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Application of the Decision Aids for Tunneling in the Gotthard and Lötschberg Base Tunnel Projects, Part 1 – Gotthard Base Tunnel

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Abstract

The Decision Aids for Tunneling (DAT), a joint development by MIT and EPFL, allow one to consider the effect of geologic and construction uncertainties on tunnel cost and time. The topic and thus the article is divided into two parts. This Part 1 concentrates on the Gotthard Base Tunnel (GBT). It will first introduce the DAT and then show their application in the planning and design phases of the GBT. Emphasis is placed on showing how decision-makers used and helped develop the DAT. The Lötschberg Base Tunnel and some other applications will be discussed in Part 2 in the next Bulletin.

Zusammenfassung

Mit den Entscheidungshilfen für den Tunnelbau (EHT), welche gemeinsam am MIT und an der EPFL entwickelt wurden, ist es möglich, die Auswirkungen geologischer und baulicher Unsicherheiten auf Tunnelbaukosten und -zeiten zu berücksichtigen. Der Artikel wird in zwei Teilen veröffentlicht. In diesem ersten Teil wird der Gotthard Basis Tunnel (GBT) behandelt. Nach einer Einführung in die EHT wird deren Anwendung in den Planungs-und Entwurfsphasen des GBT beschrieben. Dabei wird betont wie die Entscheidungsträger in der Entwicklung und im Gebrauch der EHT mitwirkten. Der Lötschberg Basis Tunnel und einige andere Anwendungen werden im zweiten Teil des Artikels im nächsten Bulletin behandelt.

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1 Introduction and History of the Decision Aids for Tunneling

The Decision Aids for Tunneling (DAT) allow one to estimate tunnel cost, time and resources subject to geologic and construction uncertainties. They were used in the project phases of both the Gotthard Base Tunnel (GBT) and Lötschberg Base Tunnel (LBT) in the 1990's.

This paper is written in the context of the series of papers on the GBT in the Swiss Bulletin. Part 1, the present paper, will concentrate on this project, while the application to the LBT as well as other transalpine tunnels will be described in Part 2. This introductory chapter starts with the outline of the paper and then discusses the history of the DAT. In the following Chapter 2 a brief description of the DAT will be provided. In Chapter 3 we will describe all the applications of the DAT in the GBT project. Chapter 4 will offer concluding remarks.

The DAT were preceded by the Tunnel Cost Model (TCM), which in turn was based on the Highway Cost Model (HCM), all developed at MIT. Both the HCM and TCM had the innovative feature of specifically considering uncertainties and thus resulting in distributions of construction cost and time. The main aspect of the TCM development consisted of formally considering geologic uncertainties, which was done with socalled parameter trees, a detailed but somewhat cumbersome approach. The TCM was very carefully developed with regular input from geologists and construction practitioners and, very importantly, a series of validations against tunnels for which detailed geologic and construction information was available. All this resulted in a series of reports (Moavenzadeh et al., 1978) and was applied in the project of the 50 km long Los Bronces tunnel in Chile. Also relevant in all this is the fact that a specific simulation language had to be developed for the TCM.

The next major steps were the creation of a much more elegant and efficient geologic model by Chan (1980), which is based on the Markov Process and allows one to include information from exploration such as borings at particular locations along the tunnel. This was applied to the cooling water tunnels of the Seabrook Nuclear Power Plant. In addition, a more efficient simulation tool called Simsuper was developed using the computer language C (later C++).

This combination and the addition of some dynamic programming capabilities formed the basis of the present DAT, which were fully developed and extensively implemented starting with the work supported by the Federal Office of Transportation (FOT) in the context of Alptransit. Specifically, the use of the DAT was suggested by the committee of experts for Alptransit, a committee that included the two railroads (SBB, BLS), the FOT and other experts. Following the Alptransit decision by the Federal Council on May 23, 1990, the «Projektleitung Bauwerke» (PLB) was created, and the firm E. Basler and Partners was charged with staff efforts for the PLB. Based on the above-mentioned preceding discussions, E. Basler and Partners, with the help of the authors of this paper, submitted a research proposal to the FOT to further develop and transfer the DAT from MIT to EPFL. This proposal was accepted on March 29, 1990. Further details will be discussed in Chapter 3, Application of the DAT to the GBT.

2 Description of the DAT

The DAT consist of four modules: Geology Module, Construction Module, Resource Module and Updating Module

In the Geology Module, the user describes geology and its uncertainties. The geologic (geotechnical) information and associated probabilities are obtained through a combination of objective information and subjective estimates by experts, and are represented by probabilistic processes, in form of Markov Chains (Chan, 1980; Ashley et al., 1981). Faults and other particularly problematic zones can also be considered with probabilistic positions and lengths. This is then used by the Geology Module to produce geological and geotechnical profiles along the tunnel with Monte Carlo simulations. The generated profiles reflect the probability of particular geological conditions occurring in certain locations of the tunnel and are then combined in ground classes, analogous to what is done, in general, by tunnel geologists and engineers (Fig. 1).

The **Construction Module** (Fig. 2) simulates the construction process through the generated geological profiles, which involves relating the geological conditions along the tunnel profile to tunneling methods. The construction process can be described in as much detail as a user desires, ranging from simple advance rates and costs per unit length for each construction method to describing all activities (e.g. drilling, loading, blasting, etc.). The Monte Carlo Method is also used to simulate the construction process. First the probabilistic geological profiles are generated, then for each generated profile the construction is simulated cycle by cycle. Cost- and time uncertainties are considered for each construction method, usually in form of triangular or lognormal distributions. It should be noted that unplanned or planned delays as well as their cost/time uncertainty can be included. Learning curves can also be considered, and construction can be differentiated between ascending and descending advance, for instance. The overall uncertainty results in cost-time scattergrams as shown in Figure 3.

Analogously, the time-distance relations with uncertainties can be represented as schematically shown in Figure 4. We will, in Chapters 3 and 4 describe how all this is done in practice.

The **Resource Module** is the third compo-

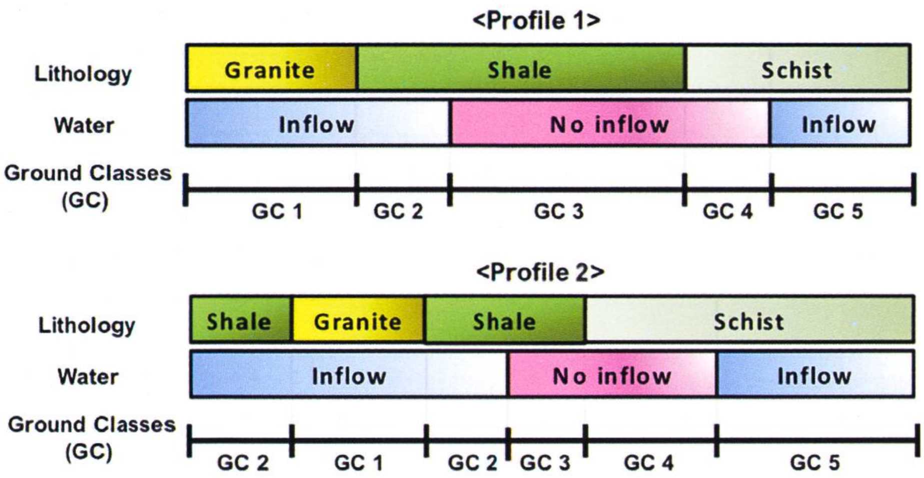

Fig. 1. Description of Geology with Ground Class Profiles Reflecting Uncertainties.

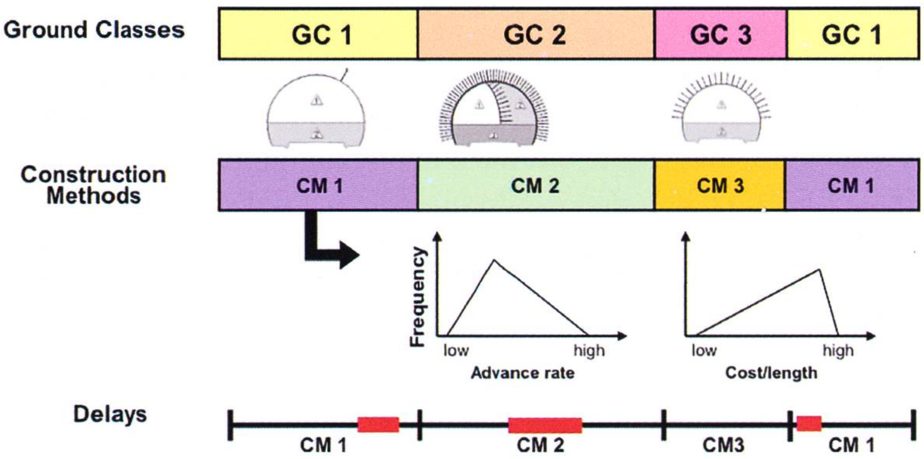

Fig. 2: Construction Simulation, Uncertainties in Construction are considered through Cost - and Time (Advance Rate) Distributions and through Delays. Note: Delays are indicated at the locations where they occur – there effect is on the time.

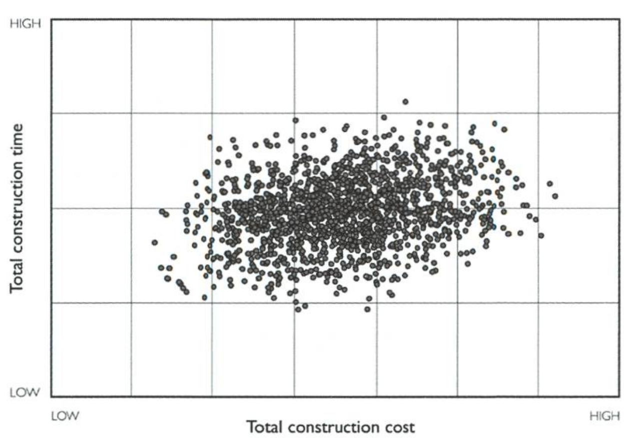

Fig. 3: Cost-Time Scattergram. Each point corresponds to a cost-time pair obtained from the combined simulations of geology and construction.

