

Research Report

TUNNEL EXCAVATION MATERIAL HANDLING USING DECISION ANALYSIS

by

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PREAMBLE

Sustainable planning of tunnel excavation materials handling is a necessity to save mineral resources, avoid waste deposits and possibly save energy. However, this planning process is complicated and affected by many uncertainties. This report describes how decision analysis can be used to deal with this. An introduction of the basics of decision analysis is followed by a brief overview of the tunnel excavation materials handling. In particular, this report presents a simulation model which uses the Decision Aids for Tunneling (DAT) and its resources part to describe and evaluate uncertainties affecting tunnel excavation materials handling. Emphasis of the simulation concept is placed on representing the activities of the tunnel materials handling process starting with excavation and ending with the reuse or final deposition of the material. An application of the simulation model to a tunnel project concludes this report and shows the suitability for decision-making.

This research will be summarized in a Master of Science Thesis at the University of Leoben. The Thesis is currently in progress and will be written by this author. In addition to this report, further investigations using the developed simulation model will be included in the Thesis.

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Chapter 1

DECISION ANALYSIS

Before applying decision analysis to Tunnel Excavation Material Handling (TEMH) it is necessary to introduce some basic notions and give a brief overview of decision analysis. In particular, the decision analysis cycle and the practical application of the decision analysis process in geotechnical engineering is discussed.

1.1 UNCERTAINTY

1.1.1 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 situation. 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.) seem unsupportable, they are widespread (Christian, 2004). Various agencies and corporations make their decisions without considering associated uncertainties (Christian, 2004). Being conservative (2.) takes

the expenses of the determined uncertainties into account which 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, in particular, 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.

1.1.2 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). These report uses the classification proposed by Einstein and Baecher (1983):

- **Type 1:** Innate 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 variable; in contrast, the epistemic uncertainty represents a lack of knowledge and is in the literature also known as ambiguity uncertainty (Paté-Cornell, 1996). Further definitions of 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, 2009). For example, following Einstein (2009), the distribution of joint (fracture) orientation which is an innate spatial variability (Type 1) has an aleatory- and epistemic component. The aleatory component is the randomness of sampled variables. 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.

1.2 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 of 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.

1.2.1 DEFINITIONS

Before explaining the principles of decision analysis, centering 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.

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 (Howard, 1966). Therefore, a decision is to pursue a course of action, and not a mental commitment to follow a course of action (Howard, 1966).

A good decision follows a logic framework of information, values, and preferences of the decision maker (Howard, 1966). In contrast, a good outcome is characterized through a high value of interest (i.e., profit) for the decision maker. Thus, a good outcome is one that is desired. To ensure good outcomes 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 (Howard, 1966).

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 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 neglect it.

1.2.2 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 1.1. "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 logic 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 1.1 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.

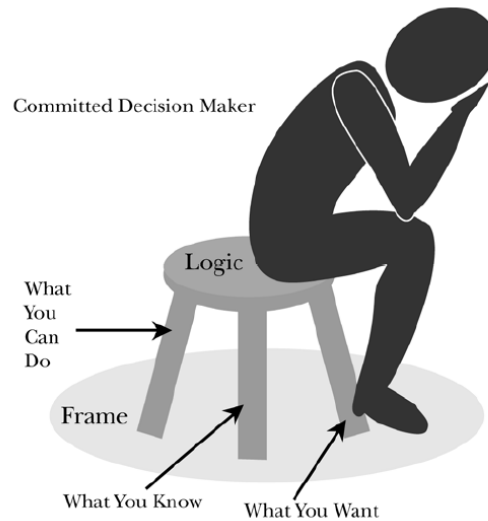


Figure 1.1: Representation of the Formal Aspects of a Decision Analysis (Howard, 2010b)

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) quotes 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.

1.2.3 DECISION ANALYSIS IN PRACTICE

The application of the decision making process is generally described through a decision analysis cycle. Figure 1.2 graphically represents the decision analysis process similar to that proposed by Howard (2010a), 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). A brief description of the main elements of this cycle, based on Howard (1966, 2010a) and Einstein (2009), is given below. Emphasis of this research is placed on the probabilistic model phase.

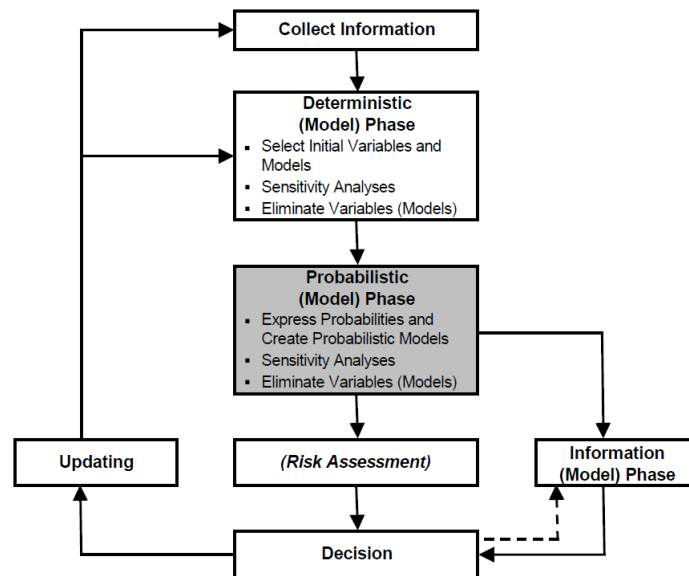


Figure 1.2: Decision Analysis Cycle (Source of Information: Einstein and Sousa (2006); Einstein (2009))

Information collection in geotechnical engineering is mainly based on the geologic/geotechnical investigations and the construction schedule of the planned construction. In addition, the collected information (for example, joints in intact rock) has to be described which can be 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 variables ¹ are included in a deterministic

¹Spetzler and Staël Von Holstein (1975) discusses the difference between state- and decision

engineering model which is suitable to model the decision problem. Deterministic models and probabilistic models in geotechnics can be, referring to Einstein (2009):

- **Performance Models**

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

- **Economic Models**

- Cost (e.g., project 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, 2009). Sensitivity Analysis of the deterministic (model) phase are, in general, performed by holding all but one variable constant. Hence, a sensitivity analysis allows on 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 and unsuitable models for the decision problem can be eliminated.

The difference between the probabilistic (model) phase in comparison to the deterministic (model) phase is that the uncertain parameters (variables) are assigned probabilities. Obtaining these probabilities is called uncertainty- or probability encoding and extensively discussed by 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). The Decision Aids for Tunneling (DAT) are a probabilistic model with mostly economic characteristics (Einstein, 2009) and used in this research.

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

$$Risk = P[U] \cdot Worth\ of\ Loss \quad (1.1)$$

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 make decisions based on the outcomes of the probabilistic (model) phase and

variables in detail.

thus it is not necessary to assign risk to the decision problem (Einstein, 2009). Other definitions of risk are discussed in Einstein (1996, 2009).

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, 2009). However, one likes to find out if gathering new information is beneficial which is the task of the information (model) phase. 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 informational 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 through again. Accordingly, the decision making process is adaptive and always based on the current state of knowledge. The decision to act is achieved if gathering new information or further analysis is unprofitable.

1.2.4 MODEL SEQUENCE

This section presents the different steps of progress of the model of the decision problem, following Howard (Howard, 2010b). In general, the model (e.g., performance- or economic model) is developed using computer programs (i.e., Decision Aids for Tunneling (DAT)). Figure 1.3 illustrates the model sequence.

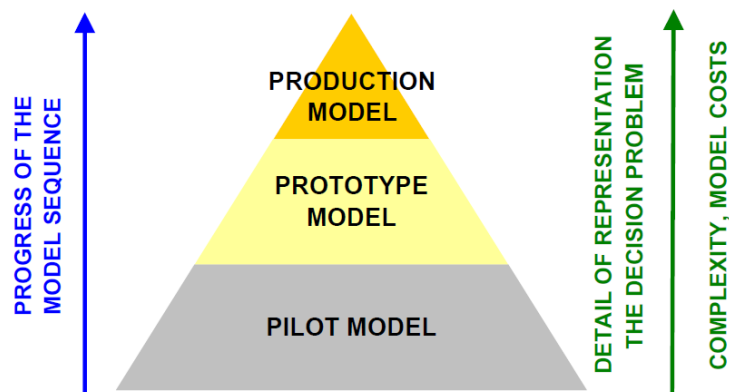


Figure 1.3: Model Sequence of a Decision Analysis (Source of Information: Howard (2010b))

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 details. 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 2

TUNNEL EXCAVATION MATERIAL HANDLING (TEMH)

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.

2.1 NEED FOR TEMH

During the construction of tunnel projects large quantities of excavation material are created. For instance, it is predicted that during the construction of the Brenner Base Tunnel, described in Chapter 5, roughly 15.5 mill. cubic meters of excavation materials in the compacted state will accrue (Bergmeister, 2010). Most of the excavated material of tunnel projects have so far been used for backfilling or tipped (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) made 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. Reuse tunnel excavation material, which is a part of the TEMH, is such a sustainable development which saves non-renewable resources, avoid waste deposit, limit nuisance of the population in the vicinity of the construction site, and possible save energy due to limited transportation. Common possibilities to reuse excavated material are using them as fill material, for instance, for embankments, and as concrete

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

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

Reuse of the excavated material can have also an economic potential; cut of transportation- and storage costs, a possible low cost preparation or purchase by the mineral processing industry can optimal the cost:benefit ratio for the project (Gertsch et al., 2000; Kruse, 2002). However, extra costs such as, for instance, the set up and operation of the recycling of the excavated material have to be considered in this cost:benefit ratio (Resch et al., 2009). Hence, muck, which is the term for excavated material which can or cannot be reused, should be planned as a resource from the beginning of tunnel design and not treated like waste (Gertsch et al., 2000).

2.2 PRINCIPLES OF THE TEMH

For the first time on a large scale, the Lötschberg Base Tunnel and the Gotthard Base Tunnel have demonstrated a practicable reuse of tunnel excavation material for concrete aggregate (Resch et al., 2009). Based on the TEMH of these tunnel projects the material flow scheme in the TEMH process with the corresponding investigations of the excavated material is described. Figure 2.1 schematically illustrates a general material flows scheme in the TEMH process.

The TEMH starts with the production of the excavated material due to the 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 their 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 as well as the geologist's assessment. Based on this "*Preliminary Material Classification*" the excavated materials are assigned excavation material classes. Examples of excavation material classes, based on Harer and Pichler (2009), are described below. These excavation material classes consider the main aims and cornerstones of the TEMH of the particular tunnel project; thus, the excavation material classes can change from project to project. It is important to note that the following characterization denotes only reusable excavated material with the term material classes. In contrast, excavated material which has to be tipped or required "*special material*"

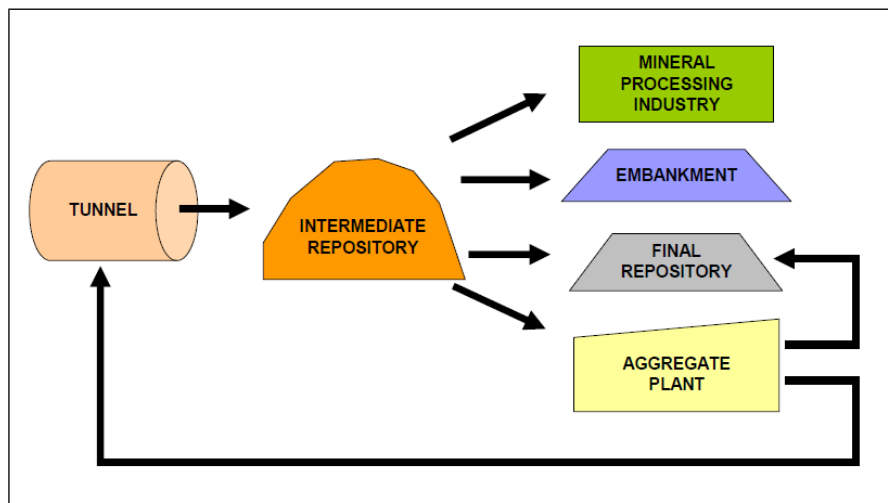


Figure 2.1: Materials Flow Scheme of the Excavated Material in the TEMH Process

which has to be purchased from regional suppliers are not assigned a so-called material class. However, these materials have to be considered because they are content of the materials management of the particular tunnel project.

- **Material Class 1:** Suitable excavated material to be recycled for graded stone and frost protection material.
- **Material Class 2:** Suitable excavated material to be recycled for the construction of load-bearing embankments and soil exchange.
- **Material Class 3:** Suitable excavated material to be recycled for the construction of noise protection embankments and terrain modeling.
- **Material Class 4:** Constructionally unsuitable excavated material to be used for filling, recultivation or tipping.
- Excavation material, which has to be disposed such as contaminated ground or formerly tipped materials, which requires treatment or secure tipping due to its composition.
- Required "*special material*", for example, for waterproofing layers, rip-rap or drywall masonry.

After this "*Preliminary Material Classification*" the excavated material classes are separately transported to the intermediate repository using muck cars 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. During this temporary storage additional investigations on the excavated material are performed to define their quality in detail. This "*Final Material Classification*"

consist, 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 material is transported to their final usage such as reusing as fill materials for embankments, purchasing by the mineral processing industry, and tipping at the final repository. At the aggregate plant the excavated material becomes aggregate of different sizes and will be reused in the shotcrete- or concrete works of the construction site.

As mentioned before, the tunneling method affects the production of the excavated material. Specifically, the production of excavated materials with hard rock TBM's, which are generally outfitted with disc cutters, influence the shape of the excavated material. In general, excavated material of TBM's from hard rock is a well-graded material containing large, flat, elongated chips with relatively few fines (Gertsch et al., 2000). However, research showed that qualified TBM muck can become aggregate for high value shotcrete or concrete if the right disc cutter spacing and suitable processing is used (Thalman, 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 (Thalman, 1996).

2.3 UNCERTAINTY AFFECTING TEMH

As discussed in Section 1.1.1, tunneling is characterized by the influence of uncertainties. These uncertainties can be structured in geologic uncertainties and construction uncertainties. Construction uncertainties are independent of the geology and for example operational variation in drill penetration (Einstein, 2004). The quality of the excavated materials such as, for example, mechanical properties depends on the encountered geology. In contrast, the time of the excavation material production can be affected by the operational variation of the tunnel advance or delays due to mishaps. Uncertainties of the processing of the excavated material can also be independent of the geology and assigned the construction uncertainties. Taken together, the production of the excavated material and their further material flows are affected by geologic- and construction uncertainties. Figure 2.2 graphically represents these main types of uncertainty affecting the TEMH process.

The particular uncertainties which affect the TEMH need to be determined. In this research, interviews with experts of the TEMH have been performed to estimate these uncertainties. Table 2.1 represents the results of these interviews by showing the five uncertainties which strongly influence the TEMH.

In addition literature research of publications, which summarize the experience of

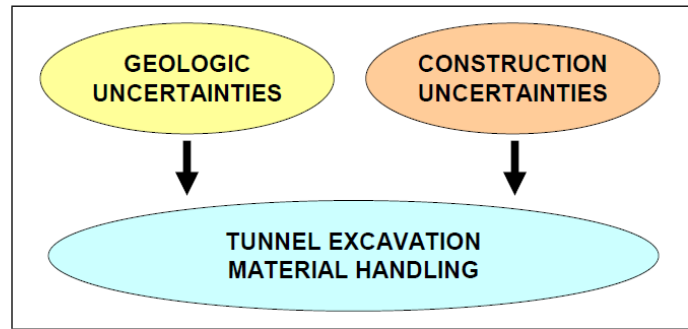


Figure 2.2: Geologic- and Construction Uncertainties affecting the TEMH

Table 2.1: Main Uncertainties Affecting the TEMH

Ranking	Uncertainty Description
1	Concept of the Excavation Materials Processing (<i>e.g., Material Flows, Processing Aggregates, etc.</i>)
2	Occurrence of Discontinuities in the Geology
3	Dislocation of Contract Section Boundaries
4	Chemical Components of the Excavated Material
5	Grading Size Curves of the Excavated Material

the materials management of recently constructed tunnel projects, determined other aspects which affect the TEMH. Lieb (2009) quoted in his paper that one of the most considerable challenges in the TEMH is the control of the excavation material production and the aggregates requirement. The essential factors of this challenge are the suitability of the excavated materials for recycling, which depends on the properties of the encountered geology, and the time gap between material production and requirement which varies due to changes of the planned construction schedule. Burger et al. (2010) noted that the movement of the breakthrough point in contrast to the planned location affects the management of the excavated material.

These examples show that the planning of the TEMH is not only affected due to the uncertainties of the TEMH process; the entire tunnel construction with their associated uncertainties has to be considered in a simulation model.

Chapter 3

THE DECISION AIDS FOR TUNNELING (DAT)

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 part of the DAT is introduced.

3.1 DESCRIPTION OF THE DAT

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 informations 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 off two major components (Figure 3.1):

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

A somewhat different way of describing the structure of the DAT is to define four components (modules): Geology module, Construction module, Resource module, and Updating module (Moret et al., 2009; Einstein, 2009).² The subdivision of the DAT into two components, shown in Figure 3.1, incorporates the Resource module and the Updating module in the Construction Simulation and Construction Management component. This build-up into two components depicts the data structure of the DAT; thus, it is used throughout this research.

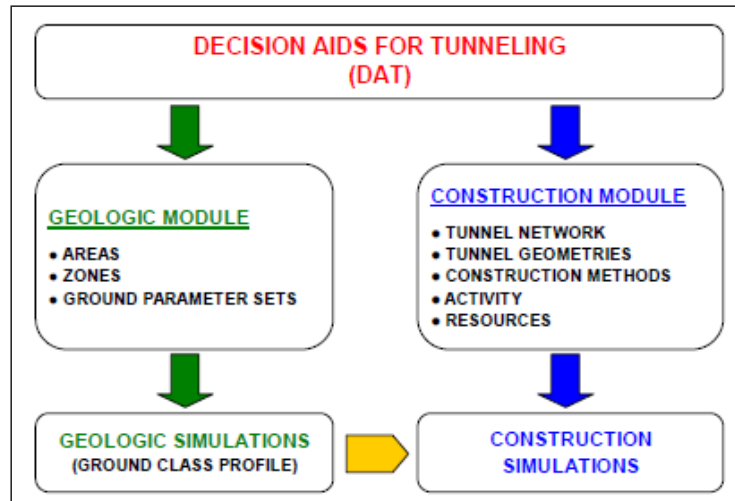


Figure 3.1: Major Components of the DAT (Min, 2008)

3.1.1 DESCRIPTION OF GEOLOGY (GEOLOGIC MODULE)

The Description of Geology 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 3.2 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.

3.1.2 CONSTRUCTION SIMULATION AND CONSTRUCTION MANAGEMENT (CONSTRUCTION MODULE)

The construction process through the "Ground Class" profile, obtained from the Geologic module, is simulated with the Construction Simulation and Construction

²Question regarding the following Paper: Treatment of Risks in Rock Engineering: Year of Publication?, Journal?, etc.

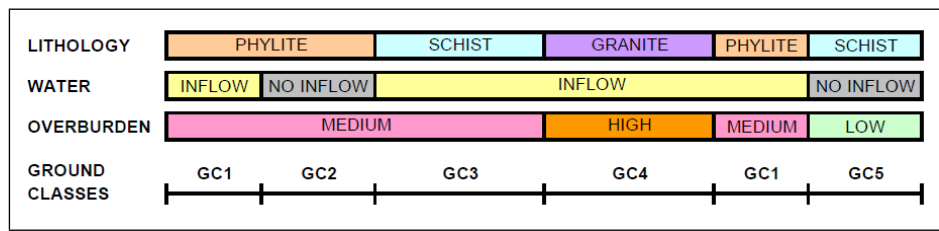


Figure 3.2: "Ground Class" Profile (Note that the same parameter states lead to the same "Ground Class", for example, "GC1".)

Management component. 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 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 due to one "Activity". For instance, one "Activity" models the entire construction cycle of Drill & Blast. A more detailed approach, describes the "Construction Method" with a series of "Activities" to express all steps (for example, drilling, loading, blasting, mucking, bolting, etc.) of each cycle of the construction performance. Hence, one cycle is simulated with an "Activity Network" which consists of one or more "Activities". Figure 3.3 schematically illustrates the relationship of the different components of the Construction module.

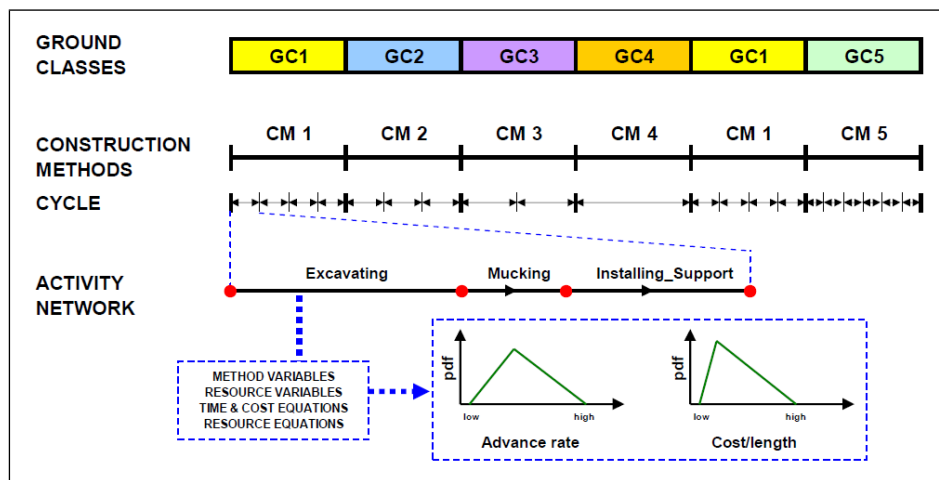


Figure 3.3: Construction Simulation

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 3.3 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. 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.

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 due to resource variables and 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 Description of Geology. Accordingly, this "Ground Class" profile is related to the corresponding "Construction Method" profile. Then the construction simulation performs cycle by cycle 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 3.4 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.

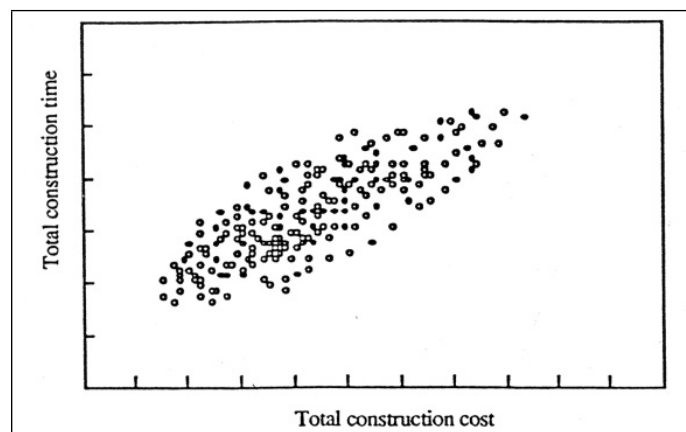


Figure 3.4: Time-Cost-Scattergram (Einstein, 2001)

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 3.5 represents a simple "Tunnel Network". A so called "Dummy" tunnel is an imaginary tunnel which is necessary to model the tunnel construction sequence correctly.

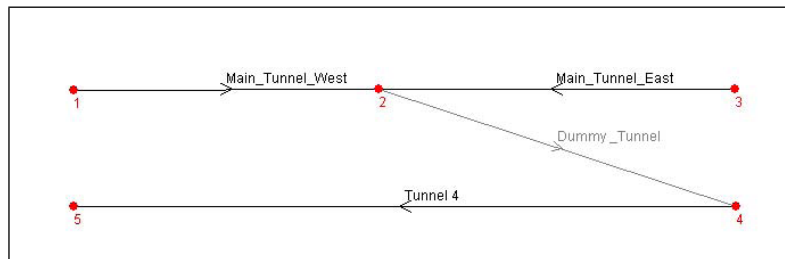


Figure 3.5: "Tunnel Network" (Min et al., 2009)

3.2 RESOURCES IN THE DAT

Currently the fourth resource model is used to model resources in the DAT. The first models were developed by Halabe (1995) and Marzer (2002). Kollarou (2002) applied the resource model with the interface MBK³ based on Marzer (2002) to simulate the excavation materials handling in the Löttschberg Base Tunnel. This research is summarized in Einstein (2001). Min (2008) enhanced the previous resource models.

3.2.1 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 model 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 measures, results in an idle time and, thus, leads to an interruption of the construction process.

The resource model of the DAT enable 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 spec-

³MBK is the abbreviation of the German word "*Materialbewirtschaftungskonzept*", which means Materials Management Concept.

ified 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 where the tunnel draws resources from or deposits into. Each resource is allocated to a specific part of the "*Repository*". These specific parts of a "*Repository*" 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 4

SIMULATION MODEL

The relationship among input variables and outcomes can be organized in a simulation model, which is developed using the DAT⁴. Referring to the discussed model sequence of Subsection 1.2.4, the developed 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 is, for instance, to include specific characteristics of a tunnel project.

In the following, the developed simulation model, which can be described as an economic (resource) model, is explained. This explanation is subdivided to the corresponding main components of the DAT, the Geology module and the Construction module. Specifically, the Construction module treats the material flows in the TEMH process. Figure 4.1 shows the material flows with related "Actions" in the TEMH process. In addition, the general appliance of the simulation model to common tunneling methods such as mechanized- and conventional tunneling is discussed.

