austrian Tunneling Method (NATM) with Drilling and Blasting. In general, the initial support measures of the NATM are shotcrete, rock bolts, lattice girders, and reinforcing steel meshes. The application of these initial support measures, using NATM, is flexible and depends on the geological conditions. Finally, the mechanized tunnel sections as well as the conventional tunnel sections will be lined with a concrete inner liner as final support. The inner liner construction starts at a certain time, which is defined in the construction schedule of the BBT.

6.5.2 TUNNEL EXCAVATION MATERIAL HANDLING OF CONTRACT SECTION WOLF

The TEMH of contract section Wolf follows the general concept of the TEMH of the BBT which was described in Section 6.4. Due to the specific conditions of contract section Wolf the material flows in contract section Wolf need further discussion.

The excavated materials of the mucking tunnel Padastertal and the lateral adit Wolf will temporarily be stored next to the portal Wolf (see Figure 6.11). After the break-through of the mucking tunnel Padastertal to the final repository Padastertal (see Figure 6.11) these materials will be transported through the mucking tunnel to the final repository Padastertal using muck trucks. Subsequently, a conveyor belt system will be installed in the lateral adit Wolf and the mucking tunnel Padastertal to transport the excavated materials of the East and West tube, the service gallery, and the MFS St. Jodok to the final repository Padastertal (see Figure 6.11). Therefore, a central material handling and loading facility will be located in a part of the MFS St. Jodok to transfer the excavated materials to the conveyor belt system. This central material handling and loading facility will consist of a small stone crusher and a conveyor feeder. Later, an additional conveyor belt system will be installed in the lateral adit Wolf and the mucking tunnel Padastertal to handle the quantities of excavated materials of the several tunnel drifts of the construction phase such as the main tunnel drifts and the service gallery excavation.

Parts of the excavated materials of contract section Ahrental, which will not be tipped at the final repository Ahrental due to limited capacity, will also be tipped at the final repository Padastertal. The transport of these materials will start after

the break-through of the tunnel drifts of contract section Wolf to contract section Ahrental will be performed (see Figure 6.13). The excavation material transport to the final repository Padastertal will use mainly the conveyors of the lateral adit Wolf and the mucking tunnel Padastertal.

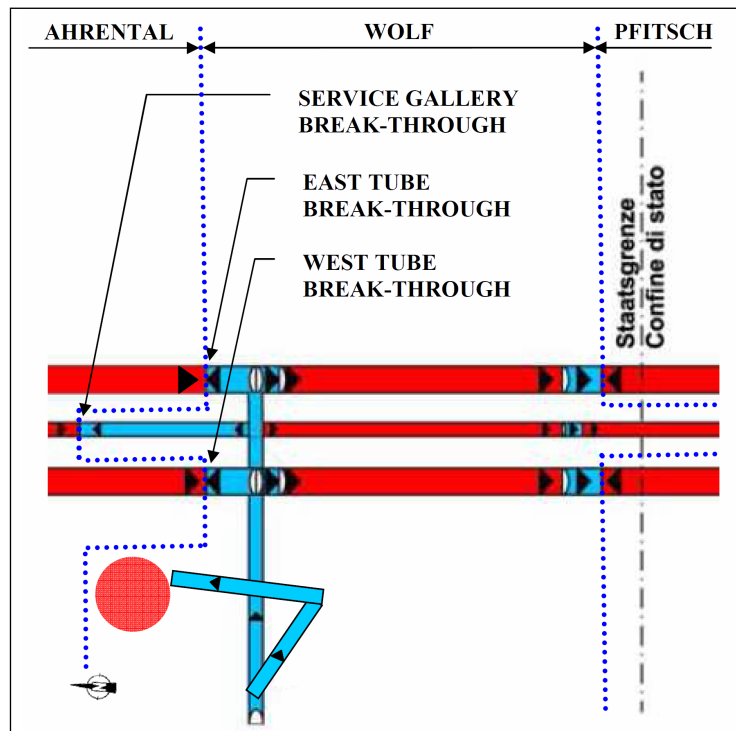


Figure 6.13: Break-Through of Contract Section Ahrental to Contract Section Wolf (Technical Report D0118-02369)

After a specific part of the final repository Padastertal is filled with the excavated materials of the construction site installation phase and the exploration phase (see Subsection 6.5.1), the aggregate plant will be constructed on this part of the repository. Hence, all the excavated materials of contract section Wolf will be transported to the final repository Padastertal, which performs, as mentioned before, also the tasks of an intermediate repository. Subsequently, excavated materials of usage class A will be recycled at the aggregate plant, usage class B materials will temporarily be stored and may be reused as fill materials or tipped at the final repository, and excavation materials of usage class C will be tipped. The recycled excavated materials will be used as shotcrete- and concrete aggregates in contract section Wolf. Accordingly, these recycled aggregates will supply parts of the initial- and final support works of contract section Wolf. The processing losses will be tipped at the final repository Padastertal or may undergo additional processing such as the separation of fines.

Chapter 7

APPLICATION OF THE SIMULATION MODEL TO CONTRACT SECTION WOLF

In this Chapter the simulation model, developed in Chapter 5, is used to simulate the TEMH process of a part of contract section Wolf. The goal of this application is to show that the simulation model provides a practically usable tool to simulate tunnel excavation and material flows in the TEMH process with the associated uncertainties. Most importantly, the assumptions, which were necessary to prepare the collected information of the BBT for the simulation model, are described. There was a need for these assumptions because at the time of the simulation the level of detail of information was, due to the early stage of the BBT project, not very accurate. Hence, emphasis is placed on the application of the simulation model to a part of contract section Wolf and not on a simulation, which breaks down all the details of contract section Wolf. Moreover, the main input windows of the DAT and specific simulation techniques, which are used for the simulation are discussed.

7.1 SIMULATION AREA

The simulation model is applied to the area of contract section Wolf, which is schematically shown in Figure 7.1. Specifically, the construction of the labeled tunnel drifts ("*TBM East Tube*", "*TBM West Tube*", "*Drill&Blast East Tube*", and "*Drill&Blast West Tube*") with the related material flows of the TEMH are simulated. The planned tunneling methods and the TEMH of contract section Wolf were described in Subsection 6.5.1 and 6.5.2, and Figure 6.11 shows the main parts of contract section Wolf. In the following, the material flows of the excavated materials,

which are simulated, are described.

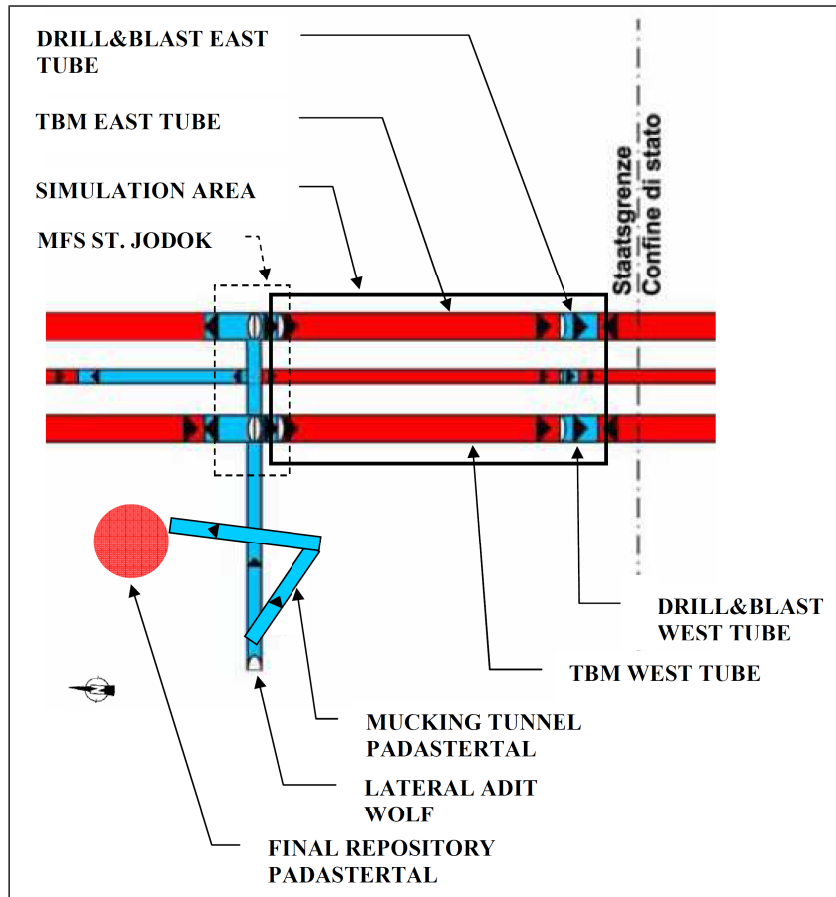


Figure 7.1: Simulation Area (bold rectangle) of Contract Section Wolf

First, the excavated materials of the TBM tunnel drives ("*TBM East Tube*" and "*TBM West Tube*") are transported with conveyors to the MFS St. Jodok. A handling and loading facility is located in the MFS St. Jodok to transfer the excavated materials to the conveyor belt system of the lateral adit Wolf and the subsequent mucking tunnel Padastertal. In the simulation model it is assumed that this MFS simulates an intermediate repository. Subsequently, the excavated materials pass the lateral adit Wolf and the mucking tunnel Padastertal using conveyors. After the excavated materials reached the final repository they are allocated to their final usage. Examples are, processing in the aggregate plant, which is located at the final repository Padastertal, temporary storage of the excavated materials at the final repository Padastertal until they are reused as fill materials or tipped at the final repository Padastertal. After processing, the recycled excavated materials are reused as aggregate for shotcrete or concrete within the contract section Wolf.

The tunnel drifts using Drill and Blast start after the TBM excavations are finished. Muck trucks are used in the simulation to transport the excavated materials

to the MFS St. Jodok. During this transport the excavated materials pass the corresponding tunnel, which was excavated by mechanized means. Subsequently, the same material flows are simulated as for the excavated materials of the preceding mechanized tunnel drifts (see above).

7.2 SIMULATION INPUTS

In order to simulate the TEMH of the simulation area several assumptions were made. This Section, which is structured in two Subsections of the geologic- and construction module inputs, discusses the assumptions and techniques used to prepare suitable input data. In addition, the input windows of the DAT, which are used for the simulation are presented.

7.2.1 GEOLOGIC MODULE INPUTS

Here, the determination of a ground class ("*Ground Class Determination*") based on the available information in the project documents of the BBT is discussed. After a ground class with its associated uncertainties is defined these results are used as input to compute the ground classes in the DAT ("*Ground Class Input*"). It is important to recall that in the simulation model each ground class is assigned a particular construction method which produces a particular excavation materials usage class (e.g., usage class A).

GROUND CLASS DETERMINATION

As mentioned before, information from the project documents of the Brenner Bastsstunnel BBT SE, in particular, the distribution of the tunneling classes and the excavation material usage classes are used to define a ground class. Several tunneling classes corresponding to the geologic conditions are provided for the BBT. Each tunneling class for mechanized- and conventional tunneling is modeled with a construction method in the DAT and generally characterized by a particular excavation sequence, support pattern, round (or cycle) length, advance rate, and cost. However, at the time of the simulation these characteristics were not available for the tunneling classes of the BBT, which made it necessary to make assumptions:

In the project documents of the BBT the tunneling classes are assigned so-called geotechnically homogeneous zones which are characterized by specific geomechanic parameters. A particular tunneling class is used for a specific geotechnically homogeneous zone. Additional tunneling classes are assigned to represent fault zones within the geotechnically homogeneous zones. Table 7.1 shows, for example, the forecast of the mechanized tunneling classes of the geotechnically homogeneous zone N30 of the BBT. The tunneling class "TBM 01" is used over the length of the geotechnically homogeneous zone N30 where no influence by faults is anticipated. The tunnel-

ing classes "TBM 02", "TBM 03", and "TBM 04" are applied over the lengths of the geotechnically homogeneous zone N30 which are predicted to be influenced by faults. A stronger influence by faults results in a "higher" tunneling class. For example, "TBM 04" has to be used over the length of the geotechnically homogeneous zone N30, which is most heavily affected by faults. Based on the forecast of the project documents of the BBT the length of "TBM 04" is 4.55 percent (30 meters) of the entire length (660 meters) of the geotechnically homogeneous zone N30. It is important to note that the names of the tunneling classes used for the simulation are different from the project documents.

Table 7.1: Prediction of Tunneling Classes within the Geotechnically Homogeneous Zone N30

Geotechnically Homogeneous Zone		Tunneling Classes		
Name	(m)	Name	(%)	(m)
N30	660	TBM 01	4.55	30
		TBM 02	68.20	450
		TBM 03	22.70	150
		TBM 04	4.55	30

It is assumed that only three conventional tunneling classes exist for the Drill and Blast tunnel drifts because the determination of the advance rates of the tunneling classes, which is based on a backcalculation using the construction schedule of the BBT (see Subsection 7.2.2), was only reasonable with three conventional tunneling classes. Due to this assumption, the anticipated distribution of the conventional tunneling classes within each ground class, which is based on the information of the project documents of the BBT, cannot be used for the conventional tunnel drifts. Therefore, also the distribution of the conventional tunneling classes within each geotechnically homogeneous zone is assumed. Table 7.2 shows the assumed distribution of the three assumed conventional tunneling classes within each geotechnically homogeneous zone. One can see in Table 7.2 that the percentage of the three conventional tunneling classes is the same for each geotechnically homogeneous zone. In contrast, the input of the mechanized tunnel drifts considers the anticipated distribution of the mechanized tunneling classes within each geotechnically homogeneous zone, due to the project documents of the Brenner Basistunnel BBT SE (see Table 7.1). As a result, the simulations of the mechanized tunnel drifts are more realistic.

Defining the occurrence of the tunneling classes in a particular geotechnically homogeneous zone in percent of the length of the geotechnically homogeneous zone has disadvantages in the simulations with the DAT. For instance, the exact location of a particular tunneling class within the geotechnically homogeneous zone as well as the location of the transition between a particular tunneling class and a subsequent

Table 7.2: Assumed Percentage of the Assumed Conventional Tunneling Classes within each Geotechnically Homogeneous Zone

Conventional Tunneling Classes	Percentage within each Geotechnically Homogeneous Zone
Drill&Blast 01	50 %
Drill&Blast 02	35 %
Drill&Blast 03	15 %

tunneling class are not defined. In addition, the transition sequence between the tunneling classes is not defined. Most importantly, this approach does not allow one to realize which combination of geologic/geotechnical parameters defines a particular tunneling class.

The classification of the excavated materials based on their final usage (described in Subsection 6.4.2) is also provided in the project documents of the BBT. Again, the excavation materials usage classes are related to the defined geotechnically homogeneous zones. Table 7.3 represents the percent values of the occurrence of the excavation material usage classes of the geotechnically homogeneous zone N30. As mentioned before, the percent values define only the percentage of the excavated materials usage class within the geotechnically homogeneous zone; the exact location and the transition sequence between the usage classes are not defined.

Table 7.3: Prediction of Excavation Material Usage Classes within the Geotechnically Homogeneous Zone N30

Geotechnical Homogeneous Zone N30	
Usage Class A	0 %
Usage Class B	30 %
Usage Class C	70 %

The above described predictions of the tunneling classes (see Table 7.1 and 7.2) and the excavation material usage classes (see Table 7.3) within a geotechnically homogeneous zone are used to define the ground classes. Figure 7.2 illustrates the procedure for defining the ground classes, which is described below:

- Firstly, each geotechnically homogeneous zone (e.g., N30) is subdivided into the corresponding tunneling classes using the predicted distribution of the tunneling classes (e.g., "TBM 01", "TBM 02", "TBM 03", and "TBM 04") within the respective geotechnically homogeneous zone. As a result the length of the predicted tunneling classes (e.g., 30 meters for "N30_TBM_01") within the geotechnically homogeneous zone is determined.

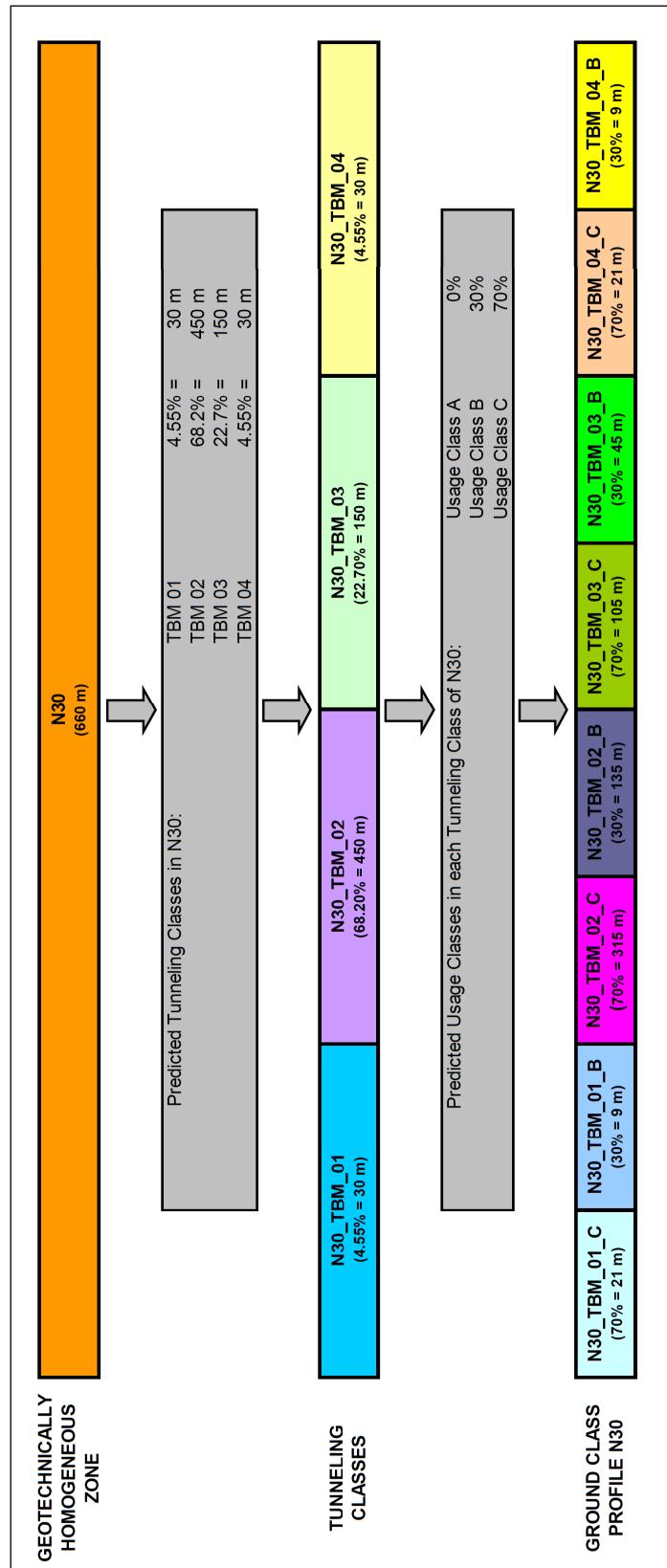


Figure 7.2: Ground Class Determination of the Geotechnically Homogeneous Zone N30

- Secondly, every tunneling class (e.g. "N30_TBM_01") is in turn subdivided into the predicted usage classes of the excavated materials (e.g., usage class A, usage class B, and usage class C), which are anticipated for the particular geotechnically homogeneous zone (e.g., N30).
- Thirdly, the ground class profile of the geotechnically homogeneous zone is determined. Each defined ground class (e.g., "N30_TBM_01.C") consists of a specific tunneling class (e.g., "TBM_01") and a specific excavation materials usage class (e.g., "C" describing the usage class C).

This procedure is repeated for each geotechnically homogeneous zone of the simulation area. It is important to mention that the transition sequence of the ground classes within a ground class profile of a geotechnically homogeneous zone is not defined. Therefore, it is assumed that a ground class profile starts with the "lowest" tunneling class (e.g., "TBM 01") and subsequently the next "higher" tunneling class (e.g., "TBM 02") follows (see Figure 7.2). The same principle is used for the distribution of the excavation material usage classes within a tunneling class (e.g., usage class C starts and usage class B follows, which is followed by usage class A, see Figure 7.2).

The geologic uncertainties in the simulation area have to be considered in the determination of the ground class profile. Prediction uncertainties of the geology are defined in the project documents of the BBT. These uncertainties subdivide the geology along the alignment of the BBT into geology zones with low, medium, high, or very high uncertainties. This collected information is used to include the geologic uncertainties of the TEMH in the simulation, which are, for example, the occurrence of discontinuities or the chemical components of the excavated materials. A semi-quantitative approach is used to include the geologic uncertainties:

The length of each ground class is characterized with a triangular probability density function. Figure 7.3 illustrates a symmetric triangular probability density function which is used to calculate the length of each ground class. The variables which specify the triangular probability density function of a ground class are the minimum value ("*min*") of the ground class length, the maximum value ("*max*") of the ground class length, and the most likely value ("*mode*") of the ground class length. These values are obtained for each determined ground class and subsequently used as input of each triangular probability function of a ground class in the DAT.

As described before, the mode length of the ground class is determined using the prediction of the tunneling classes and the prediction of the excavation material usage classes within each geotechnically homogeneous zone in the project documents of the BBT. Figure 7.2, shows the mode lengths of the ground classes of the geotechnically homogeneous zone N30. Correlating this mode length of a ground class with the corresponding qualitative specification of the prediction uncertainties of the geology (low, medium, high, and very high from the BBT project documents) enables one to

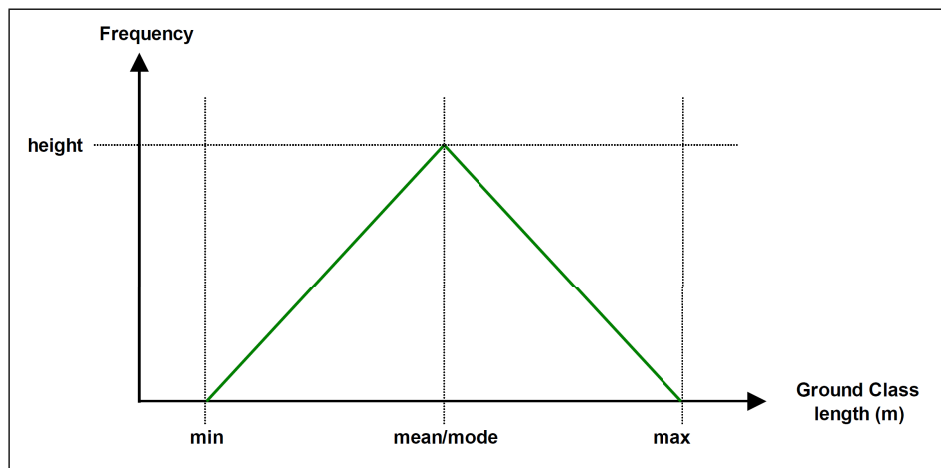


Figure 7.3: Triangular Probability Density Function of a Ground Class Length

calculate the minimum- and maximum length of the ground classes. Table 7.4 shows the simple semi-quantitative approach, which is used to determine the minimum- and maximum lengths of each ground class. In addition, Figure 7.4 schematically illustrates the probabilistic determination of the length of a ground class. The actually simulated length of a ground class in the simulation varies within the range between the minimum- and the maximum ground class length and is selected for each geology simulation with the random generator of the DAT.

Table 7.4: Range of Values for the Ground Class Lengths

Prediction Uncertainty	Minimum Length (m)	Maximum Length (m)
low	95% of the mode length	105% of the mode length
medium	90% of the mode length	110% of the mode length
high	80% of the mode length	120% of the mode length
very high	70% of the mode length	130% of the mode length

After the minimum-, mode-, and maximum lengths of each ground class are determined these values are used as input of the geologic module of the DAT. Therefore, the main input windows of the geologic module are discussed below.