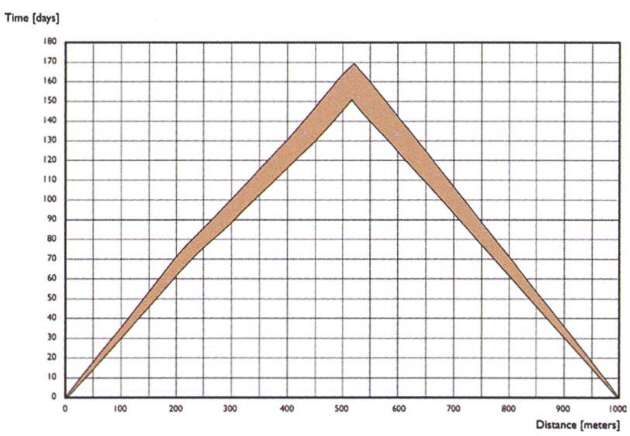

Fig. 4: Time – Distance Diagram.

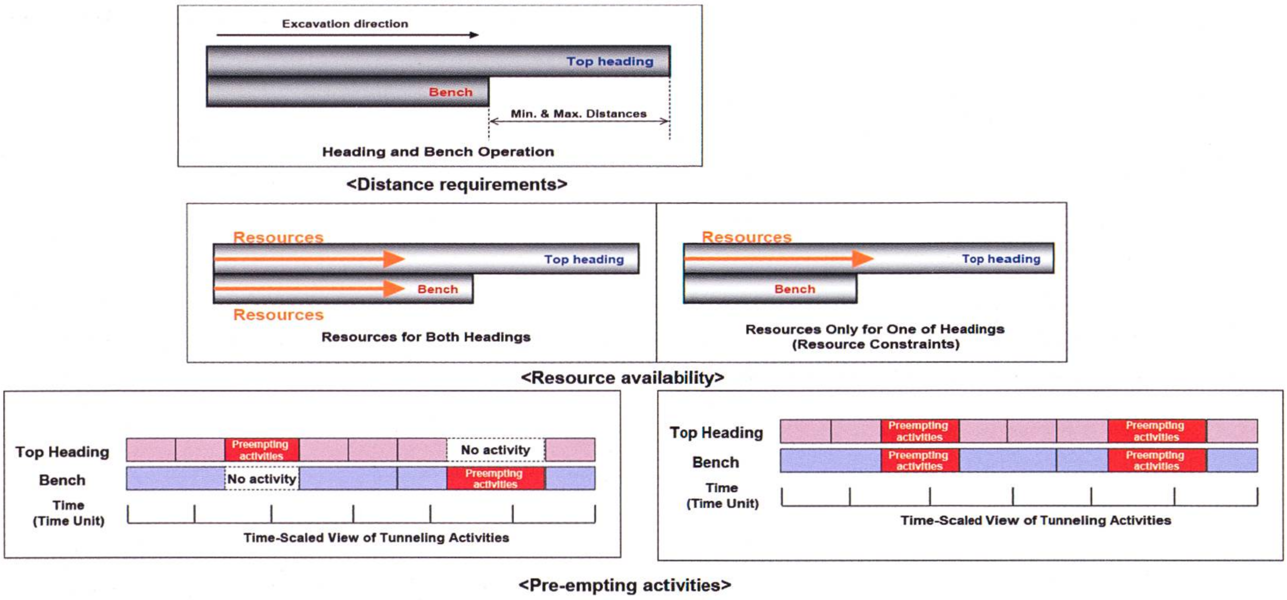

Fig. 5: Resource Module – Example Heading and Bench Construction (after Min, 2008). The Resource Module Considers: Distance Requirements – Minimum and maximum length of heading, Resource Availability – Work in both heading and bench (left), or only in one (right), Pre-empting Activities. Left: A preempting activity in the heading prevents an activity in the bench, and vice versa, Right: coordinated activities.

nent of the DAT and allows one to consider the scheduling and assessment of resources required or produced in tunnel construction. The resources considered range from crews, to equipment, to material moving in and out. The scheduling is accommodated by a systematic calendar (Marzer, 2001; Min, 2008) that considers, for instance, limitations related to time and day. Min (2008; see also Min and Einstein, 2016) advanced the resource model such that one can determine an optimal construction plan that minimizes cost and time under constraints of resource availability, geometry and interfering (preempting) activities. Figure 5 shows the principles of this resource module for a heading and bench operation. What is of particular interest in many tunnels is the removal and reuse of muck, specifically its reuse as concrete aggregate. This is schematically shown in Figure 6 for the Brenner Base tunnel, and it was applied both in the Gotthard- and Lötschberg Base Tunnels (see Chapter 3 and Part 2).

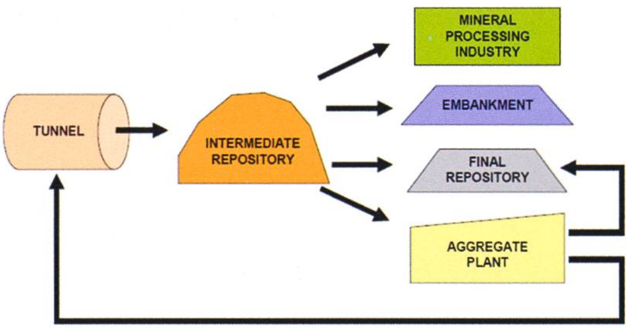

Fig. 6: DAT Resource Module. Schematic of Removal and Reuse of Muck for Brenner Base Tunnel (after Ritter et al., 2013).

The fourth DAT module allows one to update the cost, time (and resource) estimates. Before going into some details on the updating modules, it is necessary to mention that there are several possibilities to update information for a tunnel project:

- Prior to construction: Additional exploration is used to reduce uncertainties in geology. This, in essence, will reduce the spread of the scattergram in Figure 3. An example of this will be shown in the LBT application in Part 2. It is interesting to note that the pre-construction exploration by itself is subject to uncertainties. Quite extensive work has been done at MIT in this context, but is only referenced here (Einstein et al., 1978; Ashley et al., 1981; Sousa et al., 2016).

- During construction: Figure 4 reflects how uncertainties produce a fan shaped time - distance diagram before construction. As construction proceeds the excavated part is represented by a line (curve) while the unexcavated part is still fan shaped (Figure 7a). One can, however, go a step further and use information in the excavated part to lower the spread of the unexcavated part (Figure 7b); see Haas and Einstein (2002). This is in essence an application of the observational method.

It is important to note that the tunneling process (excavation, support) is updated through the predicted geology. The original geology and thus the ground classes as described earlier are modified with Bayesian updating. The definition of the ground classes remains as originally specified but their distribution changes. Consequently, the relation between construction methods and ground classes also remains the same but the distribution of construction methods and thus cost, time and resources change. It is also possible to change the relation «ground class – construction method», and this has been done both with the Lötschberg- and Sucheon- (Min et al., 2008) tunnels but purely deterministically. In principle, the latter type of updating could be also done following Bayesian methods but so far was not.

In addition to these four major components there are additional smaller ones, for instance to investigate the effect of correlations (Moret and Einstein, 2012), and a small, but extensible, database of advance rates of real tunnels, which has been developed in the framework of the European project NETTUN (2017).

3 Applications of the DAT for the Gotthard Base Tunnel

As mentioned in Chapter 1, the FOT accepted the research proposal jointly submitted by EPFL and E. Basler Partners to transfer and further develop the DAT. Specifically, this involved:

- Further development of the geology and construction modules such that practitioners can apply them.
- Transfer of the underlying computer code from MIT to EPFL such that it can be used there and then by others in Switzerland.
- Application of the DAT in an example having practical significance and involving the Alptransit professionals (engineers, geologists).

The example was not defined but it became quickly clear that the so-called «systems decision» would be practically relevant and could show the applicability of the DAT. This was completed in 1991 followed in 1992 by the study of the shaft concept for the Sedrun shafts and, in 1993, by an assessment of the materials management, both as requested by the Engineers for the GBT. In 1997 the FOT charged EPFL to conduct a detailed cost-time study for both the GBT and the LBT to check the cost/time estimates obtained by the project engineers. These phases, as they apply to the GBT, will be described below, and will be done in a way to avoid duplication, i.e. only

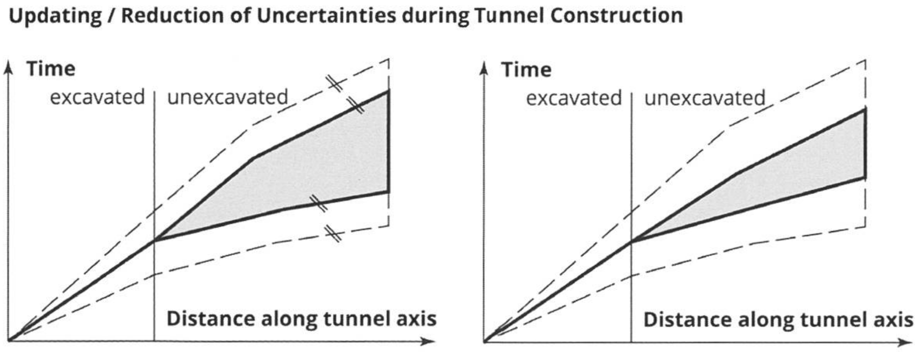

Fig. 7: Left - Predicted progress is replaced by actual progress; uncertainty in unexcavated part remains
Right - Updated prediction reduces uncertainty in unexcavated part.

significant differences between the following and preceding phase will be described. As will be seen, all this will not only provide a reasonably complete description of the DAT application but will highlight the progress of the GBT project in the 1990's. The reports on which the following is based are listed in the bibliography.

3.1 Systems Study

In 1990 three possible tunnel systems as schematically shown in Figure 8a were under consideration. This was still for the original project as shown with the 50 km long longitudinal profile in Figure 8b. As described in Chapter 2, the geology and construction process with uncertainties are required as input. The input was obtained through formal questioning on 28 and 29 May 1991. The geology questioning on 28 May involved the geologists Dres. Etter, Leu and Schneider and the construction questioning on May 29 Dr. Amberg, Mr. König, and Dr. Schneider. The questioning was done by Professors Egger and Descoeudres and Mr. Dudt, of EPFL and Professor Einstein of MIT. Also present were Messrs. Smith FOT, Flury GBT and Schuster and Derendinger, E. Basler & Partners.

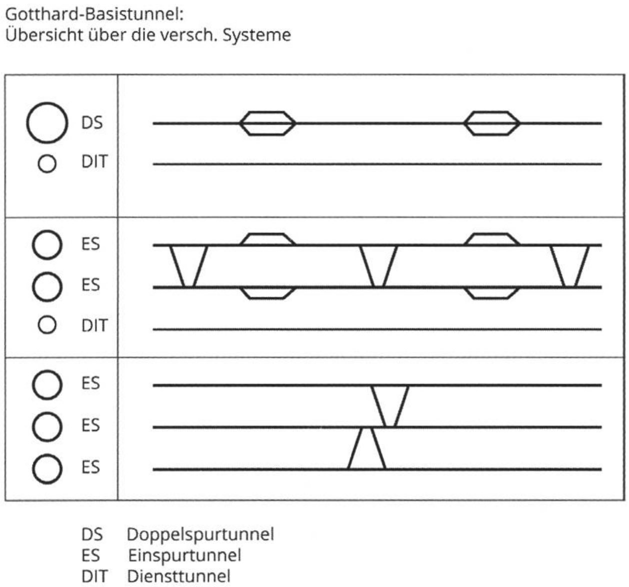

Fig. 8a: GBT Tunnel Systems, ES - Single Track Tunnel. DS-Two Track Tunnel, DIT - Service Tunnel.