4.1 THE GEOLOGY MODULE

Emphasis of this Section is placed on the implementation of the excavation materials classification in the Geology module. Figure 4.2 represents the general build-up 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, explorations and investigations regarding the excavation materials properties are included ("Muck Classes"). Therefore, each preliminary "Ground Class", for example "GC1", is extended with the predicted excavation materials classes. This procedure ensures that each final "Ground Class", for example "GC1.A", consists of a particular excavation materials

⁴Chapter 3 discusses the principles of the DAT. The SIMJAVA User's Manual (Min et al., 2009) is recommended for further studies.

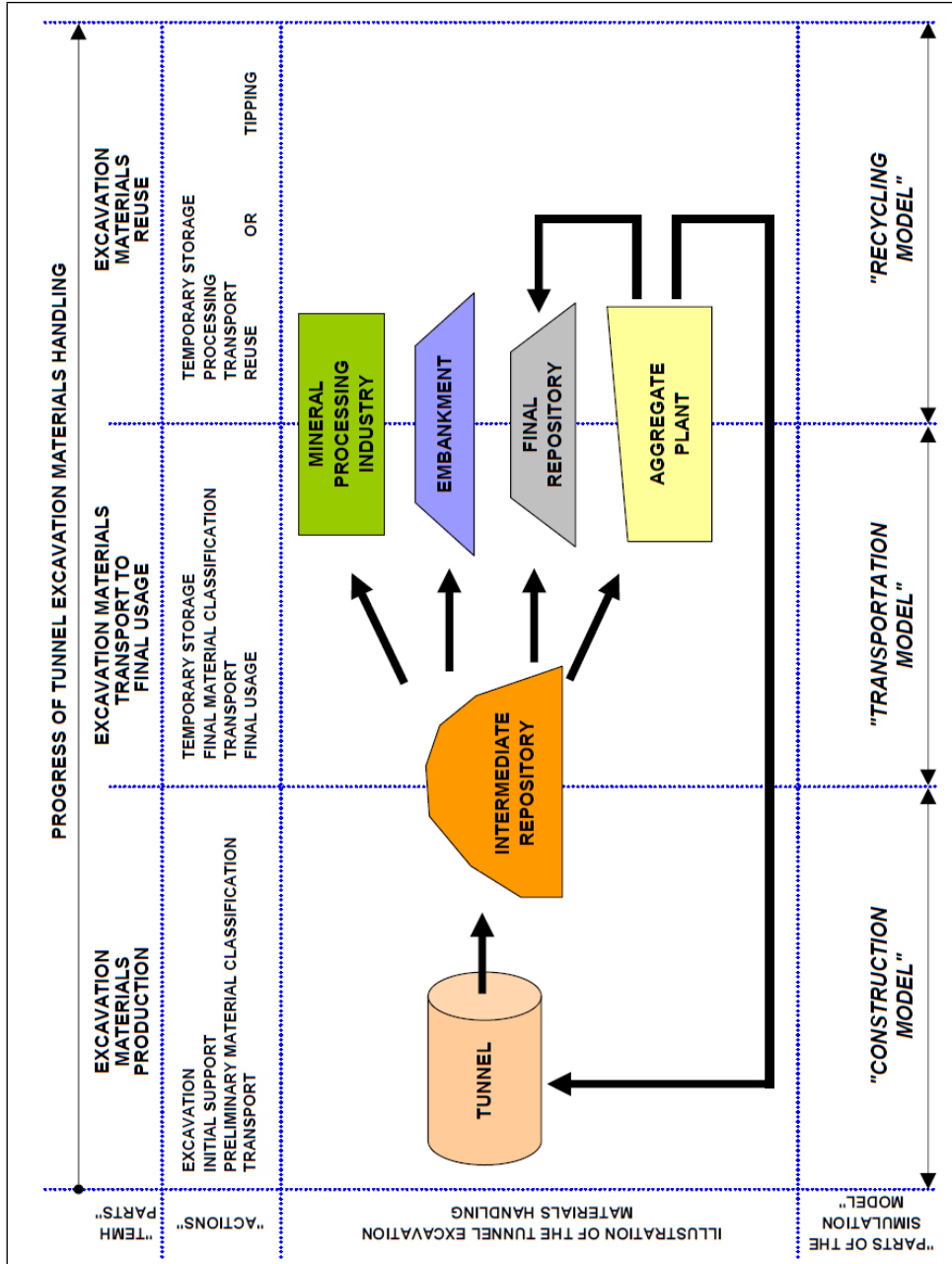


Figure 4.1: Material Flows in the TEMH Process

class. Hence, the Geology module in the simulation model guarantees 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 formulated excavation materials classes. In reality, the *"Preliminary Material Classification"* is based on a correlation of the geologic exploration, laboratory testing during the exploration- and design phase, and the engineering geologist's estimation of the excavated materials at the tunnel face.

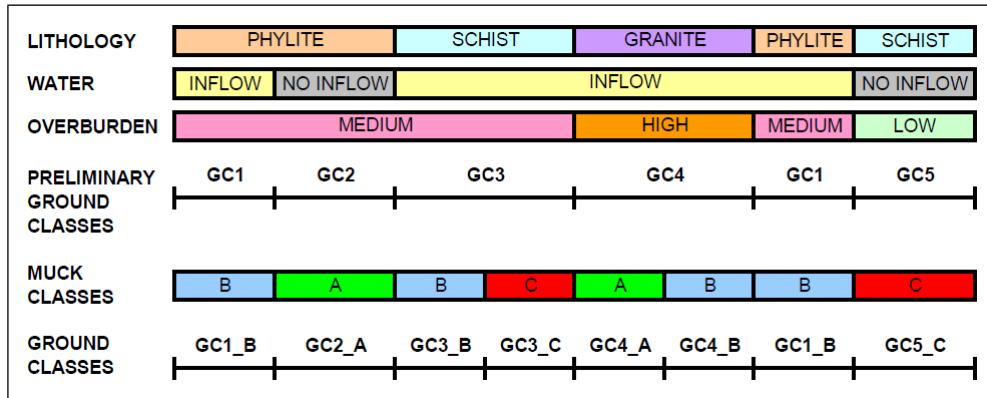


Figure 4.2: *"Ground Class" profile with Implementation of the "Preliminary Material Classification" ("Muck Classes")*

It is important to remember that the DAT allows 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.

4.2 THE CONSTRUCTION MODULE

The Construction module of the simulation model simulates the construction process through the *"Ground Class" profile* with the related TEMH. This involves relating the *"Ground Classes"* to corresponding *"Construction Methods"*. Figure 4.3 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 for the corresponding *"Ground Class"* as well as the amount of the excavated materials class.

Figure 4.4 illustrates the structure of the standard *"Tunnel Network"*⁵ of the developed simulation model. This *"Tunnel Network"* models the tunnel construction

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 tunnels which are necessary to perform the simulations.

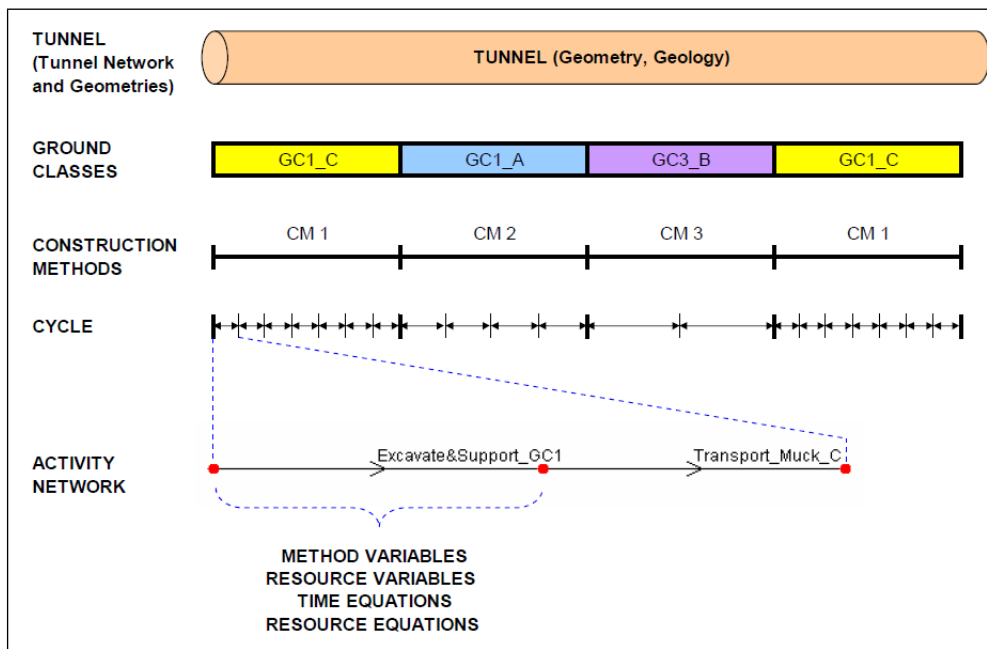


Figure 4.3: Relationship between Tunnel Geometry, Geologies, Construction Methods, Activities, and Time/Resource Equations in the Simulation Model

performance as well as the related TEMH of a particular tunnel, starting with excavation and ending with the reuse or final deposition of the material. 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 performs for each simulation. Further, "Construction Methods" are assigned to each part of the simulation model. Figure 4.1 shows which part of the "Tunnel Network" of the simulation model treats which part of the TEMH process. Table 4.1 summarizes these relations and shows which parts with the corresponding subparts, such as the "Excavation", "Excavation with TEMH", "Muck Transport", "Processing", and "Inner Liner" treat which resources.

The subparts of the "Tunnel Network" such as the "Excavation", "Excavation with TEMH", "Muck Transport", and "Processing" start at the same time of the simulation model. In contrast, the construction of the inner liner ("Inner Liner") starts a certain time after the starting of the tunnel construction ("Excavation"). Therefore, in the "Tunnel Network" the "Inner Liner" subpart is related with a "Dummy Tunnel" to the "Start Node" of the "Excavation" subpart (Figure 4.4). To model the duration between the start of the "Excavation" and the start of "Inner Liner" the DAT allows the user to define a "Time Delay"⁶ between the start of the "Excavation" and the "Inner Liner".

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

Table 4.1: Simulation Tasks of the Parts of the Simulation Model

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

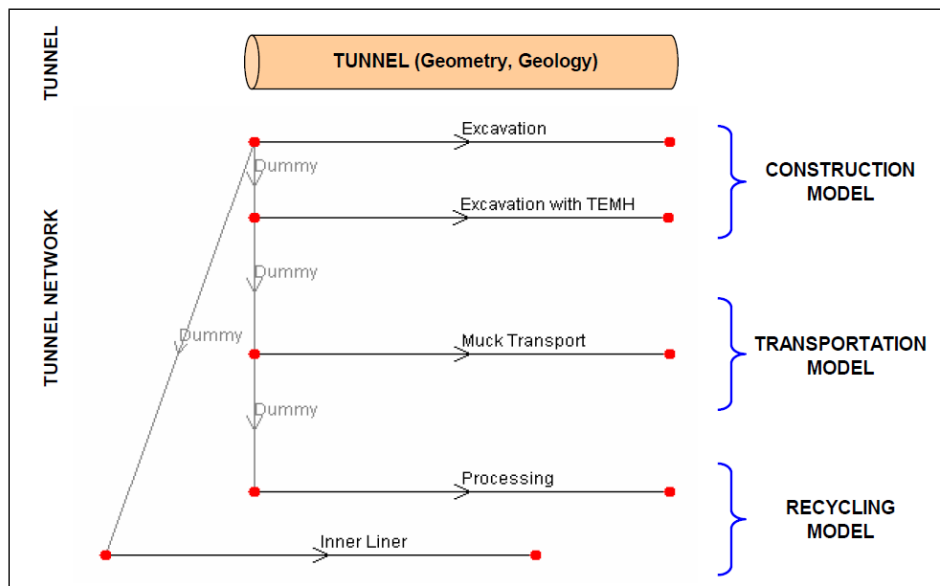


Figure 4.4: Structure of the "Tunnel Network" of the Simulation Model

It is important to note that each part of the "Tunnel Network" of the simulation model treats only the resources which are related to the simulation tasks of this particular part. For instance, the "Recycling Model" deals only with the excavated materials which are related to the final usage and the reuse of the recycled excavation materials. In contrast, the excavation materials which are related to the intermediate repository are treated in the "Construction Model" and "Transportation Model" because these material flows in the TEMH are only previous material flows of the "Recycling Model". Figure 4.5 schematically illustrates this procedure. However, the time of the previous material flows in the TEMH process has to be considered in the subsequent parts and subparts of the simulation model to simulate the progress of the TEMH accurately. For this reason, "Activities", which are used to simulate only the time of the previous material flows, are specified with the appendix "_noRes" to demonstrate that these "Activities" are not assigned excavation materials.

The Subsections 4.2.1 to 4.2.3 briefly discuss the parts of "Tunnel Network" of the simulation model, followed by an explanation of the tasks of the resources part of the DAT in the simulation model.

4.2.1 CONSTRUCTION MODEL

The "Construction Model" consists of two subparts; the "Excavation" and the "Excavation with TEMH". Both subparts perform for each simulation. The "Excavation" subpart treats the activities of the tunnel construction performance 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

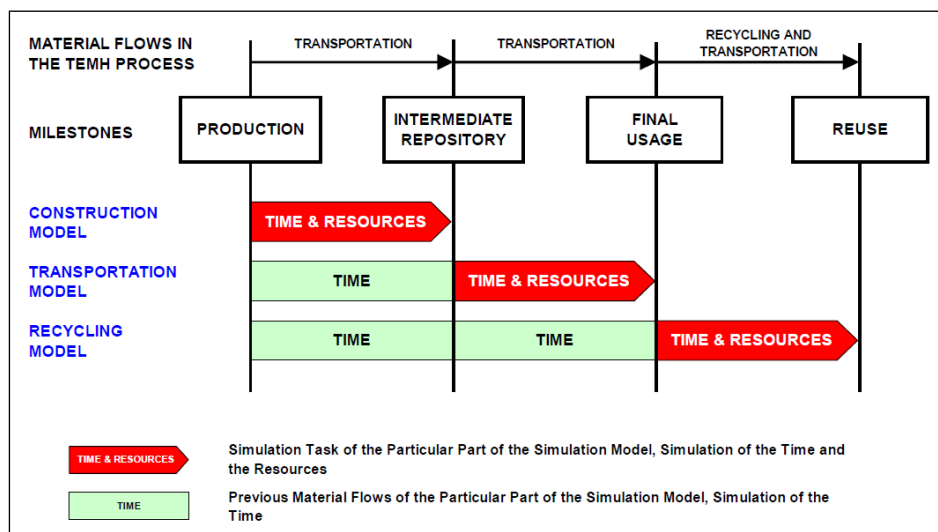


Figure 4.5: Previous Material Flows and Simulation Tasks of the Parts of the Simulation Model

with TEMH" simulates the construction of the particular tunnel and, in addition, the production of the excavated materials, the "Preliminary Material Classification" of the excavated materials, the transport of the excavated materials to the intermediate repository, and a possible reuse of the recycled excavation materials as 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.

4.2.2 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. The "Final Material Classification" 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 previous material flows of the excavated materials. However, the "*Transportation Model*" does not include the production of the excavated materials and their transport to the intermediate repository, which are the simulation tasks of the "*Construction Model*".

4.2.3 RECYCLING MODEL

The "*Recycling Model*" consist of two subparts; the "*Processing*" and the "*Inner Liner*", which perform in each simulation. Processing of suitable excavated material classes to recycled excavation materials such as, for instance, concrete aggregate is simulated with the "*Processing*" subpart of the "*Recycling Model*". Again, the "*Processing*" considers only the time and not the resource production or usage of the previous material flows of the excavated materials. Reusing the recycled excavation materials is modeled with the "*Inner Liner*" subpart, which reuses the recycled excavation materials, for instance, in the concrete of the inner liner. As explained before the "*Inner Liner*" starts a certain time after the other subparts of the "*Tunnel Network*" of the simulation model; thus, the "*Inner Liner*" does not consider the time of the previous material flows.

4.2.4 RESOURCES IN THE SIMULATION MODEL

The resources part of the Construction module of the DAT, shown in Figure 3.1, is extensively used in the developed simulation model to simulate the material flows in the TEMH. Therefore, it has to be defined 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, and the recycled excavation materials. The classification of the excavated materials is, in general, based on their reuse properties and was discussed in Chapter 2. Furthermore, for each "*Activity*" one has to define what resources are used or produced. Resource equations are used to specify the amount of these resources used or produced due to a specific "*Activity*". Time equations compute the required time of this "*Activity*". Subsequently, a "*Repository*" for the entire simulation model is created where the "*Tunnels*" draw resources from or deposit into. This "*Repository*" covers the entire TEMH process (Figure 4.1) because the DAT enables 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 class A; in contrast, "*Final_Rep_Muck_C*" denotes the part of the final repository where the excavation materials class C is tipped. This procedure allows one to incorporate the location of the particular repository within the TEMH process. Figure 4.6

shows a possible subdivision of the intermediate repository into as many "Stocks" as excavation materials classes are defined.

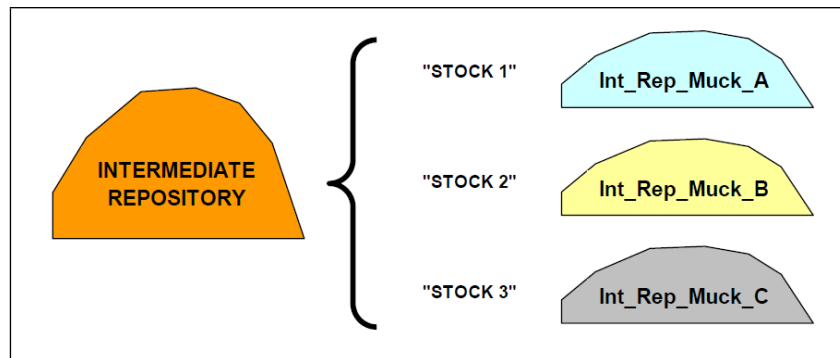


Figure 4.6: Intermediate Repository Subdivided into "Stocks"

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 model because they enable one to incorporate the specific capacity of each repository of the TEMH process in the simulation model.

As mentioned in the Description of Geology (Section 4.1) the DAT enables one to consider geologic uncertainties in the simulations. In addition, the Construction module of the DAT allows to incorporate construction uncertainties which are independent of the geology. In particular, construction uncertainties which affect the TEMH can be considered. These uncertainties are, for example, modeled as probability distributions and assigned to variables of the time equations and resource equations.

At this point the structure of the developed simulation model is explained. However, the TEMH is affected by the tunneling method. Specifically, the cyclic operation of tunneling has to be considered Min (2008). This cyclic operations yields a cyclic production and a cyclic transportation of the excavated materials. For example, a muck car is repetitively used to transport the excavated materials from the tunnel face to the intermediate repository at the tunnel portal. Hence, Section 4.3 and 4.4 apply the simulation model to common tunneling methods such as mechanized- and conventional tunneling. Emphasis is placed on the "Activity Networks" of the sub-parts of the "Tunnel Network" of the simulation model. 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 4.3 shows one example of how "Activities" are labeled if they are related to their corresponding "Ground Class".

4.3 MODELING MECHANIZED TUNNELING

To model the TEMH process of mechanized tunneling, each part and subpart of the "Tunnel Network" of the simulation model (Figure 4.4) has to perform. The following Subsections explain each part for mechanized tunneling.

4.3.1 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. The "Excavation with TEMH" treats the construction of the same tunnel and, in addition, the handling of the excavated materials between the tunnel face and the intermediate repository.

Figure 4.7 illustrates the general "Activity Network" of the "Excavation" part of the "Construction Model" for mechanized tunneling, which is repeated for each cycle of the construction process. The "Activity" "Excavate&Support" treats the excavation of the tunnel as well as the initial support. The maintenance on the tunnel boring machine (TBM) is simulated through the "Activity" "Maintenance".



Figure 4.7: "Activity Network" Modeling the "Excavation" subpart of the "Construction Model" for Mechanized Tunneling

Figure 4.8 shows the "Activity Network" of the "Excavation with TEMH" part of the "Construction Model". In addition to the "Excavation" part of the "Construction Model" the TEMH is considered. Therefore, the "Activity" "Transport_Muck" deals with the transportation of the excavated materials from the cutter head of the tunnel boring machine to the intermediate repository using a conveyor. 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 and muck transportation with a conveyor to the intermediate repository is considered. In addition, 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. Hence, the tunnel advance depends on both the "Activity" "Excavate&Support" and the "Activity" "Transport_Muck". This interdependence has to

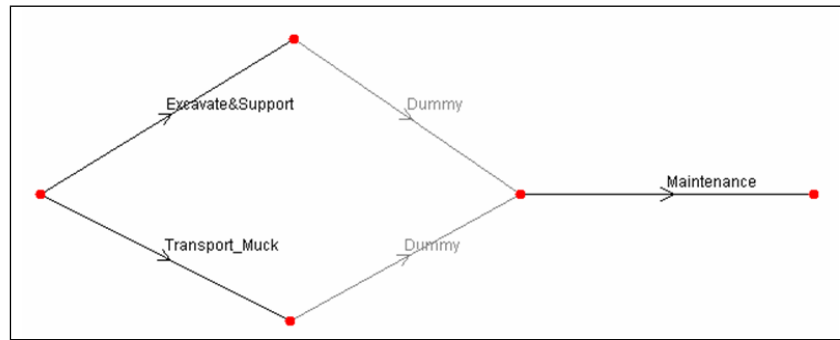


Figure 4.8: "Activity Network" Modeling the "Excavation with TEMH" subpart of the "Construction Model" for Mechanized Tunneling

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") or the time to deal with the excavated materials ("Transport_Muck") is included in the construction time; the longer lasts one (critical path) is the one that is used. For example, if "Excavate&Support" consumes more time than the simultaneous "Transport_Muck" the time of the entire "Activity Network" is the sum of the time of "Excavate&Support" and "Maintenance". It is important to realize that the "critical path concept" does not work if, for instance, the "Activity" "Excavate&Support" produces a resource and "Transport_Muck" uses this particular resource. In this case, both "Activities" ("Excavate&Support" and "Transport_Muck") influence the calculated time of the entire "Activity Network".⁷ For this reason, in the "Excavation with TEMH" only the "Activity" "Transport_Muck" is assigned excavation materials classes.

Time equations are assigned to each "Activity" to calculate the time of each "Activity". Equation (4.1) and Equation (4.2) 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 additional variables (for example, "excavate&support_adv_rate" and "maintenance_adv_rate") are introduced in the time equation; they express the advance rate of the corresponding "Activity". The advance rate is generally described as a velocity (e.g., meters per day) and varies from "Ground Class" to "Ground Class".

$$\text{Excavate\&Support Time} = \frac{\text{round_length}()}{\text{excavate\&support_adv_rate}} \quad (4.1)$$

⁷The paragraph "Activity Status" on page 86 of the SIMJAVA User's Manual (Min et al., 2009) explains why both "Activities" affect the calculated time if one "Activity" uses the particular resource which is produced from the other "Activity".

$$\text{Maintenance Time} = \frac{\text{round_length}()}{\text{maintenance_adv_rate}} \quad (4.2)$$

Equation (4.3) 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 section area (e.g., square meters) of the particular tunnel, the "loosening_factor", in example, the loosening of the excavated materials after the excavation, and the "conveyor_capacity", in example, the capacity (e.g., cubic meters per day) of the conveyor.

$$\text{Transport_Muck Time} = \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{conveyor_capacity}} \quad (4.3)$$

As discussed in Section 4.1, 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 (4.4) shows the resource equation, which is used for the "Activity" "Transport_Muck". These produced amounts of the different classes of the excavated materials are related to the corresponding "Stocks" of the "Repository". For instance, the produced muck "GC1_Muck_A" is temporarily stored at "Int_Rep_Muck_A".

$$\text{Muck Produced TBM} = \text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor} \quad (4.4)$$

The "Activity" "Excavate&Support" considers in addition to the tunnel excavation also the initial support, such as, for example, rock bolts, shotcrete, and segments. It is important to note that recycled excavation materials with suitable properties can be used as aggregate for shotcrete or segments. Therefore, the "Excavation with TEMH" subpart simulates the reuse of the recycled excavation materials ("Concrete Aggregate") in the "Activity" "Excavate&Support".⁸ The concrete aggregate consumption of the initial support is computed as

$$\text{Initial Support Aggregate TBM} = \text{conc_vol} \cdot \text{round_length}() \cdot \text{agg_factor} \quad (4.5)$$

where the variable "conc_vol" expresses the volume of shotcrete or segments per length of the actual performed cycle (e.g., cubic meters per meter), and the variable "agg_factor" the portion of concrete aggregates within the concrete volume.

⁸The recycling of the excavated materials to "Concrete Aggregate" is explained in Subsection 4.3.3.

At this point of the TEMH the excavated material classes have reached the intermediate repository. The following material flows in the TEMH process need further discussion.

4.3.2 TRANSPORTATION MODEL APPLIED TO MECHANIZED TUNNELING

The task of the "Transportation Model" are to simulate 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" and operational aspects has to be included in the "Transportation Model" for mechanized tunneling.