GROUND CLASSES INPUTS

The geology of the simulated area is modeled with an "Area", which is the uppermost level of the input of the geologic module of the DAT (see Subsection 4.1.1 and Figure

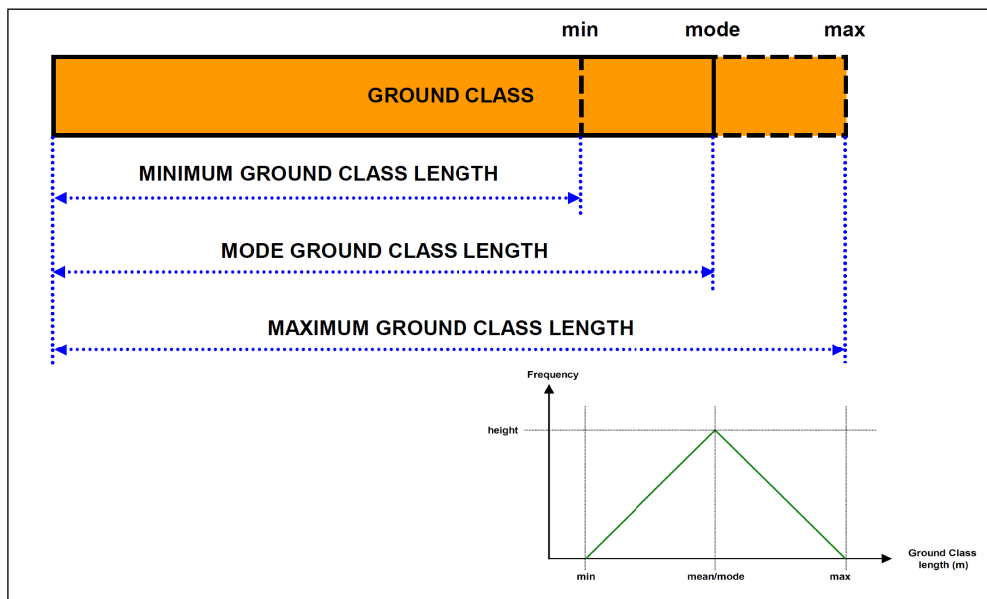


Figure 7.4: Probabilistic Ground Class Length Determination

4.1).¹¹ Figure 7.5 illustrates the "Area" input window. Here, this area represents the entire simulation area of the contract section Wolf beginning with the geotechnically homogeneous zone N24 and ending with the geotechnically homogeneous zone N34. The length of the simulation area is 9 378 meters (see "Area Length" box).

Subsequently, the area is subdivided into as many "Zones" as ground classes are defined. Zones are the basic unit of geology in the DAT and, in general, declare a length of ground, and what it consists of (Min et al., 2009). A specific "Ground Parameter Set" (e.g., "GP Set Nb 65" see "Ground Parameter Set" box in Figure 7.6) is defined for each zone. Such a ground parameter set generally consists of several "Ground Parameters", which define the geologic/geotechnical conditions in the zone. Each ground parameter usually has several "Parameter States". An example is the ground parameter "Lithology" which can have the parameter states "Phylite", "Schist", and "Granite" (see Figure 4.2). A specific combination of the parameter states of different ground parameters results in a particular ground class. For example, the combination of the parameter states "Phylite", "Inflow", and "Medium" always defines the ground class "GC1" in Figure 4.2. One can see that this standard procedure results that a zone can have multiple ground classes.

However, as mentioned before, the tunneling classes of the BBT and, thus, the subsequent ground classes (see Figure 7.2) are not defined by such a combination of geologic/geotechnical parameters. Hence, the input of the ground classes has to use a different approach for this application, which allows one to consider the collected

¹¹The Simjava User's Manual (Min et al., 2009) discusses the input structure of the geologic module of the DAT in detail.

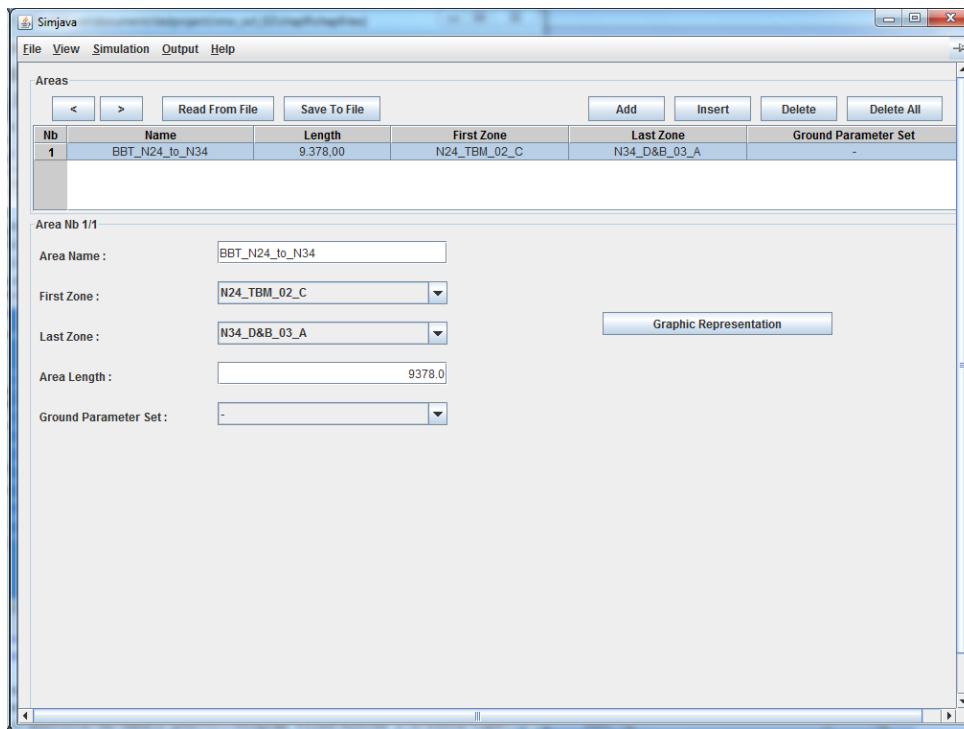


Figure 7.5: Area Input Window

information of the project documents of the BBT such as, for instance, the variable lengths of the ground classes, due to the uncertainty about geology. In this approach, a zone directly treats a particular type of ground class and is indicated by the name of this ground class (e.g., "N34_D&B_03_A", see "Zone Name" box in Figure 7.6). For each ground parameter set, which is defined for each determined ground class of the simulation area (see Figure 7.7), an auxiliary ground parameter (e.g., "GP01", see "Ground Parameter" panel in Figure 7.8) with one parameter state (e.g., "dummy", see "Deterministic Values" panel in Figure 7.8) is defined. This parameter state stays the same till the end position of the zone is reached and, thus, produces a zone which consists of one specific type of ground class. In Figure 7.8 the parameter state "dummy" of the "Ground Parameter Set Nb 65", which is the ground parameter set of the last zone of the simulation area ("N34_D&B_03_A"), stays the same till the end position of the zone (9 378 meters) is reached. The end position value uses the start point of the area ("BBT_N24.to.N34") as reference point (see "Deterministic Values" panel in Figure 7.8). The start point of the zone ("N34_D&B_03_A") is defined by the end position of the preceding zone ("N34_D&B_03_B").

As mentioned before, the uncertainty about the length of each ground class can be included in the input of the DAT due to this approach. Therefore, the determined minimum-, mode-, and maximum lengths of each ground class are used to define the length of a zone. The length of a zone is defined in the zone input window using

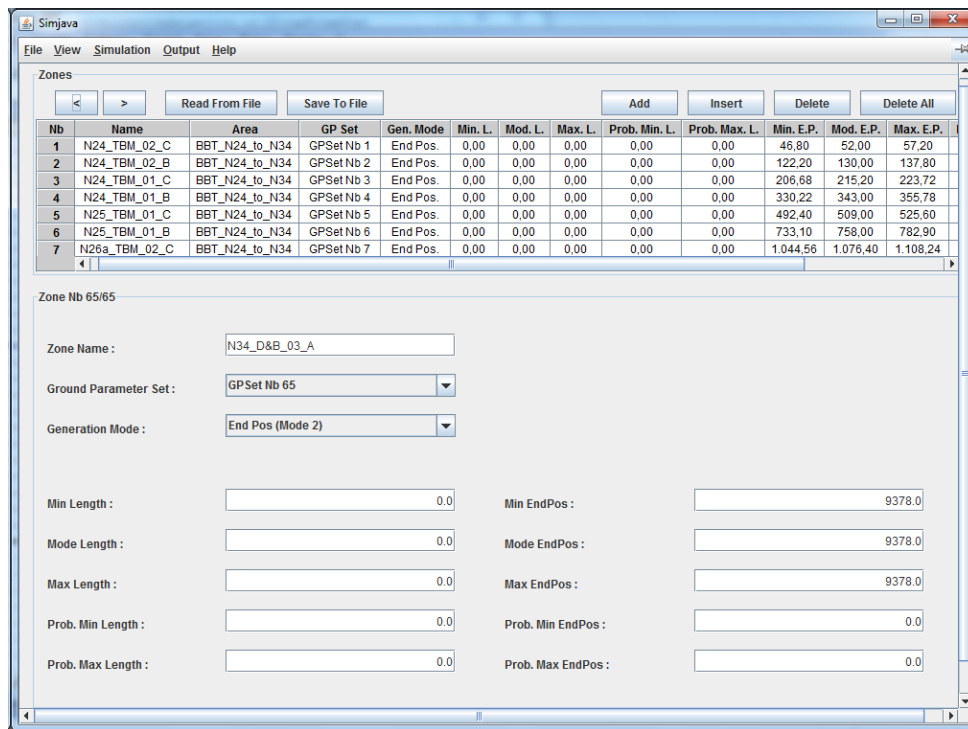


Figure 7.6: Zone Input Window with End Point Definition

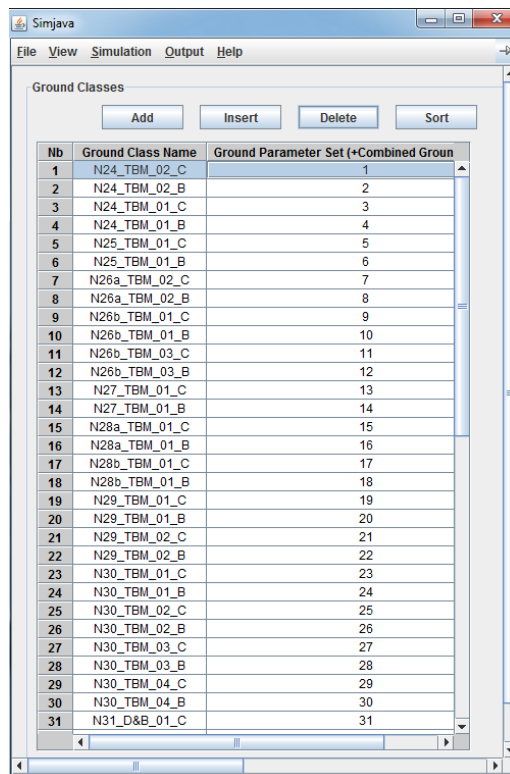


Figure 7.7: Ground Classes Input Window

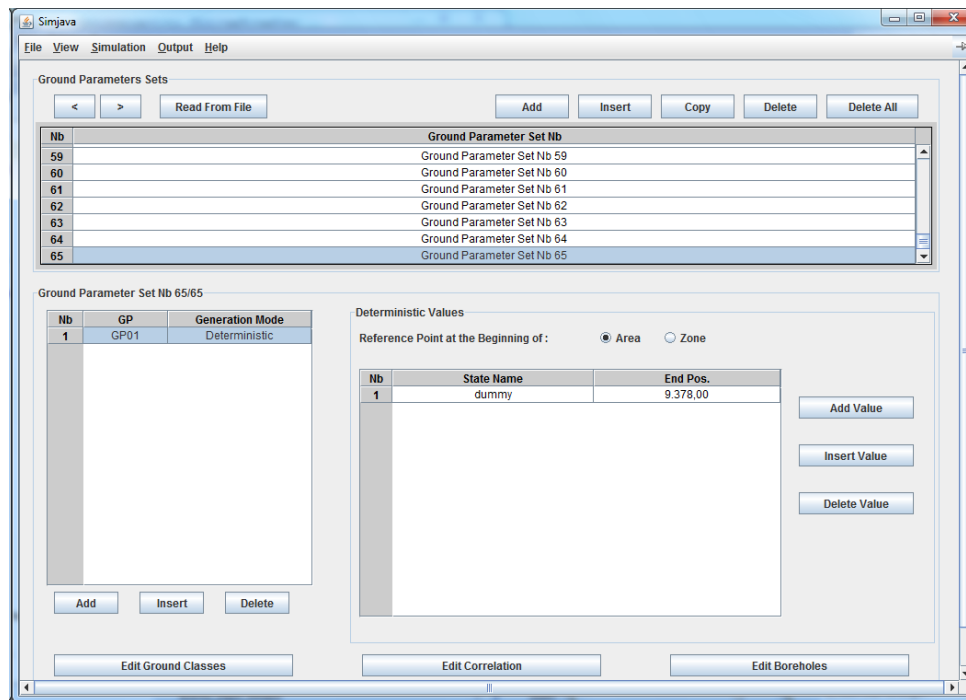


Figure 7.8: Ground Parameter Input Window

"End Pos (Mode 2)" (see Figure 7.6, "Generation Mode" box). End Pos (Mode 2) generates the zone lengths based on the estimated end point location of each zone. For this reason, the determined minimum-, mode-, and maximum lengths of each ground class are summed to calculate the minimum- ("Min EndPos"), mode- ("Mode EndPos"), and maximum end position ("Max EndPos") of each zone. In Figure 7.6 the minimum-, mode-, and maximum end positions have the same value (9 378 meters) because the zone "N34_D&B.03_A" is the last zone of the area and, thus, the end position of this zone is a known value. The end positions are related to the starting point of the area. The Appendix shows the minimum-, mode-, and maximum end positions of each ground class of the simulation area, which are used as input of the zones. With this approach and input of a zone, which is shown in Figure 7.6, the random generator of the DAT automatically generates the length of the zone based on the triangular probability density function of the respective type of ground class (see Figure 7.4).

Figure 7.9 represents a computed ground class profile of the simulation area. Each simulation run computes a different ground class profile due to the included uncertainties about geology. The upper bar illustrates the area, the middle bar the zones and the lower bar a ground class profile. Each color of the middle bar specifies a zone and each color of the lower bar a ground class. One can see in the detail (dashed rectangle) of Figure 7.9 that a zone can have two ground classes of the same type. For example, in the zone "N33_D&B.03_C" the ground class "N33_D&B.03_C"

occurs twice. This is so because the end position of a zone is based on a selected value of the respective triangular probability density function and, thus, can be greater than the end position of the respective ground parameter state (e.g., "dummy", see "Deterministic Values" panel in Figure 7.8), which is based on the mode end position of the triangular probability density function. In such a case, the DAT automatically uses for the remaining length of the zone the related ground class of the ground parameter set (see Figure 7.7) of the zone. As a result, each zone consists in this approach of one type of ground class (see detail (dashed rectangle) of Figure 7.9). Furthermore, in this approach the variable lengths of the ground classes, due to the uncertainties about geology, are considered in the input of the zones.

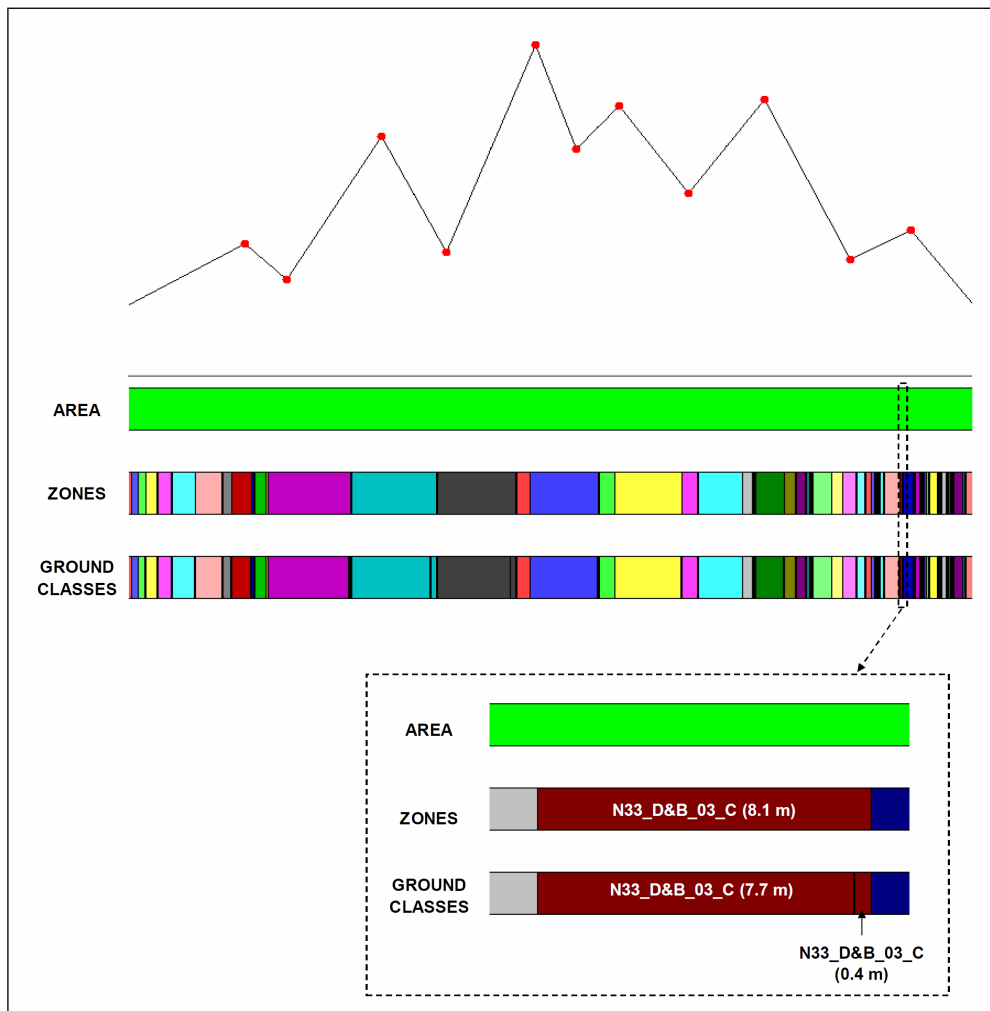


Figure 7.9: Simulated Ground Class Profile for the Simulation Area

7.2.2 CONSTRUCTION MODULE INPUTS

This Subsection discusses the inputs of the construction module (see Section 5.2) in order to simulate the construction process through the computed ground class profiles with the related material flows in the TEMH process. For this reason, the general tunnel network of the simulation model (see Figure 5.4) is applied to each tunnel drift of the simulation area (see Figure 7.1). Figure 7.10 represents this tunnel network of the simulation area. In the tunnel network "TBM East Tube" and "TBM West Tube" are subdivided into two tunnels ("TBM_East_01" and "TBM_East_02" as well as "TBM_West_01" and "TBM_West_02"). This is done because in the current version of the DAT a "Repository" can simulate only a tunnel with a maximum length of 5 000 meters.¹² The "TBM East Tube" and the "TBM West Tube" are longer than 5 000 meters which made this subdivision necessary. All geotechnically homogeneous zones less than 5 000 meters are assigned to "TBM_East_01" and "TBM_West_01". The remaining geotechnically homogeneous zones are modeled with "TBM_East_02" and "TBM_West_02".

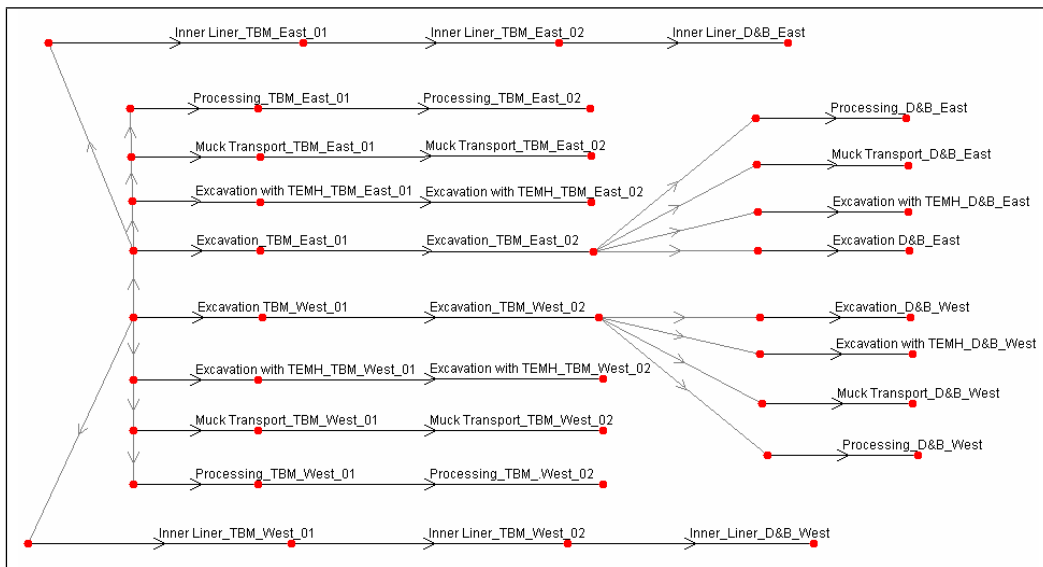


Figure 7.10: Tunnel Network of the Simulation Area

Each tunnel of the tunnel network is characterized in the tunnel information window which pops-up when a tunnel is selected to be edited. Figure 7.11 shows the tunnel information window for the tunnel "Excavation_TBM_East_01" which characterizes, for example, the tunnel geometry, the tunnel length which is defined with "Begin Location" and "End Location", the related "Repository", and the "Time Delay". The "Time Delay" input (see "Time Delay" panel in Figure 7.11) considers the

¹²This 5 000 meters limitation in the DAT can be changed in future.

fact that the East tunnel drives follow the West tunnel drives after 95 days, given the construction schedule of the BBT.

The screenshot shows the 'Tunnel Informations' window with the following details:

- Tunnel 1/47**
 - Name: Excavation_TBM_East_01
 - Dummy Tunnel:
 - Opposite Tunnel: -
 - Area: BBT_N24_to_N34
 - Geometry: Geometry No 2
 - Beginning Location: 0.0
 - End Location: 4458.0
 - Graphic Position: 0.0
 - Minimum Fixed Cost: 0.0
 - Mode Fixed Cost: 0.0
 - Maximum Fixed Cost: 0.0
 - Minimum Time Cost: 0.0
 - Mode Time Cost: 0.0
 - Maximum Time Cost: 0.0
- Time Delay Table**

Time	Min Dur.	Mode Dur.	Max Dur.
0	95	95	95
- Position Delay Table**

Position	Min Dur.	Mode Dur.	Max Dur.
----------	----------	-----------	----------
- Up and Down Table**

Position

- Repositories Table**

Nb	Repository	Position
----	------------	----------
- Structure Variables Table**

Nb	Name	Min.	Mode	Max.	Prob. Min.	Prob. Max.	Corr. 1
----	------	------	------	------	------------	------------	---------

Figure 7.11: Tunnel Information Window

As described in Section 5.2, the simulation of the construction process considers the tunneling method; the mechanized tunnel drifts ("*TBM East Tube*" and "*TBM West Tube*") are simulated differently than the conventional tunnel drifts ("*Drill&Blast East Tube*" and "*Drill&Blast West Tube*"). The mechanized tunnel drifts use for their corresponding construction methods the activity networks which are explained in Section 5.3. In contrast, the construction methods of the conventional tunnel drifts are simulated with the activity networks of Section 5.4. In the following, the input of the construction methods, their associated activities, and the resources are discussed.

To simplify the simulation, the corresponding crossover tunnels are not considered.¹³ In addition, it is assumed that the TBM tunnel drifts as well as the Drill and Blast tunnel drifts have a constant cross sectional area and a constant initial- and final support per tunnel meter. There is a need for these assumptions because

¹³Min (2003) discussed the simulation of crossover tunnels with the DAT in detail.

detailed information regarding the tunneling classes of the BBT were not available at the time of the simulation.¹⁴ Table 7.5 relates the modeled tunnel drifts with their assumed constant cross sectional area and their assumed constant consumption of shotcrete or concrete for the initial- or the final support.