In the geology questioning, the so-called «prognosis sections» (called Zones in the DAT) were discussed and defined, first without any length and uncertainty estimates. Figure 9 schematically shows these 13 zones. Their lengths and related uncertainties were then estimated using the standard probability wheel (see Vick, 2002). The results are shown in Table 1. This was followed by the determination of parameters and parameter states, which are summarized in Table 2. As will be seen below, this was greatly simplified later. The uncertainties were obtained through the Markov Process developed by Chan (1980) and consisted of 1. Estimating the average length of a parameter state, e.g. «gneiss-granite» and 2. Estimating the transition probability, i.e. the probability of e.g. «gneiss-granite» to be followed by «schist». With this information, the parameter profiles as schematically shown in Figure 1 were obtained, which then lead to the ground class profiles as also shown in this figure.
The ground classes were then associated with the construction classes in the construction questioning of the second day. The construction classes were the «excavation

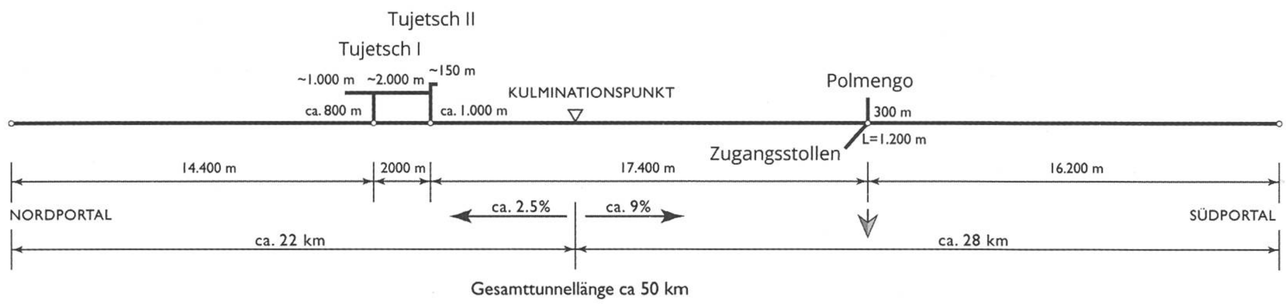

Fig. 8b: GBT Schematic Longitudinal Profile.

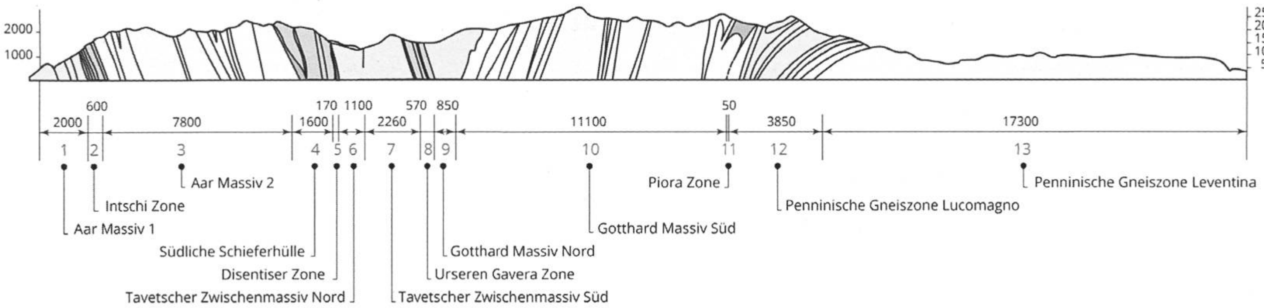

Fig. 9: GBT Geologic Profile.

Nr.		< Min	Min	wahrscheinlich	Max	> Max
1	Aarmassiv_1	3 %	2000 m	2100 m	1200 m	3 %
2	Intschi	8 %	300 m	600 m	800 m	5 %
3	Aarmassiv_2	5 %	7300 m	6800 m	8500 m	15 %
4	Südliche Schieferhülle	15 %	1000 m	1600 m	1700 m	5 %
5	Disentiserzone	20 %	0 m	100 m	200 m	20 %
6	Tavetscher_ZM_Nord	10 %	1350 M	1650 M	1950 m	0 %
7	Tavetscher_ZM_Süd	9 %	1750 m	2100 m	2450 m	13 %
8	Urseren_Garverazone	20 %	190 m	490 m	790 m	10 %
9	Gotthardmassiv_Nord	8 %	3700 m	4700 m	5200 m	5 %
10	Gotthardmassiv_Süd	5 %	7600 m	8000 m	9400 m	5 %
11	Piorazone	10 %	0 m	25 m	50 m	20 %
12	Lucomagnodecke	5 %	250 m	1100 m	3200 m	5 %
13	Leventinadecke	5 5	18750 m	19250 m	19750 m	5 %

Eingegebene Längen der 13 Prognoseabschnitte.

Tab. 1: Prescribed Lengths of the 13 Prognosis-Sections.

LITHOLOGIE (3 Zustände)	STÖRZONEN (4 Zustände)	SCHIEFERUNG (3 Zustände)
. *'Gneis-Granit'* . *Schiefrig* . *Phyllit*	. *Ungestörter Bereich* . *Duktile Störung* . *Spröde Störung mit wenig Wasser* . *Spröde Störung mit viel Wasser*	. *Orientierung 70°N – 70°S (steil)* . *Orientierung 45° - 70° (mittel)* . *Orientierung 0° - 45° (flach)*
KLÜFTUNG (2 Zustände) . *Nicht intensiv geklüftet (Abstand > 50 cm)* . *Intensiv geklüftet mit hohem Wasserzufluss*	ÜBERLAGERUNG (3 Zustände) *Mittlere Überlagerung: <1000 m* *Hohe Überlagerung: 1000 m – 1500 m* *Sehr hohe Überlagerung: > 1500 m*	

Tab. 2: Five Parameters and Their Parameter States as Selected by the Geologists.

support» classes as shown for a single-track tunnel in Figure 10 and also listed in Table 3.

The two-day questioning was followed by an extensive analysis of the results in which contradictions and redundancies were eliminated. Importantly, the cost and time (cost per unit length, advance/day) including their distributions were estimated by the engineers. All this was done through electronic exchange and everything was finalized in a meeting with all the engineers on 9 July 1991.

This very detailed and extensive questioning seems to be unusual. However, it is necessary and used in many cases where detailed uncertainty- and risk analyses are conducted. Other practical examples are the standard process used by the Department of Transpor-

LITHOLOGIE Lithology	STÖRZONEN Faulting	ÜBERLAGERUNG Overburden		GEBIRGS-KLASSE*
Gneis – 'Granit'	Ungestört	Wenig	(< 1000 m)	W1 / EW1
Gneis – 'Granit'	Ungestört	Mittel	(1000 – 1500 m)	M1 / EM1
Gneis – 'Granit'	Ungestört	Hoch	(> 1500 m)	H1 / EH1
Gneis – 'Granit'	Störung	Wenig	(< 1000 m)	W3 / EW3
Gneis – 'Granit'	Störung	Mittel	(1000 – 1500 m)	M3 / EM3
Gneis – 'Granit'	Störung	Hoch	(> 1500 m)	H3 / EH3
Schiefer	Ungestört	Wenig	(< 1000 m)	W2 / EW2
Schiefer	Ungestört	Mittel	(1000 – 1500 m)	M2 / EM2
Schiefer	Ungestört	Hoch	(> 1500 m)	H3 / EH3
Schiefer	Störung	Wenig	(< 1000 m)	W3 / EW3
Schiefer	Störung	Mittel	(1000 – 1500 m)	M3 / EW3
Schiefer	Störung	Hoch	(> 1500 m)	H3 / EH3
Phyllit	Ungestört	Wenig	(<1000 m)	W3 / EW3
Phyllit	Ungestört	Mittel	(1000 – 1500 m)	M3 / EM3
Phyllit	Ungestört	Hoch	(>1500 m)	H3 / EH3
Phyllit	Störung	Wenig	(< 1000 m)	W3 / EW3
Phyllit	Störung	Mittel	(1000 – 1500 m)	M3 / EM3
Phyllit	Störung	Hoch	(> 1500 m)	H3 / EH3

Gebirgsklassenzuordnung bei TBM-Vortrieb
* GEBIRGSKLASSE/ AUSBRUCHSKLASSE Groundclass/Excavation-Support Class (see Figure 10)

Tab. 3: Groundclasses for TBM-Excavation (including excavation-support classes as shown in Figure 10).

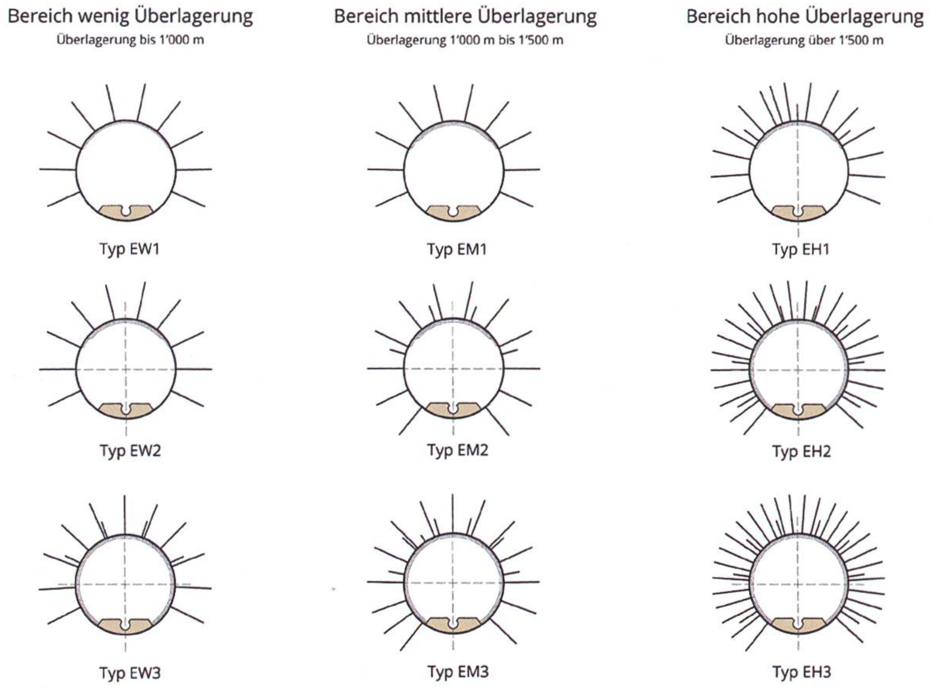

Fig. 10. GBT Excavation-Support Classes. The profiles indicate: Radial lines - bolts or injection bolts, circular black line - steel set, thin circular double line - shotcrete support, bottom – prefabricated invert element.

tation of Washington State, USA (see e.g. Reilly et al., 2004) and by the Metropolitan Tunnel Authority of New York City, for instance.