Figure 4.9 shows the "Activity Network" of the "Transportation Model" if mechanized tunneling is applied. This "Activity Network" uses a similar structure as the "Activity Network" of the "Excavation with TEMH" subpart of the "Construction Model", shown in Figure 4.8. Hence, the "critical path concept", which is explained at page 31, is used. This "critical path concept" allows one to simulate the concurrent tunnel construction ("Excavate&Support_noRes") and the handling of the excavated materials from the cutter head to the final usage ("Transport_Muck_noRes", "Temporary_Storage", and "Transport_Final_Usage").

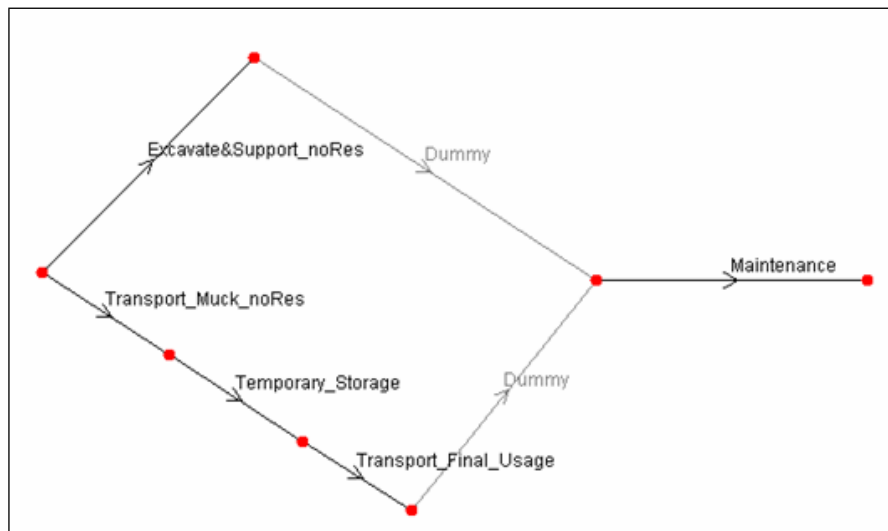


Figure 4.9: "Activity Network" Modeling the "Transportation Model" of Mechanized Tunneling

Equation (4.6) and (4.7) are used to incorporate the time of the previous material flows in the "Transportation Model". The time of these previous material flows in the TEMH process are simulated with the "Activities" "Excavate&Support_noRes" and "Transport_Muck_noRes". Note that Equation (4.6) and (4.7) are equal to Equation (4.1) and (4.3), which calculate the same time in the "Construction Model".

$$\text{Excavate\&Support_noRes Time} = \frac{\text{round_length}()}{\text{excavate\&support_adv_rate}} \quad (4.6)$$

$$\text{Transport_Muck_noRes Time} = \frac{\text{round_length}() \cdot \text{cross_section}}{\text{conveyor_capacity}} \cdot \text{loosening_factor} \quad (4.7)$$

The temporary storage time of the excavated materials at the intermediate repository is computed with Equation (4.8). The additional variable "*temporary_storage_adv_rate*" (e.g., cubic meters per day) considers the required time to investigate the volume of the excavated materials ("*Final Material Classification*") which is produced during one cycle as well as an additional storage time due to operational aspects.

$$\text{Temporary_Storage Time} = \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{temporary_storage_adv_rate}} \quad (4.8)$$

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

$$\text{Transport_Final_Usage Time} = \frac{\text{round_length}() \cdot \text{cross_section}}{\text{conveyor_capacity}} \cdot \text{loosening_factor} \quad (4.9)$$

The maintenance time on the tunnel boring machine is calculated with Equation (4.10). This time equation is equal to Equation (4.2).

$$\text{Maintenance Time} = \frac{\text{round_length}()}{\text{maintenance_adv_rate}} \quad (4.10)$$

The "*Activity*" "*Transport_Final_Usage*" is assigned the excavation material classes of the intermediate repository and the final usage to calculate the amount of the excavated materials which are removed of the intermediate repository and subsequently transported to their final usage. Equation (4.11) calculates the amount of the excavated material of the intermediate repository which is used to transport to the final

usage. The same amount which is subsequently transported to their final usage is calculated with Equation (4.12).

$$Muck\ Used\ TBM = round_length() \cdot cross_section \cdot loosening_factor \quad (4.11)$$

$$Produced\ Muck\ Final\ Usage\ TBM = round_length() \cdot cross_section \cdot loosening_factor \quad (4.12)$$

The amounts of the excavated material classes which are transported to the different final usages are related to corresponding "Stocks" of the "Repository". Thus, at the end of the "Transportation Mode" the excavated material classes have reached their final usage. Excavation 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 are qualified for recycling need further discussion.

4.3.3 RECYCLING MODEL APPLIED TO MECHANIZED TUNNELING

After the "Transportation Model" the excavated materials have reached their final usage. Recycling of the excavated materials class, which is suitable for recycling, has to be modeled. In tunneling the most common recycling is the processing of excavated materials to concrete aggregates. This processing is performed, in general, within an aggregate plant. Figure 4.10 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 aggregates. In general, two types of outputs exist: "valuable" products, and "non valuable" products. The sum of the quantity of the accruing outputs has to be equal to the quantity of the input flow. If, for example, the input flow is the excavated materials class, which is predicted to be recycled to concrete aggregates, the output flows are the aggregates for concrete and the processing losses. 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 aggregates.

The "Recycling Model" (Figure 4.4) consists of two subparts; the "Processing", and the "Inner Liner" which treats the reuse of the "valuable" products on the construction site. Figure 4.11 represents the "Activity Network" modeling the processing part of the "Recycling Model" if mechanized tunneling is used. The time of the previous material flows such as "Excavate&Support_noRes", "Transport_Muck_noRes",

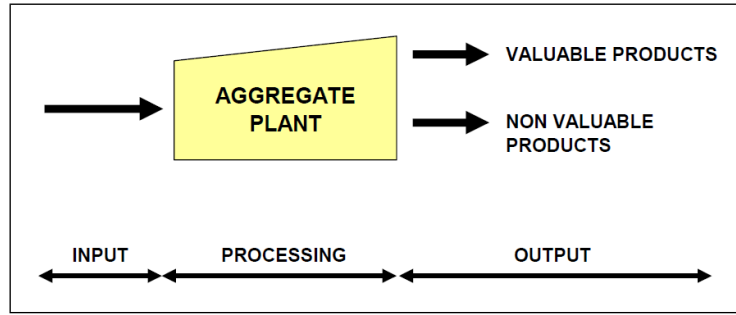


Figure 4.10: Material Flows Related to Processing

"Temporary_Storage", "Transport_Final_Usage_noRes", and "Maintenance" has to be considered in the "Recycling Model". Equation (4.13) to (4.17) calculate the time of these previous material flows. Note that similar Equations were used in the "Construction Model" and "Transportation Model" for mechanized tunneling.

$$Excavate\&Support_noRes\ Time = \frac{round_length()} {excavate\&support_adv_rate} \quad (4.13)$$

$$Transport_Muck_noRes\ Time = \frac{round_length() \cdot cross_section}{conveyor_capacity} \cdot loosening_factor \quad (4.14)$$

$$Temporary_Storage\ Time = \frac{round_length() \cdot cross_section \cdot loosening_factor}{temporary_storage_adv_rate} \quad (4.15)$$

$$Transport_Final_Usage_noRes\ Time = \frac{round_length() \cdot cross_section}{conveyor_capacity} \cdot loosening_factor \quad (4.16)$$

$$Maintenance\ Time = \frac{round_length()} {maintenance_adv_rate} \quad (4.17)$$

The "Activities" "Preprocessing_Storage" and "Processing" model the simulation tasks of the "Processing" subpart of the "Recycling Model". "Preprocessing_Storage" deals with the temporary storage time of the excavated materials before the processing of the particular excavated materials in the aggregate plant begins. This temporary storage time can be expressed as

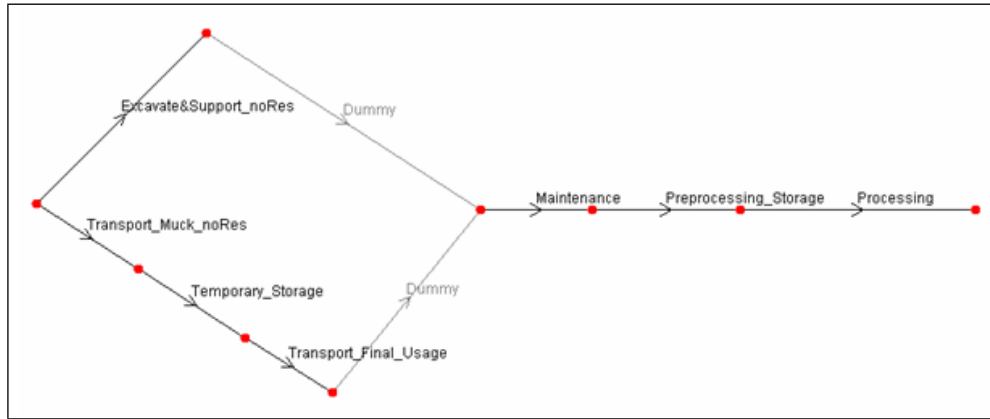


Figure 4.11: "Activity Network" Modeling the "Recycling Model" of Mechanized Tunneling

$$\text{Preprocessing_Storage Time TBM} = \frac{\text{round_length}()}{\text{preprocessing_storage_adv_rate}} \quad (4.18)$$

where the variable "preprocessing_storage_adv_rate" expresses the advance rate of "Preprocessing_Storage" in, for example, meters per day. The "preprocessing_storage_adv_rate" is generally judged by processing experts.

The "Activity" "Processing" simulates the processing performance. Therefore, Equation (4.19) calculates the processing time. The processing advance rate ("processing_adv_rate") is based on judgment of processing experts which are familiar with the time consumption of the processes within the aggregate plant. Further, "processing_adv_rate" has to consider the time consumption of additional investigations on the recycled aggregates. These additional investigations are, for instance, laboratory testing to determine the properties of the excavated materials after the processing.

$$\text{Processing Time TBM} = \frac{\text{round_length}()}{\text{processing_adv_rate}} \quad (4.19)$$

The amount of excavated materials which are suitable for recycling has to be removed of the final usage "Stock" of the "Repository" to simulate the excavation materials consumption of the recycling process. Therefore, the "Activity" "Processing" is assigned the suitable excavation materials class of final usage. This excavation materials class represents the input flow of the processing. Equation (4.20) calculates the amount of the excavated material which is used for the processing.

$$\text{Used Muck Final Usage TBM} = \text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor} \quad (4.20)$$

Equation (4.21) and Equation (4.22) represent the resource equations of the output flows of the processing and are assigned "Processing". Each of these two resource equations treats one of the products ("valuable" products and "non valuable" products) of the processing process. The "valuable" products are for example the produced concrete aggregates of mechanized tunneling. The variables "processing_success_factor" and "processing_loss_factor" characterize the processing success and depend on the excavation material properties and the used processing aggregates. Due to the fact that no materials disappear during the processing the sum of the "processing_success_factor" and the "processing_loss_factor" has to be equal one. The values of these variables are, again, judged by processing experts.

$$\begin{aligned} \text{Produced Concrete Aggregates TBM} &= \text{round_length}() \cdot \text{cross_section} \cdot \\ &\quad \text{loosening_factor} \cdot \\ &\quad \text{processing_success_factor} \end{aligned} \quad (4.21)$$

$$\begin{aligned} \text{Non Valuable Product} &= \text{round_length}() \cdot \text{cross_section} \cdot \\ &\quad \text{loosening_factor} \cdot \text{processing_loss_factor} \end{aligned} \quad (4.22)$$

After the processing, the amount of 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 "Concrete Aggregate Storage", of the "Repository". Subsequently, these concrete aggregates are removed of this "Stock" and reused in different concrete works on the construction site which is the simulation task of the "Inner Liner" subpart. Examples of such concrete works are initial support measures using shotcrete or the construction of the inner liner. The "non valuable" products are, in general, tipped at the final repository and, thus, related to the "Stock" which represents the final repository.

Recycling of excavated materials to concrete aggregates and reusing them to construct the inner liner has been recently performed in tunneling (Teuscher et al., 2007; Lieb, 2009). The "Inner Liner" incorporates this reuse in the simulation model. Figure 4.12 represents the "Activity Network" of the "Inner Liner". It can be seen that the previous material flows in the TEMH are not considered in the "Inner Liner" subpart of the "Recycling Model".

The "Activity" "Inner Liner" simulates the entire construction of the inner liner. Equation (4.23) computes the time to construct the inner liner. Therefore, the additional variable "inner_liner_adv_rate" expresses the advance rate of the entire

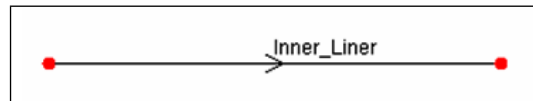


Figure 4.12: "Activity Network" Modeling the Reuse of Recycled Excavated Materials of mechanized tunneling in the Inner Liner

construction process of the inner liner. In general, this advance rate is expressed in meters per day.

$$Inner_Liner\ Time\ TBM = \frac{round_length()}{inner_liner_adv_rate} \quad (4.23)$$

Equation (4.24) is used to simulate the concrete aggregate consumption of the inner liner performance. The concrete aggregates are taken from the produced concrete aggregates of mechanized tunneling, which is calculated in Equation 4.21. If the amount of recycled concrete aggregates does not satisfy the concrete aggregates demand of the inner liner additional concrete aggregates have to be supplied. In general, these additional concrete aggregates are purchased from regional suppliers.

$$Inner\ Liner\ Aggregate\ TBM = conc_vol \cdot round_length() \cdot agg_factor \quad (4.24)$$

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

4.4 MODELING CONVENTIONAL TUNNELING

This Section discusses the simulation of conventional tunneling. Therefore, each part of the "Tunnel Network" of the developed simulation model (Figure 4.4) has to perform. In the following Subsections, similar to Section 4.3, each part and subpart of the developed simulation model is explained.

4.4.1 CONSTRUCTION MODEL APPLIED TO CONVENTIONAL TUNNELING

As mentioned before, the "Construction Model" is structured in two subparts; the "Excavation" and the "Excavation with TEMH". The "Activity Network" of the "Excavation" subpart for conventional tunneling is represented in Figure 4.13. This "Activity Network" considers "Activities" which simulate the tunnel construction performance or "Activities" which affect the "Activities" of the tunnel construction performance. For instance, the "Activity" "Load" affects the tunnel construction performance because the "Activity" "Initial_Support" can only be performed if the

excavated materials are removed next to the tunnel face. Other "Activities" which are related to the TEMH process are not considered in the "Excavation" subpart.

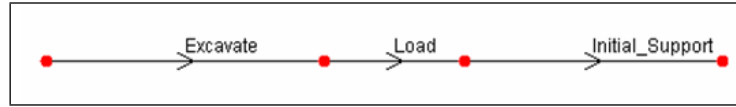


Figure 4.13: "Activity Network" Modeling the "Excavation" subpart of the "Construction Model" for Conventional Tunneling

Equation (4.25), (4.26), and (4.27) are the time equations of the "Activities" "Excavate", "Load", and "Initial_Support". The variables "excavate_adv_rate", "load_adv_rate", and "support_adv_rate" express the advance rates (e.g., meters per day) of the corresponding "Activities".

$$\text{Excavate Time} = \frac{\text{round_length}()}{\text{excavate_adv_rate}} \quad (4.25)$$

$$\text{Load Time} = \frac{\text{round_length}()}{\text{load_adv_rate}} \quad (4.26)$$

$$\text{Initial_Support Time} = \frac{\text{round_length}()}{\text{support_adv_rate}} \quad (4.27)$$

Figure 4.14 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. In contrast to the mechanized tunneling simulation, it is assumed that muck cars are used to transport the excavated materials to the intermediate repository. To compute the time of each "Activity" of the "Excavation with TEMH" subpart time equations are used. The time of the "Activities" "Excavate", "Load", and "Initial_Support" are again computed with the Equations (4.25), (4.26), and (4.27). In addition, the time of the "Activity" "Unload" can be expressed as

$$\text{Unload Time} = \frac{\text{round_length}()}{\text{unload_adv_rate}} \quad (4.28)$$

where the variable "unload_adv_rate" specifies the advance rate of the "Activity" "Unload" in, for instance, meters per day.

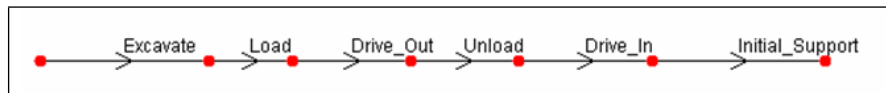


Figure 4.14: "Activity Network" Modeling the "Excavation with TEMH" subpart of the "Construction Model" for Conventional Tunneling

Equation (4.29) simulates the time of the excavation material transport from the tunnel face to the corresponding intermediate repository using muck cars. This

transport is simulated with the "Activities" "Drive_out" and "Drive_in". Equation (4.29) is structured in three lines. Line 1 expresses the transportation time of one muck car between the tunnel face and the intermediate repository. 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 cars simultaneously used in the mucking process. The additional variables of Equation (4.29) express the velocity (e.g., meters per day) of the muck cars ("*muck_car_velocity_drive_out*"), the number of the used muck cars ("*number_muck_cars*"), and the average capacity (e.g., cubic meters) of one muck car ("*capacity_muck_cars*"). Note that the time equation for "Drive_In" is equal to Equation (4.29); however, the transport velocity of the muck cars can change between "Drive_In" and "Drive_Out" because only the muck cars of "Drive_Out" are fully loaded with excavated materials.

$$\begin{aligned}
 \text{Drive_Out Time} = & \frac{\text{round_start_position}()}{\text{muck_car_velocity_drive_out}} \cdot \\
 & \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{capacity_muck_car}} \cdot \\
 & \frac{1}{\text{number_muck_cars}}
 \end{aligned} \tag{4.29}$$

The special feature of Equation (4.29) is the distance-based internal function "*round_start_position()*". This distance-based function considers the progress of the tunnel in the "*Travel distance*" (Figure 4.15) of the excavated materials. Hence, "*round_start_position()*" considers that the tunnel moves forward from one cycle to the next cycle and returns the position (e.g., meters) of the current excavated tunnel before the cycle starts. Min (2008) discusses the distance-based capability in detail.

To calculate the amount of the excavated materials during the conventional tunnel construction, which are subsequently transported to the intermediate repository, the "Activity" "Unload" is assigned excavation material classes. Equation (4.30) expresses the resource equation, which calculates the amount of the produced excavation materials. These produced amounts of muck are related to the respective "Stocks" of the "Repository" which model the intermediate repository.

$$\text{Muck Produced D\&B} = \text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor} \tag{4.30}$$

Reuse of recycled excavation materials as shotcrete aggregate for the initial support is considered in the "Activity" "Install_Support". Equation (4.31) is assigned to "Install_Support" to calculate the amount of the reused recycled excavation materials.

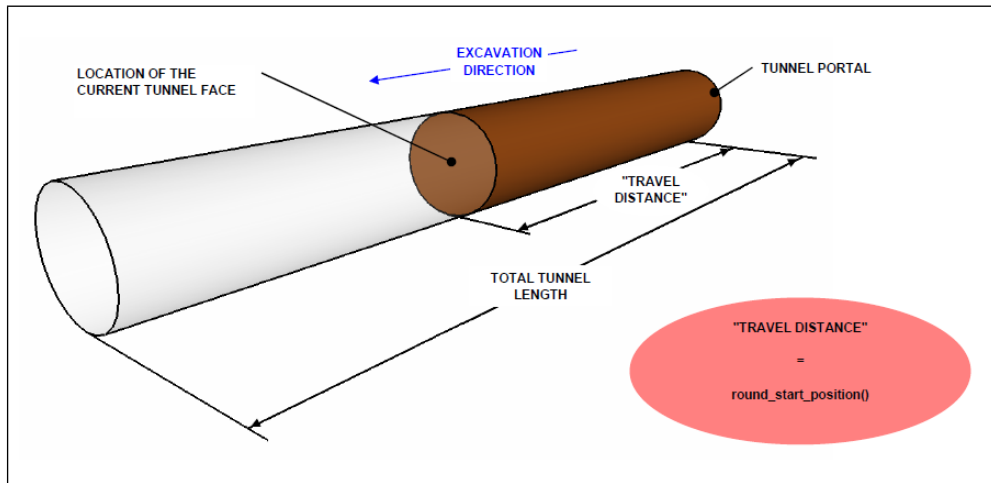


Figure 4.15: The "Travel Distance" of the Excavated Materials

$$Initial_Support\ Aggregate\ D\&B = conc_vol \cdot round_length() \cdot agg_factor \quad (4.31)$$

At this point, the excavated materials are produced, preliminary classified to the defined excavation material classes, and transported to the intermediate repository. The simulation of the subsequent material flows in the TEMH process need to be described.

4.4.2 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 4.16 represents the "*Activity Network*" of the "*Transportation Model*" which simulates conventional tunneling. This "*Activity Network*" considers the time of the previous material flows of the TEMH process. The additional "*Activities*" "*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.

The Equations (4.32) to (4.36) calculate the time of the "*Activities*" "*Excavate*", "*Load*", "*Drive_Out*" as well as "*Drive_In*", and "*Initial_Support_noRes*". These "*Activities*" incorporate the time of the previous material flows in the TEMH process in the "*Transportation Model*". Note that these Equations are equal to the corresponding Equations of the "*Construction Model*".

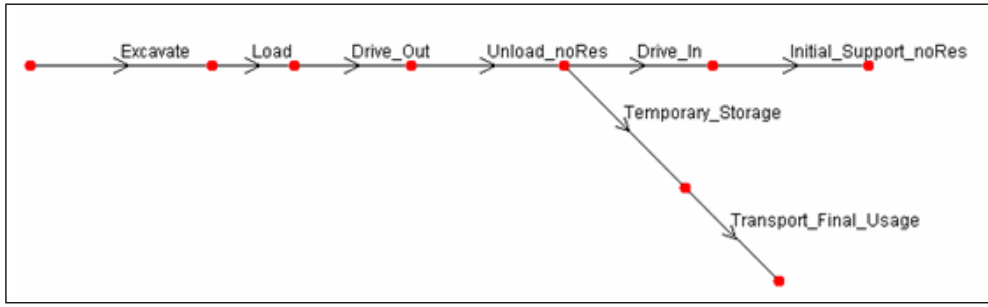


Figure 4.16: "Activity Network" Modeling the "Transportation Model" of Conventional Tunneling

$$Excavate\ Time = \frac{round_length()}{excavate_adv_rate} \quad (4.32)$$

$$Load\ Time = \frac{round_length()}{load_adv_rate} \quad (4.33)$$

$$Drive_out\ Time = \frac{round_start_position()}{muck_car_velocity_drive_out} \cdot \frac{round_length() \cdot cross_section \cdot loosening_factor}{capacity_muck_car} \cdot \frac{1}{number_muck_cars} \quad (4.34)$$

$$Unload_noRes\ Time = \frac{round_length()}{unload_adv_rate} \quad (4.35)$$

$$Initial_Support_noRes\ Time = \frac{round_length()}{support_adv_rate} \quad (4.36)$$

The temporary storage time of the excavated materials at the intermediate repository due to the "Final Material Classification" as well as operation aspects is expressed with

$$Temporary_Storage\ Time = \frac{round_length()}{temporary_storage_adv_rate} \quad (4.37)$$

where the additional variable "temporary_storage_adv_rate" specifies the advance rate (for example, meters per day) of the "Temporary Storage".

Equation (4.38) calculates the time of the excavation material transport between the intermediate repository and their final usage ("*Transport_Final_Usage*") if a conveyor is used.

$$\text{Transport_Final_Usage Time} = \frac{\text{round_length()} \cdot \text{cross_section}}{\text{conveyor_capacity}} \cdot \text{loosening_factor} \quad (4.38)$$

Figure 4.17 subdivides the "*Activity Network*" into three parts. After the "*Activity*" "*Unload_noRes*" a branch with the "*Activities*" "*Temporary_Storage*" and "*Transport_Further_Purpose*" 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 ("*Install_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*").

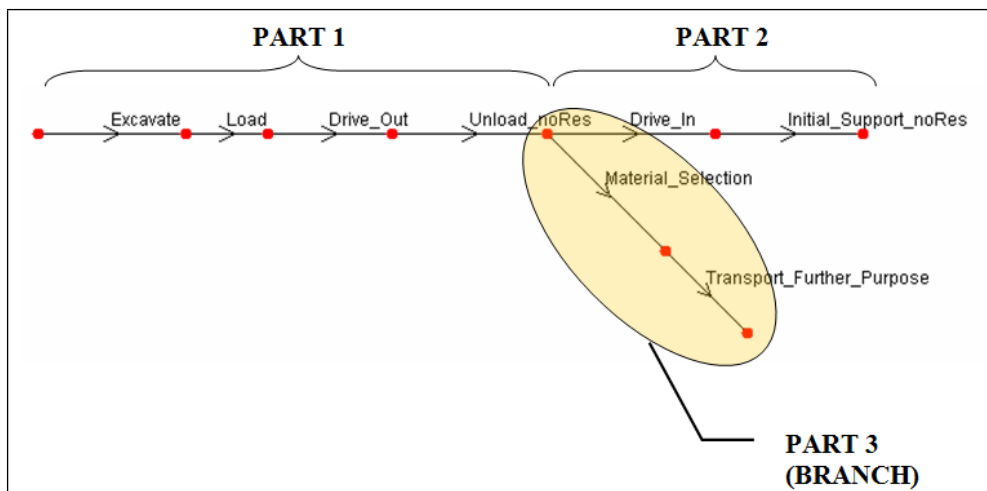


Figure 4.17: Parts of the "*Activity Network*" Modeling the "*Transportation Model*" of Conventional Tunneling

Excavation material classes of the intermediate repository and the final usage are assigned to the "*Activity*" "*Transport_Final_Usage*". Equation (4.39) calculates the

amount of the excavated materials which are removed of the intermediate repository and subsequently transported to the final usage. The same amount of the excavated materials which is transported to final usage is calculated with Equation (4.40).

$$Muck\ Used\ D\&B = round_length() \cdot cross_section \cdot loosening_factor \quad (4.39)$$

$$Produced\ Muck\ Final\ Usage\ D\&B = round_length() \cdot cross_section \cdot loosening_factor \quad (4.40)$$

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. Excavation material classes with properties to recycle them will be discussed in the following Subsection.