Table 7.5: Assumed Cross Sectional Area and Assumed Shotcrete/Concrete Consumption of the Initial- and Final Support

Tunnel Drift	Cross Sectional Area (m ²)	Shotcrete/Concrete Initial Support (m ³ /m)	Concrete Final Support (m ³ /m)
TBM East Tube	75.43	8.70	10.70
TBM West Tube	75.43	8.70	10.70
Drill&Blast East Tube	65.40	4.20	10.70
Drill&Blast West Tube	65.40	4.20	10.70

Construction methods, which simulate the tunneling classes in the DAT, specify method variables such as the round (or cycle) length, the advance rate and cost. As mentioned before, the tunneling classes of the BBT were not characterized with specifications such as the tunnel support pattern, the tunnel geometry or the advance rate at the time of the simulation. For this reason, the advance rates of the tunneling classes are backcalculated based on the available construction schedule of the BBT. Table 7.6 shows the backcalculated advance rates, which specify the tunnel construction advance without the related TEMH for the assumed tunneling classes. As noted before, it is assumed that only three Drill and Blast tunneling classes exist because it was not possible to backcalculate reasonable advance rates for all the predicted tunneling classes for Drill and Blast construction. In addition, full-face excavation is assumed for the Drill and Blast tunneling classes. Table 7.6 shows the advance rate of the construction of the inner liner which is also backcalculated from the construction schedule. Considering the construction schedule of the BBT, the lining advance rate is the same for the mechanized- and conventional tunneling drifts. How this backcalculated or assumed advance rates are used as input in the DAT is discussed below.

As mentioned before, a tunneling class of the BBT is modeled with a construction method in the DAT. This means that a construction method has to consider the backcalculated or assumed advance rate of the corresponding tunneling class. To do this, the advance rates in Table 7.6 are used to determine the duration of the corresponding construction methods. However, the duration of a construction method is in the DAT calculated through the corresponding activity network. Such activity networks (e.g., the activity network of the "Excavation" subpart of conventional tunneling, see Figure 7.12) consist of several activities such as, for example, "Excavate",

¹⁴These assumptions could be changed in future if additional information will be available.

Table 7.6: Advance Rates of the Tunneling Classes and the Lining

Construction Methods	Advance Rate (m/day)
TBM 01	12.67
TBM 02	9.83
TBM 03	6.83
TBM 04	1.67
Drill&Blast 01	4.00
Drill&Blast 02	3.00
Drill&Blast 03	2.00
Inner Liner	10.40

"Load", and "Initial_Support". These activities are specified with corresponding time equations to compute the duration of each activity (e.g., "D1", "D2", and "D3" in Figure 7.12). After the duration of each activity of the activity network is computed, the sum of these durations defines the duration of the entire activity network and, thus, the duration of the corresponding construction method. This duration of the construction method is the same as the duration of the corresponding tunneling class, due to the considered advance rate of the corresponding tunneling class (e.g., "advance_rate_Drill&Blast 01", see Figure 7.12). One can see that the method variables "excavate_advance_rate", "loading_time", and "supporting_time", are backcalculated values based on the respective advance rate (e.g., "advance_rate_Drill&Blast 01", see Figure 7.12). In addition, this backcalculation considers the relation between the activities of a specific activity network. For example, it is well known that the duration of the tunnel excavation exceeds the duration of loading the excavated materials; thus, the duration of the activity "Excavate" is estimated as a multiple of the duration of the activity "Load".

To define the duration of the subsequent activity networks of the simulation model, namely the "Excavation with TEMH" subpart, the "Muck Transport" subpart, and the "Processing" subpart, the backcalculated variables of the preceding subpart ("Excavation" subpart) and estimated values obtained through experts or due to experience are used. Figure 7.13 shows the "Excavation with TEMH" subpart of conventional tunneling, which is based on the preceding "Excavation" subpart (see Figure 7.12), due to the parallel structure of the tunnel network of the simulation model (see Subsection 5.2.1). Hence, the "Excavation with TEMH" subpart consists of "reused" activities of the "Excavation" subpart. Such "reused" activities are the activities "Excavate", "Load", and "Initial_Support_Res", which use in their time equations the backcalculated method variables of the preceding "Excavation" subpart. As a result, the durations "D1", "D2", and "D3" of these "reused" activities stay

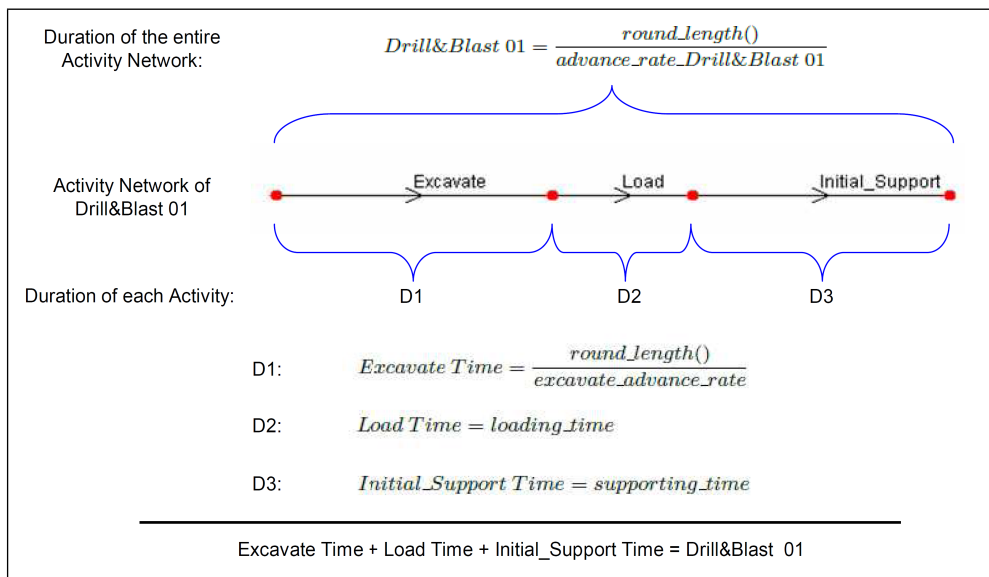


Figure 7.12: Backcalculation of the Duration of an Activity Based on the Backcalculated or Assumed Advance Rate of the Corresponding Tunneling Class

the same as in the preceding "Excavation" subpart (see Figure 7.12). The additional activities such as "Drive_Out", "Unload", and "Drive_In" describe the material flows in the TEMH process. The durations of these activities ("D4", "D5", and "D6") are obtained from experts or based on experience.

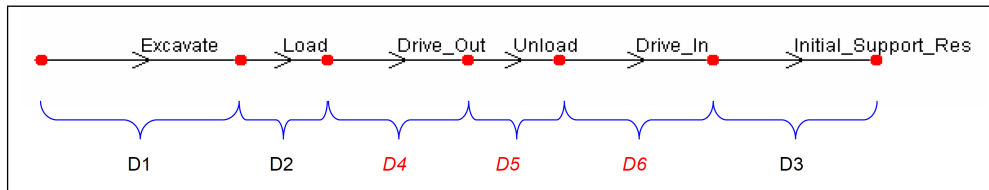


Figure 7.13: Estimate of the Durations of Additional Activities in Subsequent Activity Networks

Construction methods are determined by a combination of a particular ground class and tunnel geometry. Eight tunnel geometries are defined for the simulation area; a separate tunnel geometry is assigned each to the "Excavation", the "Inner Liner", the "Excavation with TEMH.East", the "Excavation with TEMH.West", the "Muck Transport.East", the "Muck Transport.West", the "Processing.East" and the "Processing.West" subpart. The tunnel geometries of the "Excavation" and the "Inner Liner" subpart treat the "East" and "West" tunnel drifts because these subparts do not consider the transport distances of the excavated materials, which change between the "East" and "West" tunnel tubes. The other subparts are assigned a specific tunnel geometry for their "East" and "West" tunnel tubes. Figure 7.11 shows the tunnel information window of the tunnel "Excavation_TBM.East.01" with

the assigned "Geometry No 2" (see "Geometry" box), which is the used tunnel geometry of the "Excavation" subpart. Each ground class of the "Excavation" subpart is assigned a specific construction method. For example, the construction method "TBM_02_C_Excavation" is assigned the combination of the tunnel geometry "Geometry No 2" ("Geometry 2" in Figure 7.14) and the ground class "N24_TBM_02_C" ("N24_TBM_02_C" in Figure 7.14). This procedure, which is called "Method Definition", is repeated for each combination of a ground class and a tunnel geometry (see Figure 7.14).

Ground Class	Geometry 1	Geometry 2	Geometry 3	Geometry 4
N24_TBM_02_C	TBM_02_C_Excavation with TEMH_East_01	TBM_02_C_Excavation	TBM_02_C_Excavation with TEMH_West_01	TBM_02_C_Muck Transport_E
N24_TBM_02_B	TBM_02_B_Excavation with TEMH_East_01	TBM_02_B_Excavation	TBM_02_B_Excavation with TEMH_West_01	TBM_02_B_Muck Transport_E
N24_TBM_01_C	TBM_01_C_Excavation with TEMH_East_01	TBM_01_C_Excavation	TBM_01_C_Excavation with TEMH_West_01	TBM_01_C_Muck Transport_E
N24_TBM_01_B	TBM_01_B_Excavation with TEMH_East_01	TBM_01_B_Excavation	TBM_01_B_Excavation with TEMH_West_01	TBM_01_B_Muck Transport_E
N25_TBM_01_C	TBM_01_C_Excavation with TEMH_East_01	TBM_01_C_Excavation	TBM_01_C_Excavation with TEMH_West_01	TBM_01_C_Muck Transport_E
N25_TBM_01_B	TBM_01_B_Excavation with TEMH_East_01	TBM_01_B_Excavation	TBM_01_B_Excavation with TEMH_West_01	TBM_01_B_Muck Transport_E
N26a_TBM_02_C	TBM_02_C_Excavation with TEMH_East_01	TBM_02_C_Excavation	TBM_02_C_Excavation with TEMH_West_01	TBM_02_C_Muck Transport_E
N26a_TBM_01_C	TBM_01_C_Excavation with TEMH_East_01	TBM_01_C_Excavation	TBM_01_C_Excavation with TEMH_West_01	TBM_01_C_Muck Transport_E
N26b_TBM_01_C	TBM_01_C_Excavation with TEMH_East_01	TBM_01_C_Excavation	TBM_01_C_Excavation with TEMH_West_01	TBM_01_C_Muck Transport_E
N26b_TBM_01_B	TBM_01_B_Excavation with TEMH_East_01	TBM_01_B_Excavation	TBM_01_B_Excavation with TEMH_West_01	TBM_01_B_Muck Transport_E

Figure 7.14: Method Definition Window, Deterministic Definition of the Construction Method

Figure 7.15 shows the construction method input window of the construction method "TBM_01_C_Excavation with TEMH_East_01". This construction method is assigned the "Excavation with TEMH_TBM_East_01" subpart of the tunnel network and simulates the mechanized tunnel construction in the tunneling class "TBM 01" as well as the transport of the excavated material of the usage class C to the intermediate repository. The method variables "excavate&support_advance_rate" and "maintaining_time", which are defined in the "Method Variables" panels, define the advance rate of the tunnel excavation with support facilities and the maintaining time of corresponding activities and are used in the corresponding time equations of these activities. Time equations for mechanized tunneling are discussed in detail in Section 5.3. In addition, the "Cycle Length" input (see "Heads" panel), which is assumed to be a meter for each construction method, defines the length of each construction cycle or round. The input of the "Heads" panel also shows that full-face excavation is assumed ("Heads Nb 1"). Figure 7.16 shows the activity network which combines all activities of the construction method "TBM_01_C_Excavation with TEMH_East_01". The activity network input window is opened by clicking the "Edit Activity Network" button, which is shown in the bottom left corner in Figure 7.15. Section 5.3 explains this activity network (see Figure 5.13) in detail.

Figure 7.17 shows the activities input window of the activity "Transport_Muck_C_East_01", which allows one to define the time-, cost-, and resource equations as well as the assigned resources of an activity. The time-, cost-, and resource equations

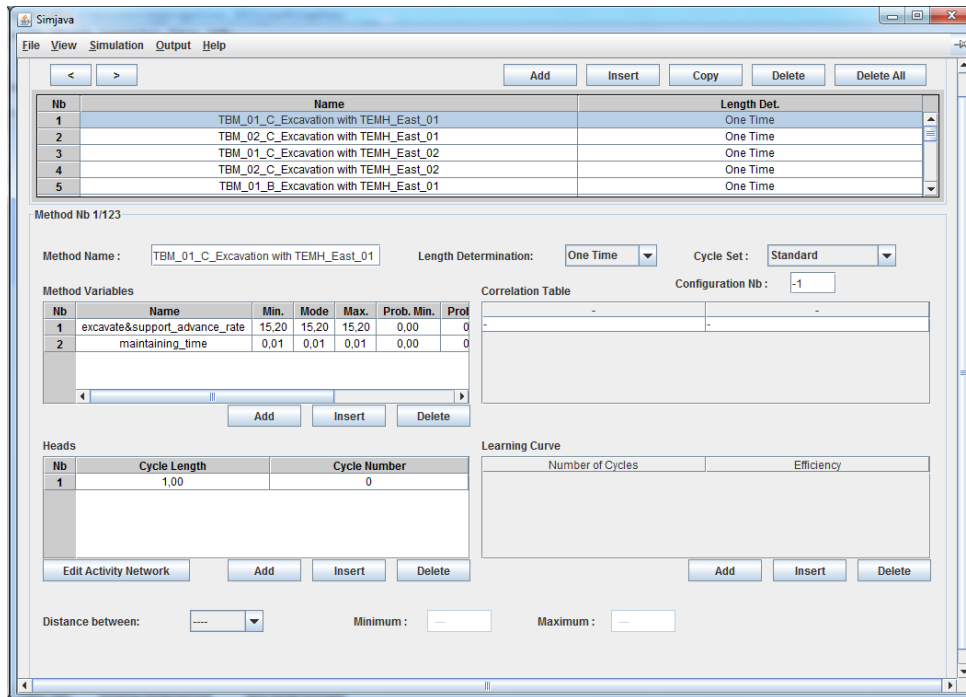


Figure 7.15: Construction Method Input Window

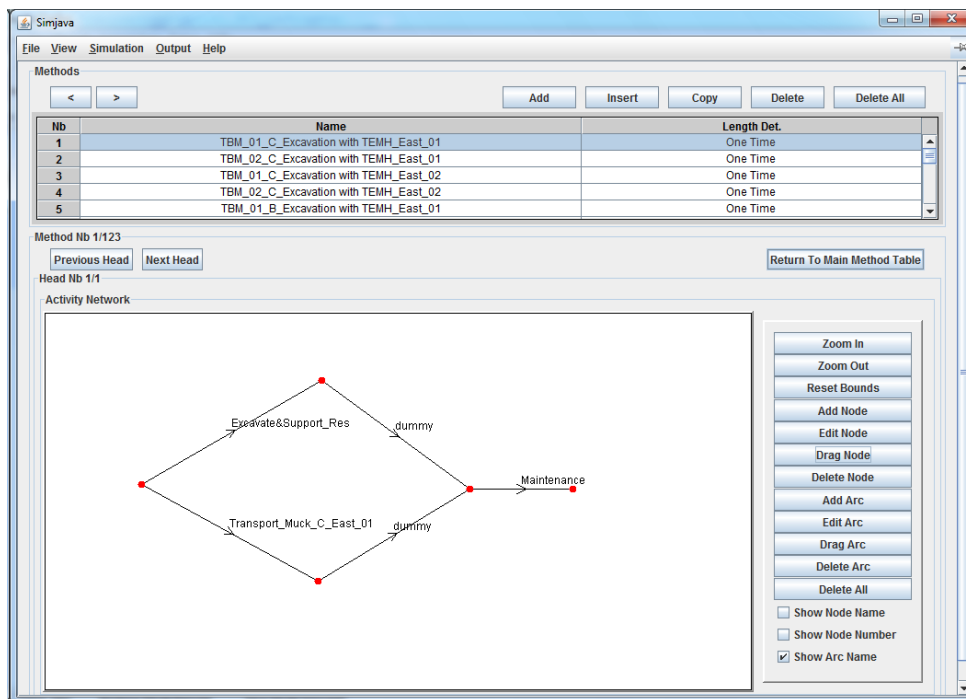


Figure 7.16: Activity Network Input Window

can be defined by the user in the respective boxes at the bottom right corner of the activities input window. In the "Time Equation" column in the upper panel ("Activities" panel) one can see the edited time equation of each activity. Moreover, the used variables (method variables, resource variables, and general variables) of the particular activity are shown. The "Method Variables" table shows the method variables of the different construction methods (e.g., *TBM_01_C_Excavation with TEMH_East_01*), which use the selected activity (i.e., *Transport_Muck_C_East_01*). These method variables are edited in the construction method window (see "Method Variables" panel in Figure 7.15) and usually have different values for each construction method. The general variables (see "General Variables" table) are variables that are not related to a particular construction method; hence, the general variables can be used for every construction method. An example of such a general variable is the assumed cross section of the mechanized tunnel drifts (*cross_section_TBM* with 75.34 square meters) and can be seen in the "General Variables" table at the bottom left corner of the activities input window (see Figure 7.17). The general variables are specified in an own input window (general variables window). In addition, the activities input window shows which construction methods use the particular activity (see "Heads" table). For instance, the activity *Transport_Muck_C_East_01* is an activity of the construction methods *TBM_01_C_Excavation with TEMH_East_01*, *TBM_02_C_Excavation with TEMH_East_01*, and *TBM_03_C_Excavation with TEMH_East_01*. The "Heads" table in Figure 7.17 also shows, as mentioned above, that each of these construction methods models full-face excavation (see "Head" column) with a cycle length of one meter (see "Cycle Length" column). The "Resources" panel (see Figure 7.17) enables one to assign resources to an activity. For instance, the activity *Transport_Muck_C_East_01* produces the resource *Muck_C_int_rep_TBM*. The variable *cross_section* (see "Variable" column in the "Resources" panel) is a resource variable and expresses also the cross sectional area of the mechanized tunnel drift (see "Det. Value" column in the "Resources" panel). In the "Resource Equations" boxes, which are below the "Resources" panel (see Figure 7.17), one can formulate the resource equations for each assigned resource (e.g., *Muck_C_int_rep_TBM*). Such a resource equation computes the used or produced amount of the respective resource (e.g., *Muck_C_int_rep_TBM*) and can be seen in the "Resource Equations" boxes of the activity input window if the respective resource is selected.

Resources are defined in the DAT, for example, to simulate the TEMH process. Figure 7.18 shows the "Resources" window, which is used to define the resources in the simulation. These resources are the excavation materials usage classes which are subdivided into the corresponding tunneling methods such as mechanized- and conventional tunneling and their location within the TEMH process (e.g., intermediate repository, final repository, and aggregate plant). For example, the resource *Muck_C_int_rep_TBM* specifies the excavated materials of usage class C, which are

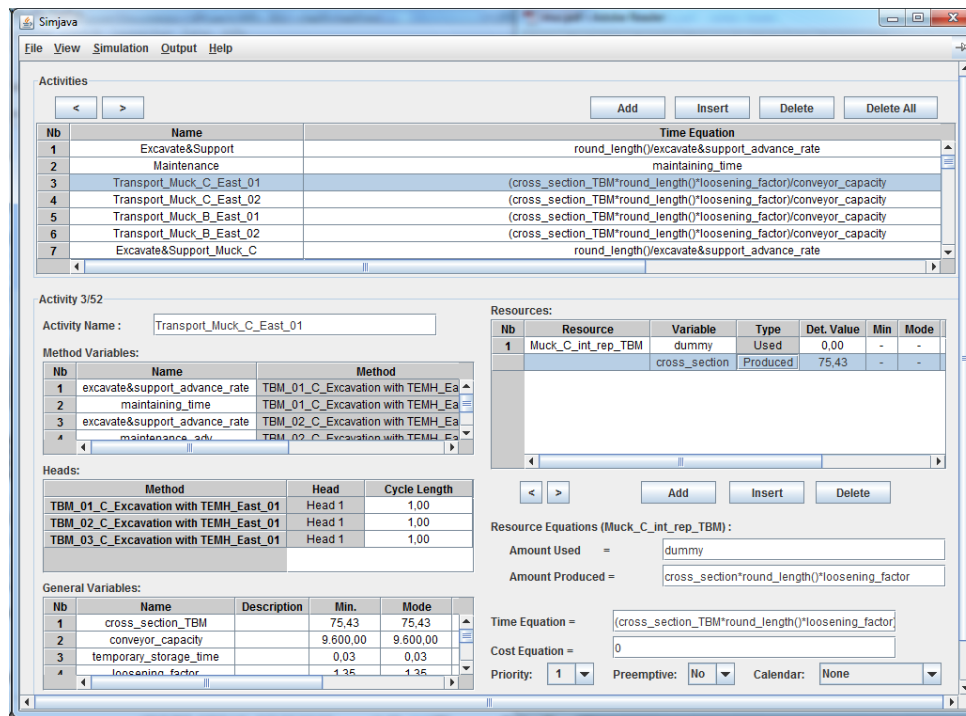


Figure 7.17: Activities Input Window

excavated due to mechanized tunneling, at the intermediate repository. The resources "*Inner.Liner.Demand*", "*Initial.Support.Demand.TBM*", and "*Initial.Support.Demand.D&B*" express the demand for concrete aggregates of the inner liner works or the demand for shotcrete aggregates of the initial support works of the mechanized- or conventional tunnel drifts. The processed aggregates, which are reused in concrete works (initial- and final support) are modeled with the resources "*Concrete.Aggregates.D&B*" and "*Concrete.Aggregates.TBM*". As mentioned before, the defined resources have to be assigned to the corresponding activities (see Figure 7.17, "Resources" panel). The corresponding resource equations of the activity (see Figure 7.17, "Resource Equations" boxes) compute the quantity of the used or produced resource.

The repositories of the TEMH process are defined in the repositories window (Figure 7.19). As discussed in Subsection 5.2.6, one "*Repository*" covers all repositories of this application. This "*Repository*" is called "*Imaginary.Repository*", which can be seen in the "*Repositories*" panel in Figure 7.19 (see "*Repository Name*" column). The "*Repository*" panel also shows the number of resources in the "*Imaginary.Repository*" (see "*Nbr of Stocks*" column). These resources are for this application all the defined resources (see Figure 7.18). Each stock (see "*Repository 1/1*" panel in Figure 7.19), which treats a specific resource, subdivides the "*Imaginary.Repository*" and, thus, models a "real" repository of the TEMH process. For instance, the stock number 1 (see line "Nb 1", "*Muck.C.int.rep.TBM*") models the

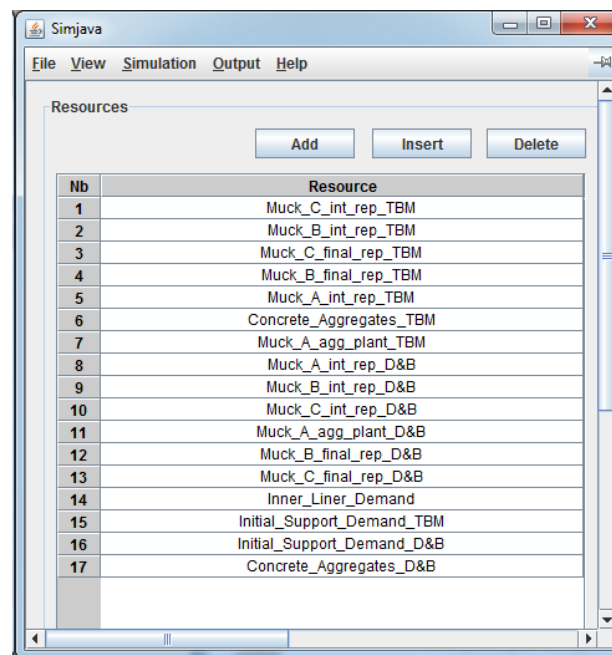


Figure 7.18: Resources Input Window

part of the intermediate repository where the excavation material usage class C of mechanized tunneling is intermediately stored. The initial-, minimum-, and maximum level of a stock define its capacity. In the simulation it is assumed that the repositories have no initial- or minimum level (see "*Initial Level*" and "*Minimum Level*" columns in the "*Repository 1/1*" panel in Figure 7.19). In contrast, a very high maximum level is assigned to each stock to avoid that the material flows wait until space is available in the stock, which can lead to an interruption of the construction process. This assumed maximum level can be changed in future to consider the available capacity of a particular intermediate- or final repository in order to determine the effect of the capacity of a repository on the material flows in the TEMH process.