The questioning resulted in the profile shown in Figure 9 and in Table 2 listing the parameters and parameter states.
The latter was greatly simplified compared to the original input and consisted only of three parameters:

Lithology: parameter states: gneiss-granite, schist, phyllite

TBM Vortrieb [k Fr./m]	Konventioneller Vortrieb [k Fr./m]
Diensttunnel (DT): W1, M1, H1: 10.20 +- 20 % W2, M2, H2: 11.45+- 10 % W3, M3, H3: 12.70 +- 10 %	Diensttunnel (DT): 12.70 +- 20 % Einspurtunnel (1T): 40.90 +- 20% Doppelspurtunnel (2T): 51.40 +- 20 %
Einspurtunnel (1T): W1, M1, H1: 18.30 +- 20 % W2, M2, H2: 28.60 +-10 % W3, M3, H3: 40.90 +-10 %	
Doppelspurtunnel (2T): W1, M1, H1: 28.90 +- 20 % W2, M2, H2: 40.15 +-10 % W3, M3, H3: 51.40 +-10 %	

	Min	Mittel	Max
Schachtstollen [k Fr./m]	25.00		27.00-29.00
Schächte [k Fr./m]	55.00		60.00-78.00
Spezialbauten (k Fr. pro Einheit)			
Dienstbahnhof	70'000		87'000-104'000
Spurwechsel (DT-1T-1T)	12'000		15'000-17'000
Spurwechsel (1T-1T-1T)	23'000	29'000	35'000
Verbindungsstollen	270	340	400

Tab. 4. Cost per Meter as Estimated by Engineers.

Disturbance/Fault [Störzone in German]: parameter states: disturbed, not disturbed
Overburden: parameter states: <1000 m, 1000-1500 m, >1500 m)

Lithology and disturbance had uncertainties while overburden is deterministic. The resulting combinations are shown in Table 3.

Construction was assumed to be with TBM except for the sections «Disentis, Tavetscher Zwischenmassiv Nord, Süd», «Urseren Gavera» in the tunnel as well as the shafts (see Fig. 9 for profile). Time and cost distributions were associated with the ground classes and are listed in Tables 4 and 5. In the time estimation the duration of installations prior to construction was also considered (not shown here). The effect of the «Piora Zone» was initially included in the unit cost and advance rate estimates but was then replaced by «block costs and times» (Table 6) and assuming that the maximum length would not exceed 50 m. This assumption was modified in the 1997 application (see Chapter 3.4.).

With all this information, the construction was simulated as shown in Figure 11.

Einspurtunnel: Vortriebsleistung [m/AT]							
Gebirgsklasse		steigender Vortrieb			fallender Vortrieb		
Nr.	Bezeichnung	Min	Mittel	Max	Min	Mittel	Max
1	W1	16.80	19.60	22.60	13.44	15.68	18.08
2	M1	15.20	17.45	19.80	12.16	13.96	15.84
3	H1	13.60	16.00	18.40	10.88	12.80	14.72
4	W2	13.50	15.00	16.50	10.80	12.00	13.20
5	M2	10.20	11.45	12.80	8.16	9.16	10.24
6	H2	7.10	8.05	9.10	5.68	6.44	7.28
7	W3	5.00	6.75	8.80	4.00	5.40	7.04
8	M3	4.70	6.00	7.30	3.76	4.80	5.84
9	H3	3.40	4.53	6.00	2.72	3.62	4.80
10	M2 Aar 2	8.90	9.90	10.90	7.12	7.92	8.72
11	H2 Aar 2	6.30	7.00	7.70	5.04	5.60	6.16
12	3 Leventina	3.60	4.50	5.40	2.88	3.60	4.32
13	Piora 1 (0-20 m)	1.20	1.70	2.60	1.20	1.70	2.60
14	Piora 2 (20-50 m)	1.50	2.00	3.00	1.50	2.00	3.00
15	Disentis	2.50	2.50	3.00	1.70	2.13	2.55
16	TZM Nord	2.80	3.50	4.20	2.38	2.98	3.57
17	TSM Süd	2.80	3.50	4.50	2.38	2.98	3.83
18	UG Zone	1.60	2.00	2.40	1.36	1.70	2.04

Wartezeit 18 AT, wenn Piora auftritt

Einspurtunnel : Laufmeterkosten [KFr/m]							
Gebirgsklasse		steigender Vortrieb			fallender Vortrieb		
Nr.	Bezeichnung	Max	Mittel	Min	Max	Mittel	Min
1	W1	21.96	18.30	14.64	24.16	20.13	16.10
2	M1	21.96	18.30	14.64	24.16	20.13	16.10
3	H1	21.96	18.30	14.64	24.16	20.13	16.10
4	W2	32.56	29.60	26.64	35.82	32.56	29.30
5	M2	32.56	29.60	26.64	35.82	32.56	29.30
6	H2	32.46	29.60	26.64	35.82	32.56	29.30
7	W3	44.99	40.90	36.81	49.49	44.99	40.49
8	M3	44.99	40.90	36.81	49.49	44.99	40.49
9	H3	44.99	40.90	36.81	49.49	44.99	40.49
10	M2 Aar 2	32.56	29.60	26.64	35.82	32.56	29.30
11	H2 Aar 2	32.56	29.60	26.64	35.82	32.56	29.30
12	3 Leventina	44.99	40.90	36.81	49.49	44.99	40.49
13	Piora 1 (0-20 m)	285.00	190.00	150.00	285.00	190.00	150.00
14	Piora 2 (20-50 m)	204.00	140.00	108.00	204.00	140.00	108.00
15	Disentis	49.10	40.90	32.70	52.78	43.97	35.15
16	TZM Nord	49.10	40.90	32.70	52.78	43.97	35.15
17	TSM Süd	49.10	40.90	32.70	52.78	43.97	35.15
18	UG Zone	49.10	40.90	32.70	52.78	43.97	35.15
Fixkosten Piora 1		65000.00	62000.00	59000.00	*)		
Fixkosten Piora 2		49000.00	49000.00	49000.00	**)		

*) Wird addiert, falls die Piora auftritt.
**) Wird zusätzlich addiert, falls die Piora länger ist als 20 Meter.

Tab. 5: Advance Rates (m/workday) and Cost per Meter used in DAT Simulation – Example Single Track Tunnel.

The resulting scattergrams are shown in Figure 12 and reveal several interesting aspects:

- There are three «clouds» for each system reflecting the block-effect of the potential Piora zone (zero ~1 m, 0-20 m, 20 -50 m length).
- The two-track tunnel results in the lowest cost but the longest time.
- Systems 2 and 3 have identical time distributions but different costs. This is caused by the fact that the single-track tunnels are excavated in parallel resulting in the same

Länge Tunnel			Blockzeiten [AT]			Behandlungskosten	Blockkosten [kFr]		
		Typ	Min	Mittel	Max	Kosten [kFr]	Min	Mittel	Max
1	m	DT	6	8	12	5'000	75	90	130
20	m	DT	15	20	30	25'000	1500	1800	2600
50	m	DT	25	35	55	60'000	4200	5000	6500
1	m	1T	10	18	26	7'000	95	170	210
20	m	1T	18	30	50	50'000	3000	3800	5700
50	m	1T	40	55	65	100'000	5400	7000	10200
1	m	2T	15	20	50	10'000	120	250	350
20	m	2T	20	40	60	75'000	4500	6000	9000
50	m	2T	60	80	120	150'000	8000	10000	15000

Tab. 6: Block Times and Costs for Piora Zone.

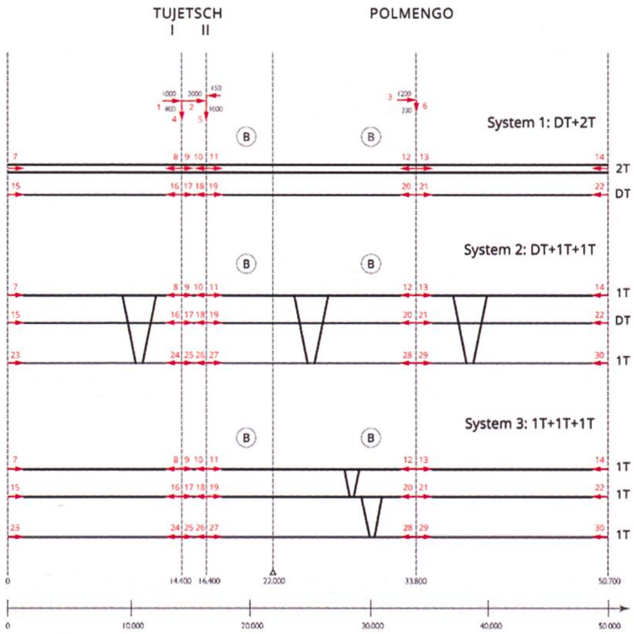

Fig. 11: GBT Schematic of Construction Simulation, Arrows indicate direction of construction, Numbers define the «simulation section».

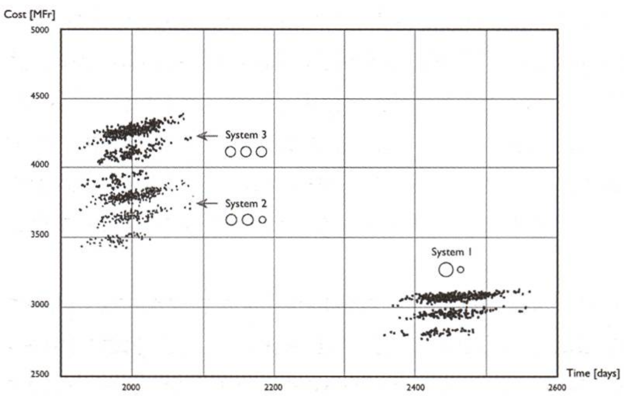

Fig. 12: GBT Systems Study – Resulting Cost-Time Scattergrams.

time but with increased cost if the third tunnel is full sized.