4.4.3 RECYCLING MODEL APPLIED TO CONVENTIONAL TUNNELING

This Subsection models the recycling of suitable excavated materials of conventional tunneling to concrete aggregates and their reuse on the construction site. Subsection 4.3.3 discusses the processing of the excavated materials of mechanized tunneling with an aggregate plant. The relations between the input- and output flows of the processing, shown in Figure 4.10, are also valid for the excavated materials of conventional tunneling.

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 4.18 represents the "Activity Network" of "Processing". This "Activity Network" considers the time of the previous material flows of the excavation materials. Equations (4.41) to (4.48) calculate these times. These Equations are equal to Equations of the "Construction Model" and "Transportation Model" which also consider these times.

$$Excavate\ Time = \frac{round_length()}{excavate_adv_rate} \quad (4.41)$$

$$Load\ Time = \frac{round_length()}{load_adv_rate} \quad (4.42)$$

$$\begin{aligned}
 \text{Drive_Out Time} &= \frac{\text{round_start_position}()}{\text{muck_car_velocity_drive_out}} \cdot \\
 &\quad \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{capacity_muck_car}} \cdot \\
 &\quad \frac{1}{\text{number_muck_cars}}
 \end{aligned} \tag{4.43}$$

$$\text{Unload_noRes Time} = \frac{\text{round_length}()}{\text{unload_adv_rate}} \tag{4.44}$$

$$\begin{aligned}
 \text{Drive_In Time} &= \frac{\text{round_start_position}()}{\text{muck_car_velocity_drive_in}} \cdot \\
 &\quad \frac{\text{round_length}() \cdot \text{cross_section} \cdot \text{loosening_factor}}{\text{capacity_muck_car}} \cdot \\
 &\quad \frac{1}{\text{number_muck_cars}}
 \end{aligned} \tag{4.45}$$

$$\text{Initial_Support_noRes Time} = \frac{\text{round_length}()}{\text{support_adv_rate}} \tag{4.46}$$

$$\text{Temporary_Storage Time} = \frac{\text{round_length}()}{\text{temporary_storage_adv_rate}} \tag{4.47}$$

$$\begin{aligned}
 \text{Transport_Final_Usage Time} &= \frac{\text{round_length}() \cdot \text{cross_section}}{\text{conveyor_capacity}} \cdot \\
 &\quad \text{loosening_factor}
 \end{aligned} \tag{4.48}$$

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 (4.49) is used to calculate the time of this temporary storage.

$$\text{Preprocessing_Storage Time D\&B} = \frac{\text{round_length}()}{\text{preprocessing_storage_adv_rate}} \tag{4.49}$$

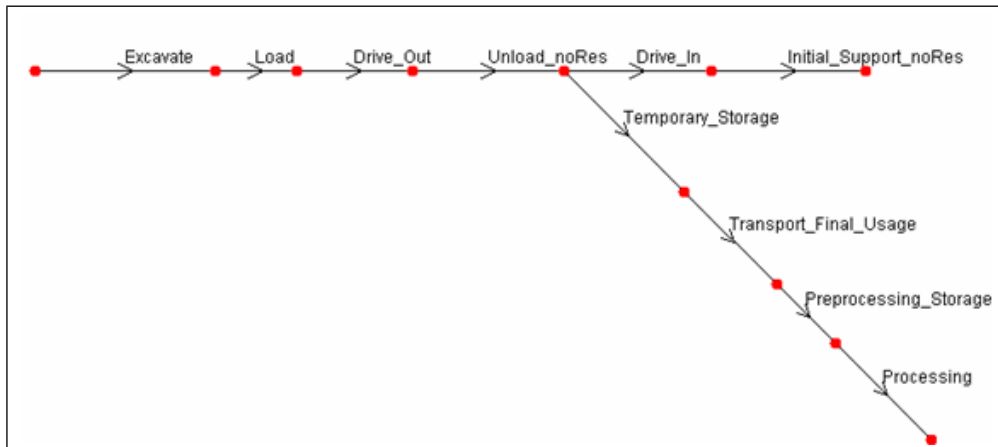


Figure 4.18: "Activity Network" Modeling the "Recycling Model" of Conventional Tunneling

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

$$\text{Processing Time } D\&B = \frac{\text{round_length}()}{\text{processing_adv_rate}} \quad (4.50)$$

Furthermore, the "Activity" "Processing" is assigned the excavation materials class of final usage as well as the "valuable" product ("Concrete Aggregate") and the "non valuable" product of the processing. Equation (4.51) calculates the amount of the suitable excavation materials class of the final usage which is used for the recycling. This amount of excavated materials is subsequently used as the input flow of the aggregate plant. The corresponding amounts of the output flows of the aggregate plant which are the "valuable" products ("Concrete Aggregate") and the "non valuable" products are computed with the Equations (4.52) and (4.53).

$$\begin{aligned} \text{Used Muck Final Usage } D\&B = \text{round_length}() \cdot \text{cross_section} \cdot \\ \text{loosening_factor} \end{aligned} \quad (4.51)$$

$$\begin{aligned} \text{Produced Concrete Aggregates } D\&B = \text{round_length}() \cdot \text{cross_section} \cdot \\ \text{loosening_factor} \cdot \\ \text{processing_success_factor} \end{aligned} \quad (4.52)$$

$$\begin{aligned} \text{Non Valuable Product} &= \text{round_length}() \cdot \text{cross_section} \cdot \\ &\quad \text{loosening_factor} \cdot \text{processing_loss_factor} \quad (4.53) \end{aligned}$$

The non valuable products are tipped at the final repository. In contrast, the produced concrete aggregates are assigned the corresponding "Stock" of the "Repository" which models the temporary storage of the concrete aggregates after the processing. These concrete aggregates are subsequently reused for concrete works on the construction site which is simulated with the "Inner Liner" subpart of the "Recycling Model".

Figure 4.19 shows the "Activity Network" of the "Inner Liner" subpart. This "Activity Network" does not consider the previous material flows of the excavated materials.

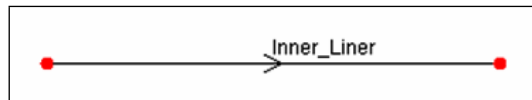


Figure 4.19: "Activity Network" Modeling the Reuse of Recycled Excavated Materials of Conventional Tunneling in the Inner Liner

Equation (4.54) is allocated to the "Activity" "Inner_Liner" to compute the time of the entire inner liner performance.

$$\text{Inner Liner Time D\&B} = \frac{\text{round_length}()}{\text{inner_liner_adv_rate}} \quad (4.54)$$

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

$$\text{Inner Liner Aggregate D\&B} = \text{conc_vol} \cdot \text{round_length}() \cdot \text{agg_factor} \quad (4.55)$$

At this point, the entire material flows of the TEMH process for conventional tunneling are modeled with the simulation model.

4.5 COMMENTS ON THE SIMULATION MODEL

The attempt 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 the excavation materials production and ending

with the reuse of the excavated materials on the construction site or tipping, has to be included. Therefore, various "*Activity Networks*", described in the previous Sections, are used. These "*Activity Networks*" show one way of modeling the TEMH process. The level of detail of the "*Activity Network*" as well as the structure depends on the respective tunneling method. Furthermore, the structure can depend on the emphasis of the simulation. For instance, a very detailed simulation of each step of the tunnel construction performance which considers the related TEMH can yield a different structure of the "*Activity Network*" than a detailed simulation of the material flows of the TEMH which considers only the main steps of the tunnel construction. Emphasis of the developed "*Activity Networks*" of this research is to simulate the main material flows of the TEMH and consider the simultaneous tunnel construction. Hence, this simulation model enables one to show effects of the TEMH on the construction performance and vice versa.

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 of the time and resource equations can have the same validity. Again, the DAT enables the user to define the "*Activity Networks*" as well as the time and resource equations on their needs.

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 5

BRENNER BASE TUNNEL (BBT) PROJECT

In Chapter 6 the developed simulation model of Chapter 4 models a part of the Brenner Base tunnel. For this reason the intent of this Chapter is to give a brief overview of the BBT project. This chapter's sources of information are project documents of the Brenner Basistunnel BBT SE and their web page (BBT SE). Supplementary literature is accordingly marked.

5.1 TUNNEL DESIGN

The Brenner Base Tunnel (Figure 5.1) with a total length of 55 km is the core element of the rail corridor Munich – Verona. It is designed as a tunnel system (Figure 5.2) with two single-track tubes, a service gallery, three multifunction stations (MFS), and different lateral adits. The average overburden along the alignment of the main tunnel tubes is about 1200 m and reaches a maximum of about 2000 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 crossover tunnels (Figure 5.3). Underneath the main tunnel tubes the service gallery, with an inner diameter of 5 m, is situated. 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 tunnel system of the BBT consists of three MFS 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 & maintenance, and a track crossover. Additionally, the MFS Steinach includes two overtaking tracks. A lateral adit for every MFS will



Figure 5.1: Project Overview (Bergmeister, 2007a)

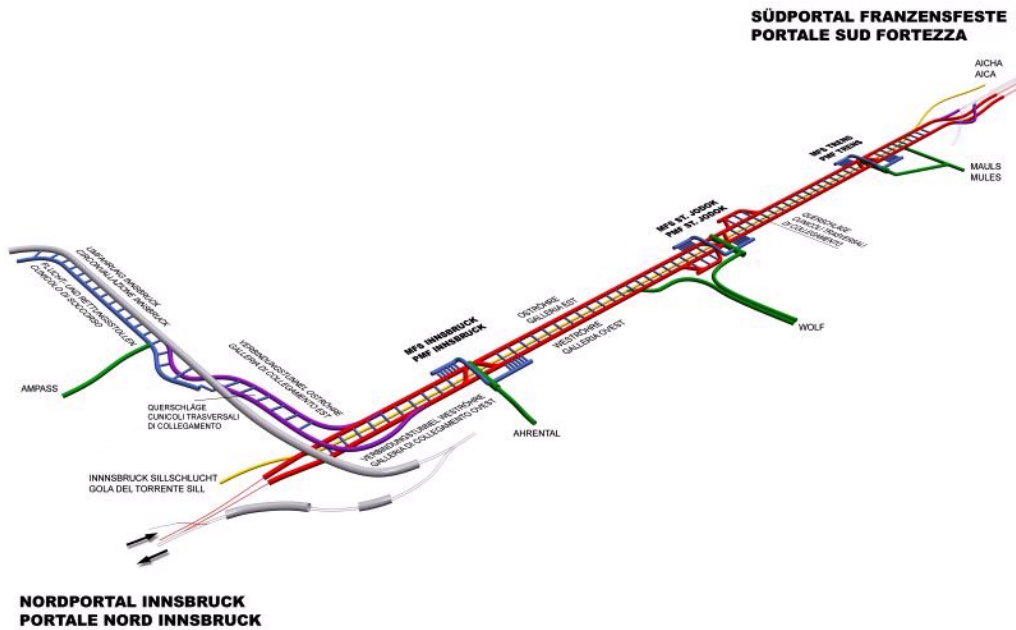


Figure 5.2: BBT's Tunnelsystem (BBT SE)

be built and used to start the MFSs. South of the MFS Innsbruck two single-track tunnels connect the BBT to the existing two-track bypass tunnel of Innsbruck. Different contract sections are set up on the basis of the Ampass, Ahrental, Wolf and Mauls lateral adits. The lateral adits also provide various working faces and shorten construction time. Based on the current knowledge of the geology (Section 5.4) along the alignment of the BBT it is predicted that about 2/3 of the main tunnel will be driven by mechanized means, in example, using tunnel boring machines. The remaining 1/3 will be constructed conventionally using the Drill & Blast method ("*conventional*" method). Other parts of the tunnel system such as, for example, the MFSs and the lateral adits will also be constructed conventionally.

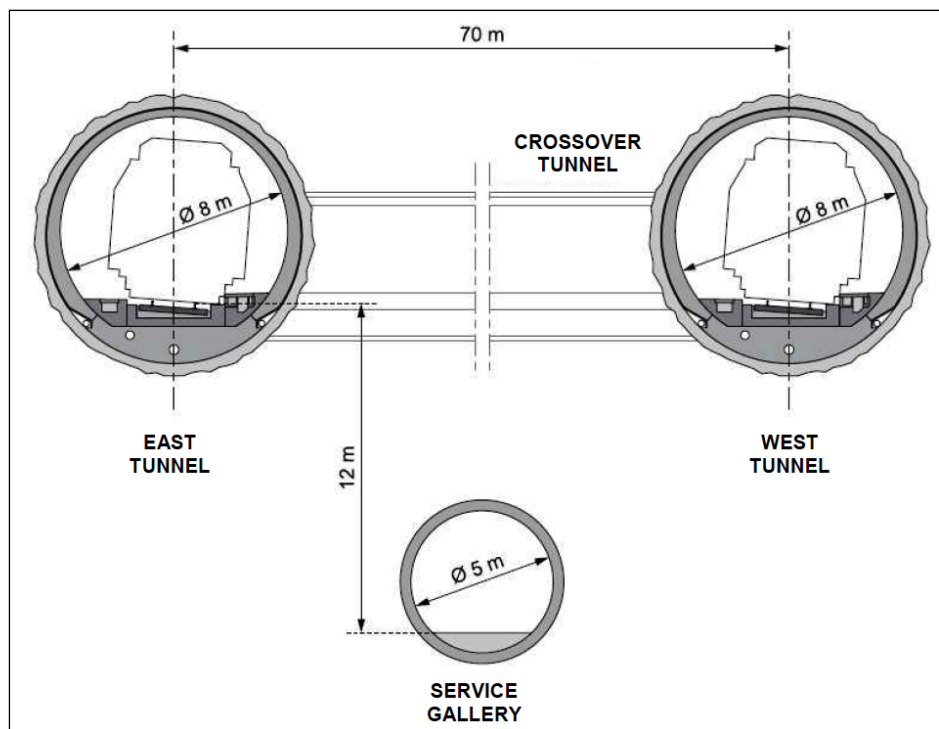


Figure 5.3: Main Tunnel Tubes' and Service Gallery's Standard Cross Sections (BBT SE)

5.2 CONTRACT SECTIONS

As can be seen in (Figure 5.4), the Austrian part of the BBT is subdivided into the following main sections:

- contract section Ampass
- contract section Innsbruck

- contract section Ahrental
- contract section Wolf

It is important to note that for reasons of logistic, subsections are and will still be decoupled from these contract sections (Bergmeister, 2007b).

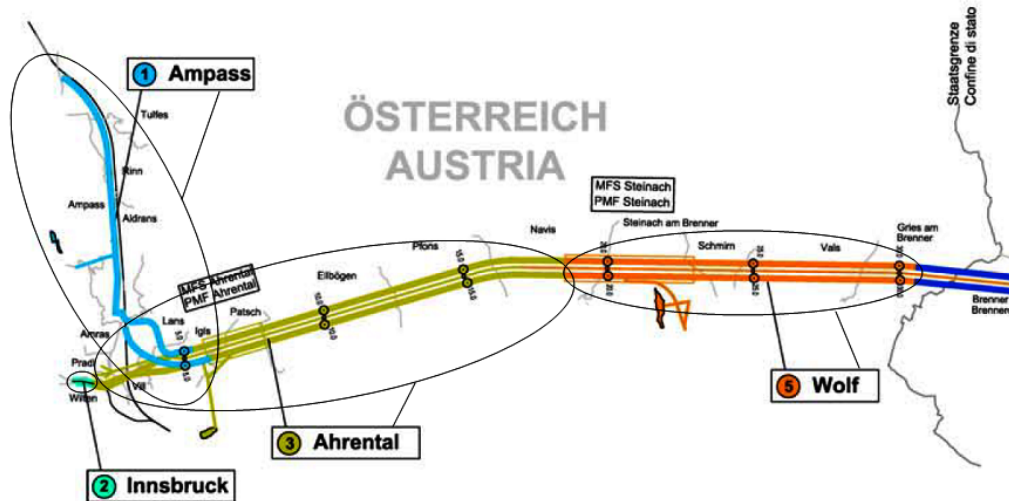


Figure 5.4: Contract sections of the BBT

5.3 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 (Figure 5.5), which is 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 (Figure 5.5) has already been completed using Drill & Blast. Work on the Innsbruck-Ahrental exploratory tunnel (5.69 km), which uses Drill & Blast as construction method, started at the beginning of December, 2009. After finishing this work, the access gallery Ahrental with a length of 2.42 km will be constructed also by means of Drill & Blast. The next sections of the exploratory features are the Saxen Tunnel and the mucking tunnel Padastertal, which will be the lateral adit of the contract section Wolf as well as the access to the final repository Padastertal. The final repository Padastertal is located in the contract section Wolf.

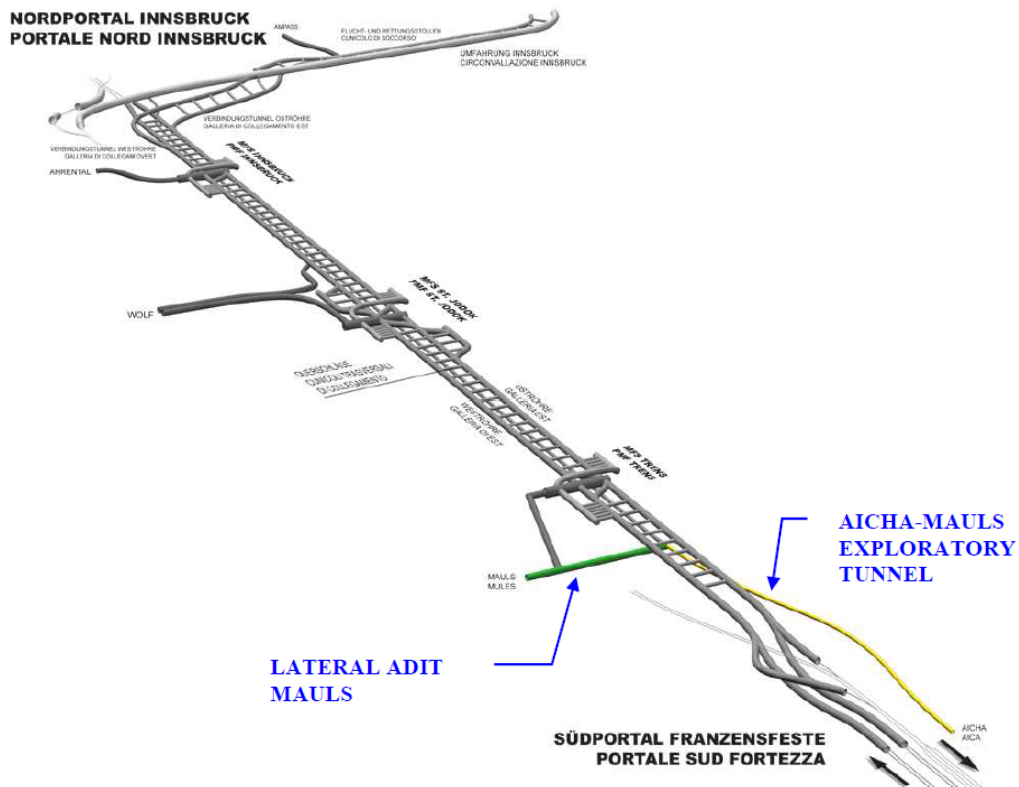


Figure 5.5: Current and Finished Tunnel Drives (BBT SE)

5.4 TUNNEL GEOLOGY

As described in Section 5.3, the exploratory measures are reasonably advanced. Figure A.1 to Figure A.3 (see Appendix A) show the main geology sections along the alignment of the Austrian part of the BBT. A brief overview of the geology, following Bergmeister (2010), is given below. Emphasis is placed on the Austrian part of the BBT. Further, predictions about the reusability of the excavated materials based on Brandner and John (2008) are included.

- **km 0 to km 14: Innsbruck Quartz Phyllite / Unterostalpin**

Generally crumbling rock behavior is expected, which can lead to shear failure and squeezing phenomena. In addition, the rock behavior of this area is essentially influenced by fault zones. There is no significant groundwater flow system mapped in the Innsbruck Quartz Phyllite section. However, in the fault zones less significant groundwater flow systems can occur. It is predicted that less than 10 per cent of the excavated materials can be reused as fill material. The residual amount of the excavated materials are tipped at the final repositories.

- **km 14 to km 19: North Marginal Zone of the Tauern Window**

The main characteristic of this area is that the conditions vary considerably. Thus, friable behavior which yields to 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 (Mislkopf Tauern fault) is presumed. Apart from that presumed fault zone, the acute-angled faults of the north-south running normal faults result in squeezing phenomena. Again, less than 10 per cent of the excavated materials are predicted to be reusable as fill materials. The rest is predicted to be dumped at the final repositories.

- **km 19 to km 28.5: Glockner Nappe**

In the southern zone an increasing extent of black Phyllites is expected, which can lead to slightly squeezing effects. However, no swelling will occur in the Anhydrites. The main lithology of this zone is Bündner Schist, which contains varying degrees 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. This fault zone can occur in damaged Limestone-rich Bündner Schist due to chemical solution. At the tunnel level, even in the fault areas, no significant groundwater flow systems are expected. Along this section the excavation material properties vary considerably. An estimate of the average amount of excavated materials reused as fill materials is about 20 per cent. The remainder of the excavated materials will 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**

In this section alternating rock conditions, such as shear features, deep-lying deconsolidation, and pronounced water ingress dominate. Anhydrite leaches and material export can result in crumbling rock and can not be precluded. In this section, excavation materials which can be recycled to concrete aggregates are predicted. A geologic subsection (Hochstegen formation) of a length of about 470 meters is predicted to be 70 per cent reusable as concrete aggregate, 20 per cent as fill materials, and 10 per cent tipped at final repositories. The remaining geologic subsections are at about 30 per cent reusable as fill materials and at 70 per cent tipped at final repositories.

- **km 30.3 to km 36.0: Central Gneiss - Brenner Boundary**

Generally, the Central Gneiss has stable rock conditions; however, joint plane solutions have to be considered. In addition, the Olper Faults (Figure A.3, "*Olperer Störungszone*") area is presumed, in which squeezing phenomena are expected. Otherwise the fault zones will not greatly influence the rock behavior. In the Central Gneiss no groundwater flow systems are predicted. However, it is presumed that in the fault zones the permeability can increase. A high

percentage, 70 – 80 per cent, of the excavated materials is predicted to be reusable as concrete aggregate. In addition, about 20 per cent of the excavated material is assumed to be used as fill materials. The remaining excavated materials are tipped at the final repositories.

5.5 BBT'S TEMH

In the following, the current stage of planning the tunnel excavation materials handling (TEMH) of the BBT is represented. At the present (Spring 2010) the framework of the TEMH such as objectives of the excavation materials management, the excavation materials classification, the repositories concept, and the transportation logistics is elaborated. It is important to mention that the current stage of planning does not implement a development of a testing plan of the excavated materials or the description of the processing steps of the excavated materials.

5.5.1 OBJECTIVES OF THE TEMH

During the construction of the BBT roughly 15.5 mill. cubic meters of excavation materials in compacted state will accrue (Bergmeister, 2010). The Brenner Basistunnel BBT SE (contractor) 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 the excavation materials handling as well as the conservation of natural resources.

5.5.2 EXCAVATION MATERIALS CLASSIFICATION

During the exploratory phase of the BBT project, detailed investigations to describe the properties of the excavation materials have been performed through the Brenner Base Tunnel BBT SE and instructed companies. These investigations are based on geological mapping, the 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 has been performed. The objective of the excavation materials classification is to first examine their possible use as concrete aggregates or fill materials (Bergmeister, 2007b).

First step of the classification is to forecast the lithologies of the excavated materials and to subdivide them into four lithology classes. Table 5.1 shows the four lithology classes with two representative lithologies of each lithology class. The entire lithology classification is represented in Mazzalai (2008a).

Table 5.1: Classification of the Predicted Lithologies in Four Lithology Classes (Source of Information: Mazzalai (2008a))

Class 1	Quaternary 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 usage classes:

- **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 disposed

The third step combines the first two steps and, thus, forecasts the percentage of each usage class within a lithology class. Table 5.2 represents this prediction.

Table 5.2: Percentage of the Usage Classes within each Lithology Class (Source of Information: Mazzalai (2008a))

	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 per cent of the excavated materials are usable as concrete aggregates. About 15 per cent can be used for embankments or other backfilling purposes. The rest of the excavated materials (roughly 79 per cent) appears, to be without further treatment, useless for construction purposes and thus transported to final repositories. However, it is mentioned in a project document (Brandner and John, 2008) that about 20 per cent of class C materials can potentially be upgraded to class B if particular processing or only a longer period of intermediate storage is applied.