The last step of the input of the construction module is to define for each tunnel of the tunnel network which "*Repository*" must be used. Therefore, in the tunnel information window the "*Imaginary_Repository*" is assigned the tunnels of the tunnel network, which model material flows in the TEMH process. One can see this procedure in the "*Repositories*" panel in Figure 7.20, which illustrates the used repository ("*Imaginary_Repository*") of the tunnel "*Processing_TBM_East_01*". The "*Position*" input (4 458 meters) represents the length of the tunnel which uses or produces resources of the "*Imaginary_Repository*". This length (4 456 meters) is the maximum length of the tunnel "*Processing_TBM_East_01*" and, as stated before, cannot exceed a length of 5 000 meters in the current version of the DAT.

As one can follow, several assumptions were necessary to provide input data for the simulations. It is important to realize that all these assumptions can be changed

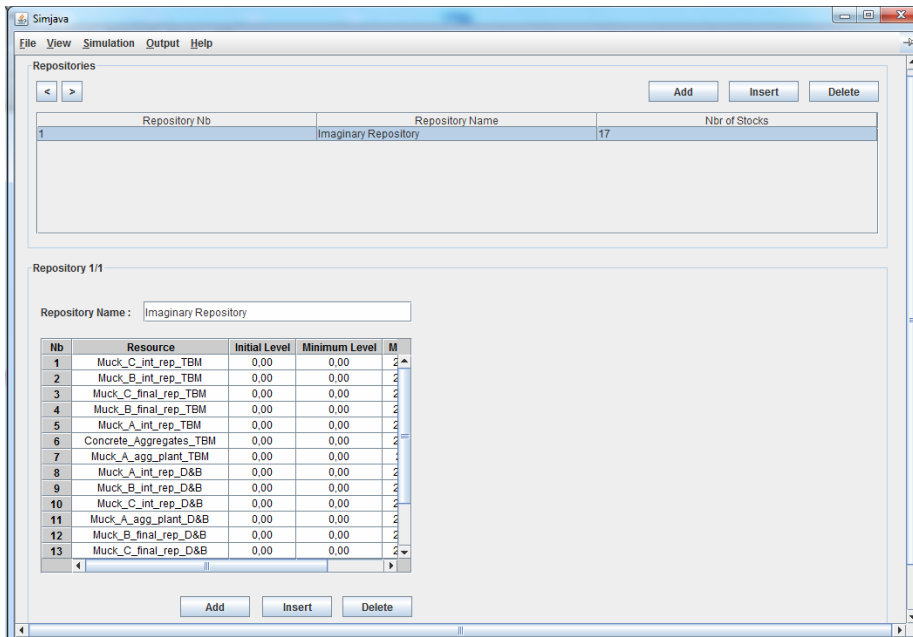


Figure 7.19: Repositories Input Window

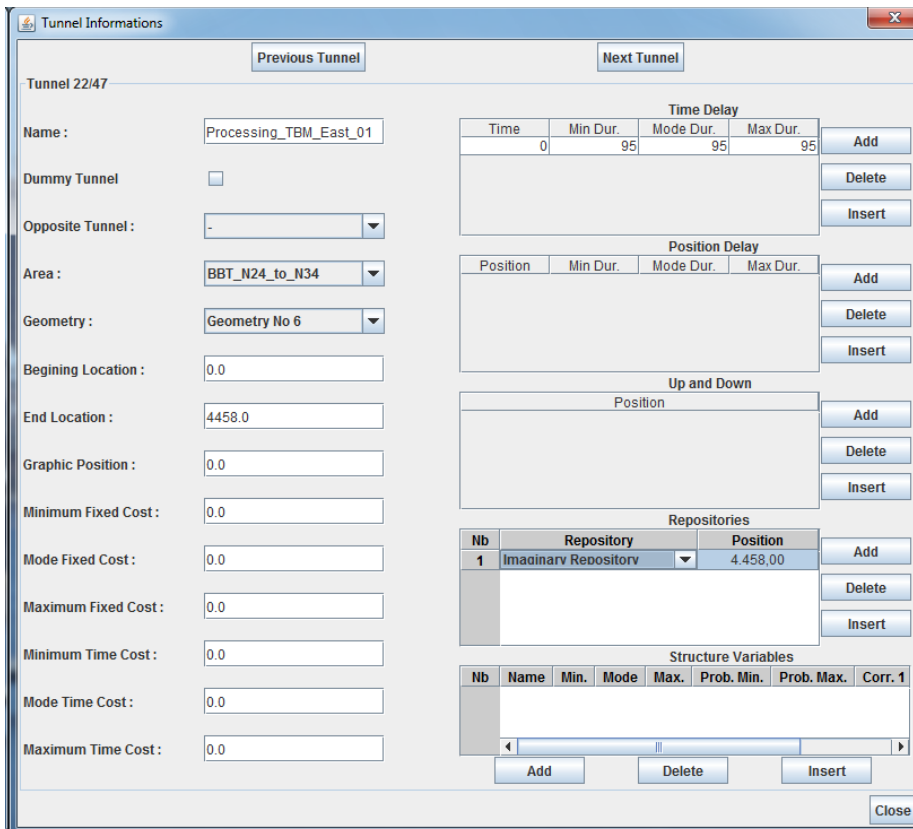


Figure 7.20: Repository Assigned to a Tunnel in the Tunnel Information Window

if further information of contract section Wolf is available. This collection of new information would update the decision analysis. Due to specific circumstances in contract section Wolf specific simulation techniques were applied and are discussed below.

7.3 SPECIFIC SIMULATION TECHNIQUES

Since the project documents of the BBT forecast that the geology of the mechanized tunnel drifts of the simulation area (see Figure 7.1) is unsuitable for concrete aggregate production, a deficit of concrete aggregates exists for the initial support of these TBM drifts. This deficit of concrete aggregates of the initial support stops the simulations in an early phase, which produces useless outputs for decision making. To avoid this stop of the simulation, the general concept of the simulation model, described in Chapter 5, is slightly modified. This modification makes use of two different simulation techniques:

- **Simulation Technique I** (see Figure 7.21) computes the amounts of concrete aggregates which are consumed due to the initial- (*"Initial Support Consumption"*) and the final support (*"Inner Liner Consumption"*). These amounts can be compared with the amount of produced (recycled) concrete aggregates (*"Produced Concrete Aggregates"*). Results of simulation technique I are used to plan the additional supply of concrete aggregates through regional suppliers. Also certain time intervals can be identified, which assure a self-supply of concrete aggregates.

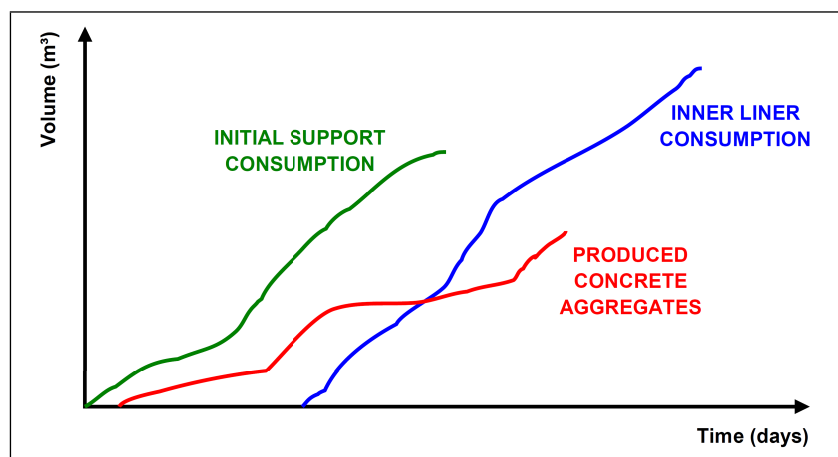


Figure 7.21: Schematic Time-Volume Plot of Simulation Technique I

- **Simulation Technique II** (see Figure 7.22) models the consumption of concrete aggregates of the initial support (*"Initial Support Consumption"*) in the

same way as simulation technique I. In contrast, the concrete aggregate consumption of the final support (inner liner) is modeled differently; the final support construction uses produced (recycled) concrete aggregates to perform. This means that the volume of produced (recycled) concrete aggregates is reduced due to the demand for concrete aggregates of the inner liner construction (see "Concrete_Aggregates" curve in Figure 7.22). If there is a deficit of produced concrete aggregates idle times will occur, which will result in an interruption of the inner liner construction. If the entire production of concrete aggregates does not satisfy the entire inner liner consumption of concrete aggregates the simulation will stop after all the produced concrete aggregates are consumed. Hence, simulation technique II is used to investigate how a possible lack of produced concrete aggregates affects the tunnel construction.

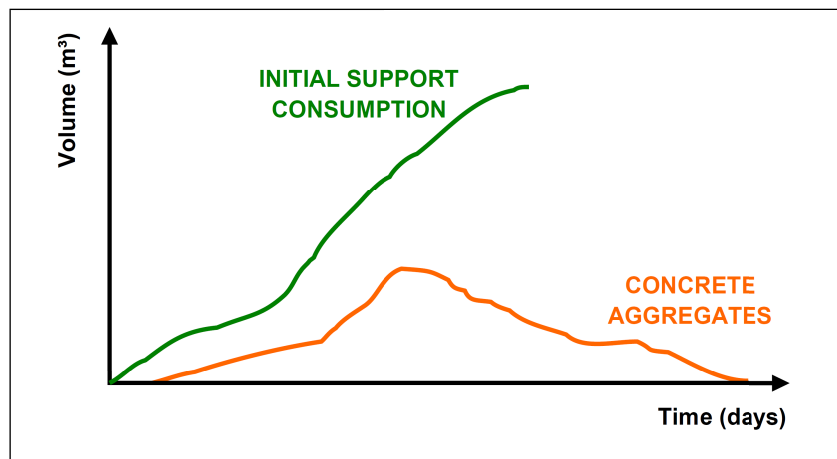


Figure 7.22: Schematic Time-Volume Plot of Simulation Technique II (Note that the "Concrete_Aggregates" curve illustrates the volume of produced concrete aggregates, which is reduced due to the inner liner consumption of concrete aggregates.)

The changes of the input between simulation technique I and II are illustrated in the Figures 7.23 and 7.24. Figure 7.23 shows the activity input window of the activity "Inner Liner" using simulation technique I. In the "Resources" panel the input of the resource "Inner_Liner_Demand" produces the required volume of concrete aggregates of the inner liner. This input results in a curve similar to the "Inner Liner Consumption" curve in Figure 7.21. In contrast, the "Resources" panel of Figure 7.24 illustrates the input of simulation technique II. One can see that in simulation technique II concrete aggregates ("Concrete_Aggregates_D&B") are used for the inner liner. This reduction of the concrete aggregates results in a curve similar to the "Concrete_Aggregates" curve in Figure 7.22. All the other inputs stay the same in both simulation techniques. In the following Chapter, outcomes of both simulation techniques are discussed.

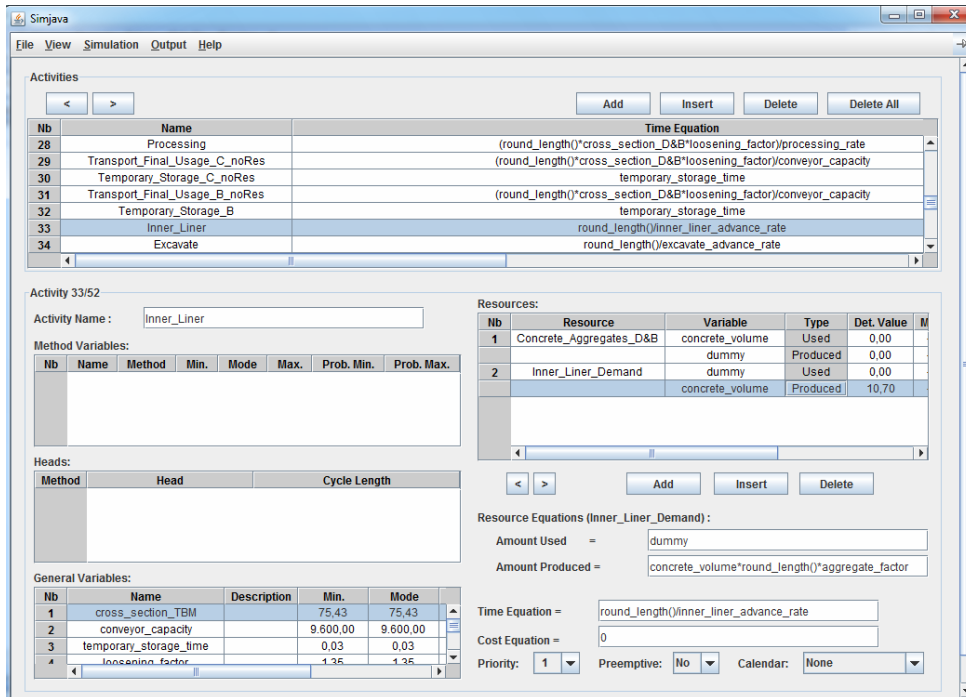


Figure 7.23: Inner Liner Activity Input Window of Simulation Technique I

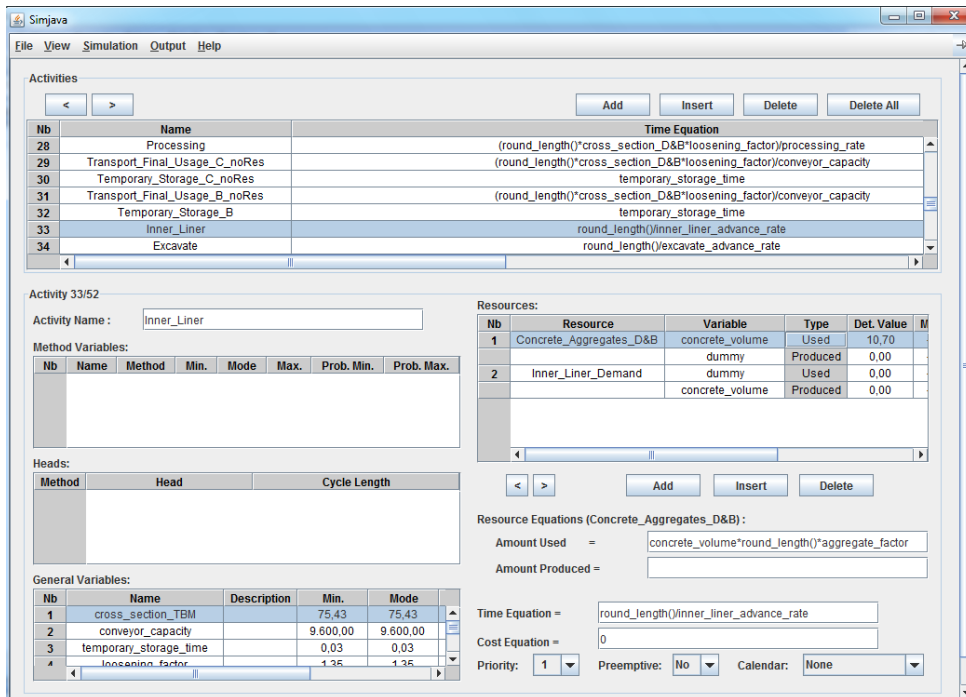


Figure 7.24: Inner Liner Activity Input Window of Simulation Technique II

Chapter 8

SIMULATION RESULTS

This Chapter shows the results of the application of the simulation model to a part of contract section Wolf (see Chapter 7) and explains how this outcomes can be used for decision making. In particular, the results of the simulation techniques I and II (see Section 7.3) are discussed. Both simulation techniques use, despite their difference, the same input considering the geologic uncertainties in the simulation area. In contrast, results of an additional simulation, which considers processing uncertainties influencing the TEMH process, are discussed. Uncertainties about the construction process are not considered because the input of the tunnel construction (e.g., advance rates of the tunneling classes) is based on too many assumptions (see Subsection 7.2.2).

8.1 RESULTS OF SIMULATION TECHNIQUE I

Results of such simulations can be presented in various ways. A particularly useful one is in the form of a time-volume plot as shown in Figure 8.1, which presents the time-volume plot of one simulation run. Another simulation run may have a different outcome due to the geologic uncertainties. Each curve illustrates a particular resource such as the defined excavation material classes of the BBT at a particular location within the TEMH process. For example, the curve *"Muck_C_fin_rep_TBM"* defines the volume of the usage class C, which is excavated in mechanized tunnel drifts, and is tipped at the final repository. On the other hand, the curve *"Muck_C_int_rep_TBM"* shows the volume of the usage class C of the TBM tunnel drifts, which is temporarily stored at the intermediate repository. One can see in Figure 1 that the significant contributions of the produced resources are the usage classes B (*"Muck_B"*) and C (*"Muck_C"*). This is to be expected due to the anticipated geology in the simulation area.

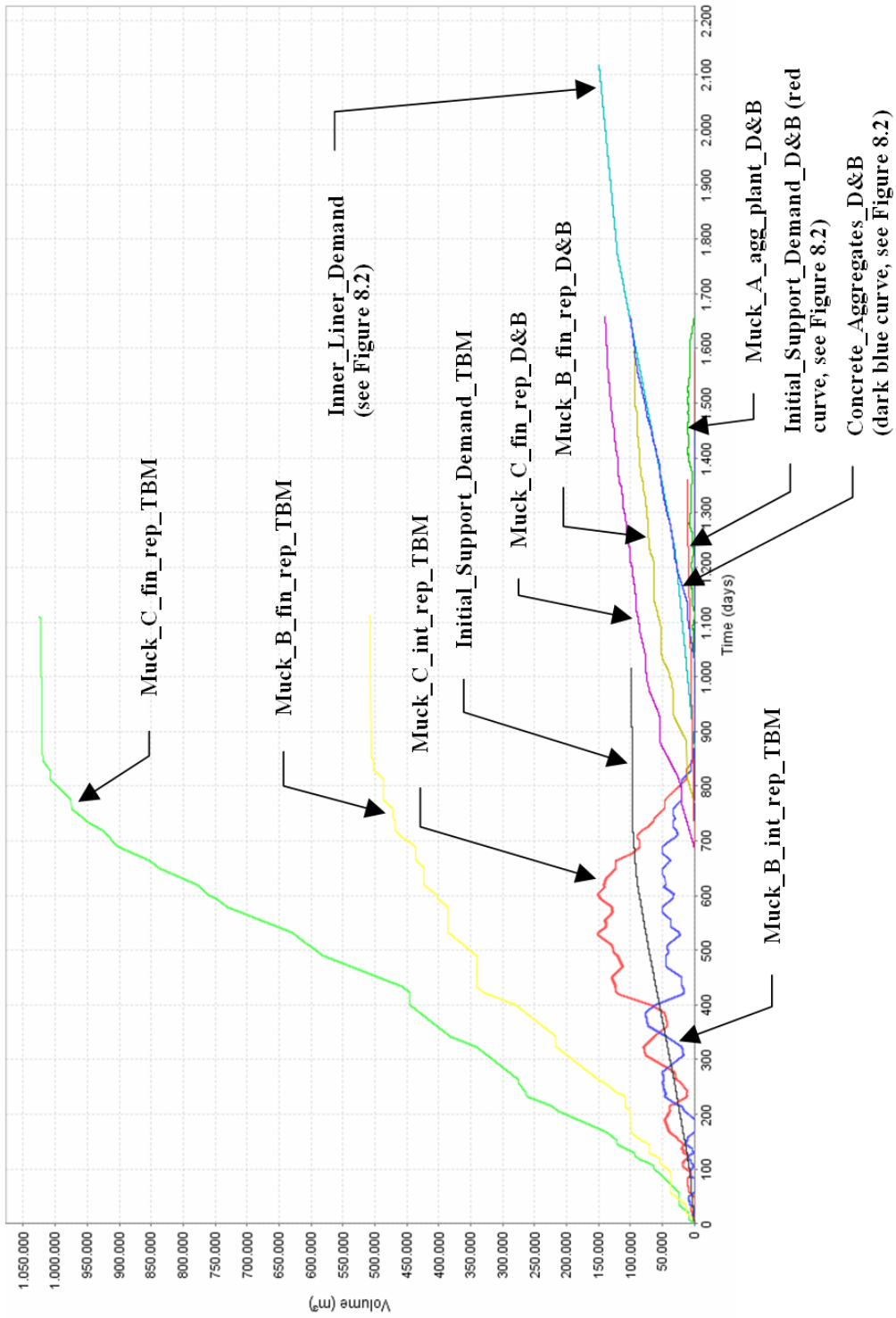


Figure 8.1: Time-Volume Plot of One Simulation Run of Simulation Technique I

It is important to mention that it is not the intent of the simulations to define the storage size of the intermediate repositories. Also, as noted before, the capacities of the specific intermediate repositories are not considered. Therefore, the obtained high volumes of the excavated materials at the intermediate repositories (see Figure 8.1) are neglected. If additional information is available, the specific capacities of the repositories can be considered in future simulations.

Figure 8.2 is a detail of Figure 8.1 and enables one to compare the consumption of concrete aggregates ("C") with the production (or recycling) of concrete aggregates ("P"). The "Concrete_Aggregates_D&B" curve indicates the produced (recycled) volume of concrete aggregates of the conventional tunnel drifts ("Drill&Blast_East Tube" and "Drill&Blast_West Tube"). Concrete aggregates, which are produced of the excavated materials of the mechanized tunnel drifts, are not obtained in the simulation results. This is so because the anticipated geology of the mechanized tunnel drifts is unsuitable to produce concrete aggregates. The "Inner_Liner_Demand" and the "Initial_Support_Demand_D&B" curves show the consumption of concrete aggregates of the entire inner liner construction and of the initial support of the conventional tunnel drifts. Figure 8.1 shows the consumption of concrete aggregates of the initial support of the TBM drives ("Initial_Support_Demand_TBM"). One can analyze Figure 8.2 by subdividing it into following time intervals:

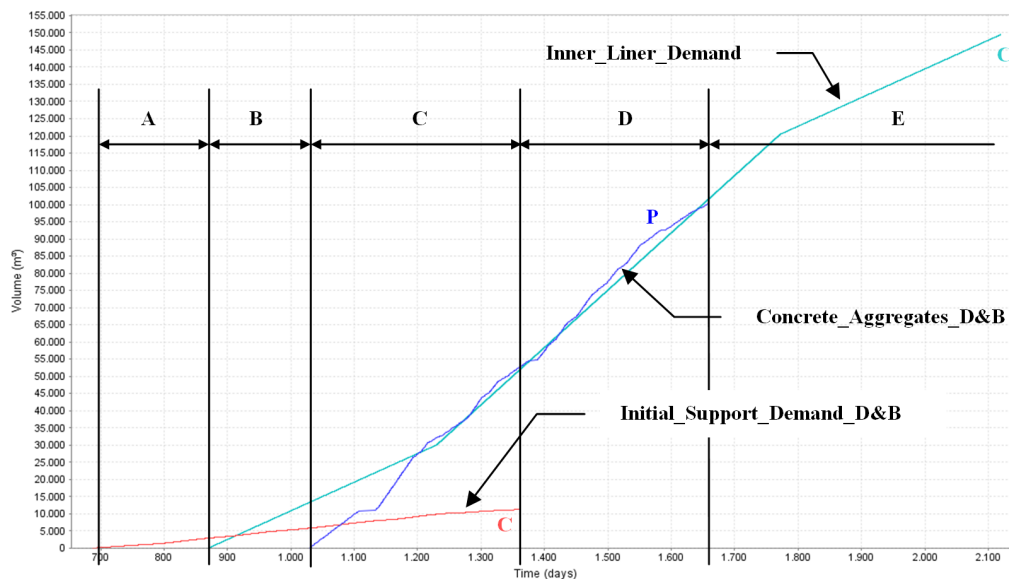


Figure 8.2: Concrete Aggregate Production (P) and Concrete Aggregate Consumption (C), One Simulation Run, Simulation Technique I

- **Time Interval A (approximately Day 687 to Day 870):** In this time interval, concrete aggregates are not produced. Concrete aggregates for the shotcrete of the Drill and Blast tunnel drifts ("Initial_Support_Demand_D&B") have to be purchased from regional suppliers.