Figures 13a and b show the time distance diagrams for one possible simulation of Systems 1 and 2, respectively, representing the different start locations and times of the tunnel sections, as well as the typical fan shape. Not surprisingly, the middle section between Tujetsch and Polmengo governs the times as then happened in reality (between Sedrun and Faido). Another interesting result is shown in Figure 14 for System 1 (the results of Systems 2, 3 are analogous). This figure represents what was done in the simulations, namely 200 geology simulations and for each geology simulation three construction simulations, the latter represented by points with the same symbol. It is quite evident that the spread caused by geologic uncertainty is much greater than the effect of uncertainties in construction for a particular geology. This reflects the fact that the experts were much less certain about geology than about the construction time/cost. Specifically, the unit cost/advance rate ranges for a particular ground class varies by a maximum 20% while the range of unit cost/advance rates between different ground classes is 200/1400%. As shown by Min et al. (2008), greater geologic than construction uncertainties are usually but not always the case.

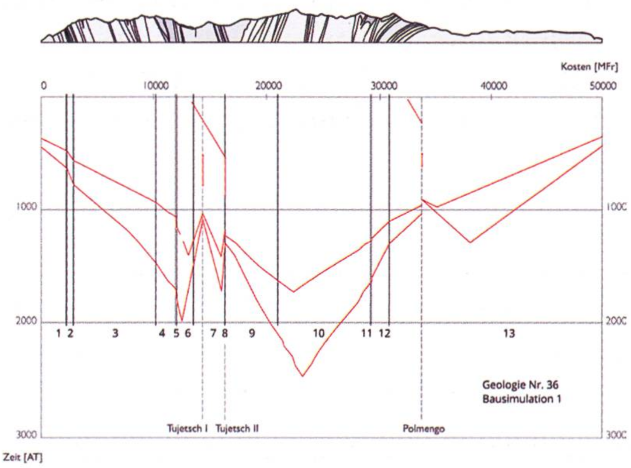

Fig. 13a: GBT Systems-Study - Resulting Time-Distance Diagrams, System 1 - Two Track Tunnel.

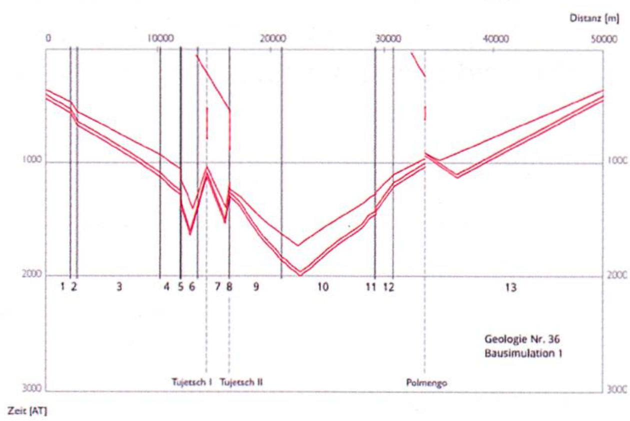

Fig. 13b: GBT Systems-Study - Resulting Time-Distance Diagrams, System 2 – Two Single -Track Tunnels and Service Tunnel.

Two additional comments can be made:
The time variation is much greater than that of the cost because the time range is affected by the «slowest» and «fastest» tunnel while the cost represents the sum of all costs, not only the extremes. The much longer duration of System 1 also explains why the scattergram of System 1 is flatter than those of systems 2 and 3.

While the systems study per se was not directly used in the final design decision, it had an influence by showing which uncertainties have the greatest influence.

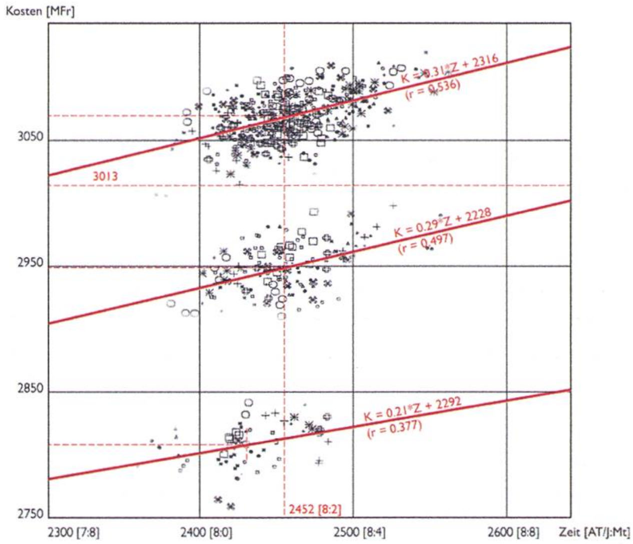

Fig. 14: GBT Detailed Scattergram for System 1 (Two Track Tunnel), Identical symbols represent three construction simulations per geology simulation – note wider spread for geology than for construction.

3.2 Shaft Concept Sedrun

This study was initiated in 1992 requested by the IG-GBT (Ingenieurgemeinschaft GBT) to EPFL. This reveals that both the transfer of the DAT was successful and, very importantly, that the involved practitioners saw the value of the DAT. It is also interesting because of what was studied and because of some of the differences in «results» compared to the systems study.

The IG-GBT wanted to investigate the effect of changing the shaft concept from the originally planned double shaft at Sedrun (previously Tujetsch) shown in Figure 15. Note also by comparison of Figures 15 and 8b that there is now an inclined adit at Faido and an adit at Amsteg as was done in the realization of the project. However, the section Amsteg-Erstfeld is still not included. The inclusion of the Amsteg adit in the simulation led to a total length of 50'700 m, compared to the original 50'000m. Figure 16 shows the specifics that were investigated, namely, the three concepts with shafts I and II or simply with only I, or only II. All this was done for tunnel system C i.e. with three single-track tunnels.

The principle of the inputs i.e. zones (prognosis sections), parameters and parameter states, cost and time were the same as in the systems study with some exceptions:

- Length of the zones/prognosis sections. In some sections, rather defining the zone lengths probabilistically, the end point locations were defined probabilistically. (In any case for each simulation it was checked

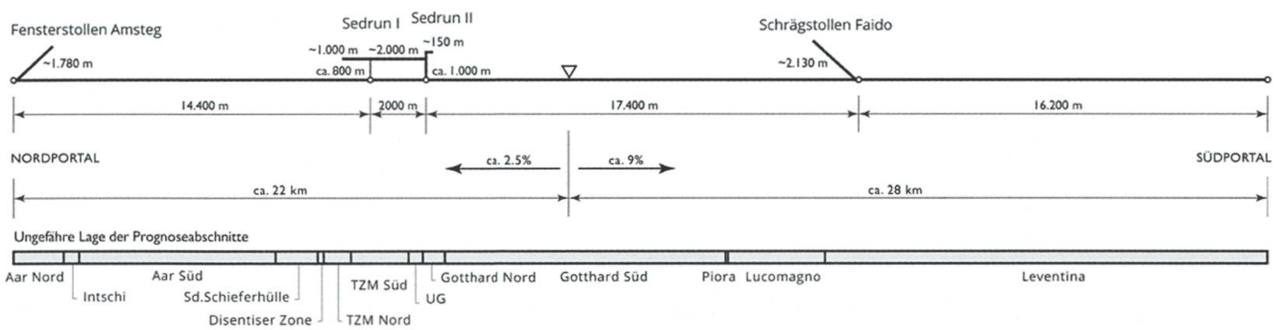

Fig. 15: GBT Shaft Concept Sedrun, Schematic Longitudinal Profile.

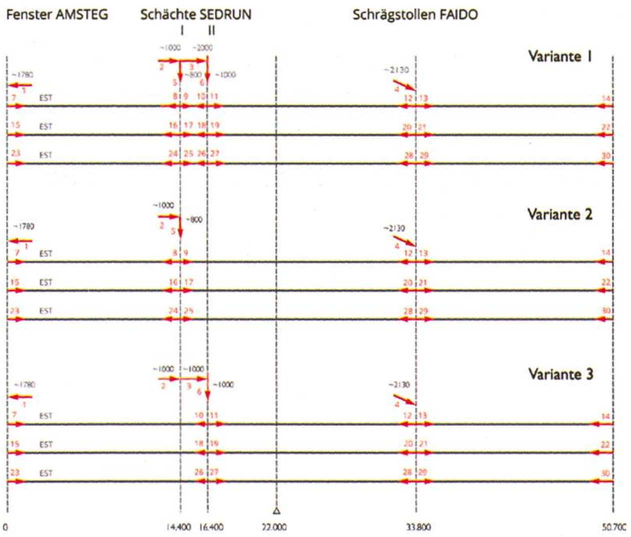

Fig. 16: GBT Shaft Concept Sedrun, Schematic of the Three Concepts and Corresponding Simulation.

that the total length equals 50700 m). See Table 7.

- In some sections (e.g. shafts, adits) the ground classes were directly assigned not via parameter states.
- The advance rate estimations were updated based on recent experience of the IG-GBT members. E.g. it was now considered that the advance rate could be 0 (e.g. «stuck» TBM). See Table 8.
- The installation periods prior to the construction starts were now also probabilistic.
- The costs were differentiated into fixed costs (major structures), time-costs (cost per work day) and costs per meter, all of these updated based on real information.

The resulting cost-time scattergrams are shown in Figure 17 and the time distance

Nr.	Abschnitt	≤	Min	wahrscheinlich	Max	≥	Was
			[m]	[m]	[m]		
1	Aarmassiv_1	3 %	2200	2400	2600	3 %	Länge
2	Intschi	8 %	400	450	500	5 %	Länge
3	Aarmassiv_2	5 %	7600	7800	8000	15 %	Länge
4	Südl. Schieferhülle	0 %	12100	12200	12270	5 %	Endpunkt
5	Clavaniev	0 %	12300	12450	12600	0 %	Endpunkt
6	Tavetscher_ZM_Nord	0 %	13450	13450	13450	0 %	Endpunkt
7	Tavetscher_ZM_Nord	0 %	15350	15450	15600	0 %	Endpunkt
8	Urseren_Garverazone	0 %	15950	16050	16200	0 %	Endpunkt
9	Gotthardmassiv_Nord	8 %	3100	3600	4100	5 %	Länge
10	Gotthardmassiv_Süd	5 %	8300	8850	9400	5 %	Länge
11	Piorazone	10 %	0	20	50	20 %	Länge
12	Lucomagnodecke	5 %	2500	3030	3600	5 %	Länge
13	Leventinadecke	0 %	50700	50700	50700	0%	Endpunkt

Streuungen der eingegebenen Längen, bzw. Laufmeter der südlichen Endpunkte der 13 Prognoseabschnitte

Tab. 7: Length or Endpoints of Prognosis Sections.