Based on the performed classification, Granite, Granite-Gneiss, and Quartzite can produce excavation materials that are suitable as concrete aggregate. Furthermore, it is assumed that a general loss of aggregates of 15 to 20 per cent will occur due to processing of the excavated materials. A significantly higher loss is expected when using TBMs.

5.5.3 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 of the quantities of the excavation materials which will be tipped in each final repository. In addition, the location of the aggregate plant is discussed.

Figure 5.6 shows a schematic overview of the locations of the final repositories of the Austrian part of the BBT and represents the forecast of the excavated materials quantities which will be tipped in each final repository. These quantities consider the usage classes B and C. Excavation materials of usage class A will be processed at an aggregate plant and used as concrete aggregates. Therefore, one aggregate plant for the entire Austrian part of the BBT is located at the final repository Padastertal because only excavated materials of the contract section Wolf (Figure 5.6) are predicted to be classified as class A materials. After the processing of these excavated materials to concrete aggregates, the recycled materials will be reused within the contract section Wolf to minimize the transport distances. Reuse possibilities of these excavated materials are, for example, concrete aggregates for the initial or final support.

If excavated materials of the other contract sections (Ampass, Innsbruck, and Ahrental; Figure 5.4) will be classified as usage class A, which is not predicted, the excavated materials will be temporary stored at the intermediate repositories which are located near the tunnel portals of the particular contract sections. Subsequently, these materials will be transported to the aggregate plant of the final repository Padastertal.

5.5.4 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 boundary conditions. The main goal of the transport logistic concept is to ensure that the environment, landscape, and the stakeholders will be interfered with as little as possible. To be in accordance with that goal, the intermediate and final repositories will be set up immediately alongside the lateral adits. Thanks to such optimization, lengthy transportation via public roads will be minimized. For instance, in the contract section Padastertal an own mucking tunnel is planned to transport the excavated materials

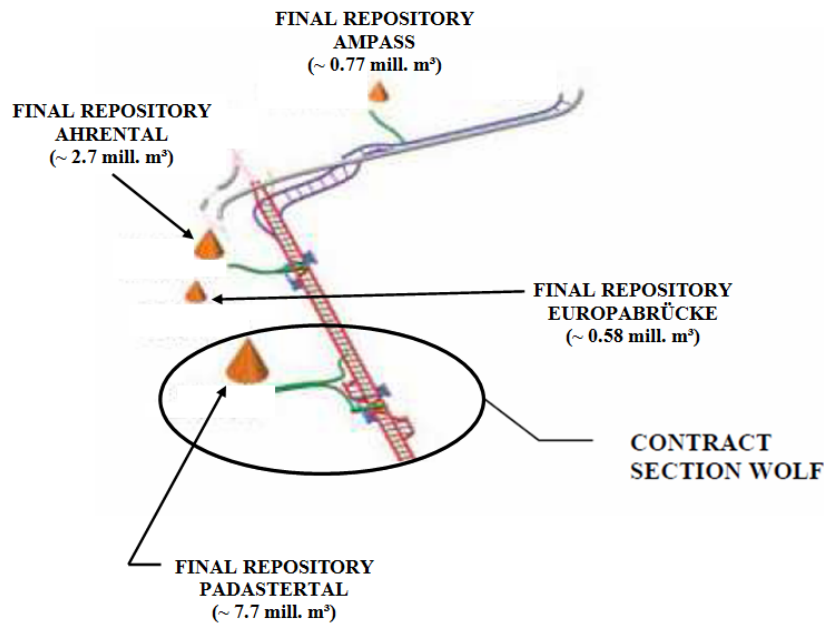


Figure 5.6: Final Repositories along the Austrian Part of the BBT (Bergmeister, 2010)

of the contracted section Wolf to the final repository Padastertal. The transportation of the excavated materials is generally designed with conveyors or roadworthy trucks.

As stated above, the transport concept varies from contract section to contract section. However, next to the portal of the different lateral adits intermediate repositories are located. These intermediate repositories serve as areas to handle the excavation materials coming from the tunnel and roadworthy trucks or conveyors which transport the excavated materials to their further purposes. Moreover, the progress of the construction performance can have impact on the transportation concept. Thus, the transportation logistics can change during the construction progress.

5.6 CONTRACT SECTION WOLF

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

- Excavation materials of usage Class A are only predicted at the contract section Wolf.
- The aggregate plant of the Austrian part of the BBT is located at the contract section Wolf.
- Recycled excavation materials are only reused within the contract section Wolf.

Thus, the developed simulation model (Chapter 4) is applied to the contract section Wolf (Chapter 6) to simulate parts of the TEMH process of the BBT. Figure 5.7 shows the main part of the contract section Wolf. In particular, the mucking tunnel Padastertal, the lateral adit Wolf and the repository Padastertal are important for the TEMH. In the following a brief overview of the construction schedule of the contract section Wolf and the TEMH is given.

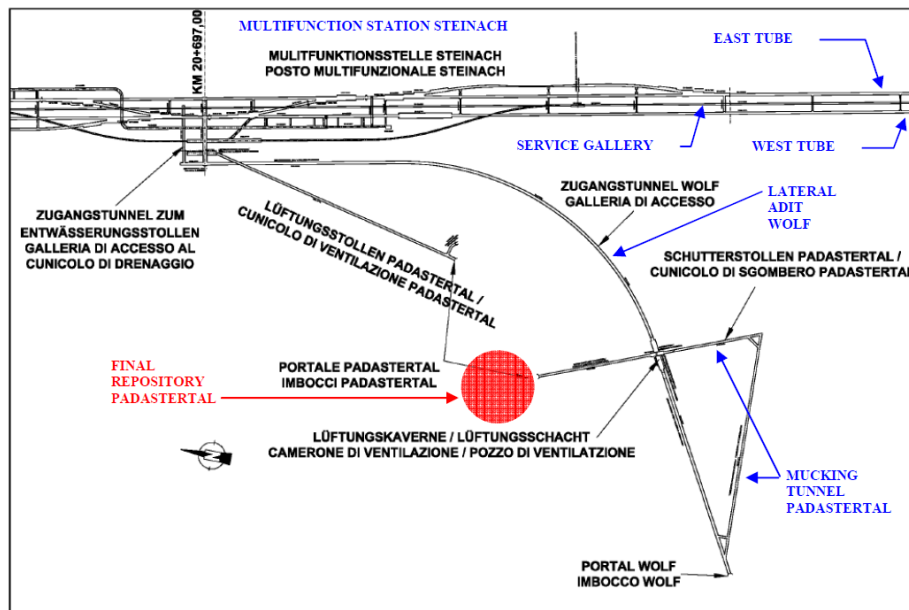


Figure 5.7: Contract Section Wolf; Original Illustration in German; Important Parts are Translated to English (Source of Information: Golser (2008))

5.6.1 TUNNELING OF CONTRACT SECTION WOLF

During the development of the construction site Wolf (Portal Wolf) the first meters of the lateral adit Wolf and the entire mucking tunnel Padastertal will be excavated. In the subsequent exploration phase, the tunnel drift of the lateral adit Wolf will continue and the excavation of the installation caverns will start. Further, the construction of the service gallery toward South and North will start. Figure 5.8 schematically illustrates which tunneling method is used for which tunnel section of the contract section Wolf. In addition, Figure 5.8 shows which tunnel drifts of the main tunnel tubes are related to the contract section Wolf; the tunnel drifts which are represented with arrowheads that point away of the lateral adit Wolf are tunnel drifts of the contract section Wolf.

In the construction phase the East and West tunnel tubes will be constructed, the excavation of the service gallery will continue, and the MFS Steinach will be constructed simultaneously. Figure 5.8 shows that the main parts of the East and West tunnel tubes as well as the service gallery will be constructed by mechanized

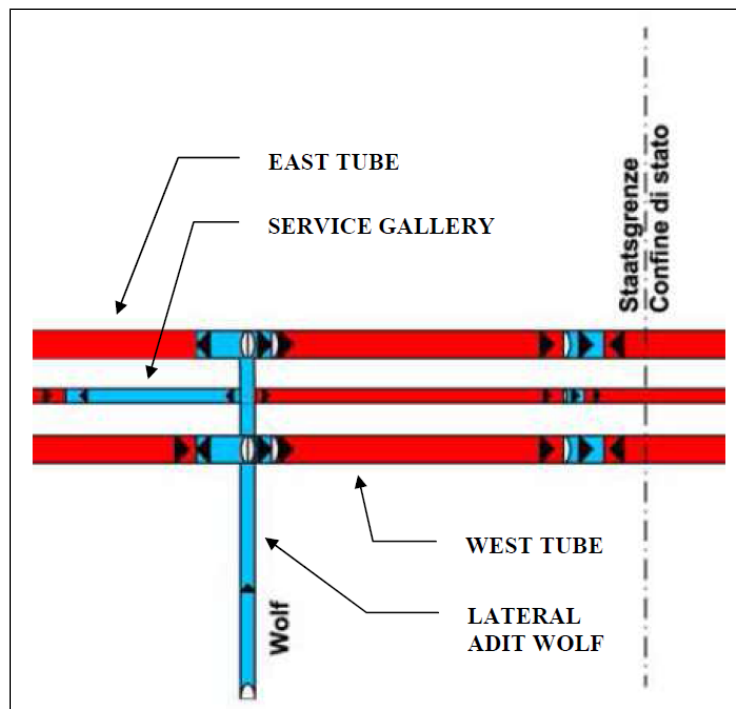


Figure 5.8: Tunneling Methods of Contract Section Wolf: Red Tunnels Are Constructed by Mechanized Means, Blue Tunnels Are Constructed Conventionally, Arrows Show the Direction of the Tunnel Advance (Source of Information: Mazzalai (2008b))

means. It is predicted to perform the mechanized tunneling sections with a single shield TBM with segments as initial support. The tunnel sections which will be constructed conventionally will use the New Austrian Tunneling Method (NATM) with Drilling & 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.

5.6.2 TEMH OF CONTRACT SECTION WOLF

The TEMH of contract section Wolf follows the general concept of the TEMH of the BBT which is described in Section 5.5. Due to the specific conditions of contract section Wolf the material flows of the excavated materials of the contract section Wolf need further discussions.

The excavated materials of the mucking tunnel Padastertal and the lateral adit Wolf will temporarily be stored next to the portal Wolf. After the break-through of the mucking tunnel Padastertal these materials will be transported through the mucking tunnel to the final repository Padastertal using muck cars. Subsequently, a

conveyor will be installed in the lateral adit and the mucking tunnel to transport the excavated materials of the East and West tube, the service gallery, and the MFS to the final repository Padastertal. Therefore, a central material charge will be located in the MFS Steinach to transfer the excavated materials to the installed conveyor. This central material charge will consist of a small stone crusher and a conveyor feeder. Further, a second conveyor will be installed in the lateral adit Wolf and the mucking tunnel Padastertal to handle the quantities of the excavated materials of the main tunnel tubes and the service gallery.

Parts of the excavated materials of the contract section Ahrental, which will not be tipped at the final repository Ahrental due to their limited space, will be tipped at the final repository Padastertal. The transport of these materials will start after the break-through of the contract section Wolf to the contract section Ahrental will be performed. Then the excavation materials transport to the final repository Padastertal will use mainly the conveyors of the lateral adit Wolf and the mucking tunnel Padastertal.

After a first part of the final repository Padastertal is filled, the aggregate plant will be constructed on this part of the repository. Hence, excavated materials of all usage classes will be transported to the final repository Padastertal. Excavated materials of usage class A will be recycled at the aggregate plant, usage class B materials will be stored temporarily and subsequently reused as fill materials, and excavation materials of usage class C will be tipped. The recycled excavated materials will be used as concrete aggregates in the contract section Wolf. Accordingly, these recycled concrete aggregates will supply parts of the initial and final support of the contract section Wolf.

Chapter 6

APPLIANCE OF THE SIMULATION MODEL

Chapter 6 uses the developed simulation model, described in Chapter 4, to simulate the TEMH process of a part of the contract section Wolf (Section 5.6). The goal of this appliance is to show that the DAT is a versatile tool to simulate the tunnel excavation and the material flows of the TEMH process with the associated uncertainties. Most importantly, the outcomes of the simulation are presented to illustrate that the simulation model can be used for decision-making. It is important to note that emphasis is placed on the appliance of the simulation model and not on a detailed simulation of the part of the contract section Wolf.

6.1 SIMULATION AREA

The developed simulation model is applied to the area of the contract section Wolf which is schematically shown in Figure 6.1. Especially, 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 modeled. The applied tunneling methods and the planned TEMH of contract section Wolf are described in Subsection 5.6.1 and 5.6.2. Figure 5.7 shows the main parts of the contract section Wolf. In the following, the material flows of the excavated materials which are simulated are described.

First, the excavated materials of the TBM tunnel drives ("*TBM East Tube*" and "*TBM West Tube*") are transported with conveyors to the multifunction station (MFS) Steinach. A central material charge is located in the MFS Steinach to transfer the excavated materials to the conveyor belt system of the lateral adit Wolf. In the simulation model it is assumed that this MFS simulates the intermediate repository with the related "*Final Material Classification*". Subsequently, the excavated ma-

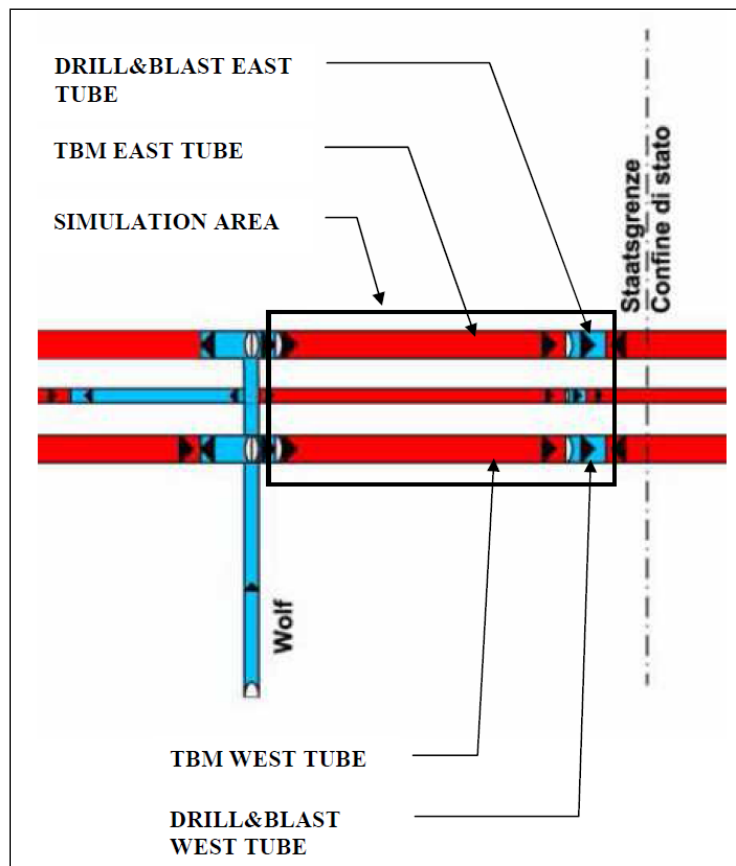


Figure 6.1: Simulation Area of Contract Section Wolf

materials of mechanized tunneling pass the lateral adit Wolf and the mucking tunnel Padastertal using conveyors. After the excavated materials reach 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 until they are reused as fill materials, purchasing of the excavated materials by the mineral processing industry, or tipping at the final repository. After the processing, the recycled excavated materials are reused as aggregate for shotcrete or concrete within the contract section Wolf.

The tunnel drifts using Drill & Blast start after the TBM excavation is finished. Muck cars are used in the simulation to transport the excavated materials to the MFS Steinach. During this transport the excavated materials pass the corresponding tunnel which was excavated by mechanized means. Subsequently, the same material flows as the excavated materials of the preceding mechanized tunnel drifts carried out are simulated.

6.2 SIMULATION INPUTS

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

6.2.1 GEOLOGIC INPUTS

This Subsection discusses the determination of a "*Ground Class*" based on the available informations of the project documents of the BBT. Therefore, the general concept of the determination of a "*Ground Class*" profile (described in Section 4.1) in the simulation model is used. It is of importance to recall that each "*Ground Class*" is assigned a particular "*Construction Method*" which produces a particular excavation materials usage class in the simulation model. After a "*Ground Class*" with their associated uncertainties is defined the inputs of the "*Ground Classes*" in the DAT are described.

GROUND CLASS DETERMINATION

Several tunneling classes according 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 characterized by a particular excavation sequence, support pattern, round length, advance rate, and cost. However, at the time of the simulation these characteristics were not available for the tunneling classes which made assumptions essential.

In the project documents of the BBT the tunneling classes are assigned so-called geotechnical homogeneous zones. A geotechnical homogeneous zone is characterized by specific geomechanic parameters. Predictions of fault zones within a geotechnical homogeneous zone are also considered in the project documents. Therefore, additional tunneling classes are assigned the geotechnical homogeneous zone to treat these fault zones. Table 6.1 shows, for example, the prediction of the mechanized tunneling classes of the geotechnical homogeneous zone N30 of the BBT. Note that the names of the tunneling classes used for the simulation are different compared to the project documents.

It is assumed that only three conventional tunneling classes exist for the Drill & Blast tunnel drifts because the determination of the advance rates of the tunneling classes was only reasonable with three conventional tunneling classes. Table 6.2 shows these conventional tunneling classes and their assumed percentage within each geotechnical homogeneous zone.

Defining the occurrence of the tunneling classes of a particular geotechnical homogeneous in per cent of the length of the geotechnical homogeneous zone has

Table 6.1: Prediction of Tunneling Classes within the Geotechnical Homogeneous Zone N30

Geotechnical 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

Table 6.2: Assumed Percentage of the Assumed Conventional Tunneling Classes within Each Geotechnical Homogeneous Zone

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

disadvantages for the simulations with the DAT. For instance, the exact location of a particular tunneling class within the geotechnical homogeneous zone as well as the location of the transition between a particular tunneling class and a subsequent tunneling class is not defined. In addition, the transition sequence between the tunneling classes is not defined. Most importantly, these approach does not allow one to realize which combination of geologic/geotechnical parameters defines a particular tunneling class.

The classification of the excavated materials regarding their final usage (described in Subsection 5.5.2) is provided in the project documents of the BBT. Again, the excavation materials usage classes are related to the geotechnical homogeneous zones. Table 6.3 represents the per cent values of the occurrence of the excavation material usage classes of the geotechnical homogeneous zone N30. As mentioned before, the per cent values define only the percentage of the excavated materials usage class within the geotechnical homogeneous zone; the exact location and the transition sequence between the usage classes are not defined.

To define the "*Ground Classes*" of the simulation area the geotechnical homogeneous zones are subdivided into the corresponding tunneling classes. Subsequently, every tunneling class of the geotechnical homogeneous zone is in turn subdivided into the predicted excavation material usage classes of the particular geotechnical homogeneous zone. This procedure results in the determination of the "*Ground Classes*" of the geotechnical homogeneous zone. Figure 6.2 illustrates the "*Ground Class*"

Table 6.3: Prediction of Excavation Material Usage Classes within the Geotechnical Zone N30

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

definition of the geotechnical homogeneous zone N30. This procedure is repeated for each geotechnical homogeneous zone of the simulation area. It is important to mention that the transition sequence of the tunneling classes is not considered in the determination of the "*Ground Classes*".

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. These information is used to include the geologic uncertainties of the TEMH, which are, for example, the occurrence of discontinuities or the chemical components of the excavated materials, in the simulation. A simple approach is used to quantify the geologic uncertainties.

The length of each *Ground Class* is characterized with a triangular probability density function. Figure 6.3 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 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 the 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 materials usage classes of the project documents of the BBT. Figure 6.2, shows the mode lengths of the "*Ground Classes*" of the geotechnical homogeneous zone N30. Correlating this mode length of a "*Ground Class*" with the corresponding qualitative specification of the prediction uncertainties (low, medium, high, and very high) of the geology enables one to calculate the minimum- and maximum length of the "*Ground Classes*". Table 6.4 shows the simple quantitative approach which is used to determine the minimum- and maximum lengths of each "*Ground Class*". In addition, Figure 6.4 schematically illustrates the probabilistic determination of the length of a "*Ground Class*". The used length of a "*Ground Class*" in the simulation varies between the range of the minimum- and maximum "*Ground Class*" lengths and is

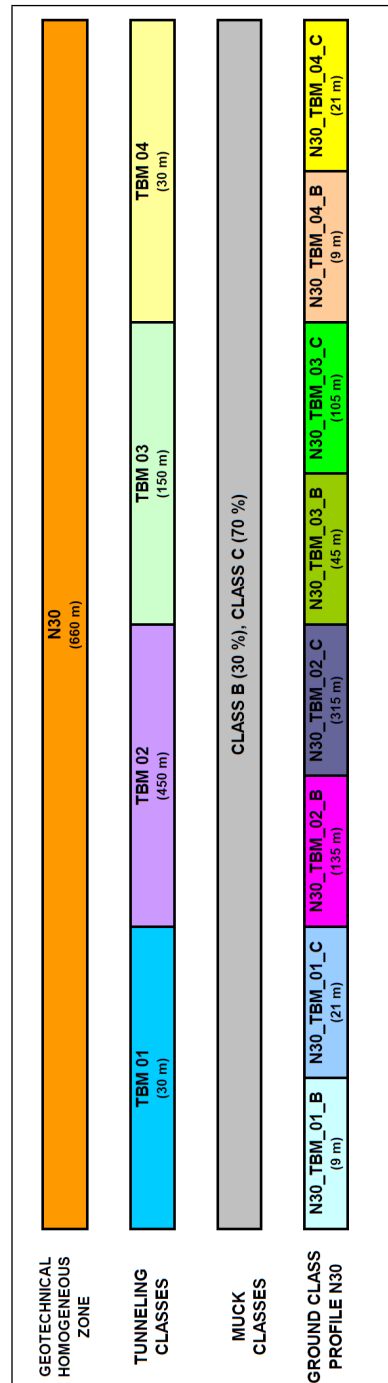


Figure 6.2: "Ground Class" Determination for the Geotechnical Homogeneous Zone N30

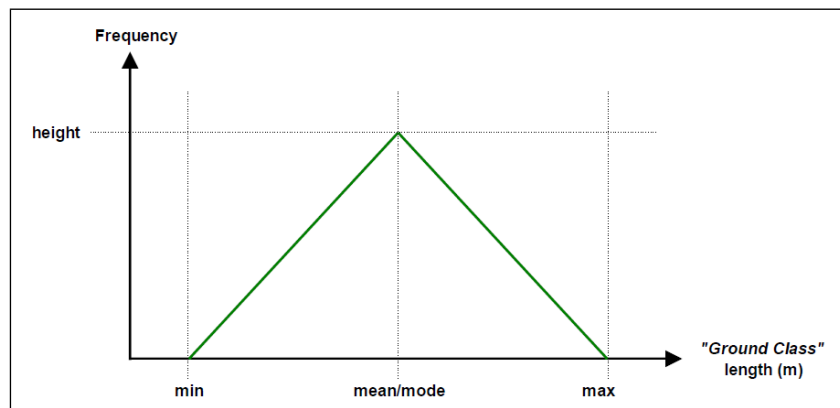


Figure 6.3: Triangular Probability Density Function of a "Ground Class" Length

selected due to a random generator of the DAT for each geology simulation.

Table 6.4: 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

The determination of the "Ground Classes" of the simulation area and their corresponding triangular probability function variables is spreadsheet-based. The results are the inputs in the DAT to simulate the "Ground Class" profile.

INPUTS OF THE GROUND CLASSES

The geology of the simulation area is modeled with an "Area" which is the top level of the input of the Geology module. Figure 6.5 illustrates the "Area" input window. This "Area" represents the entire simulation area of the contract section Wolf beginning with the geotechnical homogeneous zone N24 and ending with the geotechnical homogeneous zone N34. Subsequently, the "Area" is subdivided into as many "Zones" as "Ground Classes" are determined for the simulation area. The extent of each "Zone", which is the basic unit of geology in the DAT, is defined using the triangular probability function of the length of each "Ground Class". The definition of the "Zone" length uses the "Generation Mode 2" (Figure 6.6, "End Pos (Mode 2)") in the DAT. "Generation 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 up to

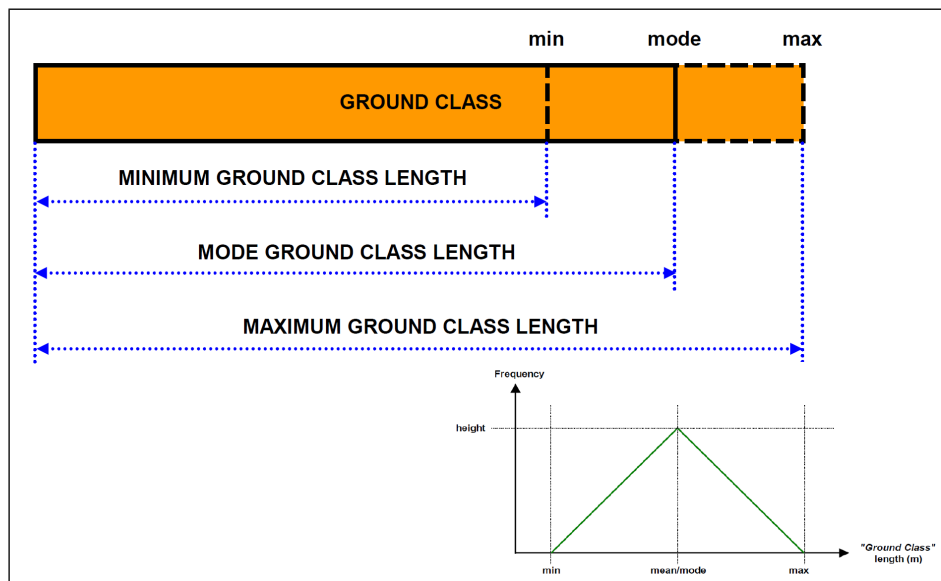


Figure 6.4: Probabilistic "Ground Class" Length Determination

calculate the minimum- ("Min EndPos"), mode- ("Mode EndPos"), and maximum end position ("Max EndPos") of each "Ground Class". The end positions are related to the starting point of the "Area". Appendix B shows the minimum-, mode-, and maximum end positions of each "Ground Class" of the simulation area. Due to this input of a "Zone", which is shown in Figure 6.6, the DAT automatically considers that the generation of the length of the "Zone" is based on a triangular probability density function. The "Zones" are defined by assigning a "Ground Parameter Set" to each "Zone". These "Ground Parameter Set" are defined by "Ground Parameters" which model geologic/geotechnical parameters. A particular combination of these geologic/geotechnical parameters defines, in general, a particular tunneling class. As mentioned before, geologic/geotechnical parameters are not assigned to tunneling classes in the project documents of the BBT. Hence, a dummy "Ground Parameter" is used to define a "Ground Parameter Set" which in turn defines a "Zone". After the determination of the "Zones" the DAT enable one to simulate the "Ground Class" profile. Figure 6.7 represents a simulated "Ground Class" profile of the simulation area. The upper (green) bar of Figure 6.7 represents the "Area". Each color of the lower (multicolor) bar specifies a particular "Ground Class" of the "Ground Class" profile.