- **Time Interval B (approximately Day 870 to Day 1029):** The construction of the inner liner, which requires concrete aggregates ("*Inner_Liner_Demand*"), starts. However, the excavated materials are still unsuitable to produce concrete aggregates. Concrete aggregates have to be supplied from regional suppliers to perform the initial support of the Drill and Blast tunnels as well as the inner liner construction.
- **Time Interval C (approximately Day 1029 to Day 1360):** Qualified excavated materials for recycling are used to produce concrete aggregates ("*Concrete_Aggregates_D&B*"). The volume of produced concrete aggregates of this time interval (about 52 500 m³) covers the aggregate consumption of the initial (about 6 000 m³) and the final support (about 38 500 m³) of this time interval. In other words, there will be enough aggregates to produce the support. The surplus concrete aggregates can be supplied in the subsequent time intervals.
- **Time Interval D (approximately Day 1360 to Day 1656):** The tunnel advances are completed at the beginning of time interval D; thus, the initial support applications ("*Initial_Support_Demand_D&B*") stop. However, the inner liner construction continues, which requires concrete aggregates ("*Inner_Liner_Demand*"). In this time interval the concrete aggregate production ("*Concrete_Aggregates_D&B*") is sufficient for a self-supply of concrete aggregates for the inner liner construction ("*Inner_Liner_Demand*").
- **Time Interval E (approximately Day 1656 to Day 2120):** Production of concrete aggregates ("*Concrete_Aggregates_D&B*") has stopped at the beginning of time interval E. Additional concrete aggregates have to be purchased from regional suppliers to meet the demand for concrete aggregates of the inner liner construction ("*Inner_Liner_Demand*").

These findings show that the production of concrete aggregates is insufficient to cover the consumption of required concrete aggregates. Only in the time intervals C and D can a self-supply of concrete aggregates be guaranteed. The remaining concrete aggregates have to be purchased from regional suppliers. Table 8.1 summarizes the volumes of consumed and produced concrete aggregates of this simulation run. As a result of this simulation run about 38 percent of the demand for concrete aggregates can be supplied by produced (recycled) concrete aggregates. One can follow that such time-volume plots can be useful for planning the materials management of a tunnel construction project.

Another way of presenting the results is in the form of a multi graph time-volume plot (see Figure 8.3), which contains 100 time versus volume simulation runs on one plot. This form of output illustrates how the geologic uncertainties affect the volume of the produced resources. One can see that each simulation run produces a different curve for each excavation materials class (e.g., "*Muck_C_fin_rep_TBM*") if

Table 8.1: Consumed and Produced Volumes of Concrete Aggregates of a Simulation Run of Simulation Technique I

Concrete Aggregates	Volumes (m ³)	
	Consumed	Produced
Initial_Support_Demand_TBM	98 282	
Initial_Support_Demand_D&B	11 206	
Inner_Liner_Demand	149 474	
Sum of Consumed Concrete Aggregates	258 962	
Concrete_Aggregates_TBM		0
Concrete_Aggregates_D&B		98 537
Sum of Produced Concrete Aggregates		98 537

it is influenced by geologic uncertainties. Specifically, the volume of the excavation material usage classes B ("*Muck_B_fin_rep_TBM*" and "*Muck_B_fin_rep_D&B*") and C ("*Muck_C_fin_rep_TBM*" and "*Muck_C_fin_rep_D&B*") are characterized by the influence of these geologic uncertainties. Such a multi graph time-volume plot can be used for decision making; for instance, one can determine the maximum storage size needed for these excavated materials. The uncertainty about geology results in a scatter of the volume of the excavated materials and can, for example, be considered in the determination of the maximum storage size of the final repositories. For instance, the volume of the TBM excavated materials of usage class C at the final repository ("*Muck_C_fin_rep_D&B*") scatters of approximately 110 000 m³ (see Figure 8.3), due to the uncertainty about geology. Considering this scatter when planning the final repositories may lead to different decisions.

As mentioned before, it is assumed that the demand for concrete aggregates of the initial- and final support is independent of geologic uncertainties. Therefore, in each simulation run the same curves are computed for the "*Initial_Support_Demand_TBM*", "*Initial_Support_Demand_D&B*", and "*Inner_Liner_Demand*" (see Figure 8.3). In future this assumption of a constant demand for concrete aggregates per tunnel meter can be changed. This change would result in a more realistic simulation, which would consider that a different geological situation requires a different demand for initial- and final support. As a result also the demand for concrete aggregates per tunnel meter would vary, due to the uncertainty about geology.

A detail of Figure 8.3 is presented in Figure 8.4, which compares the concrete aggregate consumption of the initial support of the conventional tunnel drifts ("*Initial_Support_Demand_D&B*") and the concrete aggregate consumption of the inner liner construction ("*Inner_Liner_Demand*") with the produced concrete aggregates of the simulation area ("*Concrete_Aggregates_D&B*"). A similar form of output is presented in Figure 8.2, which shows only the findings of one simulation run. In contrast,

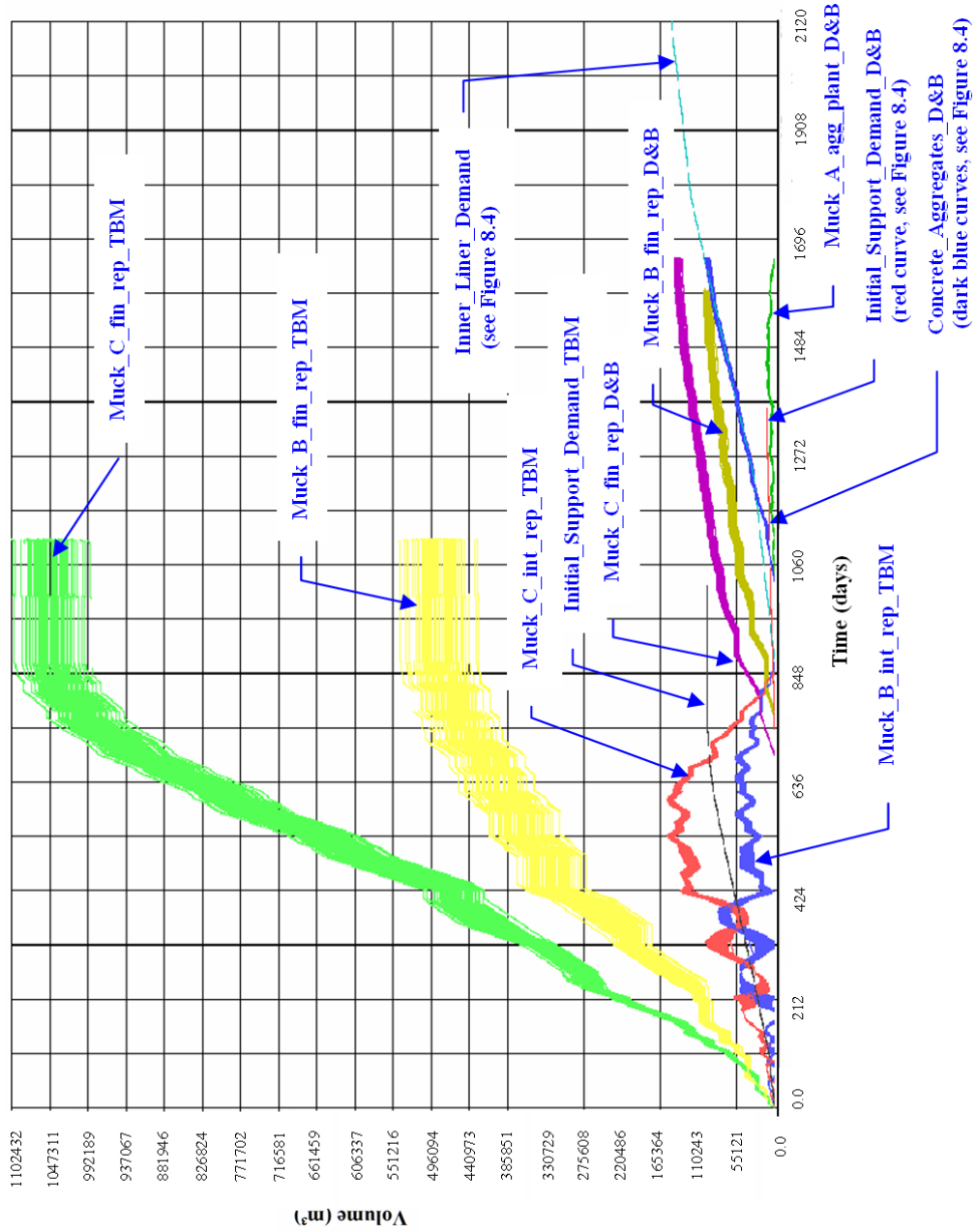


Figure 8.3: Multi Graph Time-Volume Plot of Simulation Technique I

Figure 8.4 illustrates the results of 100 simulation runs, which involve the influence of the geologic uncertainty on the produced volume of concrete aggregates. As one can see in Figure 8.4, the uncertainty about the geology changes the volume of produced concrete aggregates. Table 8.2 shows the minimum-, mean-, and maximum volume of the produced concrete aggregates. These results show that the volume of produced concrete aggregates scatters about 6 000 m³. Furthermore, Table 8.2 shows how the percentage of self-supplied concrete aggregates changes due to uncertainty about geology.

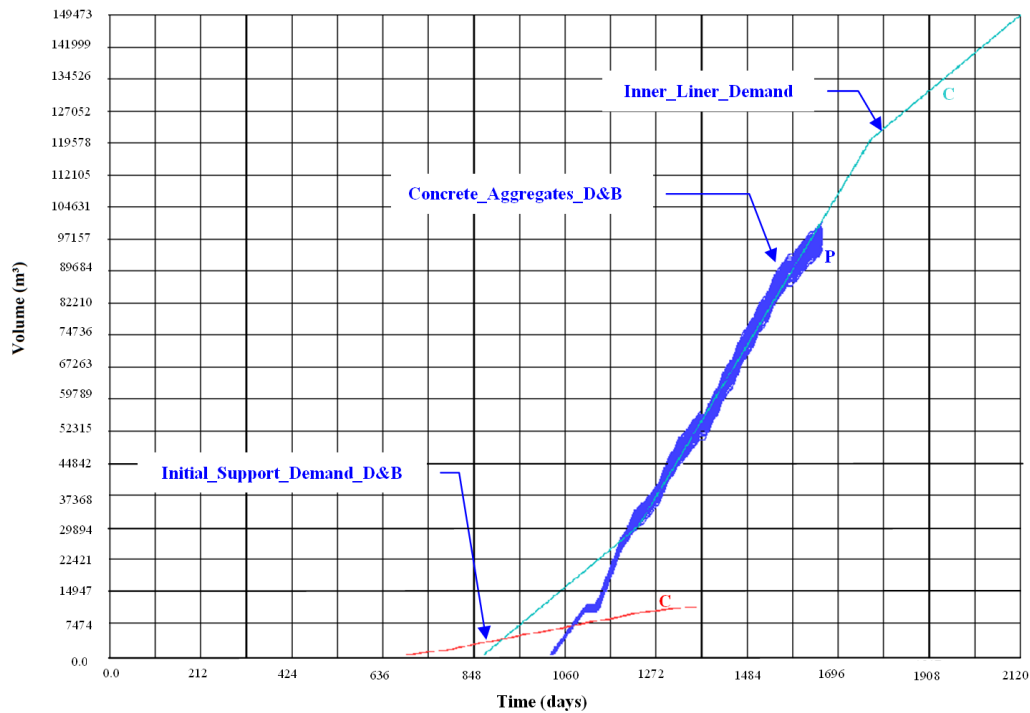


Figure 8.4: Concrete Aggregate Production (P) and Concrete Aggregate Consumption (C), Multiple Simulations (100 Simulation Runs), Simulation Technique I

Table 8.2: Produced Concrete Aggregates Influenced by Geologic Uncertainty

Concrete_Aggregates_D&B	Volume (m ³)	Self-Supply (%)
Minimum Volume of 100 Simulation Runs	93 760.96	36.2
Mean Volume of 100 Simulation Runs	97 264.80	37.6
Maximum Volume of 100 Simulation Runs	99 763.40	38.5

Time-volume scattergrams (see Figure 8.5) are another practically useful form of output. Each point in Figure 8.5 represents the total time, which is necessary to produce the concrete aggregates since the construction of the "Drill&Blast West

Tube” started, versus the total volume of produced concrete aggregates of the excavated materials of the *”Drill&Blast West Tube”*. To produce the complete diagram multiple simulations (100 runs) are performed; each of these simulations produces a particular point in Figure 8.5. The reasons for the scatter of the points are the different ground class profiles underlying each simulation run, which are a result of the geologic uncertainties included in the simulations. One can see in Figure 8.5 that the geologic uncertainties influence the volume and the time of the produced (recycled) concrete aggregates. This finding can also be seen in Figure 8.4. Due to the fact that it is assumed that the *”Drill&Blast East Tube”* and *”Drill&Blast West Tube”* are excavated in each simulation run through the same ground class profile and have the same length and cross section, the same time-volume scattergrams are computed for the *”Drill&Blast East Tube”* (see Figure 8.6) and *”Drill&Blast West Tube”* (see Figure 8.5). As a result the minimum-, mean-, and maximum volume of produced concrete aggregates are the same for both tubes. Figure 8.7 illustrates this by showing the results of both tunnel drifts in one time-volume scattergram. In this scattergram the plotted points of both tubes of each simulation run overlap. In addition, Figure 8.7 includes the normal approximations, histograms, and the linear regression of the cloud of points.

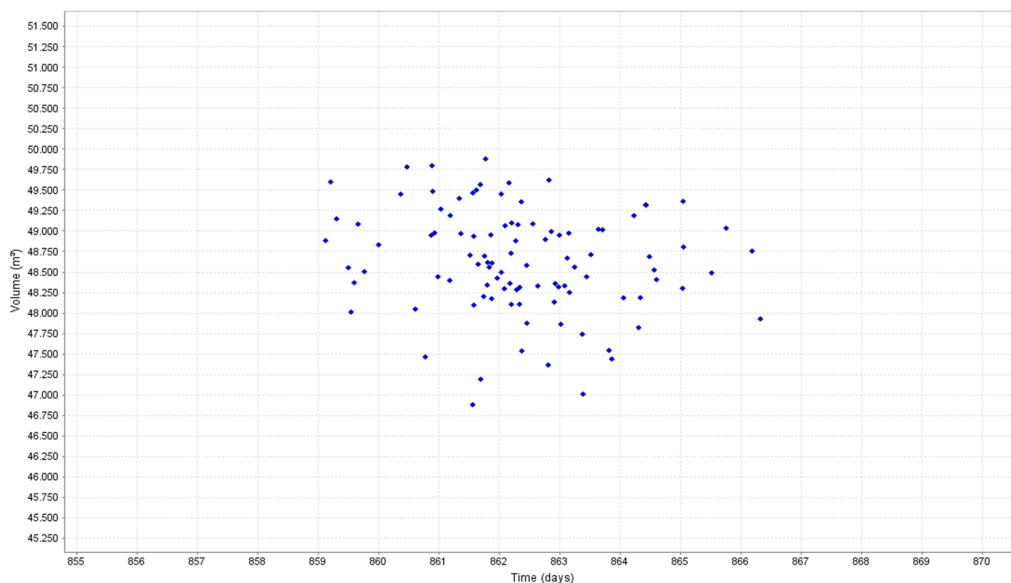


Figure 8.5: Time-Volume Scattergram of the Produced Concrete Aggregates of the *”Drill&Blast West Tube”* (min. Volume = 46 880.48 m³, mean Volume = 48 632.40 m³, max. Volume = 49 881.70 m³)

Another form of output is a position-time plot (see Figure 8.8), which presents the advance of tunnel construction with the particular TEMH. Each tunnel of the tunnel network of the simulation area (see Figure 7.10) is presented in Figure 8.8 with a corresponding curve. The *”Mechanized Tunnel Drifts”* rectangle surrounds

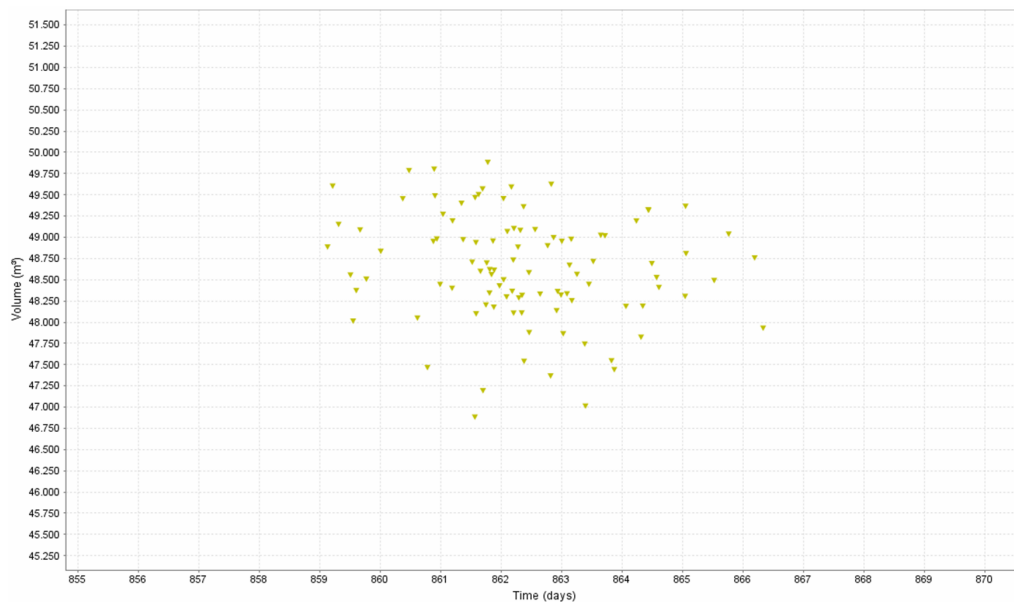


Figure 8.6: Time-Volume Scattergram of the Produced Concrete Aggregates of the "Drill&Blast East Tube" (min. Volume = 46 880.48 m³, mean Volume = 48 632.40 m³, max. Volume = 49 881.70 m³)

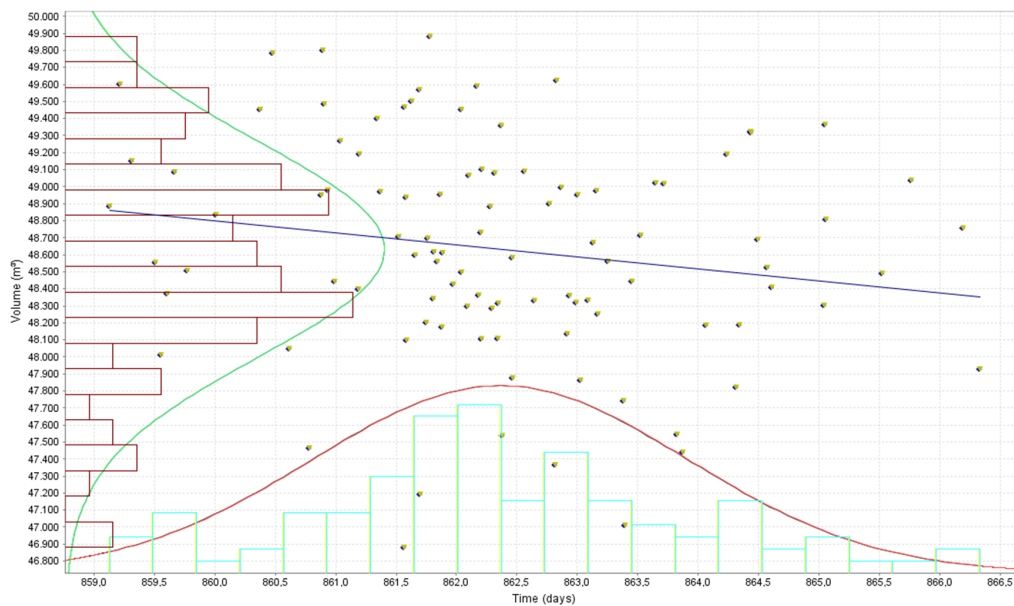


Figure 8.7: Time-Volume Scattergram of the Produced Concrete Aggregates of the "Drill&Blast East Tube" (▼) and "Drill&Blast West Tube" (■) Including Standard Statistics such as the Normal Approximation on Time (red curve) and Volume (green curve) of the Cloud of Points, the Linear Regression (blue curve) of the Cloud of Points, and Histograms of the Time (vertical bars) and Volume (horizontal bars); (min. Volume = 46 880.48 m³, mean Volume = 48 632.40 m³, max. Volume = 49 881.70 m³)

the curves which specify the TBM tunnel drives ("*TBM East Tube*" and "*TBM West Tube*"). Figure 8.9 illustrates these curves of the mechanized tunnel drives in detail. The "*Drill & Blast Tunnel Drifts*" rectangle surrounds the curves of the conventional excavation ("*Drill&Blast East Tube*" and "*Drill&Blast West Tube*"), which are shown in detail in Figure 8.10. All the curves which are not surrounded by a rectangle belong to the inner liner construction and are shown in detail in Figure 8.12.

The intent of such a position-time plot is to illustrate the time duration of each component of the TEMH process (e.g., the transport of the excavated materials from the tunnel face to the intermediate repository) and how such a component may affect the tunnel construction performance. This is possible due to the parallel structure of the general tunnel network of the simulation model (see Subsection 5.2.1), which successively includes components of the TEMH process in the parts and subparts of the general tunnel network. As explained in Subsection 5.2.1, the curves of different subparts of the tunnel network can overlap if components of the TEMH process perform simultaneously with the preceding tunnel construction or the preceding material flows in the TEMH process (see Figure 5.8). In the following the outcome of the mechanized tunnel drifts with the related TEMH is discussed (see Figure 8.9).