Gebirgsklasse		Steigender Vortrieb [m/AT]				Fallender Vortrieb [m/AT]		
Nr.	Bezeichnung	Mittel	Min	Mode	Max	Min	Mode	Max
1	W1	19.60	.00	24.50	34.30	.00	19.60	27.44
2	M1	17.45	.00	21.81	30.54	.00	17.45	24.43
3	H1	16.00	.00	20.00	28.00	.00	16.00	22.40
4	W2	15.00	.00	18.75	26.25	.00	15.00	21.00
5	M2	11.45	.00	14.31	20.04	.00	11.45	16.03
6	H2	8.05	.00	10.06	14.09	.00	8.05	11.27
7	W3	6.75	.00	8.44	11.81	.00	6.75	9.45
8	M3	6.00	.00	7.50	10.50	.00	6.00	8.40
9	H3	4.53	.00	5.66	7.93	.00	4.53	6.34
10	M2 Aar2	9.90	.00	12.38	17.33	.00	9.90	13.86
11	H2 Aar2	7.00	.00	8.75	12.25	.00	7.00	9.80
12	M3 Leventina	4.50	.00	5.62	7.88	.00	4.50	6.30
13	Piora 1 (0-20 m)	1.70	.00	2.12	2.97			
16	Piora 2 (20-50 m)	2.00	.00	2.50	3.50			
18	Konv. Vortrieb	2.00	.00	2.50	3.50	.00	2.12	2.98
19	Fenster Amsteg	6.00	.00	7.50	10.50			
20	Stollen Sedrun	5.00	.00	6.25	8.75			
21	Schächte	3.00	.00	3.75	5.25			
22	Schrägstollen Faido	3.60	.00	4.50	6.30			
1 – 12 konventioneller Vortrieb		6.50	.00	8.13	11.38	.00	6.50	9.10

Vortriebsleistungen in den verschiedenen Gebirgsklassen beim Einspurtunnel-System

Tab. 8: Advance Rates (m/workday) One Track Tunnel.

diagrams in Figures 18a, b, and c. There are several interesting results both per tunnel section and by comparison with the systems study (Chapter 3.1).

- The cost distributions of the three shaft concepts overlap, with alternative 2 somewhat lower than the others. The costs of concepts 1 and 3 are about the same and even a bit higher for 3 although the total shaft length is shorter for the latter. This can be explained by the longer construction time and thus the associated time costs for alternative 3 (see Figure 18c).
- The scattergrams are now much more time equidimensional compared to those of the systems study. This can be explained by the reduced time spent, which in turn can be explained by the reduced length-uncertainty of the zones as can be seen by comparing Tables 1 and 7. The reduction of uncertainties reflects additional explorations and studies in the zones Clavaniev, TZM-UG. This shows that the DAT can be used to estimate the effect of additional information as mentioned in Chapter 2 under updating.
- There are significant time differences between the three alternatives as shown in Figures 18a, b, and c. Locating the shaft(s) within the zones that have the slowest advance rates (Clavaniev-TZM-UG) has thus a major effect.

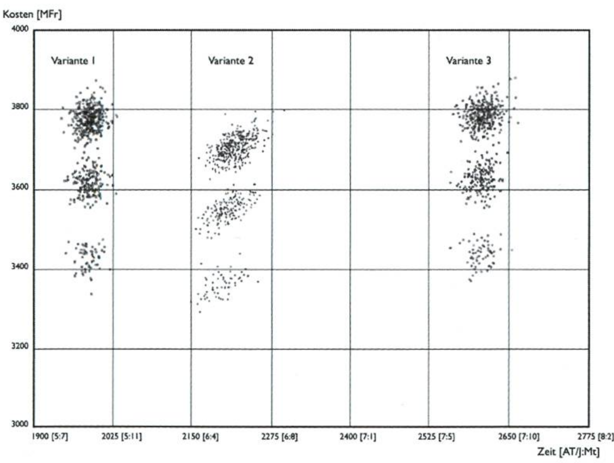

Figure 17: GBT Shaft Concept Sedrun – Resulting Cost-Time Scattergrams (Three clouds per alternative «Variante» reflect the effect of the Piora zone).

- As before, the consideration of the Piora zone has mostly a cost effect (the clouds for each concept in Figure 17 mostly overlap regarding the time). This can be quite different and will be discussed in Chapter 3.4.

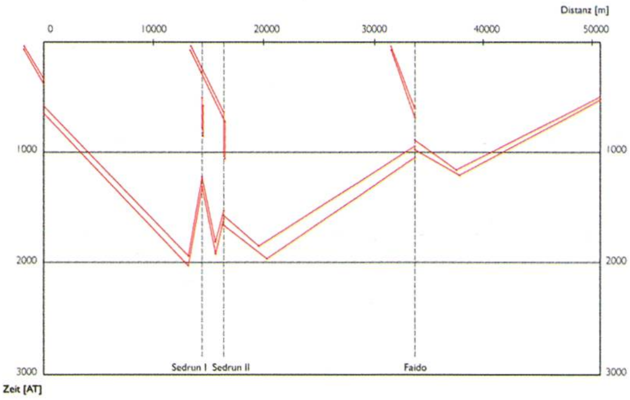

Fig. 18a: GBT Shaft Concept Sedrun – Resulting Time-Distance Diagrams, System C Three Single-Track Tunnels - Shaft Concept 1 (2 shafts).

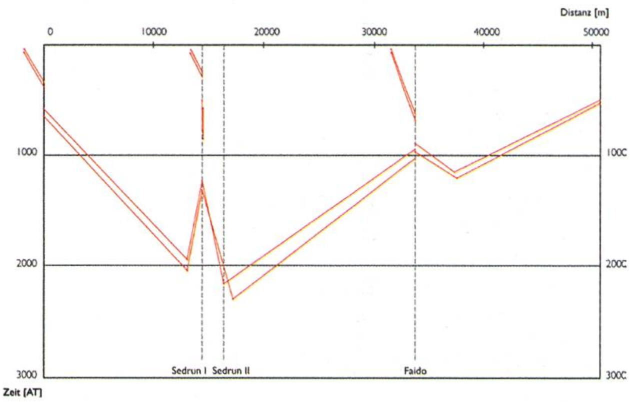

Fig. 18b: GBT Shaft Concept Sedrun – Resulting Time-Distance Diagrams, System C Three Single-Track Tunnels - Shaft Concept 2 (1 shaft).

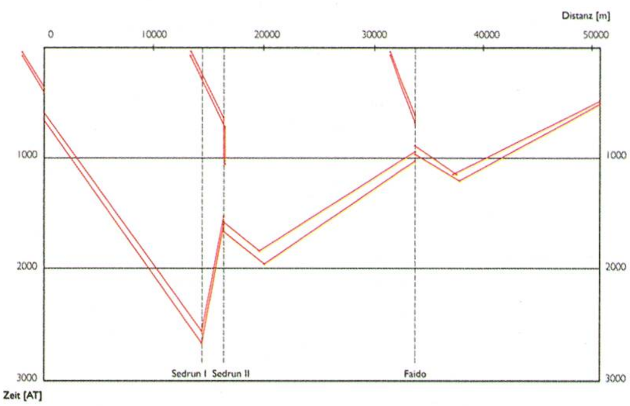

Fig. 18c: GBT Shaft Concept Sedrun – Resulting Time-Distance Diagrams, System C Three Single-Track Tunnels - Shaft Concept 3 (1 shaft).

- Interestingly, the additional experience and information obtained by the IG-GBT led to greater uncertainties in the advance rates as can be seen when comparing Tables 5 and 8. This then leads to the scattergram results in Figure 19, which by comparison with Figure 14 show that the construction time scatter is now similar to the geologically caused scatter.

3.3 Materials Management.

This study was again initiated by the IG-GBT. Now, in addition to practically using the DAT as was done in the shaft study, the engineers contributed to further development of the DAT. The study was requested in December 1992 with major work done in the first three months of 1993. The tunnel/shaft system was the one with two shafts at Sedrun. The geology was as before but subdivided into 19 rather than 13 prognosis sections

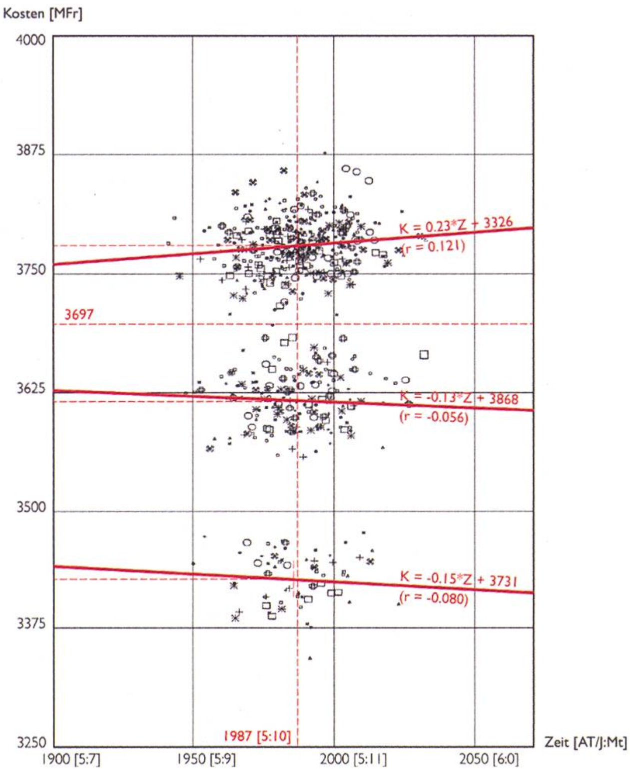

Fig. 19: GBT Detailed Scattergram for System C (Three Single Track Tunnels) - Concept 1 (2 shafts), Identical symbols represent three construction simulations per geology simulation – note similar spread for geology as for construction.

while the groundclasses were essentially the same. The construction simulation now specifically considered caverns at Amsteg, Sedrun, and Faido.

Two changes, learning curves and material (resource) management, were made compared to the previous use of the DAT in the GBT. Learning was considered through modified advance rates as follows:

Normal advance rate reduced: In month 1 to 50 %, in month 2 to 70 %, in month 3 to 80 %, in months 4 and later no reduction.