6.2.2 CONSTRUCTION INPUTS

The construction inputs Subsection discusses the inputs of the Construction module (Section 4.2) which simulates the construction process through the "Ground Class" profile with the related material flows in the TEMH process. The general "Tunnel

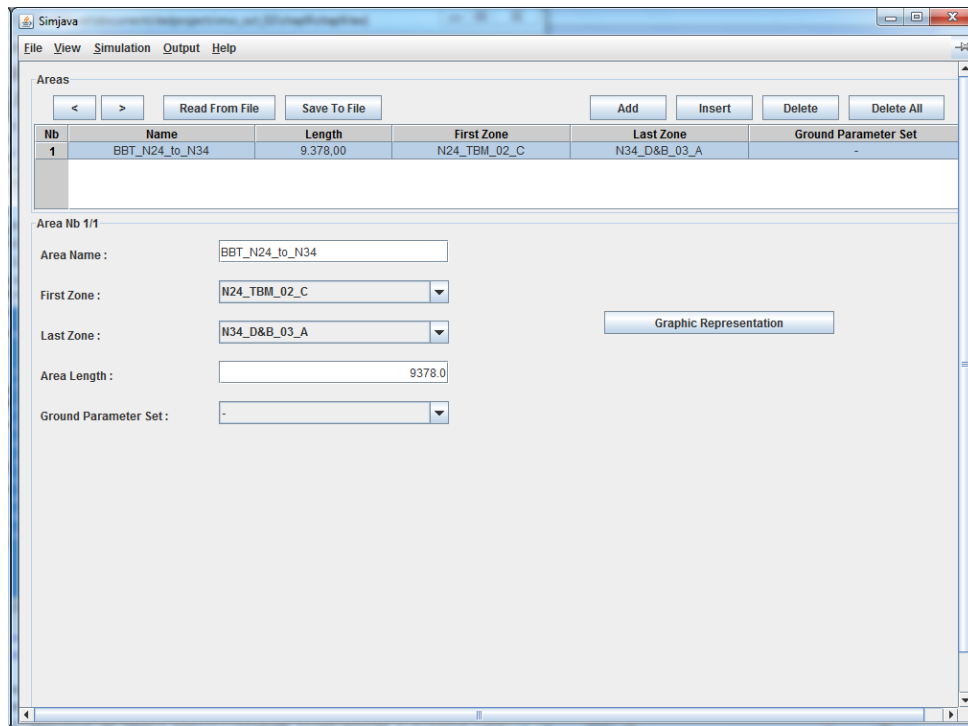


Figure 6.5: "Area" Input Window

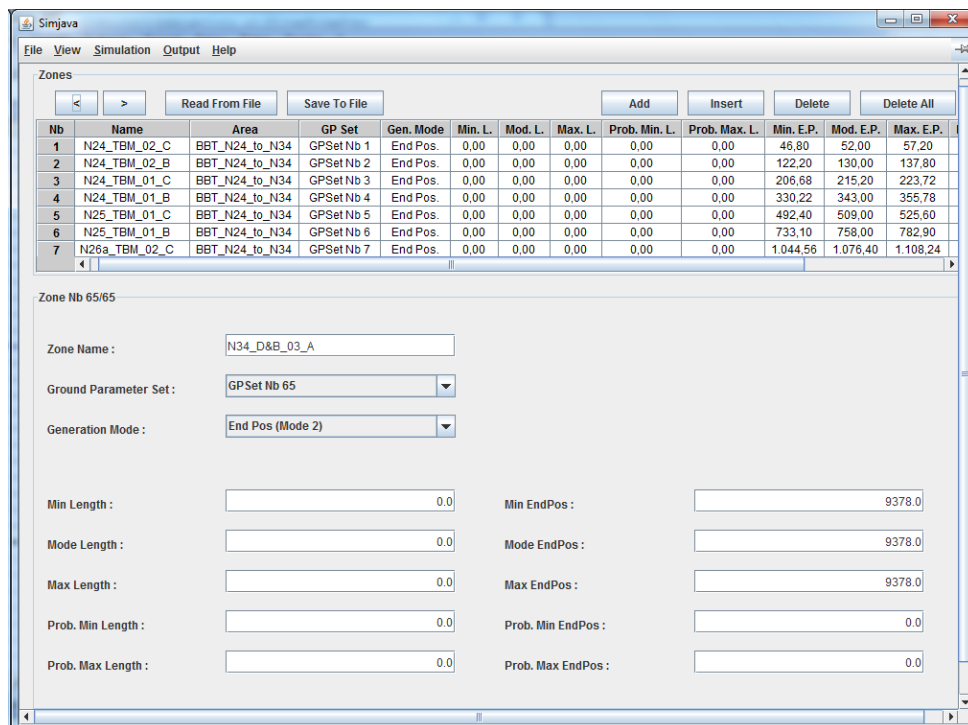


Figure 6.6: "Zone" Input Window with End Point Definition

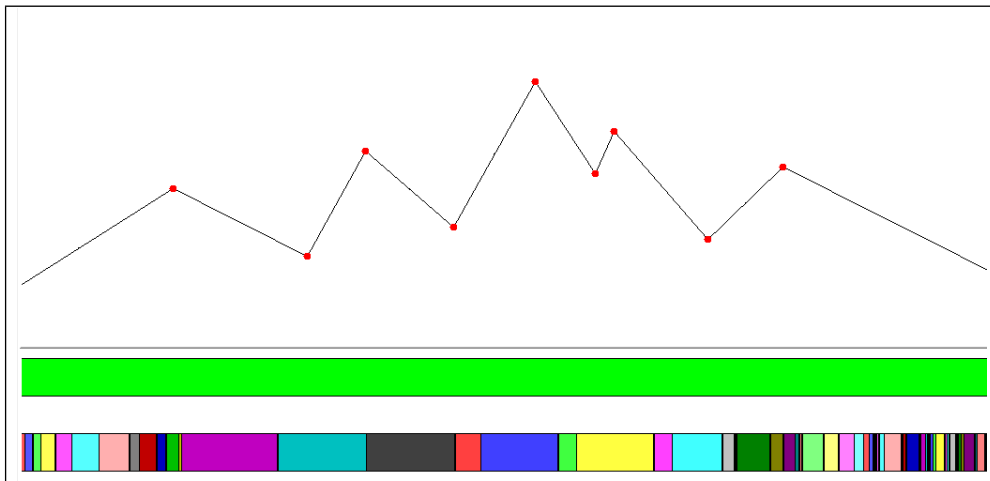


Figure 6.7: Simulated "Ground Class" Profile for the Simulation Area

Network" (Figure 4.4) of the developed simulation model is used for each tunnel drift. Figure 6.8 represents the "Tunnel Network" of the simulation area. The "Tunnels" of the "Tunnel Network" with the appendix "TBM.East.01" and "TBM.East.02" model the "TBM East Tube". There is a need for two "Tunnels" because a "Repository" in the DAT can simulate only a tunnel with a maximum length of 5000 meters. The "TBM East Tube" as well as the "TBM West Tube" are longer than 5000 meters; thus, all geotechnical homogeneous zones before 5000 meters are assigned the "TBM.East.01 Tunnels". The "TBM.East.02 Tunnels" model the remaining geotechnical homogeneous zones of the mechanized tunnel drifts. The same procedure is used for the "TBM West Tube".

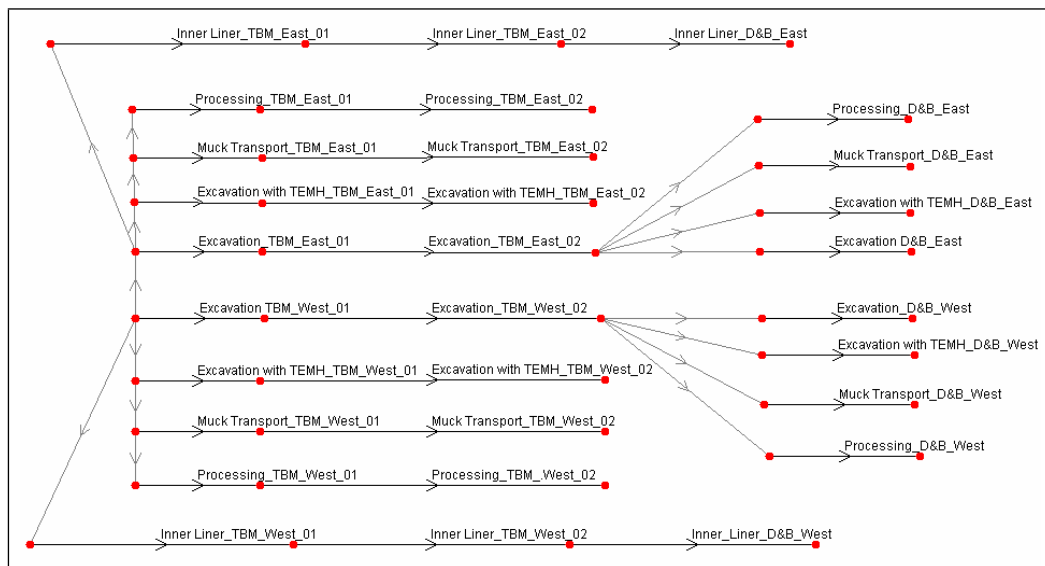


Figure 6.8: "Tunnel Network" of the Simulation Area

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 6.9 shows the "Tunnel Information" window of "Excavation_TBM_East_01" which characterizes, for example, the used "Area", 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 considers that the East tunnel drives follow the West tunnel drives after 95 days.

The screenshot shows the "Tunnel Informations" window for "Tunnel 1/47". The window contains several input fields and tables:

- 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

On the right side, there are three tables, each with "Add", "Delete", and "Insert" buttons:

- 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

Below these tables are two more tables:

- Repositories Table:**

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

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

At the bottom right, there are "Add", "Delete", "Insert", and "Close" buttons.

Figure 6.9: "Tunnel Information" Window

As described in Section 4.2, 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 4.3. In contrast, the "Construction Methods" of the conventional tunnel drifts are simulated with the "Activity Networks" of Section 4.4. In the following, the assumptions of the construction inputs as well as the inputs of the "Construction Methods", their associated "Activities", and the resources are

discussed.

To simplify the simulation the corresponding crossover tunnels are not considered. Min (2003) discussed the simulation of crossover tunnels with the DAT in detail. In addition, it is assumed that the TBM tunnel drifts as well as the Drill & Blast tunnel drifts have a constant cross section area and a constant consumption of initial- and final support per tunnel meter. There is a need for these assumptions because detailed informations regarding the tunneling classes of the BBT were not available at the time of the simulations. Table 6.5 relates the tunnel drifts of the simulation with their assumed constant cross section area and their assumed constant consumption of shotcrete or concrete for the initial- or the final support.

Table 6.5: Cross Section Area and Concrete Aggregate Consumption of the Initial- and Final Support

Tunnel Drift	Cross Section Area (m ²)	Shotcrete/Concrete Initial Support (m ³ /m)	Concrete Final Support (m ³ /m)
TBM East Tube	72.38	8.71	7.82
TBM West Tube	72.38	8.71	7.82
Drill&Blast East Tube	65.40	2.84	7.82
Drill&Blast West Tube	65.40	2.84	7.82

"*Construction methods*", which simulate the tunneling classes in the DAT, specify method variables such as the round (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 back calculated based on the construction schedule of the BBT. Table 6.6 shows the back calculated 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 & Blast tunneling classes exist because it was not possible to back calculate reasonable advance rates for all the tunneling classes of Drill & Blast. In addition, full face excavation is assumed for the Drill & Blast tunneling classes. Table 6.6 shows the advance rate of the construction of the inner liner which is also back calculate from the construction schedule. Considering the construction schedule of the BBT, the lining advance rate is equal for the mechanized- and conventional tunneling drifts.

The advance rates of the tunneling classes are used in the DAT to define the time consumption of a "*Construction Method*". It is of importance to realize that an advance rate of Table 6.6 specifies the advance rate of the entire "*Activity Network*" of the "*Construction Method*". As shown, for instance, in Figure 4.7, the "*Activity Networks*" consist of several "*Activities*" such as "*Excavate&Support*" and "*Maintenance*". Hence, the sum of the time consumption of the "*Activities*" has to be equal

Table 6.6: 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

to the time consumption of the "Construction Method". For this reason, the advance rates of the "Activities" of the "Excavation" subpart of the "Tunnel Network" are back calculated from the corresponding advance rate of the "Construction Method". The subsequent "Activity Networks" of the simulation model which are the "Activity Networks" of the "Excavation with TEMH", the "Muck Transport", and the "Processing" use these back calculated advance rates and judged advance rates for the additional "Activities". The main construction inputs are described below.⁹

"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 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". Figure 6.9 shows the "Tunnel Information" window of the "Tunnel" "Excavation_TBM_East_01" with the assigned "Geometry No 2". The link between a "Construction Method", a particular "Ground Class", and the tunnel geometry is shown in Figure 6.10.

Figure 6.11 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" of the simulation area and simulates the mechanized tunnel construction with the tunneling class "TBM 01" as well as the transport of the excavated materials to the intermediate repository. The "Method Variables" "excavate&support_adv_rate" and "maintenance_adv_rate", which are shown in Figure 6.11, define the advance rates of the corresponding "Activities" and are used in their time equations. Time equations of mechanized tunneling are in detail discussed in

⁹The SIMJAVA User's Manual Min et al. (2009) discusses the inputs of the Construction Module in detail.

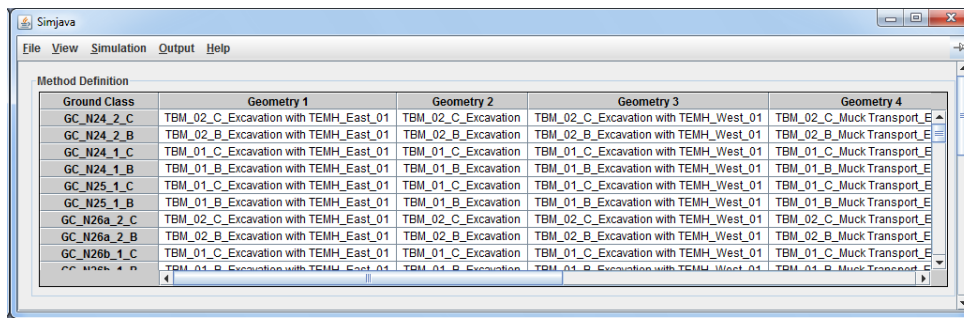


Figure 6.10: "Method Definition" Window, Deterministic Definition of the "Construction Method"

Section 4.3. In addition, the "Cycle Length" input, which is assumed to be a meter for each "Construction Method", defines the length of each construction cycle or round. Figure 6.12 shows the "Activity Network" which combines the "Activities" of "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 Figure 6.11. Section 4.3 explains this "Activity Network" in detail.

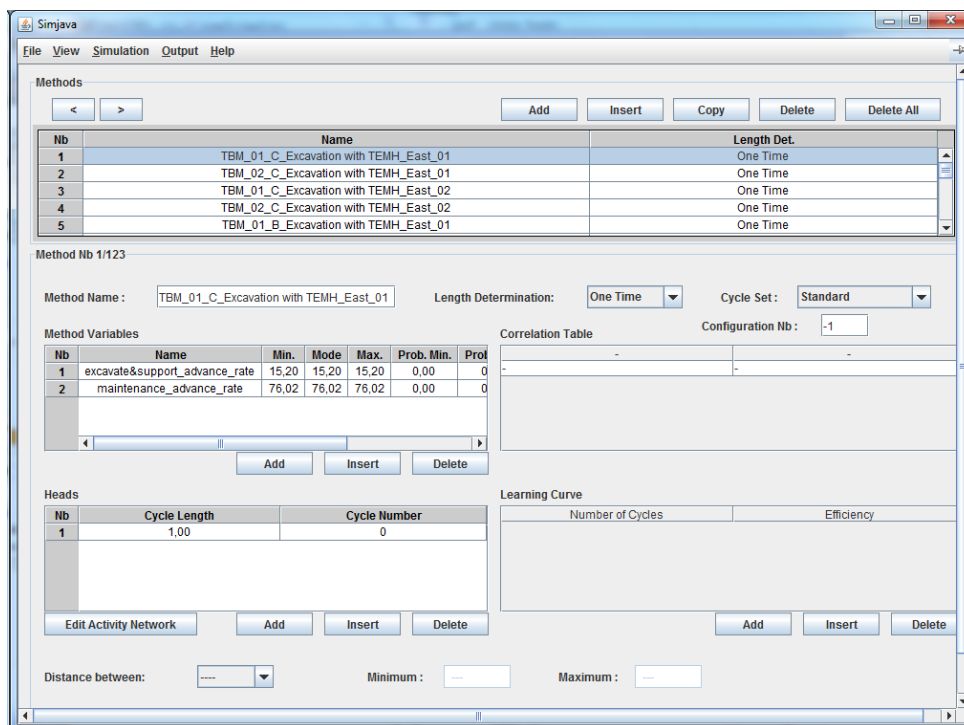


Figure 6.11: "Construction Method" Input Window

Figure 6.13 shows the "Activity" 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". Moreover, the

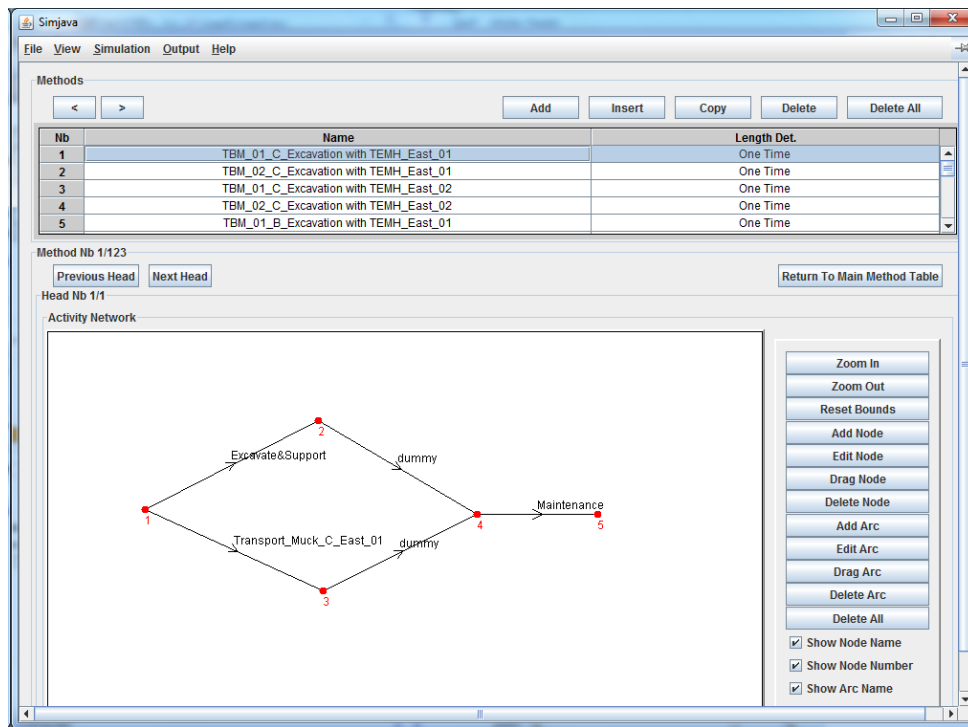


Figure 6.12: "Activity Network" Input Window

used variables ("Method Variables", "Resource Variables" and "General Variables") of the particular "Activity" are shown. The "General Variables" are variables that are not related to a particular "Construction Method"; hence, they can be used for every "Activity". In addition, the "Activity" input window shows which "Construction Method" uses the particular "Activity".

Resources are defined in the DAT to simulate the TEMH process. Figure 6.14 shows the "Resources" window which is used to define the resources of the simulation. These resources are the excavation materials usage classes which are subdivided into the corresponding tunneling method and their location (e.g., intermediate or final repository) within the TEMH process. One can see in Figure 6.13 that the defined resources have to be assigned the corresponding "Activities". The corresponding resource equations of the "Activity" compute the quantity of the used or produced resource.

The repositories of the TEMH process are defined in the "Repositories" window (Figure 6.15). As discussed in Subsection 4.2.4, one "Repository" covers the entire repositories of the simulation area. This "Repository" is called "Simulation Area". The "Stocks" subdivide the "Repository" and model the "real" repository for a particular resource. The initial-, minimum-, and maximum level of a "Stock" defines their capacity. In the simulation it is assumed that the repositories have no initial-, and minimum level. A very high maximum level is assigned each "Stock" to avoid

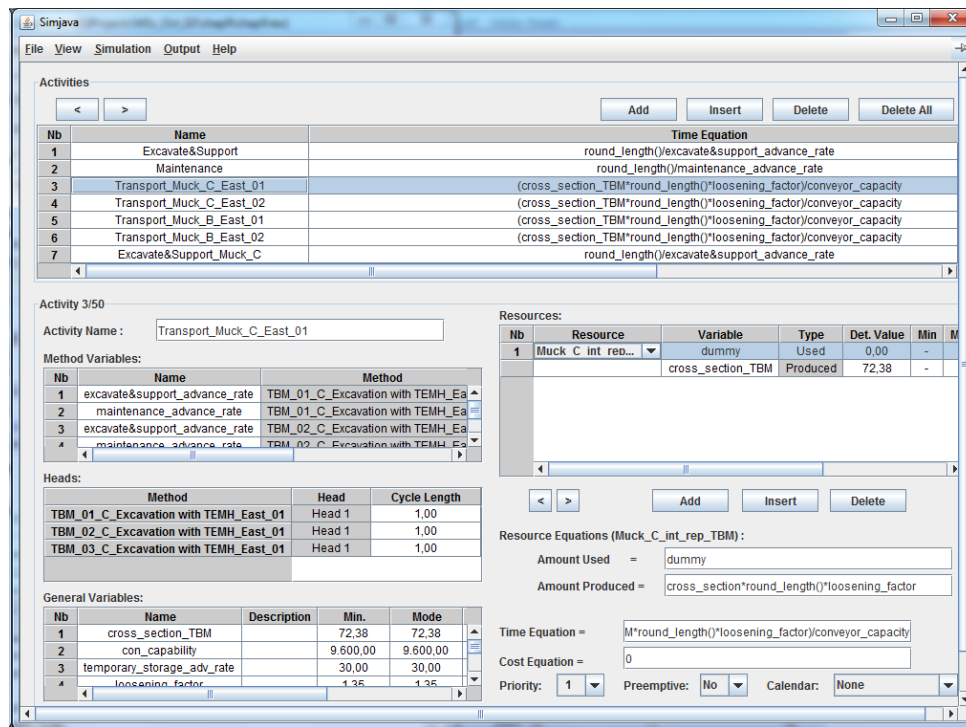


Figure 6.13: "Activity" Input Window

that the material flows wait until space is available in the "Stock" which can lead to an interruption of the construction process.

The last step of the construction input is to define for each "Tunnel" of the "Tunnel Network" what repository must be used. Therefore, in the "Tunnel Information" window the "Repository" of the simulation model is assigned the corresponding "Tunnels" of the "Tunnel Network". Figure 6.16 illustrates this procedure for the "Tunnel" "Processing_TBM_East_01". The "Repository Position" represents the "Tunnel's" length which uses or produces resources of the respective "Repository".

Several simulations were performed during this research. The construction uncertainties which affect the TEMH such as, for example, the uncertain time consumption of the "Final Material Classification" or the "Processing", and the uncertain "Processing" success are simulated with a sensitivity analysis. This analysis considers the geologic uncertainties based on the triangular density function and holds for one analysis all but one variable constant. The change of this variable uses judged extreme values (minimum or maximum value) of these variable or parameter. This procedure includes the uncertain concept of the excavation material processing, which was based on the interviews with the experts the main uncertainty of the TEMH process (see Section 2.3), in the simulation model. The output of this sensitivity analysis will be discussed in the Master of Science Thesis.