As discussed in Chapter 5, the simulation task of the "*Excavation*" subpart is to model the tunnel construction such as the tunnel excavation and the initial support (see Table 5.1). In contrast, the simulation task of the "*Excavation with TEMH*" subpart is to model the excavation material production, a preliminary excavation material classification ("*Preliminary Material Classification*"), and the subsequent transport of the excavated materials to the intermediate repository (see Table 5.1). Furthermore, the "*Excavation with TEMH*" subpart has to consider the time of the preceding "*Excavation*" subpart due to the parallel structure of the simulation model (see Subsection 5.2.1). Thus, one can expect that the "*Excavation with TEMH*" subpart consumes more time than the preceding "*Excavation*" subpart. However, in Figure 8.9 the "*Excavation*" and "*Excavation with TEMH*" curves of each mechanized tunnel drift of the simulation area overlap (e.g., "*Excavation_TBM_West_01*" and "*Excavation with TEMH_TBM_West_01*") and, thus, consume the same amount of time. This is so because the transport of the excavated materials between the cutter head and the intermediate repository (MFS St. Jodok, see Figure 7.1) can go on simultaneously with the mechanized tunnel excavation and the initial support. The reason for this overlap is the activity network of the "*Excavation with TEMH*" subpart (see Figure 5.13), which takes the concurrent tunnel construction (excavation and initial support) and the muck transport of a tunnel boring machine into account. Therefore, the tunnel construction (excavation and initial support) and the related components of the TEMH go on simultaneously. One can follow that the mechanized tunnel excavation and the corresponding initial support work last longer (critical path)

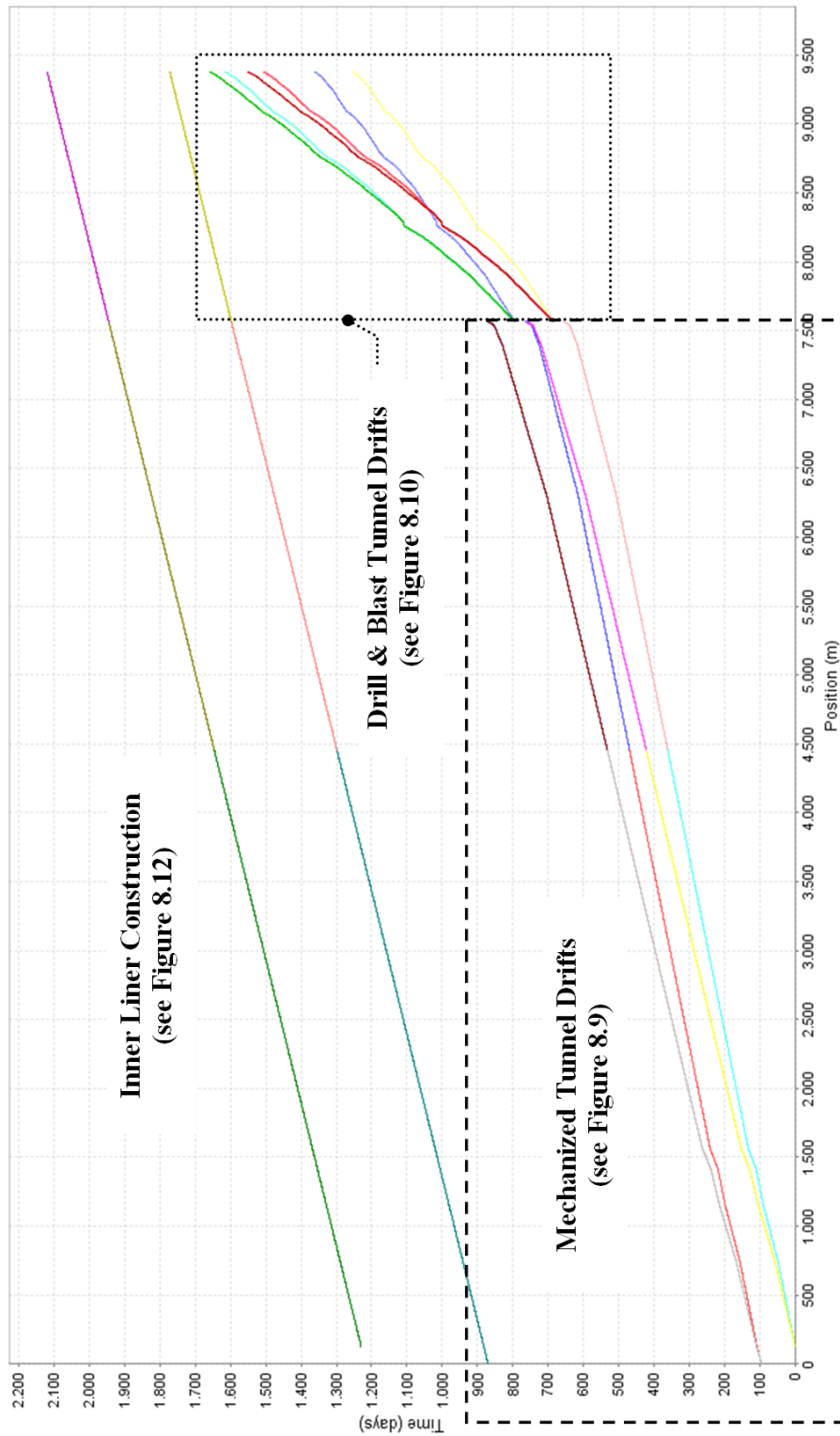


Figure 8.8: Position-Time Plot of One Simulation Run of Simulation Technique I

than the transport of the excavated materials to the MFS St. Jodok.¹⁵ This finding shows that the transport of the excavated materials to the intermediate repository is not a factor holding back the mechanized tunnel construction performance.

The *"Final Material Classification"* as well as the transport of the excavated materials from the MFS St. Jodok to the final repository Padastertal (see Figure 7.1) is modeled with the *"Muck Transport"* subpart of the tunnel network, which considers also the time of the preceding *"Excavation with TEMH"* subpart, due to the parallel structure of the simulation model (see Subsection 5.2.1). The *"Muck Transport"* curves consume more time than the preceding *"Excavation with TEMH"* curves (see Figure 8.9) because the transport and material classification consumes additional time. The difference between an *"Excavation with TEMH"* curve and the corresponding *"Muck Transport"* curve expresses the duration of the *"Final Material Classification"* and the transport of the excavated materials from the MFS St. Jodok to the final repository Padastertal. For example, the time difference between the *"Excavation with TEMH_TBM_West_01"* curve and the *"Muck Transport_TBM_West_01"* curve specifies this additional transport and material classification time of the *"TBM_West_01"* tube.

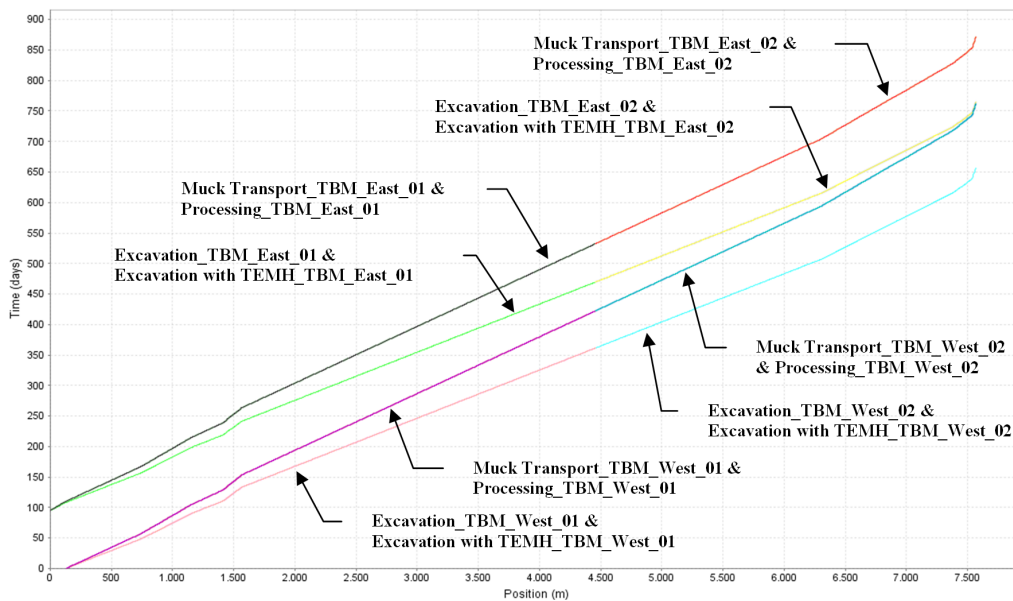


Figure 8.9: Position-Time Plot of the Mechanized Tunnel Drifts of One Simulation Run of Simulation Technique I

Along the alignment of the mechanized tunnel drifts qualified geology for processing to concrete aggregates is not anticipated. Hence, additional time for processing is not computed when simulating the TBM drives with the related TEMH. As a result the *"Processing"* curves, which would model a possible processing, overlap with the

¹⁵Subsection 5.3.1 discusses the activity network of the *"Excavation with TEMH"* subpart for mechanized tunneling and the critical path approach in detail.

preceding "Muck Transport" curves. For instance, the "Processing_TBM_West_01" and the "Muck Transport_TBM_West_01" curves overlap (see Figure 8.9).

Figure 8.10 shows the position-time plot of the Drill and Blast tunnel drifts of Figure 8.8 in detail. As one can see, the tunnel excavation (e.g., "Excavation_D&B_West") is affected by the transport of the excavated materials from the tunnel face to the MFS St. Jodok (e.g., "Excavation with TEMH_D&B_West") because the "Excavation_D&B_West" curve does not overlap with the "Excavation with TEMH_D&B_West" curve. This result depicts the cyclic characteristic of conventional tunneling where the tunnel excavation performance is generally influenced due to the mucking process. However, the outcomes of the simulations show that the "Final Material Classification" and the subsequent transport of the materials from the MFS St. Jodok to the final repository Padastertal (see Figure 7.1) using conveyor systems (e.g., "Muck Transport_D&B_West") can partially go on during the time of the tunnel excavation with the related mucking process (e.g., "Excavation with TEMH_D&B_West"). Only a small time gap between the "Excavation with TEMH" curves and the "Muck Transport" curves of the conventional tunnel drifts occurs (see Figure 8.11). This time gap illustrates the additional time consumption of the transport of the excavated materials from the MFS St. Jodok to the final repository Padastertal. The reason for this nearly simultaneous transport and tunnel excavation is the activity network, of the "Transportation Model" of conventional tunneling (see Figure 5.24). This activity network considers that parts of the tunnel construction (e.g., initial support, see "Part 2" in Figure) can go on simultaneously with the "Final Material Classification" and the transport of the excavated materials from MFS St. Jodok to the final repository Padastertal (see "Part 3" in Figure 5.24).

Along the alignment of the Drill and Blast tunnel drifts qualified geology for processing is anticipated; thus, some amounts of excavated materials undergo the recycling process. The curves of "Processing_D&B_West" and "Processing_D&B_East" include the additional time consumption of processing (see Figure 8.10), which starts at the time of the separation of the processing curves ("Processing_D&B_West" and "Processing_D&B_East") from the respective muck transport curves ("Muck Transport_D&B_West" and "Muck Transport_D&B_East"). The position and time (approximately day 1 029) where this production of concrete aggregates starts is characterized in Figure 8.10.

Figure 8.12 shows the inner liner advance of the different tunnel drifts, which stays the same over the entire simulation area due to the assumed constant advance rate of the inner liner construction (see Table 7.6). Furthermore, Figure 8.12 illustrates the scheduled starting point of the inner liner construction (day 870).

Results of multi graph position-time plots are not shown because in this application the considered uncertainty about geology does not significantly influence the construction time.

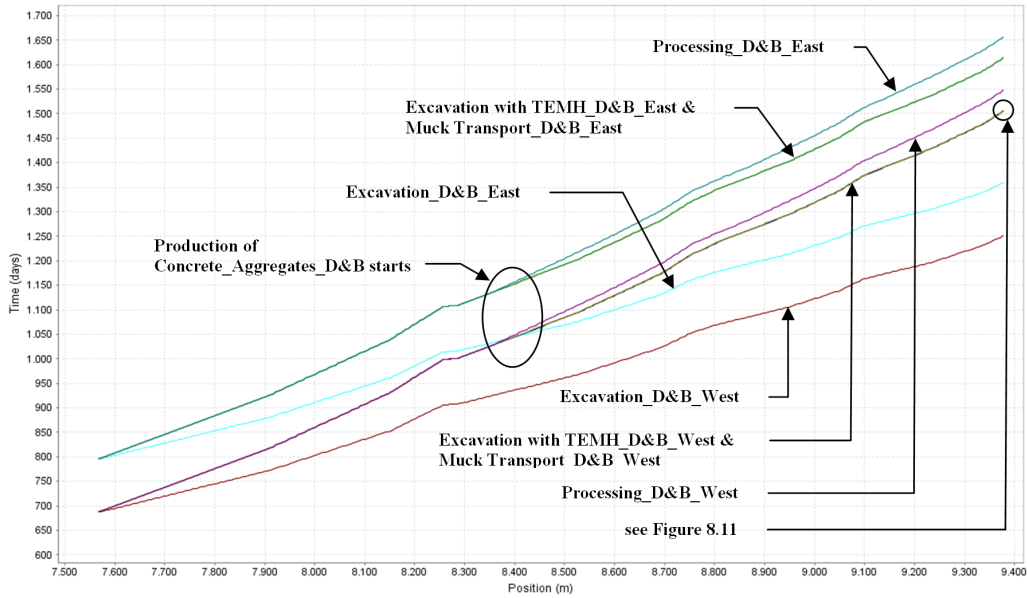


Figure 8.10: Position-Time Plot of the Drill and Blast Tunnel Drifts of One Simulation Run of Simulation Technique I

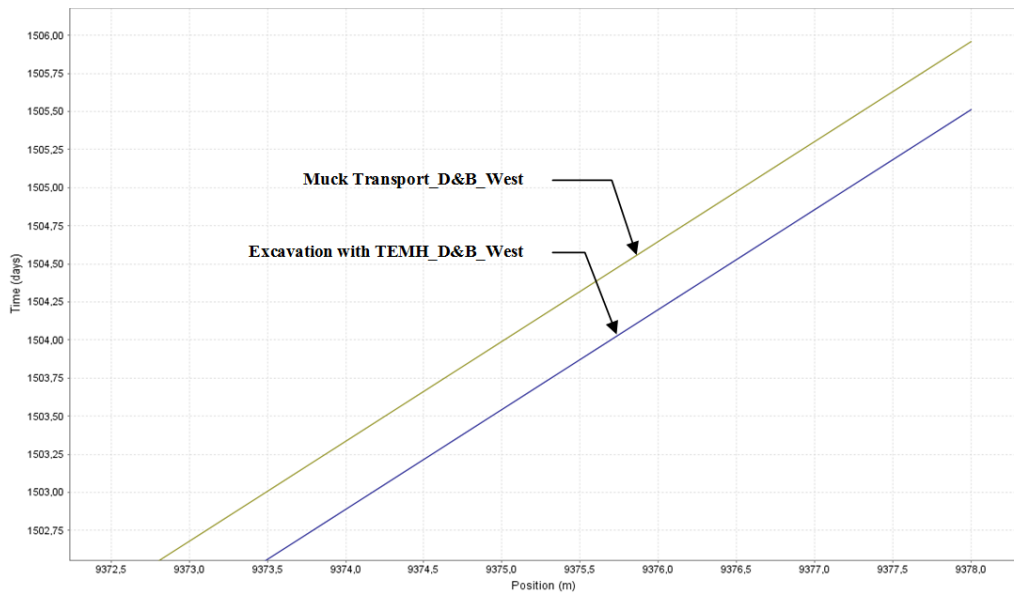


Figure 8.11: Detail Position-Time Plot of the Drill and Blast Tunnel Drifts of One Simulation Run of Simulation Technique I

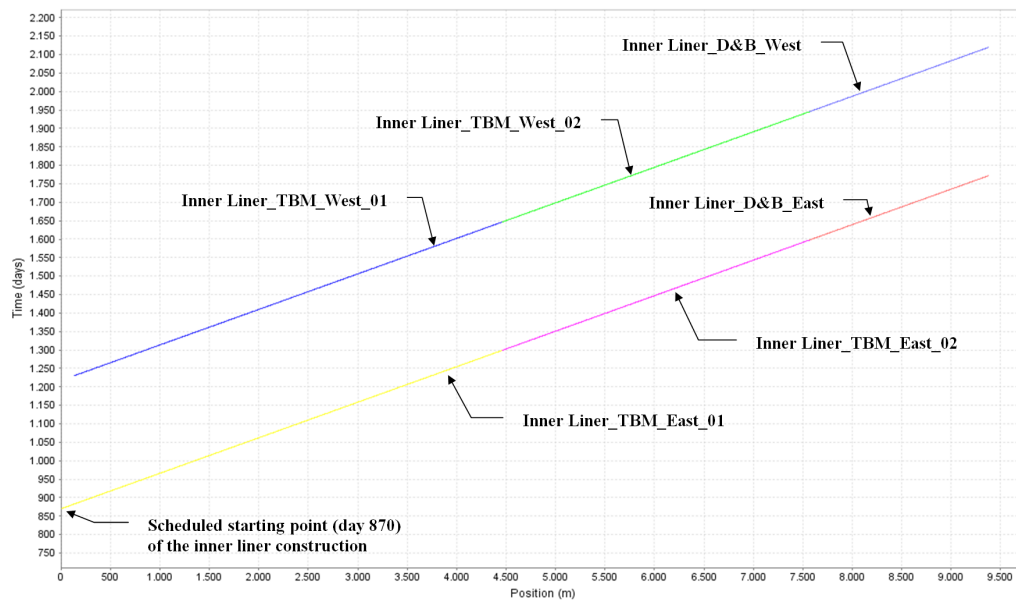


Figure 8.12: Position-Time Plot of the Inner Liner Construction of One Simulation Run of Simulation Technique I

8.2 RESULTS OF SIMULATION TECHNIQUE II

The differences between the results of the simulation technique II to the simulation technique I are discussed in the following. Figure 8.13 illustrates a time-volume plot of a run with simulation technique II. This plot shows the produced (recycled) volume of concrete aggregates of the conventional tunnel drifts ("*Concrete_Aggregates_D&B*") which is reduced due to the demand for concrete aggregates of the inner liner construction. This reduction continues as long as enough produced concrete aggregates are available and will stop the simulation due to a lack of resources (see Figure 8.14) if all the produced concrete aggregates are consumed (day 1 710). In addition, the "*Initial_Support_Demand_D&B*" curve is included in Figure 8.13, which allows one to compare this plot with the related plot of simulation technique I (see Figure 8.2). The "*Concrete_Aggregates_D&B*" curve of simulation technique II is a combination of the "*Concrete_Aggregates_D&B*" and the "*Inner_Liner_Demand*" curves of simulation technique I. The other curves, which are shown in Figure 8.1, which is an outcome of simulation technique I, stay the same in both simulation techniques.

The outcomes of simulation technique II can also be presented in a multi graph time-volume plot. Figure 8.15 presents the "*Concrete_Aggregates_D&B*" curves of simulation technique II and the "*Initial_Support_Demand_D&B*" curves in a multi graph time-volume plot of 100 runs. The distribution of the "*Concrete_Aggregates_D&B*" curves is a result of the geologic uncertainties.

As a result of the insufficient self-supply of concrete aggregates (lack of resources), the construction of the inner liner cannot start at the scheduled time (day 870, see

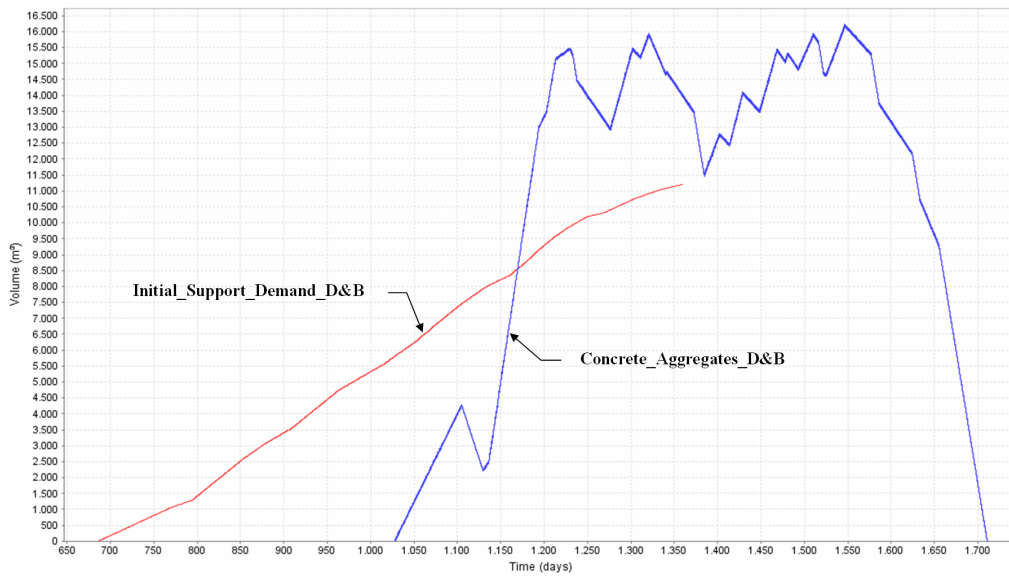


Figure 8.13: Produced Concrete Aggregates Reduced due to the Consumption of Concrete Aggregates of the Inner Liner, One Simulation Run, Simulation Technique II

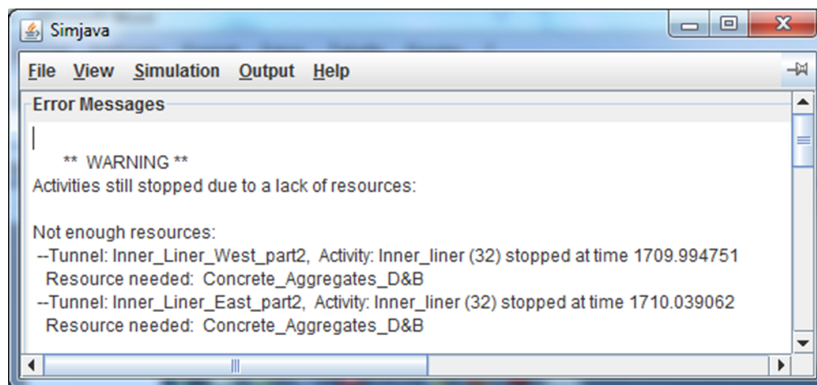


Figure 8.14: Error Message due to a Lack of Resources ("Concrete_Aggregates_D&B")

Figure 8.12) without supplying additional concrete aggregates from regional suppliers. One can see in Figure 8.16 that the inner liner starts at day 1 029 if the simulation solely considers recycled concrete aggregates. Hence, if simulation technique II is used the inner liner construction waits until produced concrete aggregates are available (see Figure 8.10). One can see that simulation technique II shows how an insufficient self-supply of concrete aggregates affects the tunnel construction performance. Moreover, Figure 8.16 illustrates that the construction of the inner liner stops at a certain time (day 1 710) due to the lack of the produced concrete aggregates. These results indicate that concrete aggregates from regional suppliers are necessary to perform the tunnel construction as scheduled.

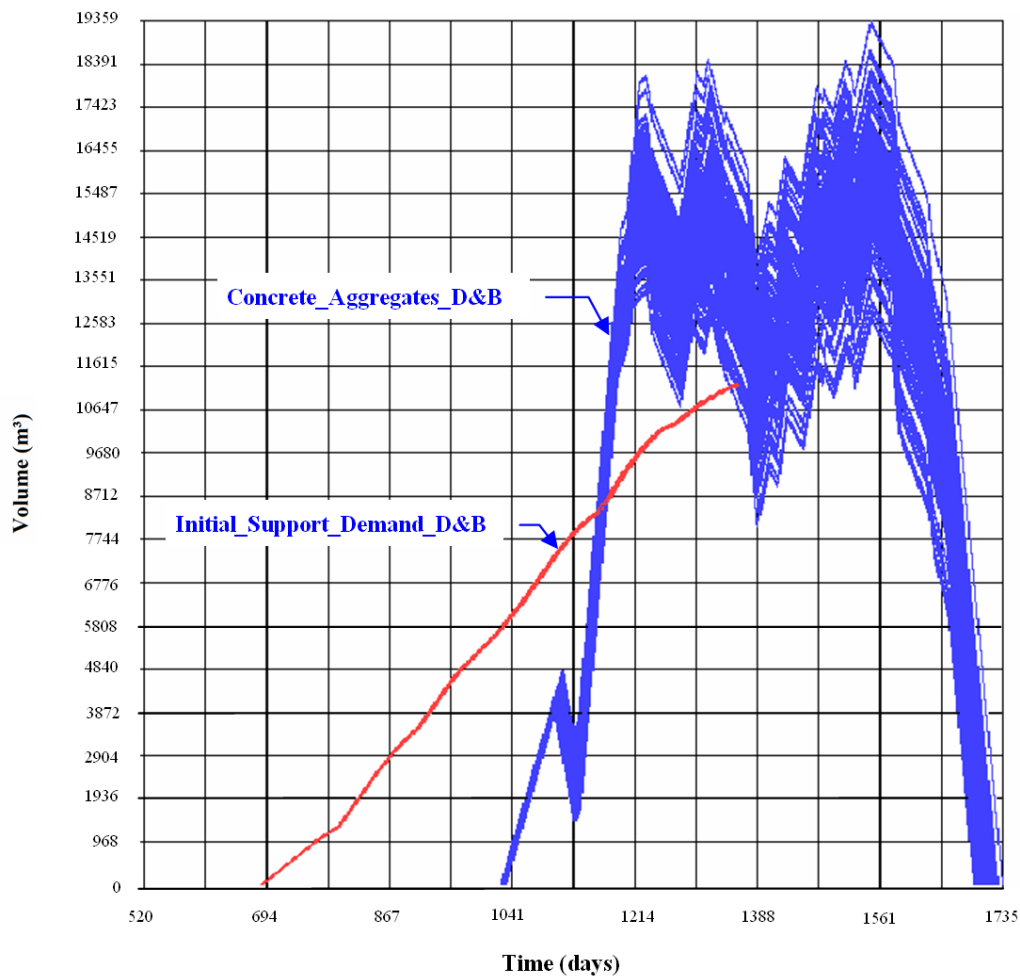


Figure 8.15: Produced Concrete Aggregates Reduced due to the Consumption of Concrete Aggregates of the Inner Liner, 100 Simulation Runs, Simulation Technique II

Comparing the outcomes of simulation technique I and simulation technique II shows their advantages and disadvantages. Simulation technique I has the advantage that the simulation does not stop due to a lack of resources. If it is assumed that insufficient resources are available during the entire construction process simulation technique I can be applied to plan the materials management. For instance, the additional supply of concrete aggregates in a certain time interval can be planned (see discussion of Figure 8.2). However, simulation technique I does not consider the influence of a temporary lack of resources on the construction performance. In contrast, simulation technique II considers this influence (see Figure 8.16). Hence, simulation technique II has the advantage to show how an insufficient self-supply of concrete aggregates influences the construction performance. On the other hand, using simulation technique II can stop the simulation at an early stage if a lack of resources occurs.