The major modification was with regard to materials management, in which production/reuse of muck (excavated material) and steel use were evaluated.
The muck was categorized in four classes:

P1 From Drill and Blast excavation; can be used as concrete aggregate 0 - 32mm
P2 From TBM excavation; can be used as concrete aggregate 0 - 8mm
P3 Can be used for fills, embankments etc.
P4 Not usable as construction material

The classification was based on the groundclasses, and the project geologist associated a particular percentage of the muck classes with each groundclass.

For the reuse as concrete aggregate two categories were defined:
V1 Aggregate for in-situ cast concrete and prefabricated elements
V2 Aggregate for shotcrete

The volumes for produced and reused materials were based on the tunnel cross-sections in the particular tunnel sections as provided by the IG-GBT, which also provided information on the time delay between production and reuse. (Note that the volumes are solid volumes not loosened; this is something that could considered in the future). Very important in this are the so-called sorting rules:

Assume that the material produced in one workday:

Is P4 If > 20%	classify as P4
Otherwise	classify as P3
Is P3	classify as P3
Is P1, P2 with > 20% small grain size	classify as P4

After initially applying these sorting rules, it became apparent that over half of P1 and P2 ended up in lower categories. This led the engineers to specify construction processes, in which P1 and P2 were separated from the very beginning (the DAT sorting rules were correspondingly adjusted). This is a very interesting practical example as to how a simulation can lead to better construction processes.

The DAT simulations were then run with this input to determine the muck flow at the five repositories Amsteg, Sedrun I, II, Faido and Biasca, and this for three scenarios: A -maximum production of P1, 2 minimum P4; B - average production of all four classes; C - minimum production of P1, 2 with maximum P4. Figure 20 shows the results for scenario A at the Sedrun II repository. Several facts are interesting:

- The scatter (range) of results is caused by uncertainties in geology and advance rates. The offset between the production (P1) and the reuse (V1) curves is as expected since excavation precedes final support installation. This is different for P2/V2 where evidently shotcrete is used from the very beginning; also, the aggregate deficit needs to be made up with supplies other than reused muck.

- Steel usage for bolts, grouted bolts, reinforcing steel and steel sets (HEB and UNP Profiles) were based on information in form of quantity per running meter provided by the IG-GBT. This resulted, for each repository, in quantity-time curves similar the V curves in Fig 20.

Running the DAT for materials management thus provided practically relevant information on the material flow, which is essential for construction planning. Regarding the DAT themselves they benefited from modifications resulting from the exchange with the engineers using them.

3.4 1997 - Study of Construction Cost and Time

The FOT charged EPFL in November 1996 to conduct a detailed cost and time study for both the GBT and LBT to double check the assumptions and results obtained by the project teams. This Chapter will comment on the GBT and only discuss differences compared to what was described in Chapters 3.1 and 3.2. The LBT results will be commented

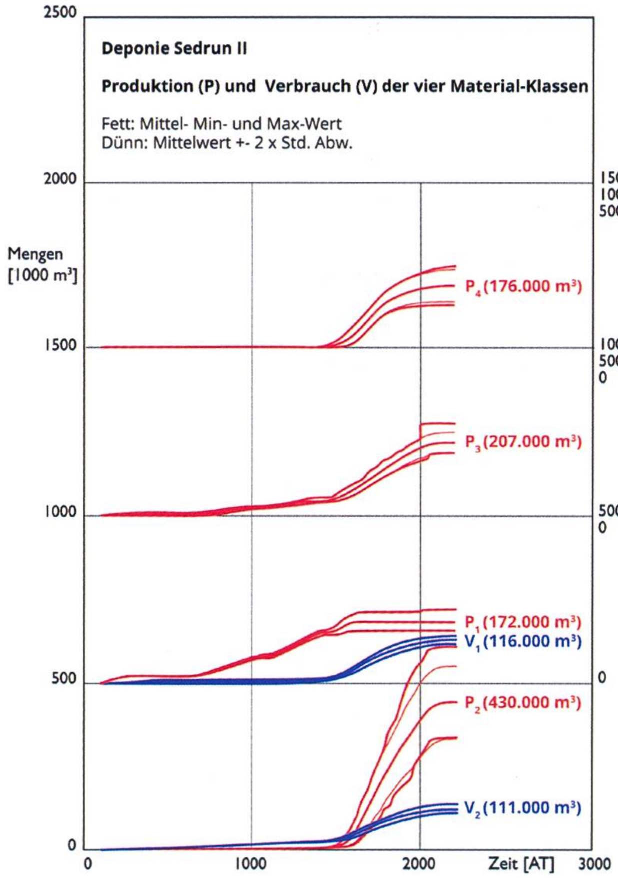

Fig. 20: GBT Material at Sedrun II Repository – Volume - Time Diagram Scenario A (Maximum production of Material Classes 1 and 2); P 1 – 4: Produced excavated material; V 1, 2: Material reused for concrete aggregate.

upon in Part 2.

The tunnel system shown in Figure 21 is now very close to what was eventually built, i.e. including the Erstfeld Section. What is different from the constructed project is the pilot tunnel and its enlargement in the Bodio Section. A problematic aspect was that the input information was not on the same level for all sections (e.g. section Erstfeld not as detailed as many of the other sections).

Recall that the DAT modeling processes consist of:

- First defining the zones (prognosis sections) with length – or end point uncertainties.
- Associate the geology in form of parameters and parameter states in the zones with ground classes including uncertainties.
- Simulate the construction process through each ground class profile using advance rates and costs with uncertainties.

The typical zone input is shown in Table 9. This example shows that again either the length-uncertainty or the end point uncertainties are specified. The program checks and corrects making certain that the total zone lengths corresponds to reality.

The ground class determinations were done somewhat differently than before since the project teams had already identified ground classes. So, these were directly applied rather than using geologic parameters and parameter states. The uncertainties were considered with the Markov process as before. Table 10 shows the ground classes for the same section as in Table 9. Several disturbed zones (fault zones) were estimated in form of length distributions (including possible zero length). The Piora zone was treated separately in the context of construction time and cost as will be shown below.

The unit costs and advance rates were described by the project teams in form of triangular distributions as was done before. Table 11 again shows an example. For the Piora zone, two alternatives were considered, reflecting that on 31 March 1996 a blowout occurred in the pilot tunnel. As described in Amberg et al. (2016) a detailed exploration and pretreatment procedure had been developed how to handle the «sugar grained» dolomite under high water pressure that occurs in the Piora zone. In «alternative 1» it was assumed that no major sugar grained dolomite

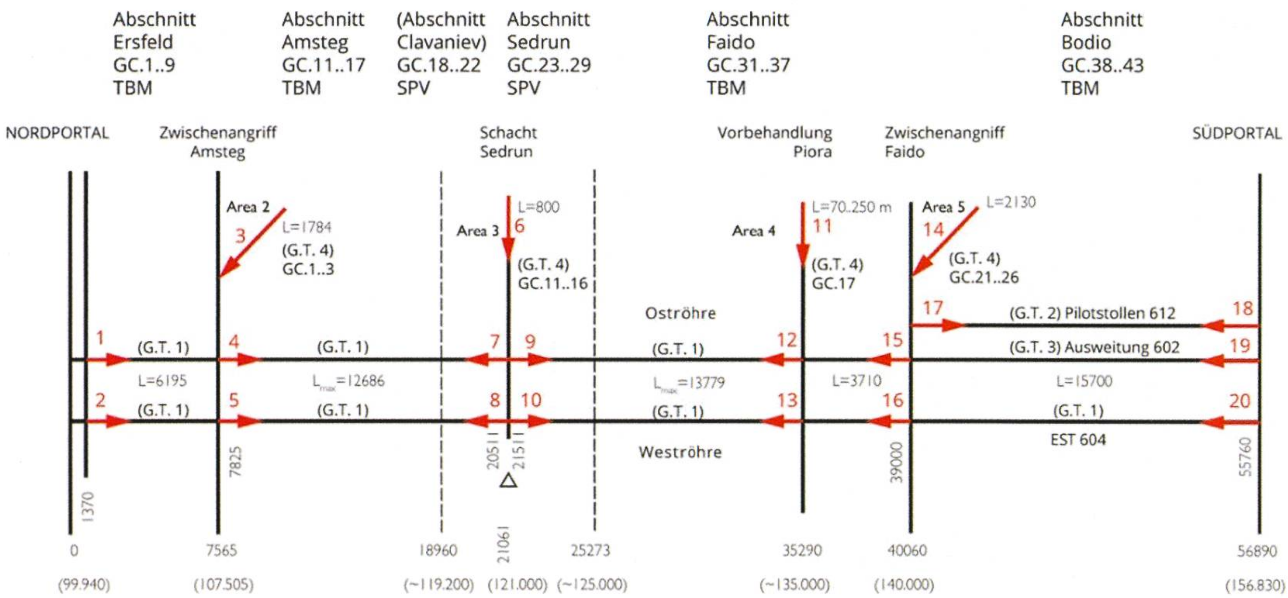

Fig. 21: GBT 1997 Study of Cost and Time – Schematic of Construction Simulation.

occurs at the tunnel level but a 10 m long disturbed zone. For the case of occurrence of the sugar-grained dolomite (alternative 2) a so-called pretreatment was assumed in form of an intermediate access (object No. 11 in Figure 21). This pretreatment would have the following consequences:

- Cost of shafts and tunnels prior to pretreatment: 50 + 60 (+/-20%) + 9.5 (+/- 25%) million sfr.
- Time prior to pretreatment: 430 work days
- Estimated length of zone to be treated: 20 to 250 m uniformly distributed
- Advance rate: 0.14 m/day deterministic
- Cost: 2.8 x 106 sfr/m deterministic

All the input information was obtained from the project teams and then double-checked by the FKGA (Fachkommission Geologie Alpentunnel) and by Professors Descoeudres/Einstein who served as experts on construction aspects. The critiques provided led to two additions:

- The original input specified a particular mean advance rate or cost/m for each ground class and that the daily variations in form of cost/time distributions occur relative to this mean value. These daily variations cancel each other out in a long tunnel resulting in relatively small distributions of cost and time for a particular ground class

1	2	3	4	5	6	7	8	9	10	11	12	13
50/50b	1	61	0.1	3	5	14	0.1					
Paradisgneise	2	62		(555)				0.1	25760	25920	26080	0.1
Streifengneise	3	63	0.1	119	140	161	0.1		25900		26229	

Column 1: Zone name
Column 2: Codes; Code 1 = length distributions in Columns 4-8; Code 2 = endpoint distributions in columns 9-13; Code 3 = length distribution combined with endpoint information in columns 4-8, 10, 12
Column 3: Zone number
Column 4-8: 4-Probability of min. length or less; 5-Minimum length; 6-Most probable length; 7-Maximum length; 8-Probability of max. Length or more
Columns 9-13: Analogous to columns 4-8 but for endpoints

Tab. 9: Typical Input for Zone Faido.