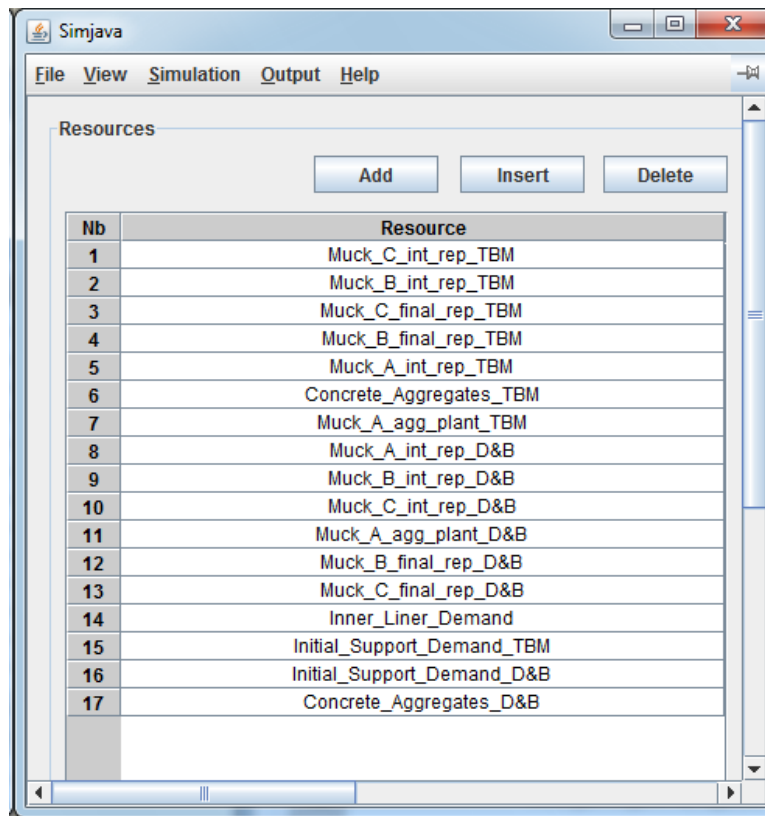


Figure 6.14: "Resources" Input Window

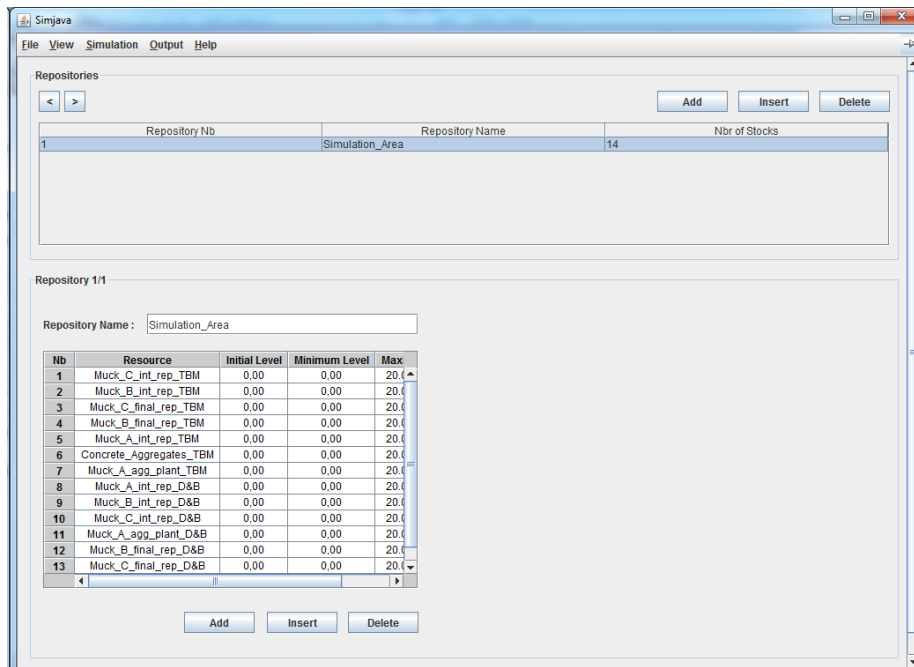


Figure 6.15: "Repositories" Input Window

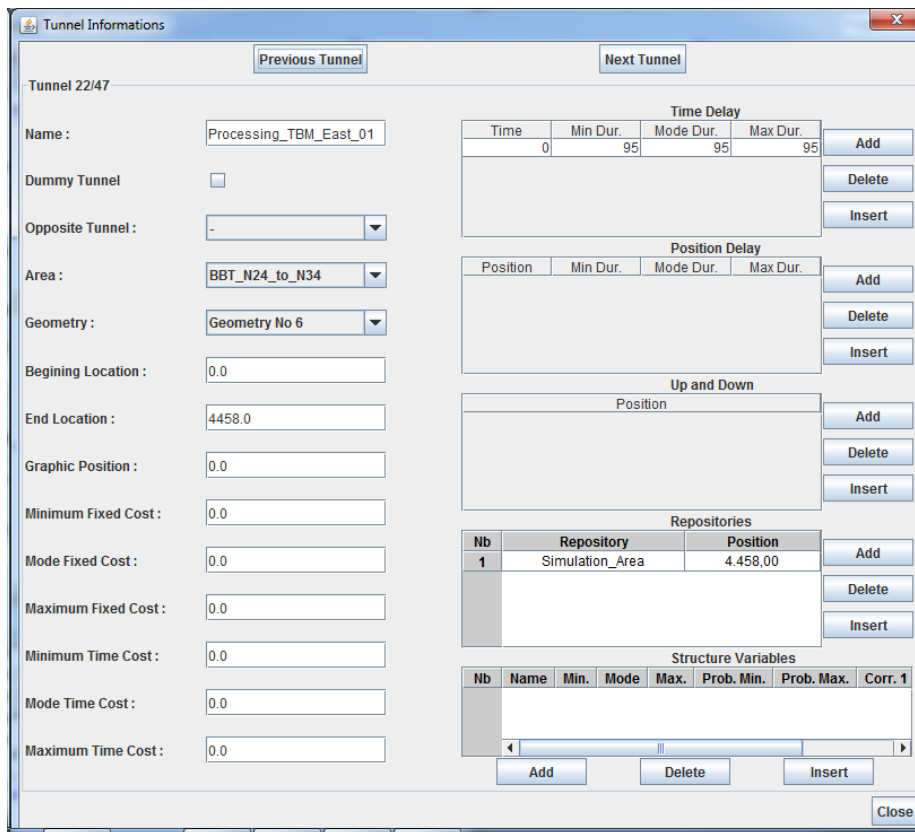


Figure 6.16: "Repository" Assigned to a "Tunnel" in the "Tunnel Information" Window

6.3 SIMULATION OUTPUTS

This Section analyzes the results of the simulation which applies the principles of the developed simulation model to the simulation area of contract section Wolf (Section 6.1). The geologic uncertainties are considered in this simulation. Further investigations of the TEMH using the developed simulation model will be discussed in the Master of Science Thesis.

Since the project documents of the BBT forecast that the excavated materials of the mechanized tunnel drifts of the simulation area are unsuitable for concrete aggregate production, one can see that a lack of concrete aggregates exists for the initial support of the TBM operations. This deficit of the produced concrete aggregates stops the simulation. For this reason, two simulation techniques are presented:

- **Simulation Technique I** computes the demand for concrete aggregates of the initial support and the inner liner. This consumption of concrete aggregates is compared with the concrete aggregate production.
- **Simulation Technique II** shows also the demand for concrete aggregates of

the initial support. In contrast, the concrete aggregate consumption of the inner liner is taken from the produced concrete aggregates. If a deficit of the produced concrete aggregates occurs the simulation will stop.

Apart from the discussed differences of simulation technique I and II, the same inputs are used. In addition, both simulation techniques use for one simulation 100 geology runs and a corresponding construction run per geology run. Taken together, one simulation consists of 100 multiple simulation runs. The considered geologic uncertainties lead to variations in the results of each multiple simulation run.

6.3.1 OUTPUTS OF SIMULATION TECHNIQUE I

The output of the simulation can be presented in various ways. Figure 6.17 shows a simulated time-volume plot which is a particularly useful form of the output. The quantities of the excavated material classes can be used to assess the performance in non-monetary terms because the volume of the excavated materials has a meaning due to its effects on the environment (Einstein, 1996). In addition, one can see in Figure 6.17 the volume of the produced concrete aggregates as well as the demand for concrete aggregates of the initial support and the inner liner.

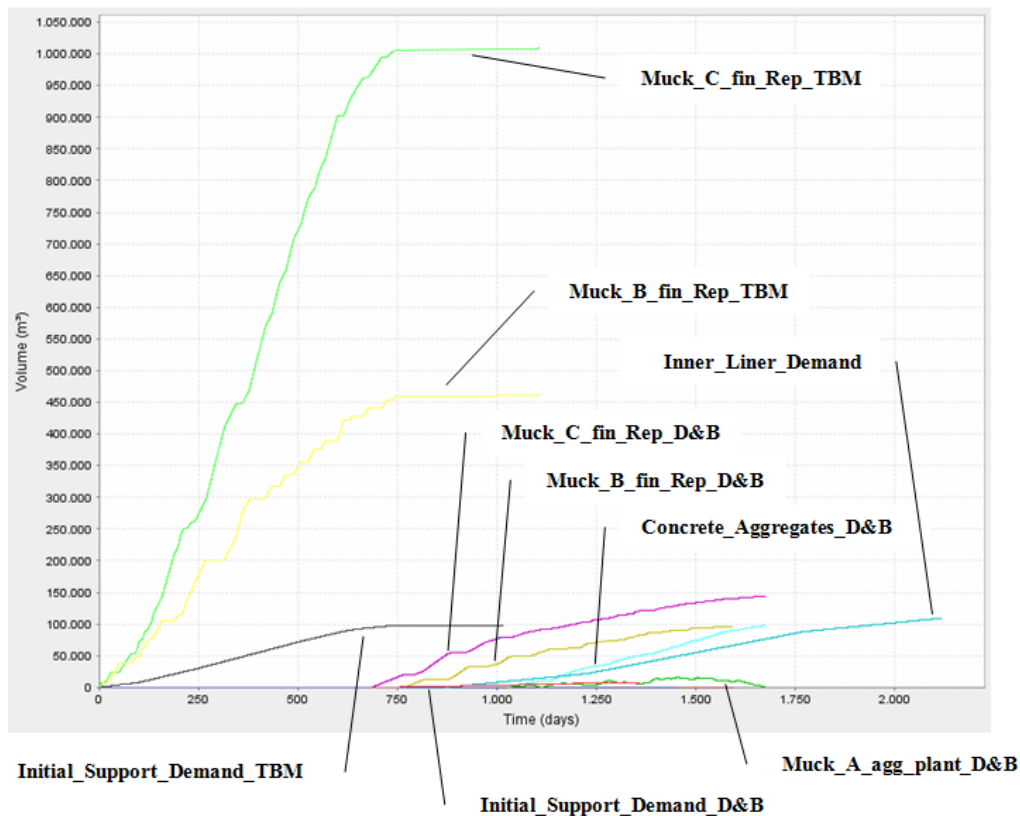


Figure 6.17: Time-Volume Plot of one Simulation Run of Simulation Technique I

Figure 6.18 shows a detailed time-volume plot of one simulation run from the Drilling & Blasting operations. In this plot the demand for concrete aggregates of the initial support ("*Initial_Support_Demand_D&B*") and the inner liner ("*Inner_Liner_Demand*") is compared with the produced concrete aggregates ("*Concrete_Aggregates_D&B*") of the simulation area. Six stages can be identified in Figure 6.18:

- **Stage A:** In stage A no concrete aggregates are produced. Concrete aggregates for the shotcrete of the initial support of the Drill & Blast operation have to be purchased from regional suppliers.
- **Stage B:** The construction of the lining starts which requires concrete aggregates. Again, the quality of the excavated materials is insufficient for concrete production; hence, concrete aggregates have to be purchased for the initial support and the inner liner.
- **Stage C:** Suitable excavation materials are recycled to concrete aggregates. These produced concrete aggregates cover parts of the aggregate consumption of the initial and final support (inner liner). Additional aggregates for the shotcrete and concrete production have to be purchased from regional suppliers.
- **Stage D:** One can see in Figure 6.18 that the production rate of the concrete aggregates is higher than the shotcrete or concrete production rate. As a result, the volume of the produced aggregates exceeds the volume of the required aggregates for the initial- and final support. The deficit of the additional concrete aggregates has to be purchased.
- **Stage E:** The tunnel advances are completed at the beginning of stage E; however, the concrete aggregates production continues. One can see that concrete aggregates are only required for the inner liner. In stage E self-sufficient supply of produced concrete aggregates is guaranteed for the inner liner. The remaining produced concrete aggregates can be stored for later usage.
- **Stage F:** The production of the concrete aggregate stops. The stored concrete aggregates of stage E as well as purchased concrete aggregates are used for the inner liner construction.

The geologic uncertainties which affect the TEMH can be seen in the multi graph time-volume plot (Figure 6.19). This plot contains all multiple simulation runs of a simulation. One can see in Figure 6.19 that, in particular, the volume of the excavation material usage classes B and C are affected by the geologic uncertainties. The distribution of these volumes can be used for decision-making; for instance, the available space of the final repository can be evaluated considering the geologic uncertainties.

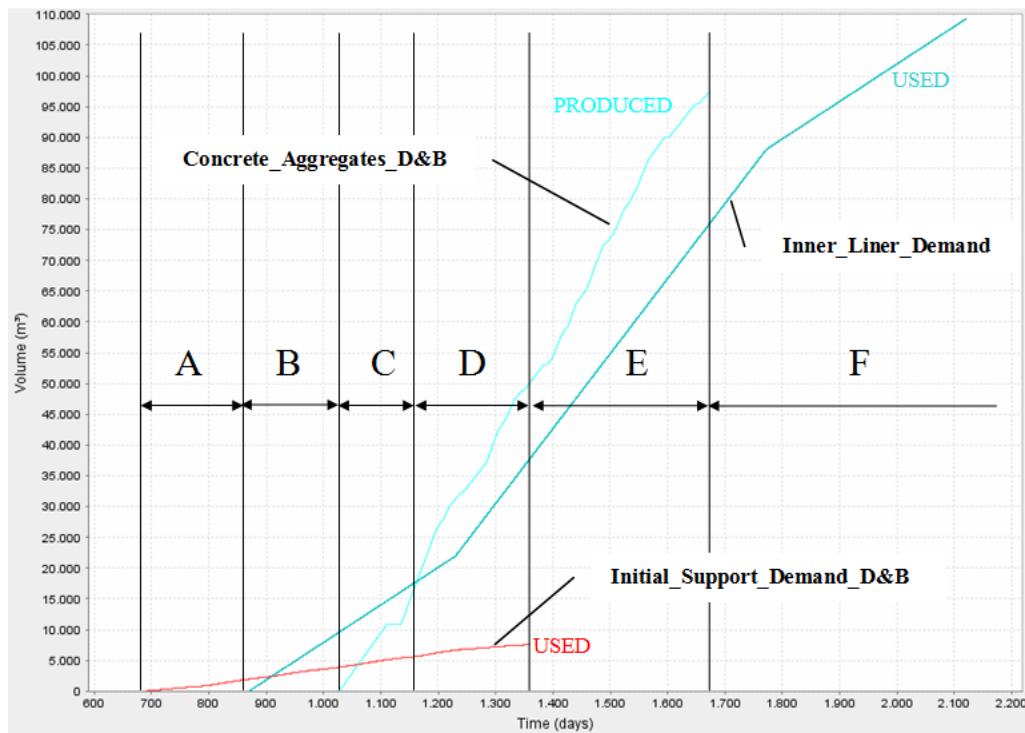


Figure 6.18: Detailed Time-Volume Plot of one Simulation Run of Simulation Technique I

Another useful output is in the form of position-time plots (Figure 6.20) which represents the advance of the tunnel construction performance with the related TEMH. Each "Tunnel" of the "Tunnel Network" of the simulation area is shown in Figure 6.20 with a particular line. This concept allows one to figure out how the material flows in the TEMH affect the construction performance. For instance, the Drill & Blast tunnel excavation of the West tunnel tube without considering the TEMH ("Excavation D&B West") performs faster than the tunnel excavation of the same tunnel which considers the excavation material transport from the excavation face to the intermediate repository ("Excavation with TEMH D&B West"). "Muck Transport D&B West" overlaps with "Excavation with TEMH D&B West" because this simulation considers that the "Final Material Classification", which requires temporary storage space, does not perform in the MFS Steinach due to limited space. Hence, based on the used "Activity Networks" of Figure 4.17 "Part 3" is not the critical path and thus the transport to the final usage performs simultaneously with the more time consuming tunnel construction. The additional time of the subsequent transport of the excavated materials from the final repository and a possible processing represents the "Processing D&B West" graph. The graphs of the "Excavation", "Excavation with TEMH", "Muck Transport" and "Processing" subpart of the particular mechanized tunnel drifts are overlapped in Figure 6.20. There are two reasons for this

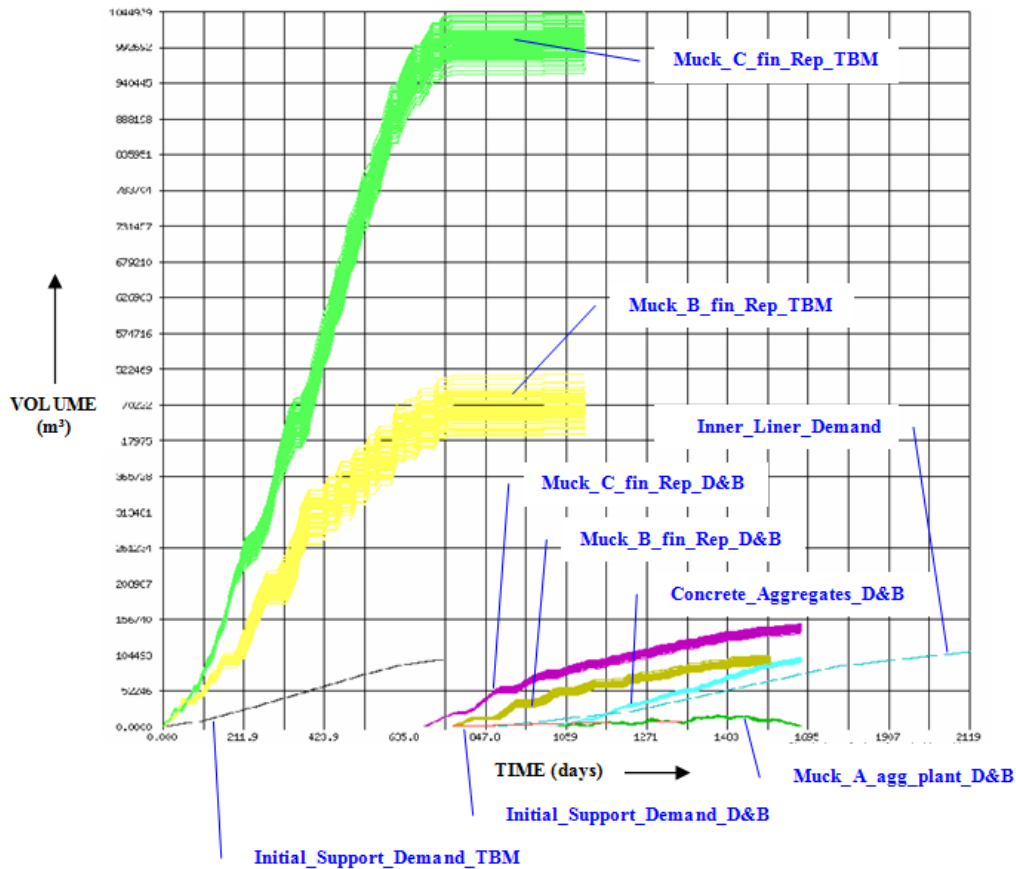


Figure 6.19: Multi Graph Time-Volume Plot of Simulation Technique I

overlapping; the transport of the excavated materials to the intermediate- and final repository can perform simultaneously with the tunnel excavation based on the used "Activity Networks" of Section 4.3 if "Excavate&Support" is the critical path, and the "Processing" does not perform due to unsuitable excavation materials in the area of the mechanized tunnel drifts. The time- and the position gaps between the different tunnel drifts as well as between the tunnel drifts and the initial support is based on the information of the construction schedule of the BBT.

Figure 6.21 represents the detailed final cost-time plot of the "Tunnel" "Processing_D&B_West" which is another form of output. As mentioned before the costs are not considered in this research; thus, no cost values are included in the simulation. However, the time variation of the performance of the tunnel excavation of the "TBM West Tube" with the related material flows in the TEMH based on the geologic uncertainties can be seen. In addition, the normal approximation as well as the time histogram are drawn in Figure 6.21. The time distribution shows the variation of the construction performance which is based on the associated uncertainties. This result shows that the time of "Processing_D&B_West" is very robust against the geologic

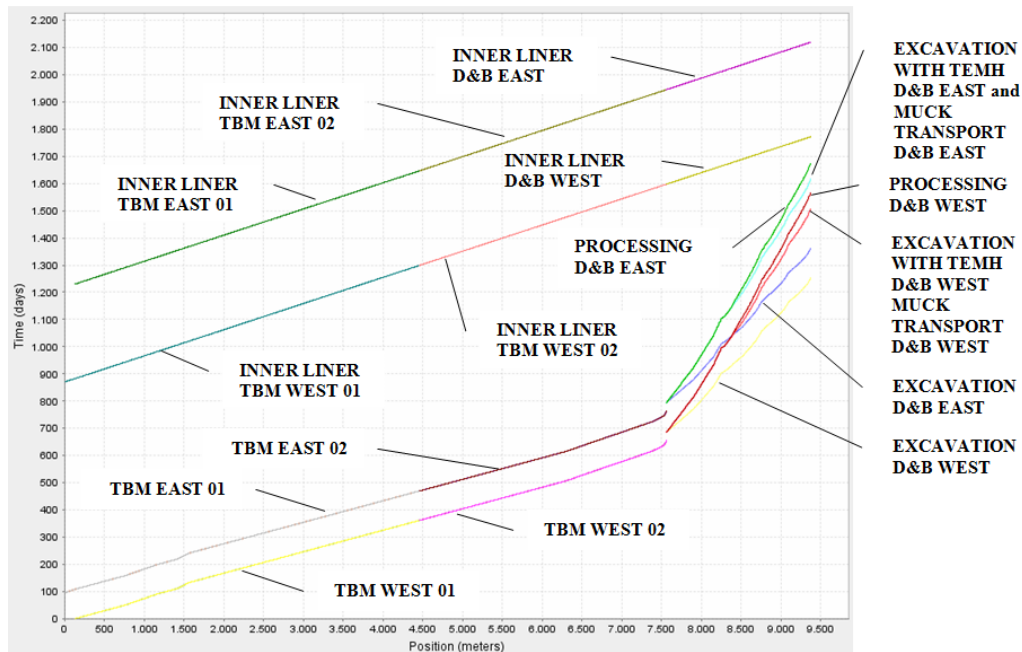


Figure 6.20: Position-Time Plot of a Simulation Run of Simulation Technique I

uncertainties.

6.3.2 OUTPUTS OF SIMULATION TECHNIQUE II

The differences of the outputs of the simulation technique II to the simulation technique I are discussed in the following.

Figure 6.22 shows the time-volume plot of a simulation run of simulation technique II. As can be seen in Figure 6.22 the graph of the concrete aggregates is reduced due to the consumption of concrete aggregates of the inner liner. Figure 6.23 shows this in detail. This reduction continues as long as sufficient produced concrete aggregates are available. At the time of the consumption of all the produced concrete aggregates the simulation stops due to a deficit of the produced concrete aggregates.

In addition, one can see in Figure 6.24 that the construction of the inner liner starts later (Day 1029) if simulation technique II is used. In contrast, the construction of the inner liner starts at day 870 (Figure 6.20) if simulation technique I is used. The reason for this later start is that the construction of the inner liner in simulation technique II waits until the produced concrete aggregates are available. One can follow that simulation technique II shows how an insufficient self-supply of the concrete aggregates, which depends on the muck quality, can affect the construction time. Moreover, Figure 6.24 shows that the construction of the inner liner stops at a certain time due to the deficit of the produced concrete aggregates. This shows that there is a need for purchasing additional concrete aggregates to finish the inner liner construction.