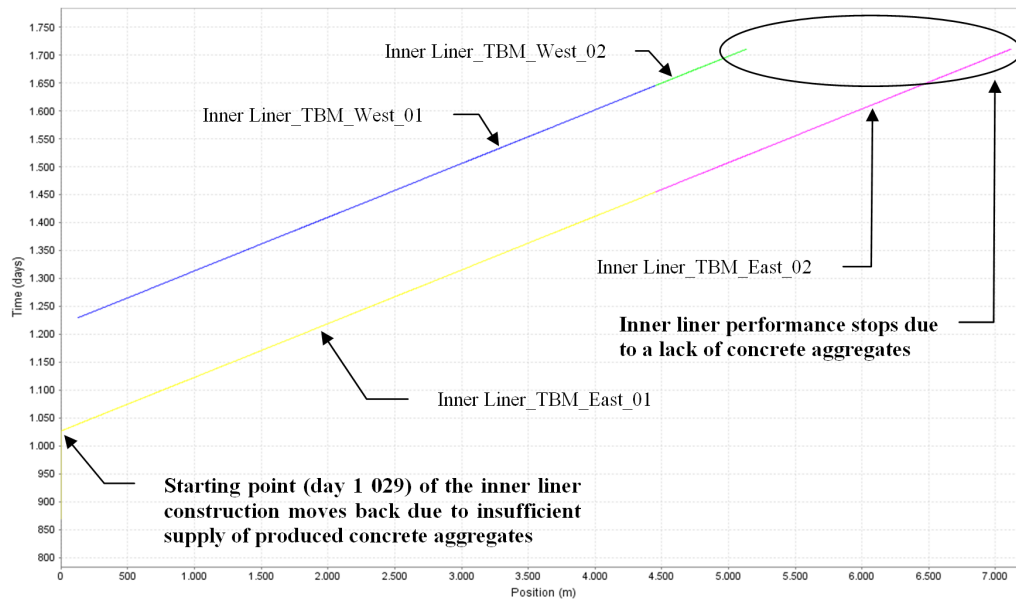


Figure 8.16: Position-Time Plot of the Inner Liner Construction of One Simulation Run of Simulation Technique II

8.3 ADDITIONAL SIMULATION RESULTS

In addition to the standard simulations (see Section 8.1 and 8.2), which only consider the geologic uncertainties, an additional simulation is performed. This additional simulation considers uncertainties about the processing of qualified excavation materials. Therefore, the time of the processing ("*processing_time*") as well as the processing success ("*processing_success_factor*") is modeled with symmetric triangular probability density functions. Table 8.3 shows the changes between the standard simulations and the additional simulation. The change of the variable "*processing_success_factor*" considers that investigations of the Brenner Basistunnel BBT SE showed that processing losses between 15 to 20 percent will occur when excavated materials of conventional tunneling are processed. The approach of the standard simulations used a more conservative value. Moreover, uncertainty about the necessary time to process one cubic meter of excavated materials ("*processing_time*") is considered. The additional simulation makes use of the simulation technique I (see Section 7.3). In the following outcomes of the additional simulation, which show differences to the standard simulations, are presented.

Figure 8.17 compares the consumption of concrete aggregates ("*Initial_Support_Demand_D&B*" and "*Inner_Liner_Demand*") with the produced concrete aggregates ("*Concrete_Aggregates_D&B*"). One can see that due to the change of the "*processing_success_factor*" (see Table 8.3) the volume of produced concrete aggregates is significantly higher than in the standard simulations (see Figure 8.4). Hence, the self-supply of concrete aggregates for the inner liner construction in the time interval

Table 8.3: Changes of the Variables "processing_time" and "processing_success_factor" in the Additional Simulation

Variables	Standard Simulations	Additional Simulation		
	min./mode/max.	min.	mode	max.
processing_time (days)	0.20	0.14	0.20	0.26
processing_success_factor ()	0.70	0.80	0.83	0.85

C and D (see Figure 8.2) is guaranteed if the simulation is based on the forecast processing success. However, the entire amount of recycled concrete aggregates is insufficient for a self-supply. Only a supporting supply of recycled concrete aggregates in specific time intervals is possible. The results obtained from the additional simulation also show that concrete aggregates have to be purchased from regional suppliers. Table 8.4 shows the minimum-, mean-, and maximum volume of the produced concrete aggregates of the additional simulation. Due to the uncertainties about processing and geology, the volume of produced concrete aggregates scatters about 9 000 m³. Moreover, the percentage of self-supplied concrete aggregates (about 45 percent) is presented and rises about 7 percent compared to the ones of the standard simulation (see Table 8.2).

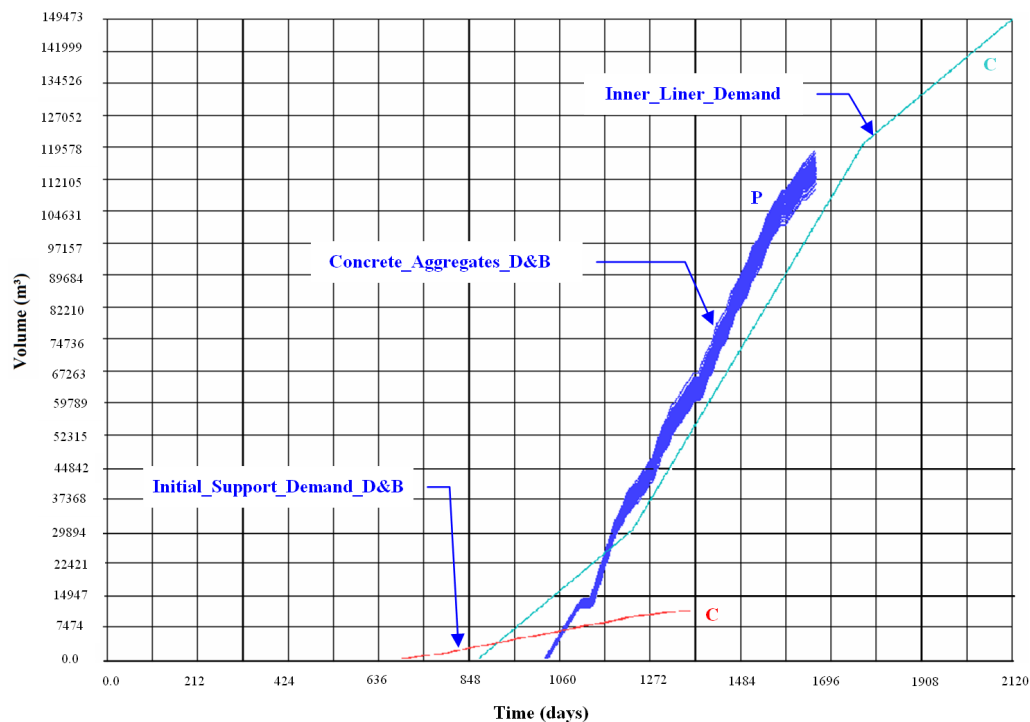
**Figure 8.17:** Concrete Aggregate Production (P) and Concrete Aggregate Consumption (C) of the Additional Simulation

Table 8.4: Produced Concrete Aggregates Influenced by Geologic Uncertainty, Additional Simulation

Concrete_Aggregates_D&B	Volume (m ³)	Self-Supply (%)
Minimum Volume of 100 Simulation Runs	109 819.11	42.4
Mean Volume of 100 Simulation Runs	114 482.10	44.2
Maximum Volume of 100 Simulation Runs	118 727.39	45.8

The time-volume scattergrams of the additional simulation (e.g., Figure 8.18) are different from the ones of the standard simulation (e.g., Figure 8.7). Due to the included processing uncertainties in the additional simulation (see Table 8.3) the construction through the ground class profiles with the particular TEHM is also influenced by uncertainties. The values of the *"processing_time"* and *"processing_success_factor"* variables are selected by the random generator of the DAT based on the respective triangular probability density function. Each time a construction method, which uses one of these variables, is applied in a simulation run, the random generator selects a new value for the respective variable. Thus, the values of the *"processing_time"* and *"processing_success_factor"* variables are different for the *"Drill&Blast_East_Tube"* and *"Drill&Blast_West_Tube"*. As a result, the cloud of points of the *"Drill&Blast_East_Tube"* is different from the one of the *"Drill&Blast_West_Tube"* (see Figure 8.18). The standard simulations, which do not consider this uncertainty about processing, obtain for the *"Drill&Blast_East_Tube"* and *"Drill&Blast_West_Tube"* the same cloud of points (see Figure 8.7). Figure 8.18 also indicates that the mean volume of concrete aggregates of one Drill and Blast Tube obtained in the additional simulation (57 241.05 m³) is about 17 percent greater than the one of the standard simulations (48 632.40 m³, see Figure 8.7), due to the higher processing success factor. Moreover, a more scattered cloud of points can be seen in Figure 8.18 (additional simulation) compared to Figure 8.7 (standard simulations). This is to be expected because the additional simulation includes in addition to the standard simulations the uncertainty about processing.

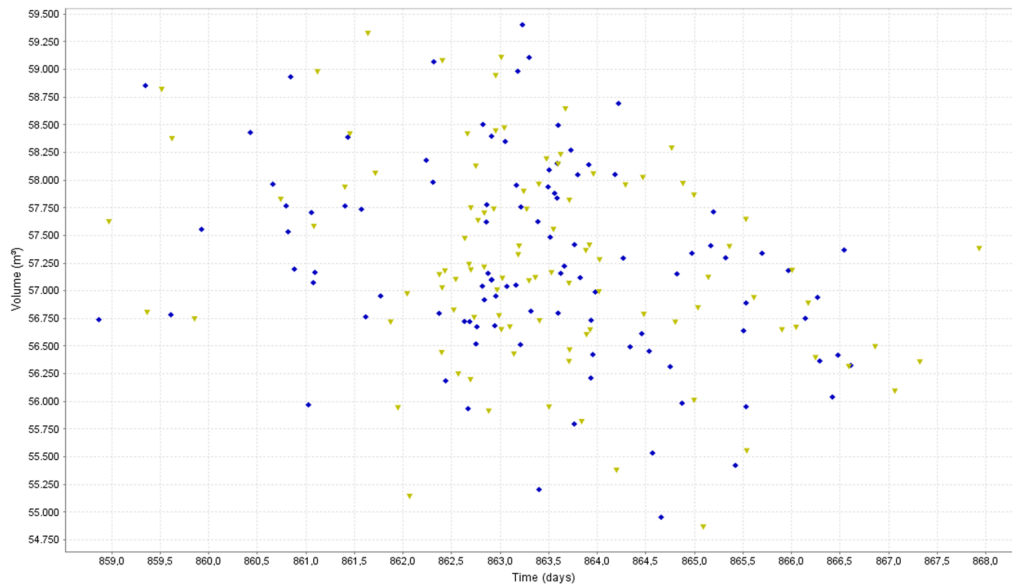


Figure 8.18: Time-Volume Scattergram of the Additional Simulation, Produced Concrete Aggregates of the "Drill&Blast East Tube" (▼) and "Drill&Blast West Tube" (■) (min. Volume = 54 864.82 m³, mean Volume = 57 241.05 m³, max. Volume = 59 403.08 m³)

Chapter 9

CONCLUSIONS AND PERSPECTIVES

A sustainable planning of a tunnel construction project has to consider the handling of the excavated materials. Although recent tunnel construction projects used sophisticated materials management systems, it is very difficult to plan the TEMH due to the variety of uncertainties affecting tunneling and the handling of the excavated materials. Therefore, it is important to determine and manage the uncertainties associated with the TEMH.

This study shows that uncertainties affecting the TEMH can be assessed and managed in a decision analysis procedure. A simulation model, which is based on the DAT and their resource module, is provided to simulate either mechanized- or conventional excavation with the particular TEMH under uncertainty. This simulation model can be described as an economic (resource) model and can be used deterministically and/or probabilistically.

In a case study, the simulation model was applied to a part of contract section Wolf of the BBT. This application proofed that the simulation model and, thus, the decision analysis procedure can be used to deal with the complexity of planning the TEMH. Various simulations were run to obtain useful outputs for decision making. A brief review of the conclusions drawn from this case study, an assessment of the DAT, and some perspectives for future research complete this thesis.

9.1 CONCLUSIONS DRAWN FROM THE SIMULATIONS

Although many assumptions were necessary due to limited project information available at the time of the application of the simulation model to a part of contract

section Wolf, following conclusions can be made:

Results from the different simulations show that the main volume of excavated materials is classified as material of the usage classes B and C. The quantity of qualified excavated materials to produce concrete- or shotcrete aggregates (usage class A) is insufficient to cover the needs of the initial- and final support. In other words, there will not be enough concrete- or shotcrete aggregates to produce the necessary support. Therefore, additional concrete aggregates will have to be purchased from regional suppliers. The additional simulation (see Section 8.3), which considers the forecast processing success of the Brenner Basistunnel BBT SE, obtained that about 45 percent of the required concrete aggregate volume can be self-supplied. In a more conservative approach (standard simulations, see Sections 8.1 and 8.2), the computed self-supply of concrete aggregates is approximately 38 percent.

Presenting the results of these simulations in time-volume plots allows one to indicate time intervals, which guarantee a self-supply with concrete- and shotcrete aggregates. This time interval is for the conducted simulations between day 1029 and day 1656. Also time intervals when aggregates have to be purchased from regional suppliers are identified. Such findings are particularly useful if the capacity of the storage facilities on the construction site is limited and shotcrete- or concrete aggregates cannot be purchased in stock.

Position-time plots of simulation technique II show the effect of the insufficient self-supply of aggregates on the inner liner construction. If recycled aggregates are solely considered in the simulations the inner liner construction will not start at the scheduled time. This is so because concrete aggregates are not available at the scheduled start of the final support. Moreover, the final support cannot be completed due to a lack of concrete aggregates. These findings indicate that concrete aggregates will have to be purchased to perform the tunnel construction as scheduled.

Time-volume scattergrams and multi graph time-volume plots illustrate the influence of the modeled uncertainties on the TEMH. The standard simulations, which consider only the uncertainty about geology, indicate that the volume of produced concrete- and shotcrete aggregates scatters about 6 000 m³. This scatter is about 6 percent of the computed maximum volume (99 763.40 m³) of aggregates of the corresponding simulation. Hence, the anticipated uncertainty about geology can cause significant changes in the volume of produced concrete- or shotcrete aggregates. The included uncertainties about processing, which are considered in the additional simulation, directly influence the volume of produced shotcrete- or concrete aggregates. As expected, the obtained volume of aggregates of the additional simulation scatter more significant (approximately 9 000 m³) than the ones of the standard simulations (approximately 6 000 m³).

The same analyzes can also be conducted for the excavated materials of usage class B, which can be reused as fill materials for embankments or backfilling. However, information regarding the demand for such materials was not available at the time

of the simulations. Hence, a detailed analyzes of excavated materials of usage class B was not performed.

9.2 ASSESSMENT OF THE DECISION AIDS FOR TUNNELING

The DAT, a computer based tool, have been applied to numerous tunnel construction projects and allow uncertainties affecting tunneling to be considered in determining construction cost and time as well as other information related to tunnel construction such as resources.

The current resource module of the DAT enables one to realistically simulate the reuse of excavated materials to produce, for example, concrete aggregates. Such a realistic simulation model considers the entire construction process of a tunnel construction project with the associated uncertainties. Therefore, the DAT first simulates the geology in order to model subsequently the construction process (mechanized- or conventional excavation) with the related TEMH through this geology. The geology and the construction process can be characterized by the influence of uncertainty. This structure of the DAT results in a materials management simulation which is subject to the geology and the construction process. Thus, the produced or required quantity of resources (e.g., concrete aggregates) is for every meter of the excavation subject to the uncertainties about the geology and the construction process. As a result, possible alterations in the schedule of a tunnel construction project due to these uncertainties are included in the simulation model and effects on the materials management can be indicated. To obtain such effects is particularly useful to control the production and requirement of a specific resource (e.g., concrete aggregates). Furthermore, materials management simulations enable one to show possible effects of the TEMH on the tunnel construction advance. However, some further developments of the resource module of the DAT are needed to make materials management simulations more attractive:

In the present resource module it is not possible to use for an activity a different resource (secondary resource) if the assigned resource (primary resource) is not available. For instance, if produced concrete aggregates (primary resource) are not available for an activity (e.g., inner liner) this activity will wait until the primary resource is available or the simulation stops if no primary resource is produced. As a matter of fact, the scheduled construction is interrupted and as a result construction time overruns are simulated. However, in reality the inner liner construction would cover the needs for concrete aggregates (secondary resource) from regional suppliers. Therefore, in the DAT the respective activity should be able to use a secondary resource (e.g., concrete aggregates from regional suppliers) at the time intervals when no primary resource is available instead of waiting for a production of the primary resource. This change in the resource module would make the simulations more

realistic and should be possible using the *"if...else"* statement in the programming language Java.¹⁶ For example, *"if"* the primary resource is zero the activity has to use the secondary resource *"else"* the activity uses the primary resource. The advantage of this development would be that the used quantity of the secondary resource (e.g. concrete aggregates from regional suppliers) is directly computed. A time-volume plot showing this computed quantity of the secondary resource can be useful to plan the supply with the regional suppliers.

Another future development of the resource module would be to change the 5 000 meters limitation in the DAT. As mentioned before, in the current version of the DAT a repository can simulate only a tunnel with a maximum length of 5 000 meters (5 000 meters limitation). This limitation makes the simulation of tunnel which is longer than 5 000 meters more difficult. A future change of this 5 000 meters limitation would definitely help to apply the simulation model.

Although various types of outputs exist in the present version of the DAT, a report file which stores the computed volumes of resources at regular time intervals is not created. Such a type of outcome could be used to analyze the computed volumes of resources at certain time intervals in detail.

Finally, the graphical output should be further developed. In particular, the multi graph time-volume and multi graph position-time plots, which plot the curves of multiple simulation runs, need further development in order for the DAT to be more attractive.

9.3 RECOMMENDATIONS FOR FUTURE WORK

Further work should update the application of the simulation model to contract section Wolf using more detailed information of contract section Wolf. Specifically, assumptions which were necessary at the time of the simulations such as, for example, the advance rates of the tunneling classes, the constant cross sectional areas, and the constant demand for initial- and final support per tunnel meter should be changed to obtain more reliable results for decision making. Moreover, more detailed information regarding the construction process or the geology should be included. Such additional information could be used to refine, for example, the activity networks of the simulation model which allows one to simulate the construction process in more detail. It would be best to perform such an update in cooperation with the project engineers of the Brenner Basistunnel BBT SE.

Another recommendation is to use and modify the simulation model for specific investigations regarding the TEMH of contract section Wolf. For instance, the transportation concept of the excavated materials (conveyor system, muck trucks, etc.), the storage capacity of the intermediate- or final repository, and the equipment and

¹⁶SIMJAVA, which is the graphical user interface to implement the DAT and used throughout this research, is programmed in Java.

machinery of the central material handling and loading facility in the MFS St. Jodok or the aggregate plant can be investigated in detail. Also, different alternatives of the planned TEMH concept can be examined.

A suggestion for future research is to focus on economic and environmental issues of recycling tunnel excavation materials. As mentioned before, the DAT can be used to determine the construction cost of a tunnel project. Naturally, this economic application of the DAT can be used to examine the profitability of recycling tunnel excavation materials. For instance, activities which model the material flows in the TEMH process (e.g. processing) are assigned with respective cost equations to compute their costs. These extra costs of the recycling can be compared with economic advantages of the TEMH process such as the saving of transport distances due to the reuse of excavated materials on the construction site. Also, a possible reduction of purchased aggregates from regional suppliers can be an economic advantage of recycling excavated materials.

From an environmental point of view, not only the amount of qualified excavated materials for recycling is of interest. A possible CO₂ reduction due to the reuse of excavated materials on the construction site can also be examined. Therefore, CO₂ has to be defined as an additional resource in the resource module of the DAT. Subsequently, each activity which produces CO₂ is assigned the resource CO₂. The amount of produced CO₂ of this activity can be determined using a specific resource equation. Again, shortened transport routes can reduce the CO₂ balance of the tunnel construction project. Otherwise, the rising cement consumption of concretes using recycled aggregates may raise the CO₂ production. A similar approach could be used to determine a possible saving of energy due to the reuse of excavated materials. It would be interesting to use the resource module of the DAT to quantitatively investigate the economic and environmental impact of recycling tunnel excavation materials.