FAIDO	Cd	No	(...)	Nb	I	II	III	IV	V	VI
					31	32	33	34	35	36
1	2	3	4	5	6	7	8	9	10	11
50/50b	1	61	(...)	6	0	0	0	0	0	1
Paradisgneise	2	62	(...)	6	0	.52	0	.44	.04	0
Streifengneise	3	63	(...)	6	.05	.50	0	.30	.15	0

Column 1-3: Zone name, code, zone number as in Table 9
Column 4: Applicable information from columns 4 or 13 in Table 9
Column 5: How many ground classes
Columns 6-11: Fraction of each ground class (here excavation support classes) in each zone (e.g 52 % Class II in Zone Paradisgneise)

Tab. 10: Groundclasses for Zone Faido.

Bezeichnung Gebirgsklasse	Code 1=SPV, 6=TBM	GT1 GK1 Nr.	Vortriebsleistungen steigender Vortrieb [m/VT]				Laufmeterkosten steigender Vortrieb [1'000 Fr./m]		
			mittel	Min.	wahrsch.	Max.	Min.	wahrsch.	Max.
1	2	3	4	5	6	7	8	9	10
I	6	1	21.0	0	25.2	37.8	10.08	12.60	15.12
II	6	2	17.0	0	20.4	30.6	11.84	14.80	17.76
III	6	3	14.0	0	16.8	25.2	12.80	16.00	19.20
IV	6	4	8.0	0	9.6	14.4	17.84	22.30	26.76
V	6	5	3.0	0	3.6	5.4	27.68	34.60	41.52
A16	6	54	0.063	0.063	0.063	0.063	1800	1800	1800
Abd_DD	1	53	0.153	0.052	0.164	0.243	166.1	316.1	966.1

Vortriebsleistungen und Laufmeterkosten pro Gebirgsklasse

Column 1: Ground Class (Excavation Support Class) Designation
Column 2: Code 1 Drill and Blast; Code 6 TBM
Column 3: Ground Class (Excavation Support Class) Number
Columns 4-7: Advance Rates in m/day; mean, minimum, most probable, maximum
Columns 8-10: Unit cost in 1000 Fr./m; minimum, most probable, maximum

Tab. 11: Unit Costs and Advance Rates – Example.

	Vortriebsleistungen		Laufmeterkosten		Verteilungsart
	Min	Max	Min	Max	uniform
Sprengvortrieb	-15%	+5%	-5%	+10%	uniform
TBM-Vortrieb	-25%	-5%	-55	+10%	uniform

Tab. 12: Variation of Mean Values of Advance Rates and Unit Costs.

profile (distributions that are smaller than the input distributions). This was corrected by considering the fact that the mean values can also vary, and this was implemented with the values shown in Table 12.

- The TBM construction simulation was refined by increasing the uncertainties related to delays and by including the learning curve.

The resulting cost-time scattergram in Figure 22 shows dramatically the effect of the Piora zone. Without the Piora zone the usual elliptical shape with a slight cost-time dependence (inclination) occurs. With the Piora zone greater costs result, and the scattergram has a completely different shape. This shape reflects the fact that below a certain length of the Piora zone there are only cost effects caused by the pretreatment but the pretreatment is finished in time such that the main tunnel is not affected. Once this length is exceeded the pre-treatment of the Piora zone has a major time effect with the related cost increase.

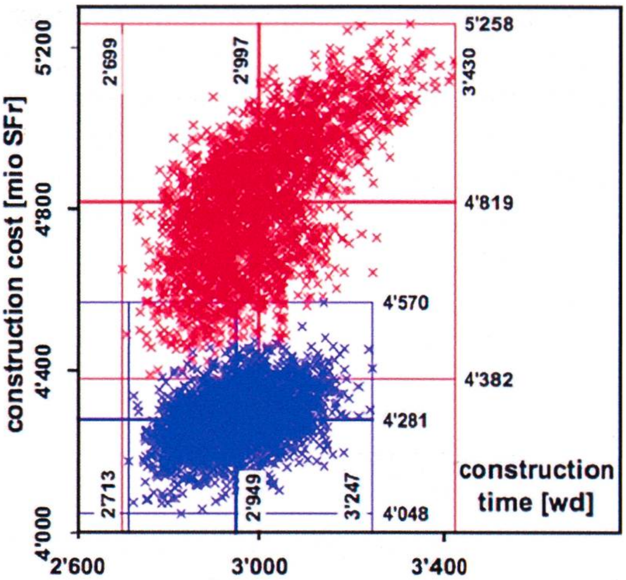

Fig. 22: GBT 1997 Study of Cost and Time - Resulting Cost - Time Scattergram Upper scatter with effect of problematic Piora zone, Lower scatter with no effect of problematic Piora zone.

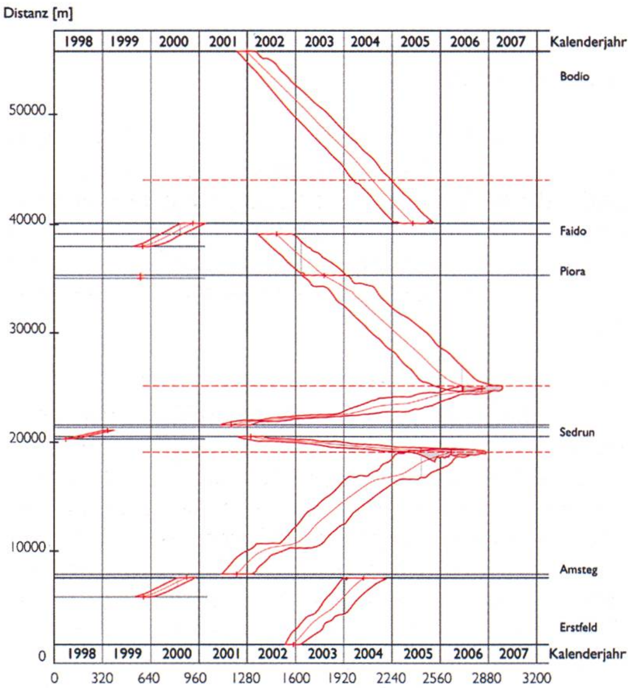

Fig. 23a: GBT 1997 Study of Cost and Time – Resulting Time-Distance Diagrams, with no effect of problematic Piora zone.

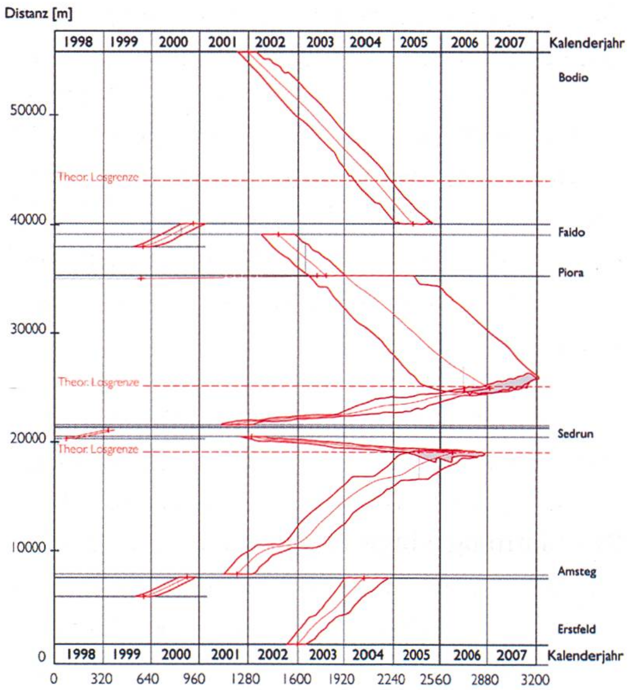

Fig. 23b: GBT 1997 Study of Cost and Time – Resulting Time-Distance Diagrams, with effect of problematic Piora zone.

This time effect is also very much visible when comparing the time - distance diagrams for the tunnel without and with Piora zone (Figures 23a, b). The diagrams are presented not only because they show the particular time effect but also the effect on total time. Without the problematic effect of the Piora zone the end times north and south of Sedrun are comparable both caused by the slow advance rates with drilling and blasting through problematic geology (TZM etc.). This is quite different with the problematic Piora zone. Diagrams like this allow one, in principle, to refigure the construction process. Fortunately, further exploration from the Piora pilot tunnel indicated that the rock at tunnel level was unproblematic and was indeed so when the main tunnel crossed the zone.

7 Concluding Remarks

Large construction projects and particularly tunnels are subject to a variety of uncertainties that affect risk. Considering these uncertainties in the planning, design and construction stages is necessary for technical, economic, social and political reasons. The leaders of the Gotthard and Lötschberg Base Tunnel projects were aware of the necessity to formally asses the effect of uncertainties, and the Decision Aids for Tunneling provided them with the instrument to do so. The specifics of the GBT application were described in this Part 1 showing how the DAT were applied and from the very beginning of the project.

As with all predictive methods the question arises how close the predictions are to the actual performance. The predicted ranges from the planning stage are comparable to what the project teams internally determined and also to the actual results. Clearly, as shown with some of the studies in this paper the predictive accuracy can be improved if regular updating takes place. Most important, and we hope to have shown this, is the willingness of the decision makers to not only use a predictive instrument such as the DAT but to get actively involved in its adaptation and further development.

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The DAT and the application to the GBT and LBT would not have been possible without the interest and help of the Alptransit decision-makers and the development work by colleagues and students. Since most of these people were involved in both projects they are mentioned here and will be again in Part 2.

The decision-makers P. Testoni of FOT, P. Zuber. P. Zbinden and E. Märki of SBB/Alptransit Gotthard, F. Kilchenmann, P. Teuscher of BLS/Alptransit Lötschberg, E. Basler, P. Schuster of E. Basler & Partners, and P. Egger of EPFL initiated, supported and made certain that the DAT were used. The geologists and engineers, many of whom are named in the text, made the practical application possible. C. Indermitte, V. Halabi, Ch. Haas, C. Marzer, S. Min, R. Moret, R. Sousa worked as postdocs or as part of their thesis research on the DAT with C. Indermitte continuing his involvement till today. In other words exemplary teamwork was involved for which the authors would like to express their sincere appreciation.

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