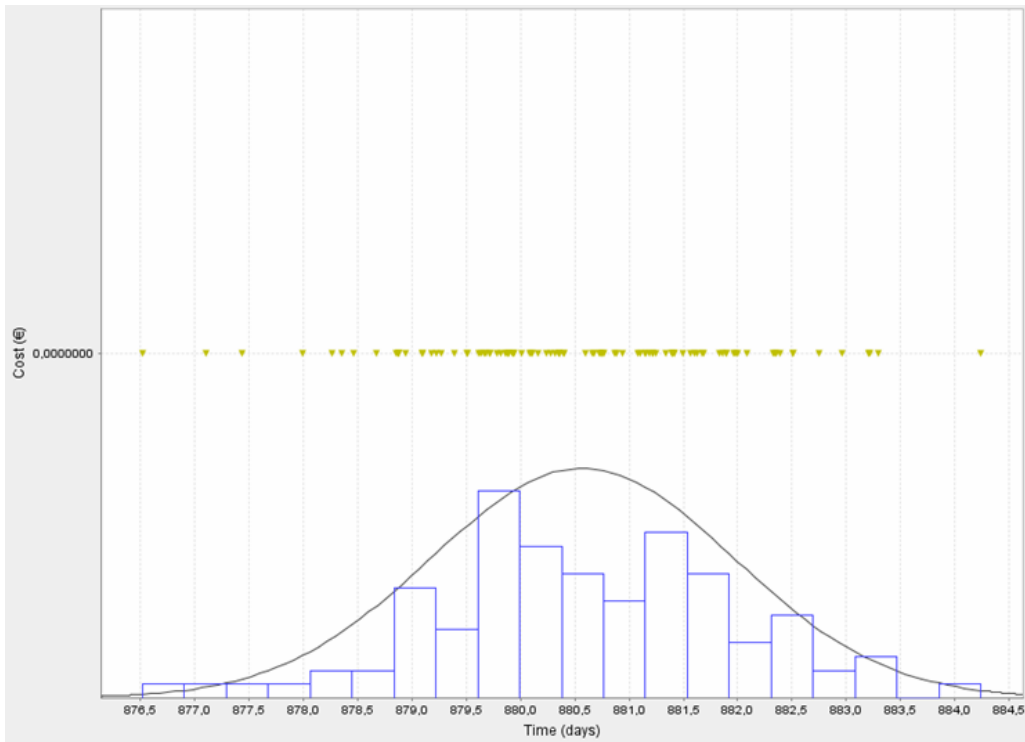


Figure 6.21: Detailed Final Cost-Time Plot of All Simulation Runs of Simulation Technique I

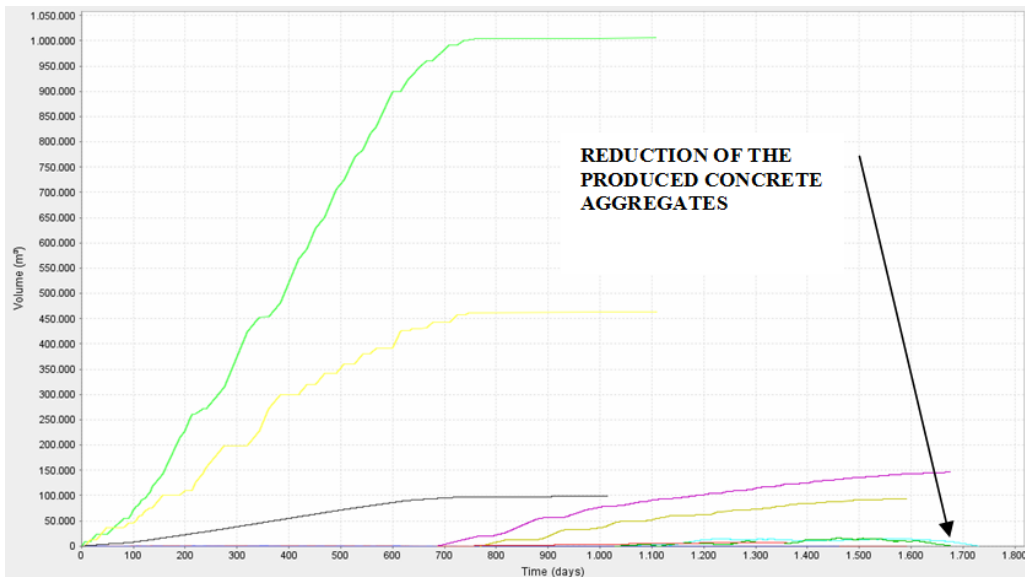


Figure 6.22: Time-Volume Plot of a Simulation Run of Simulation Technique II

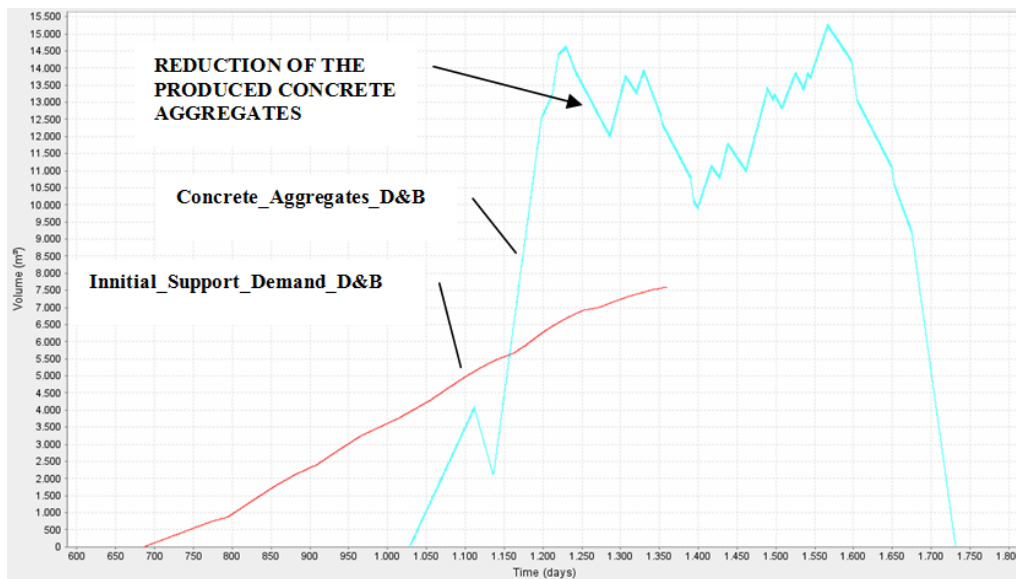


Figure 6.23: Reduction of the Produced Concrete Aggregates of the Drill & Blast operation; Time-Volume Plot of a Simulation Run of Simulation Technique II

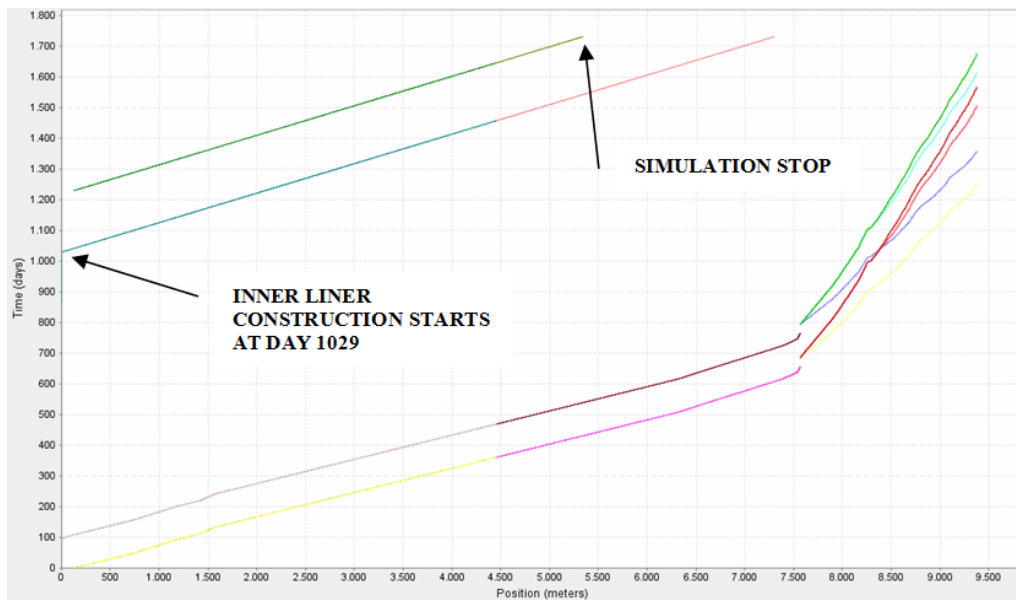


Figure 6.24: Position-Time Plot of a Simulation Run of Simulation Technique II

Comparing the outcomes of simulation technique I and simulation technique II shows their advantages and disadvantages. Taken together, simulation technique I has the advantage that the simulation does not stop due to a lack of resources which is the disadvantage of simulation technique II. If it is assumed that sufficient resources are available during the entire construction process simulation technique I can be used for planning the materials management such as the additional supply of concrete aggregates at a certain time stage (see discussion of Figure 6.18). However, simulation technique I does not consider the impact of a temporary lack of resources. In contrast, simulation technique II considers the influences on the construction performance if a temporary deficit of resources exist. Hence, simulation technique II enables one to show, for instance, how an insufficient recycling of excavated material to concrete aggregate can hold back the construction performance.

Chapter 7

SUMMARY AND CONCLUSIONS

Planning the tunnel excavation material handling (TEMH) is a problem of decision-making under uncertain conditions. This report shows that the uncertainties affecting the TEMH process can be assessed and represented in a decision analysis procedure. In particular, an economic model of the probabilistic (model) phase of the decision analysis cycle is introduced which simulates the entire material flows of the TEMH process; starting with the excavation of the material and ending with reuse or tipping. The simulation model is applied to a part of the Brenner Base tunnel to show its practicability. One can see that the outcomes of the simulation model can serve as aids for decision-making and thus can improve the planning of the TEMH.

Bibliography

- G. B. Baecher. Site Exploration: A Probabilistic Approach. *Massachusetts Institute of Technology*, (Doctoral Thesis), 1972. [cited at p. 2]
- BBT SE. Web Page of Brenner Basistunnel BBT SE, 2010. URL www.bbt-se.com. [cited at p. 51, 52, 53, 55, 108]
- K. Bergmeister. Alpenquerende Tunnel: Projektübersicht und Materialbewirtschaftung beim Brenner Basistunnel. *Beton- und Stahlbetonbau*, 102(1):19–23, 2007a. ISSN 00059900. [cited at p. 52, 108]
- K. Bergmeister. Brenner Base Tunnel: Link between Munich and Verona. *Tunnel*, 2007(01):9–20, 2007b. [cited at p. 54, 57]
- K. Bergmeister. Brenner Base Tunnel : Stage reached by Construction. *Tunnel*, 2010(01):6–17, 2010. [cited at p. 9, 54, 55, 57, 60, 108]
- R. Brandner. BBT SE, Technical Report D0154-00031: Geologie, Geologisches Modell, 02-29-2008. 2008. [cited at p. 100, 101, 102, 109]
- R. Brandner and M. John. BBT SE, Technical Report D0154-00044: Ausbruchmaterial und Eigenschaften, 02-29-2008. 2008. [cited at p. 55, 58]
- G. H. Brundtland. *Our Common Future*. Oxford University Press, UK, 1987. [cited at p. 9]
- D. Burger, B. Kohlböck, and C. Schoitsch. Geotechnics and mass balance of the earthworks for the second tube of the Tauern Tunnel / . Geotechnik und Massenbilanz der Erdbauprojekte der zweiten Röhre Tauerntunnel. *Geomechanics and Tunneling*, 3(4):391–401, Aug. 2010. ISSN 18657362. [cited at p. 13]
- 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. 1, 2]

- 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. 2]
- H. H. Einstein. Risk and Risk Analysis in Rock Engineering. *Tunnelling and Underground Space Technology*, 11(2):141–155, 1996. [cited at p. 7, 83]
- H. H. Einstein. The Decision Aids for Tunnelling (DAT) - a Brief Review. *Tunnelling Technology*, pages 37–51, 2001. [cited at p. 15, 18, 19, 107]
- H. H. Einstein. Decision Aids for Tunneling: Update. *Transportation Research Record: Journal of the Transportation Research Board*, 1892:199–207, Jan. 2004. ISSN 0361-1981. [cited at p. 12, 15]
- H. H. Einstein. Treatment of Risks in Rock Engineering. *Working Paper (Unpublished)*, Massachusetts Institute of Technology, pages 1–26, 2009. [cited at p. 3, 5, 6, 7, 16, 107]
- H. H. Einstein and G. B. Baecher. Probabilistic and statistical methods in engineering geology. *Rock Mechanics and Rock Engineering*, 16(1):39–72, Feb. 1983. ISSN 0723-2632. [cited at p. 1, 2]
- 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. 5, 107]
- 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. 6]
- M. H. Faber. Risk and Safety in Engineering. *Scriptum, Lecture Notes, ETH Zürich*, 2009. [cited at p. 2]
- 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, Oct. 2000. ISSN 08867798. [cited at p. 10, 12]
- H. Golser. BBT SE, Technical Report D0118-02916-10: Bauwerksplanung - Einreichplanung, 02-29-2008, 2008. [cited at p. 61, 108]
- C. Haas. Updating in the "Decision Aids for Tunneling". *Massachusetts Institute of Technology*, (Master of Science Thesis), 2000. [cited at p. 27]
- C. Haas and H. H. Einstein. Updating the Decision Aids for Tunneling. *Journal of Construction Engineering and Management*, 128(1):40–48, 2002. ISSN 07339364. [cited at p. 27]

- V. B. Halabe. Resource Modeling for DAT. *Massachusetts Institute of Technology*, (Doctoral Thesis), 1995. [cited at p. 19]
- G. Harer and P. Pichler. Solutions for the sustainable reduction of the tipping requirement at the Koralm tunnel /. Lösungen zur nachhaltigen Verringerung des Deponieerfordernisses beim Koralmtunnel. *Geomechanics and Tunnelling*, 2(5): 627–632, 2009. [cited at p. 10]
- R. A. Howard. Decision Analysis: Applied Decision Theory. In *Proceedings of the Fourth International Conference on Operational Research*, pages 55–71, New York, 1966. Wiley-Interscience. [cited at p. 3, 5]
- R. A. Howard. The Evolution of Decision Analysis. <http://decision.stanford.edu/library/ronald-a.-howard/the-evolution-of-decision-analysis-1/the-evolution-of-decision-analysis>, (Download: 15-06-2010):1–7, 2010a. [cited at p. 3, 4, 5]
- R. A. Howard. The Foundations of Decision Analysis Revisited. <http://www.usc.edu/dept/create/assets/001/50843.pdf>, (Download: 15-06-2010):1–44, 2010b. [cited at p. 3, 4, 7, 107]
- 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, 2007. ISSN 07339364. [cited at p. 5]
- C. Kollarou. Excavation Materials Handling in the Loetschberg Base Tunnel using Decision Aids for Tunneling (DAT). *Massachusetts Institute of Technology*, (Master of Science Thesis), 2002. [cited at p. 19]
- M. Kruse. Preparing the excavated Material at the Gotthard Base Tunnel. *Tunnel*, 5:27–34, 2002. [cited at p. 10]
- 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. 2]
- R. H. Lieb. Materials management at the Gotthard Base Tunnel - experience from 15 years of construction. *Geomechanics and Tunnelling*, 2(5):619–626, Oct. 2009. ISSN 18657362. [cited at p. 13, 38]
- C. Marzer. Decision aids for tunneling (DAT): development of the resource model. *Massachusetts Institute of Technology*, (Final Report), 2002. [cited at p. 19]
- P. Mazzalai. BBT SE, Technical Report D0118-04340: Ausbruchmaterialbewirtschaftungskonzept, 02-29-2008. 2008a. [cited at p. 57, 58, 110]

- P. Mazzalai. BBT SE, Technical Report D0118-02369: Bauleistungskonzept Österreich, 02-29-2008. 2008b. [cited at p. 62, 108]
- S. Min. The Application of Decision Aids for Tunneling (DAT) to the Sucheon tunnel in Korea. *Massachusetts Institute of Technology*, (Master of Science Thesis), 2003. [cited at p. 76]
- S. Min. Development of the Resource Model for the Decision Aids for Tunneling (DAT). *Massachusetts Institute of Technology*, (Doctoral Thesis), 2008. [cited at p. 15, 16, 19, 29, 41, 107]
- S. Min, Y. Moret, C. A. Indermitte, C. Marzer, and H. H. Einstein. Decision Aids for Tunneling SIMJAVA. *Massachusetts Institute of Technology*, (User's Manual), Jan. 2009. doi: 10.3141/1656-02. [cited at p. 19, 21, 24, 31, 77, 107]
- Y. Moret, R. L. Sousa, and H. H. Einstein. The Decision Aids for Tunneling (DAT) - Introduction and recent Applications in Portugal. In *Tunnels for High-Speed Railways*, pages 1–17, 2009. [cited at p. 16]
- E. M. Paté-Cornell. Uncertainties in risk analysis: Six levels of treatment. *Reliability Engineering & System Safety*, 54(2-3):95–111, Nov. 1996. ISSN 09518320. [cited at p. 2]
- D. Resch, K. Lassnig, R. Galler, and F. Ebner. Tunnel excavation material - high value raw material. *Geomechanics and Tunnelling*, 2(5):612–618, Oct. 2009. ISSN 18657362. [cited at p. 9, 10]
- 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. 5, 6]
- P. Teuscher, C. Thalmann, A. Fetzer, and C. Carron. Alpenquerende Tunnel: Materialbewirtschaftung und Betontechnologie beim Lötschberg-Basistunnel. *Beton- und Stahlbetonbau*, 102(1):2–10, Jan. 2007. ISSN 00059900. [cited at p. 38]
- 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). *ETH Zürich*, (Doctoral Thesis), 1996. [cited at p. 12]

Appendices

Appendix A

GEOLOGICAL LONGITUDINAL SECTIONS

Figure A.1 to Figure A.3 illustrate the main geology sections along the alignment of the Austrian part of the BBT. Subsection 5.4 briefly discusses these geology sections.

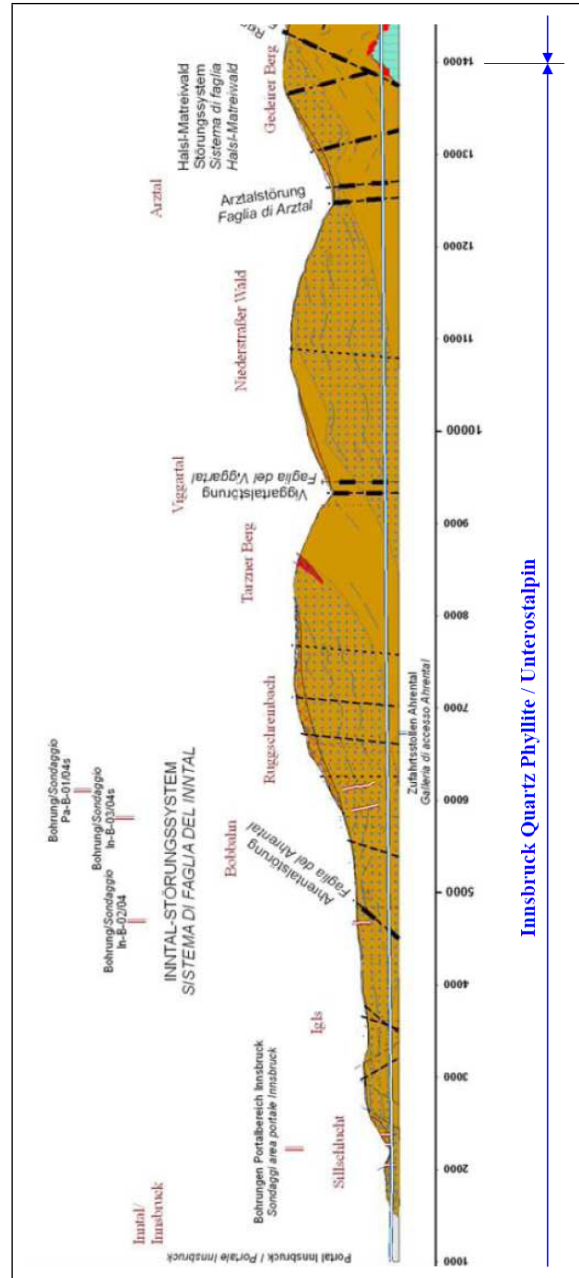


Figure A.1: Geological Longitudinal Section 01 of the Austrian Part of the East Tube of the BBT (Source of Information: Brandner (2008))

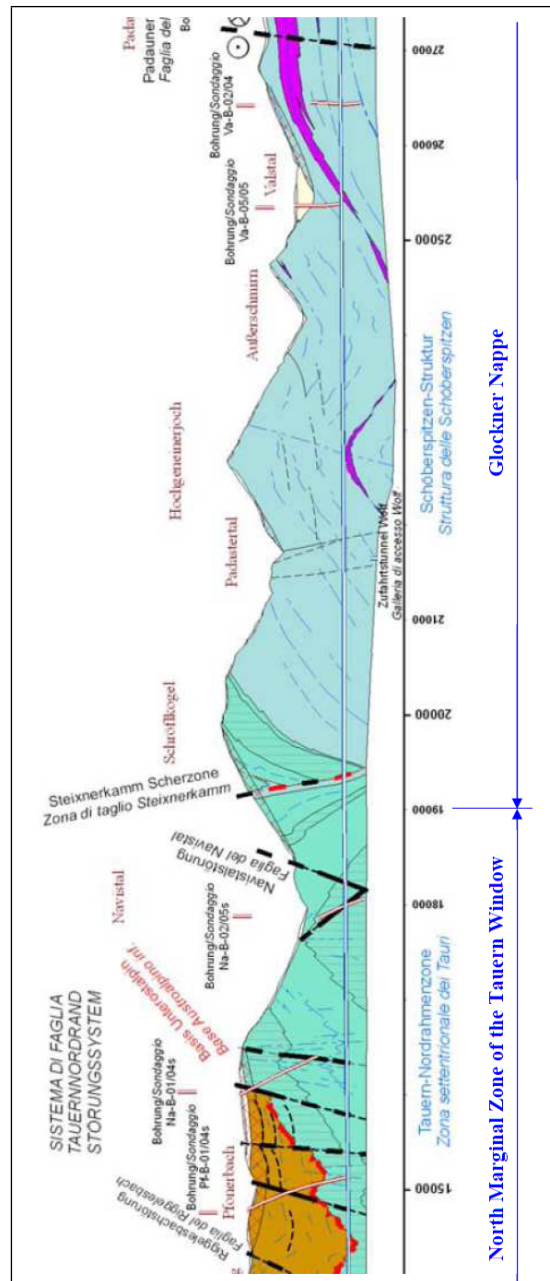


Figure A.2: Geological Longitudinal Section 02 of the Austrian Part of the East Tube of the BBT (Source of Information: Brandner (2008))

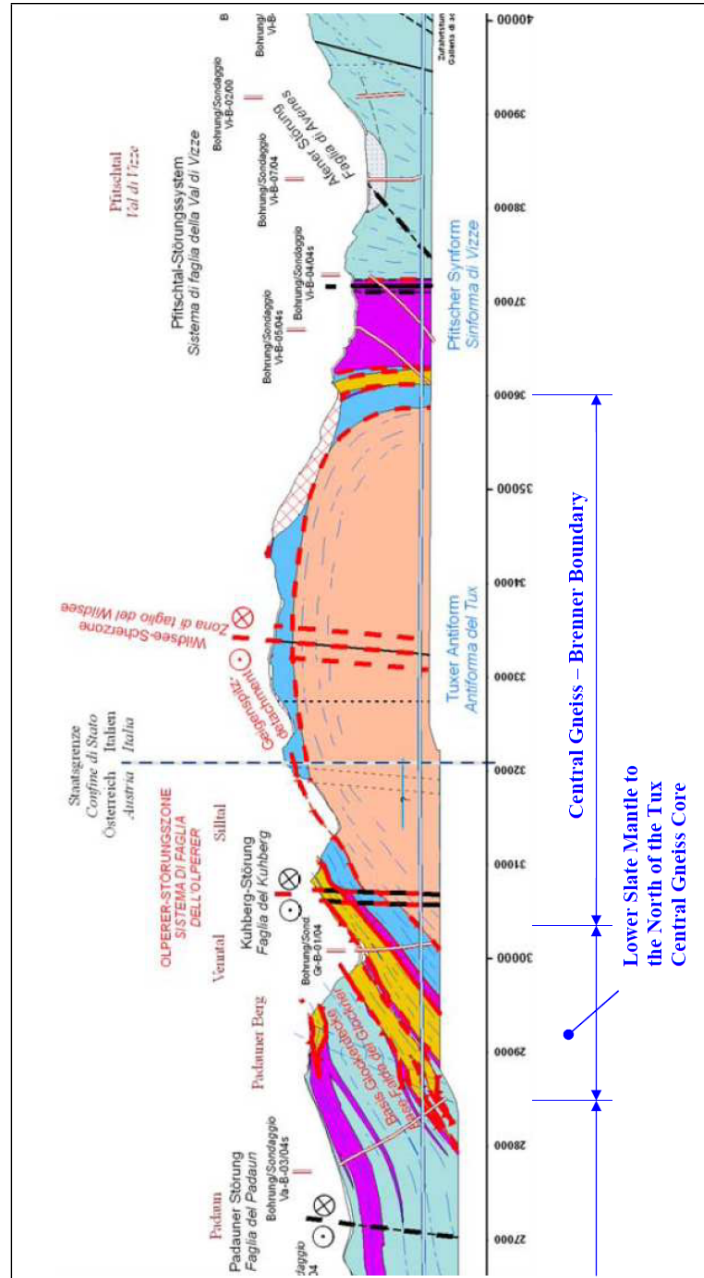


Figure A.3: Geological Longitudinal Section 03 of the Austrian Part of the East Tube of the BBT (Source of Information: Brandner (2008))

Appendix B

SIMULATION INPUTS

Table B.1 shows the end positions of each "*Ground Class*". These end positions are the input data of the "*Zones*" in the Geology Module of the DAT and used to simulate the "*Ground Class*" profile.

Table B.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

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