BIBLIOGRAPHY

- G. B. Baecher. *Site Exploration: A Probabilistic Approach*. PhD thesis, Massachusetts Institute of Technology, 1972. [cited at p. 4]
- K. Bergmeister. Alpenquerende Tunnel: Projektübersicht und Materialbewirtschaftung beim Brenner Basistunnel. *Beton- und Stahlbetonbau*, 102(1):19–23, 2007a. [cited at p. 62, 147]
- K. Bergmeister. Brenner Base Tunnel: Link between Munich and Verona. *Tunnel*, 2007(01):9–20, 2007b. [cited at p. 72]
- K. Bergmeister. Brenner Base Tunnel : Stage reached by Construction. *Tunnel*, 2010(01):6–17, 2010. [cited at p. 11, 13, 65, 72, 75, 148]
- G. H. Brundtland. *Our Common Future*. Oxford University Press, UK, 1987. [cited at p. 11]
- J. T. Christian. Geotechnical Engineering Reliability: How Well Do We Know What We Are Doing? *Geotechnical and Geoenvironmental Engineering*, 130(10):985–1003, 2004. [cited at p. 3, 4]
- J. T. Christian, C. C. Ladd, and G. B. Baecher. Reliability Applied to Slope Stability Analysis. *Journal of Construction Engineering and Management*, 120(12):2180–2207, 1994. [cited at p. 4]
- H. H. Einstein. Risk and Risk Analysis in Rock Engineering. *Tunnelling and Underground Space Technology*, 11(2):141–155, 1996. [cited at p. 9]
- H. H. Einstein. The Decision Aids for Tunnelling (DAT) - a Brief Review. *Tunnelling Technology*, pages 37–51, 2001. [cited at p. 17, 20, 146]
- H. H. Einstein. Decision Aids for Tunneling: Update. *Transportation Research Record: Journal of the Transportation Research Board*, 1892:199–207, 2004. [cited at p. 17, 21]

- H. H. Einstein. Treatment of Risks in Rock Engineering. *Beiträge zum 7. Geotechnik-Tag in München, Risiko und Sicherheit in der Geotechnik. Technische Universität München, Zentrum Geotechnik*, pages 95–117, 2008. [cited at p. 5, 7, 8, 9, 18, 146]
- H. H. Einstein and G. B. Baecher. Probabilistic and statistical methods in engineering geology. *Rock Mechanics and Rock Engineering*, 16(1):39–72, 1983. [cited at p. 3, 4]
- H. H. Einstein and R. L. Sousa. Warning System for Natural Threats. In *2006 ECI Conference on Geohazards*, pages 1–37, Lillehammer, 2006. [cited at p. 7, 146]
- H. H. Einstein, D. A. Labreche, M. J. Markow, and G. B. Baecher. Decision Analysis applied to rock tunnel exploration. *Engineering Geology*, 12:143–161, 1978. [cited at p. 8]
- M. H. Faber. Risk and Safety in Engineering. Lecture Notes, Swiss Federal Institute of Technology Zurich (ETH), 2009. [cited at p. 4]
- L. Gertsch, A. Fjeld, B. Nilsen, and R. Gertsch. Use of TBM muck as construction material. *Tunnelling and Underground Space Technology*, 15(4):379–402, 2000. [cited at p. 12, 14]
- C. Haas. Updating in the "Decision Aids for Tunneling". Master's thesis, Massachusetts Institute of Technology, 2000. [cited at p. 36]
- C. Haas and H. H. Einstein. Updating the Decision Aids for Tunneling. *Journal of Construction Engineering and Management*, 128(1):40–48, 2002. [cited at p. 36]
- V. B. Halabe. *Resource Modeling for DAT*. PhD thesis, Massachusetts Institute of Technology, 1995. [cited at p. 21]
- G. Harer and P. Pichler. Solutions for the sustainable reduction of the tipping requirement at the Koralm tunnel. *Geomechanics and Tunnelling*, 2(5):627–632, 2009. (In German and English). [cited at p. 12]
- R. A. Howard. Decision Analysis: Applied Decision Theory. In *Proceedings of the Fourth International Conference on Operational Research*, pages 55–71, New York, 1966. [cited at p. 5, 7, 8]
- R. A. Howard. The Evolution of Decision Analysis. Lecture Notes, Stanford Decisions and Ethics Center, 2010a. (<http://decision.stanford.edu/library/ronald-a-howard/the-evolution-of-decision-analysis-1/the-evolution-of-decision-analysis> am 15-06-2010). [cited at p. 5, 6, 7]
- R. A. Howard. The Foundations of Decision Analysis Revisited. Lecture Notes, Stanford Decisions and Ethics Center, 2010b. (Download: <http://www.usc.edu/dept/create/assets/001/50843.pdf> am 15-06-2010). [cited at p. 5, 6, 9, 146]

- K. S. Karam, J. S. Karam, and H. H. Einstein. Decision Analysis Applied to Tunnel Exploration Planning. I: Principles and Case Study. *Journal of Construction Engineering and Management*, 133(5):344–353, 2007. [cited at p. 7]
- C. Kollarou. Excavation Materials Handling in the Lötschberg Base Tunnel using Decision Aids for Tunneling (DAT). Master's thesis, Massachusetts Institute of Technology, 2002. [cited at p. 2, 21]
- M. Kruse. Preparing the excavated Material at the Gotthard Base Tunnel. *Tunnel*, 5:27–34, 2002. [cited at p. 12, 15, 16]
- S. Lacasse and F. Nadim. Uncertainties in characterising soil properties. In *Uncertainty in the Geologic Environment: From Theory to Practice, Geotechnical Special Publication No. 58*, volume 201, pages 49–75, New York, 1996. ASCE. [cited at p. 4]
- R. H. Lieb. Materials management at the Gotthard Base Tunnel - experience from 15 years of construction. *Geomechanics and Tunnelling*, 2(5):619–626, 2009. (In German and English). [cited at p. 12, 14, 15, 48]
- C. Marzer. Decision aids for tunneling (DAT): development of the resource model (Final Report). Massachusetts Institute of Technology, 2002. [cited at p. 21]
- S. Min. The Application of "Decision Aids for Tunneling (DAT)" to the Sucheon tunnel in Korea. Master's thesis, Massachusetts Institute of Technology, 2003. [cited at p. 95]
- S. Min. *Development of the Resource Model for the Decision Aids for Tunneling (DAT)*. PhD thesis, Massachusetts Institute of Technology, 2008. [cited at p. 17, 18, 21, 38, 52, 60, 146]
- S. Min, Y. Moret, C. A. Indermitte, C. Marzer, and H. H. Einstein. *Decision Aids for Tunneling - SIMJAVA - User's Manual*. Massachusetts Institute of Technology, 2009. [cited at p. 21, 33, 38, 40, 89, 146]
- Y. Moret, R. L. Sousa, and H. H. Einstein. The Decision Aids for Tunneling (DAT) - Introduction and recent Applications in Portugal. In *FEUP - DEC Workshop "Tunnels for High-Speed Railways"*, pages 1–17, 2009. [cited at p. 18]
- E. M. Paté-Cornell. Uncertainties in risk analysis: Six levels of treatment. *Reliability Engineering & System Safety*, 54(2-3):95–111, 1996. [cited at p. 4]
- H. Raiffa and R. L. Schlaifer. *Applied statistical decision theory*. Harvard Business School, Cambridge, Massachusetts, 1964. [cited at p. 7]
- D. Resch, K. Lassnig, R. Galler, and F. Ebner. Tunnel excavation material - high value raw material. *Geomechanics and Tunnelling*, 2(5):612–618, 2009. (In German and English). [cited at p. 11, 12]

- R. L. Sousa. *Risk Analysis for Tunneling Projects*. PhD thesis, Massachusetts Institute of Technology, 2010. [cited at p. 14]
- C. S. Spetzler and C.-A. S. Staël Von Holstein. Probability Encoding in Decision Analysis. *Management Science*, 22(3):340–358, 1975. [cited at p. 8]
- M. Steiger. *IT-gestütztes Risikomanagementmodell für Tunnelbauprojekte mit Hilfe von Bayes'schen Netzen und Monte-Carlo-Simulationen*. PhD thesis, ETH Zürich, 2009. (In German). [cited at p. ix]
- Technical Report D0118-02369. Bauleistikkonzept Österreich. Brenner Basistunnel BBT SE, P. Mazzalai, 29-02-2008 . (In German and Italian). [cited at p. 61, 64, 77, 79, 147, 148]
- Technical Report D0118-02916-10. Bauwerksplanung - Einreichplanung. Brenner Basistunnel BBT SE, H. Golser, 29-02-2008 . (In German and Italian). [cited at p. 61, 67, 76, 147, 148]
- Technical Report D0118-04340. Ausbruchmaterialbewirtschaftungskonzept. Brenner Basistunnel BBT SE, P. Mazzalai, 29-02-2008 . (In German and Italian). [cited at p. 61, 72, 73, 150]
- Technical Report D0154-00031. Geologie, Geologisches Modell. Brenner Basistunnel BBT SE, R. Brandner, 29-02-2008 . (In German and Italian). [cited at p. 68, 69, 70, 147, 148]
- Technical Report D0154-00044. Ausbruchmaterial und Eigenschaften. Brenner Basistunnel BBT SE, R. Brandner and M. John, 29-02-2008 . (In German and Italian). [cited at p. 61, 65, 73]
- P. Teuscher, C. Thalmann, A. Fetzer, and C. Carron. Alpenquerende Tunnel: Materialbewirtschaftung und Betontechnologie beim Lötschberg-Basistunnel. *Beton- und Stahlbetonbau*, 102(1):2–10, 2007. [cited at p. 15, 48]
- C. Thalmann. *Beurteilung und Möglichkeiten der Wiederverwertung von Ausbruchmaterial aus dem maschinellen Tunnelvortrieb zu Betonzuschlagstoffen (Characterisation and possibilities of the utilisation of excavated rock material by tunneling boring machines as concrete and shotcrete aggregates)*. PhD thesis, Swiss Federal Institute of Technology Zurich (ETH), 1996. (In German). [cited at p. 14, 15, 16]
- www.bbt-se.com. Web Page of Brenner Basistunnel BBT SE, 2010. URL www.bbt-se.com. [cited at p. 61, 63, 64, 66, 147]

APPENDIX: END POSITIONS OF THE GROUND CLASSES

Table 9.1 shows the end positions of each determined ground class. These end positions are the input data of the zones in the Geology Module of the DAT and used to compute the ground class profiles. One can see that the determined end positions quantify the uncertainty about geology using symmetric triangular probability density functions.

Table 9.1: End Positions of the Ground Classes

GROUND CLASSES	LENGTH (m) DETERMINISTIC	END POSITIONS (m)		
		MIN	MODE	MAX
N24_TBM_02_C	52.00	46.80	52.00	57.20
N24_TBM_02_B	78.00	122.20	130.00	137.80
N24_TBM_01_C	85.20	206.68	215.20	223.72
N24_TBM_01_B	127.80	330.22	343.00	355.78
N25_TBM_01_C	166.00	492.40	509.00	525.60
N25_TBM_01_B	249.00	733.10	758.00	782.90
N26a_TBM_02_C	318.40	1044.56	1076.40	1108.24
N26a_TBM_02_B	79.60	1148.04	1156.00	1163.96
N26b_TBM_01_C	209.60	1323.68	1365.60	1407.52
N26b_TBM_01_B	52.40	1407.52	1418.00	1428.48
N26b_TBM_03_C	120.00	1514.00	1538.00	1562.00
N26b_TBM_03_B	30.00	1562.00	1568.00	1574.00
N27_TBM_01_C	895.00	2284.00	2463.00	2642.00
N27_TBM_01_B	895.00	3268.50	3358.00	3447.50
N28a_TBM_01_C	880.00	4150.00	4238.00	4326.00
N28a_TBM_01_B	220.00	4414.00	4458.00	4502.00
N28b_TBM_01_C	744.00	5164.80	5202.00	5239.20
N28b_TBM_01_B	186.00	5378.70	5388.00	5397.30
N29_TBM_01_C	736.00	6087.20	6124.00	6160.80
N29_TBM_01_B	184.00	6298.80	6308.00	6317.20
N29_TBM_02_C	480.00	6764.00	6788.00	6812.00
N29_TBM_02_B	120.00	6902.00	6908.00	6914.00
N30_TBM_01_C	21.00	6927.95	6929.00	6930.05
N30_TBM_01_B	9.00	6937.55	6938.00	6938.45
N30_TBM_02_C	315.00	7237.25	7253.00	7268.75
N30_TBM_02_B	135.00	7381.25	7388.00	7394.75
N30_TBM_03_C	105.00	7487.75	7493.00	7498.25
N30_TBM_03_B	45.00	7535.75	7538.00	7540.25
N30_TBM_04_C	21.00	7557.95	7559.00	7560.05
N30_TBM_04_B	9.00	7567.55	7568.00	7568.45
N31_D&B_01_C	213.90	7760.51	7781.90	7803.29
N31_D&B_01_B	131.10	7899.89	7913.00	7926.11
N31_D&B_02_C	149.73	8047.76	8062.73	8077.70
N31_D&B_02_B	91.77	8145.32	8154.50	8163.68
N31_D&B_03_C	64.17	8212.25	8218.67	8225.09
N31_D&B_03_B	39.33	8254.07	8258.00	8261.93
N31_TBM_01_C	18.60	8274.74	8276.60	8278.46
N31_TBM_01_B	11.40	8286.86	8288.00	8289.14

GROUND CLASSES	LENGTH (m) DETERMINISTIC	END POSITIONS (m)		
		MIN	MODE	MAX
N32a_D&B_01_C	23.50	8309.15	8311.50	8313.85
N32a_D&B_01_B	47.00	8353.80	8358.50	8363.20
N32a_D&B_01_A	164.50	8506.55	8523.00	8539.45
N32a_D&B_02_C	16.45	8537.81	8539.45	8541.10
N32a_D&B_02_B	32.90	8569.06	8572.35	8575.64
N32a_D&B_02_A	115.15	8675.99	8687.50	8699.02
N32a_D&B_03_C	7.05	8693.85	8694.55	8695.26
N32a_D&B_03_B	14.10	8707.24	8708.65	8710.06
N32a_D&B_03_A	49.35	8753.07	8758.00	8762.94
N32b_D&B_01_B	20.00	8777.00	8778.00	8779.00
N32b_D&B_02_B	14.00	8791.30	8792.00	8792.70
N32b_D&B_03_B	6.00	8797.70	8798.00	8798.30
N33_D&B_01_C	30.00	8825.00	8828.00	8831.00
N33_D&B_01_B	30.00	8855.00	8858.00	8861.00
N33_D&B_01_A	90.00	8939.00	8948.00	8957.00
N33_D&B_02_C	21.00	8966.90	8969.00	8971.10
N33_D&B_02_B	21.00	8987.90	8990.00	8992.10
N33_D&B_02_A	63.00	9046.70	9053.00	9059.30
N33_D&B_03_C	9.00	9061.10	9062.00	9062.90
N33_D&B_03_B	9.00	9070.10	9071.00	9071.90
N33_D&B_03_A	27.00	9095.30	9098.00	9100.70
N34_D&B_01_B	28.00	9123.20	9126.00	9128.80
N34_D&B_01_A	112.00	9226.80	9238.00	9249.20
N34_D&B_02_B	19.60	9255.64	9257.60	9259.56
N34_D&B_02_A	78.40	9328.16	9336.00	9343.84
N34_D&B_03_B	8.40	9343.56	9344.40	9345.24
N34_D&B_03_A	33.60	9378.00	9378.00	9378.00

LIST OF ABBREVIATIONS

Abbreviation	Definition
BBT	Brenner Base Tunnel
DAT	Decision Aids for Tunneling
MFS	Multifunction Station
NATM	New Austrian Tunneling Method
TBM	Tunnel Boring Machine
TEMH	Tunnel Excavation Material Handling

LIST OF FIGURES

2.1	Representation of the Formal Aspects of a Decision Analysis (Howard, 2010b)	6
2.2	Decision Analysis Cycle (Einstein and Sousa (2006) and Einstein (2008))	7
2.3	Model Sequence of a Decision Analysis (Howard, 2010b)	9
3.1	Materials Flow Scheme of the Excavated Material in the TEMH Process	13
4.1	Major Components of the DAT (Min, 2008)	18
4.2	Ground Class Profile	19
4.3	Construction Simulation	19
4.4	Time-Cost Scattergram (Einstein, 2001)	20
4.5	Tunnel Network (Min et al., 2009)	21
5.1	Material Flows in the TEMH Process	24
5.2	Ground Class Profile with Implementation of the " <i>Preliminary Material Classification</i> " (" <i>Excavation Material Classes</i> ")	25
5.3	Relationship between Tunnel Geometry, Geology (Ground Classes), Construction Methods, Activities, and Time/Resource Equations in the Simulation Model	26
5.4	Structure of the Tunnel Network of the Simulation Model	28
5.5	Time of the Preceding Subpart Considered in the Current Subpart . .	29
5.6	Activities of a Preceding Subpart of the Tunnel Network Used in the Activity Network of the Current Subpart of the Tunnel Network . . .	29
5.7	Subparts in a Schematic Position-Time Plot	30
5.8	Overlap of two Subparts in a Schematic Position-Time Plot	31
5.9	Modeling of a Simultaneous Performance in the Simulation Model . .	31
5.10	Preceding Material Flows and Simulation Tasks of the Subparts of the Tunnel Network	32
5.11	Intermediate Repository Subdivided into Stocks	37

5.12	Activity Network Modeling the " <i>Excavation</i> " Subpart of the " <i>Construction Model</i> " for Mechanized Tunneling	39
5.13	Activity Network Modeling the " <i>Excavation with TEMH</i> " Subpart of the " <i>Construction Model</i> " for Mechanized Tunneling	40
5.14	Activity Network Modeling the " <i>Muck Transport</i> " Subpart of the " <i>Transportation Model</i> " for Mechanized Tunneling	43
5.15	Simulation of the Excavation Material Handling between the Intermediate Repository and the Final Usage in Two Tasks	44
5.16	Material Flows Related to Processing	45
5.17	Activity Network Modeling the " <i>Processing</i> " Subpart of the " <i>Recycling Model</i> " of Mechanized Tunneling	46
5.18	Simulation of the Handling of the Excavated Materials during the Processing by the Activity " <i>Processing</i> "	47
5.19	Activity Network Modeling the Reuse of Recycled Excavated Materials of Mechanized Tunneling in the Inner Liner	49
5.20	Activity Network Modeling the " <i>Excavation</i> " Subpart of the " <i>Construction Model</i> " for Conventional Tunneling	50
5.21	Activity Network Modeling the " <i>Excavation with TEMH</i> " Subpart of the " <i>Construction Model</i> " for Conventional Tunneling	51
5.22	The " <i>Travel Distance</i> " of the Excavated Materials	52
5.23	Activity Network Modeling the " <i>Transportation Model</i> " of Conventional Tunneling	54
5.24	Parts of the Activity Network Modeling the " <i>Transportation Model</i> " of Conventional Tunneling	56
5.25	Activity Network Modeling the " <i>Processing</i> " Subpart of Conventional Tunneling	57
5.26	Activity Network Modeling the Reuse of Recycled Excavated Materials of Conventional Tunneling in the Inner Liner	60
6.1	Project Overview (Bergmeister, 2007a)	62
6.2	BBT's Tunnelsystem (www.bbt-se.com)	63
6.3	Main Tunnel Tubes' and Service Gallery's Standard Cross Sections (www.bbt-se.com)	64
6.4	Contract Sections of the Austrian Part of the BBT (Technical Report D0118-02369)	64
6.5	Current and Finished Tunnel Drives (www.bbt-se.com)	66
6.6	Lateral Adit Wolf, Mucking Tunnel Padastertal, Final Repository Padastertal (Technical Report D0118-02916-10)	67
6.7	Geological Longitudinal Section 01 of the Austrian Part of the East Tube of the BBT (Technical Report D0154-00031)	68
6.8	Geological Longitudinal Section 02 of the Austrian Part of the East Tube of the BBT (Technical Report D0154-00031)	69

6.9	Geological Longitudinal Section 03 of the Austrian Part of the East Tube of the BBT (Technical Report D0154-00031)	70
6.10	Final Repositories Along the Austrian Part of the BBT (Bergmeister, 2010)	75
6.11	Contract Section Wolf (Technical Report D0118-02916-10)	76
6.12	Tunneling Methods of Contract Section Wolf: Red Tunnels Are Constructed by Mechanized Means, Blue Tunnels Are Constructed Conventionally, Arrowheads Show the Direction of the Tunnel Advance (Technical Report D0118-02369)	77
6.13	Break-Through of Contract Section Ahrental to Contract Section Wolf (Technical Report D0118-02369)	79
7.1	Simulation Area (bold rectangle) of Contract Section Wolf	82
7.2	Ground Class Determination of the Geotechnically Homogeneous Zone N30	86
7.3	Triangular Probability Density Function of a Ground Class Length	88
7.4	Probabilistic Ground Class Length Determination	89
7.5	Area Input Window	90
7.6	Zone Input Window with End Point Definition	91
7.7	Ground Classes Input Window	91
7.8	Ground Parameter Input Window	92
7.9	Simulated Ground Class Profile for the Simulation Area	93
7.10	Tunnel Network of the Simulation Area	94
7.11	Tunnel Information Window	95
7.12	Backcalculation of the Duration of an Activity Based on the Back-calculated or Assumed Advance Rate of the Corresponding Tunneling Class	98
7.13	Estimate of the Durations of Additional Activities in Subsequent Activity Networks	98
7.14	Method Definition Window, Deterministic Definition of the Construction Method	99
7.15	Construction Method Input Window	100
7.16	Activity Network Input Window	100
7.17	Activities Input Window	102
7.18	Resources Input Window	103
7.19	Repositories Input Window	104
7.20	Repository Assigned to a Tunnel in the Tunnel Information Window	104
7.21	Schematic Time-Volume Plot of Simulation Technique I	105
7.22	Schematic Time-Volume Plot of Simulation Technique II	106
7.23	Inner Liner Activity Input Window of Simulation Technique I	107
7.24	Inner Liner Activity Input Window of Simulation Technique II	107

8.1	Time-Volume Plot of One Simulation Run of Simulation Technique I .	110
8.2	Concrete Aggregate Production (P) and Concrete Aggregate Consumption (C), One Simulation Run, Simulation Technique I	111
8.3	Multi Graph Time-Volume Plot of Simulation Technique I	114
8.4	Concrete Aggregate Production (P) and Concrete Aggregate Consumption (C), Multiple Simulations (100 Simulation Runs), Simulation Technique I	115
8.5	Time-Volume Scattergram of the Produced Concrete Aggregates of the "Drill&Blast West Tube"	116
8.6	Time-Volume Scattergram of the Produced Concrete Aggregates of the "Drill&Blast East Tube"	117
8.7	Time-Volume Scattergram of the Produced Concrete Aggregates of the "Drill&Blast East Tube" (▼) and "Drill&Blast West Tube" (■) Including Standard Statistics such as the Normal Approximation on Time (red curve) and Volume (green curve) of the Cloud of Points, the Linear Regression (blue curve) of the Cloud of Points, and Histograms of the Time (vertical bars) and Volume (horizontal bars)	117
8.8	Position-Time Plot of One Simulation Run of Simulation Technique I	119
8.9	Position-Time Plot of the Mechanized Tunnel Drifts of One Simulation Run of Simulation Technique I	120
8.10	Position-Time Plot of the Drill and Blast Tunnel Drifts of One Simulation Run of Simulation Technique I	122
8.11	Detail Position-Time Plot of the Drill and Blast Tunnel Drifts of One Simulation Run of Simulation Technique I	122
8.12	Position-Time Plot of the Inner Liner Construction of One Simulation Run of Simulation Technique I	123
8.13	Produced Concrete Aggregates Reduced due to the Consumption of Concrete Aggregates of the Inner Liner, One Simulation Run, Simulation Technique II	124
8.14	Error Message due to a Lack of Resources	124
8.15	Produced Concrete Aggregates Reduced due to the Consumption of Concrete Aggregates of the Inner Liner, 100 Simulation Runs, Simulation Technique II	125
8.16	Position-Time Plot of the Inner Liner Construction of One Simulation Run of Simulation Technique II	126
8.17	Concrete Aggregate Production (P) and Concrete Aggregate Consumption (C) of the Additional Simulation	127
8.18	Time-Volume Scattergram of the Additional Simulation, Produced Concrete Aggregates of the "Drill&Blast East Tube" (▼) and "Drill&Blast West Tube" (■)	129

LIST OF TABLES

3.1	Main Uncertainties Affecting the TEMH Based on a Questionnaire which Was Answered by Experts	15
5.1	Simulation Tasks of the Components of the Simulation Model	27
5.2	Types of "Reused" Activities in the Simulation Model	35
6.1	Classification of the Predicted Lithologies in Four Lithology Classes (Technical Report D0118-04340)	72
6.2	Percentage of the Usage Classes within each Lithology Class (Technical Report D0118-04340)	73
6.3	Volumes of Excavation Material Usage Classes Compared to Concrete Aggregate Need	74
7.1	Prediction of Tunneling Classes within the Geotechnically Homogeneous Zone N30	84
7.2	Assumed Percentage of the Assumed Conventional Tunneling Classes within each Geotechnically Homogeneous Zone	85
7.3	Prediction of Excavation Material Usage Classes within the Geotechnically Homogeneous Zone N30	85
7.4	Range of Values for the Ground Class Lengths	88
7.5	Assumed Cross Sectional Area and Assumed Shotcrete/Concrete Consumption of the Initial- and Final Support	96
7.6	Advance Rates of the Tunneling Classes and the Lining	97
8.1	Consumed and Produced Volumes of Concrete Aggregates of a Simulation Run of Simulation Technique I	113
8.2	Produced Concrete Aggregates Influenced by Geologic Uncertainty	115
8.3	Changes of the Variables "processing_success_factor" and "processing_time" in the Additional Simulation	127
8.4	Produced Concrete Aggregates Influenced by Geologic Uncertainty, Additional Simulation	128

9.1 End Positions of the Ground Classes 142