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Application of the Decision Aids for Tunneling in the Gotthard and Lötschberg Base Tunnel Projects, Part 2 - Lötschberg Base Tunnel, Other Transalpine Tunnels and Further Development

Herbert Einstein [1], François Descoeudres [2], Jean-Paul Dudt [3]

Abstract

This is the second of a two-part set of articles. In Part 1 the Decision Aids for Tunnel-ing (DAT) were introduced and their application to the Gotthard Base tunnel were described in detail. In this Part 2 applications to the Lötschberg Base Tunnel and other transalpine tunnels will be described first followed by brief descriptions of new developments both regarding tunnels and applications to other types of infrastructure.

[1] Professor of Civil and Environmental Engineering, MIT, Room 1-342, MIT, Cambridge MA 02139, USA, einstein@mit.edu

[2] Hon. Prof. EPFL, Route de Meinier 155 CH1252 Meinier, f.descoeudres@bluewin.ch

[3] Formerly: Laboratoire de Mécanique des Roches (LMR), EPFL. Currently: Ch. des Clos 103, 1024 Ecublens, Switzerland, email: dudt@tvtmail.ch

1 Introduction

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 Gotthard Base Tunnel (GBT) in the Swiss Bulletin. While the preceding Part 1 concentrated on the development and applications of the DAT for the GBT project, this Part 2 will discuss the application to the LBT; it will also describe the use of the DAT in other transalpine tunnels and in other applications. Specifically, Chapter 2 will describe the DAT application in the LBT followed in Chapter 3 by summaries of what was done for other transalpine tunnels. Since the DAT are still undergoing further developments and to show their versatility Chapter 4 will describe other relevant applications. The concluding remarks in Chapter 5 will try to put both Parts 1 and 2 in the context of decision-making under uncertainty for large infrastructure projects.

2 Application of the DAT to the LBT

The first specific use of the DAT for the LBT was for the Northern Pilot Tunnel Frutigen-Mitholz followed by the 1997 GBT-LBT study mentioned in Part 1 Section 3.4 and an estimation of completion time in 2002. In addition, a M.Sc. thesis at MIT applied the DAT for resource management. Below we discuss issues that are different from what was presented before. Again, the reports on which the following is based are listed in the bibliography.

2.1 Pilot-Tunnel Frutigen - Mitholz

The BLS Alptransit AG charged EPFL in 1993 to compare time and cost for this pilot tunnel as information changed both regarding geology and construction from 1993 to 1994. The original geology used during the bid phase was updated with information from a boring near the southern end of the pilot tunnel. This led to changes in the original type profiles (reflecting the underlying groundclasses) as shown in Figure 1. However, these changes seem to offset each other when combined with construction cost and time as can be seen when comparing Figures 2 a and b. On the other hand, once the bid was submitted and the engineers updated their estimates (Table 1) a significantly different cost-time spread resulted (Fig. 2c). Updating information can thus have quite different effects depending on the particular case.

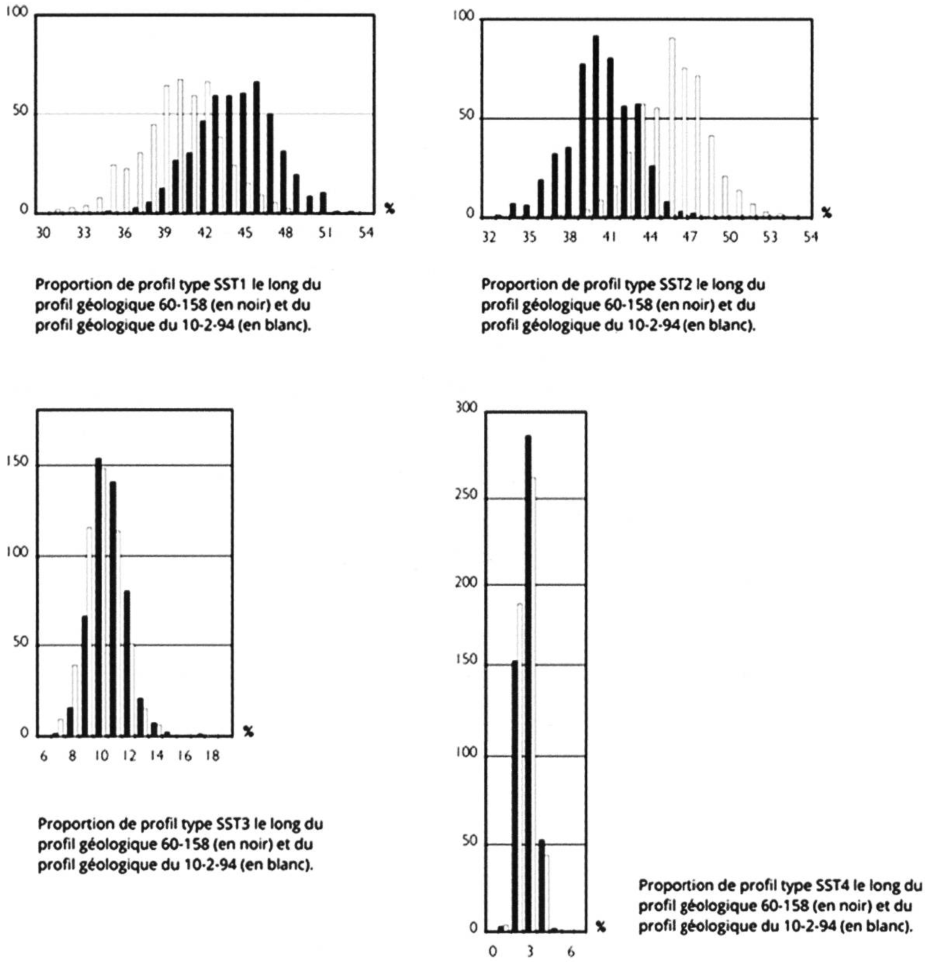

Fig. 1: LBT Pilot Tunnel Frutigen- Mitholz, Comparison of the Cumulative Length of Four Different «Type-Profiles», Black: Original estimate; White: Updated Estimate.

Profil Type	Vitesse moyenne µ [m/jour]	Valeurs utilisées dans les simulations (distr. triang.) min. (0 µ)	probable (1.25 µ)	max. (1.75 µ)
SST1	42.3	0.00	52.88	74.03
SST2	33.0	0.00	41.25	57.75
SST3	25.9	0.00	32.38	45.33
SST4	10.0	0.00	12.50	17.50
SST5	35.4	0.00	44.25	61.95
SST6	23.6	0.00	29.50	41.30
SST7	10.2	0.00	12.75	17.85
SST8	10.1	0.00	12.65	17.70

Tab. 1. Original and Updated Advance Rates.

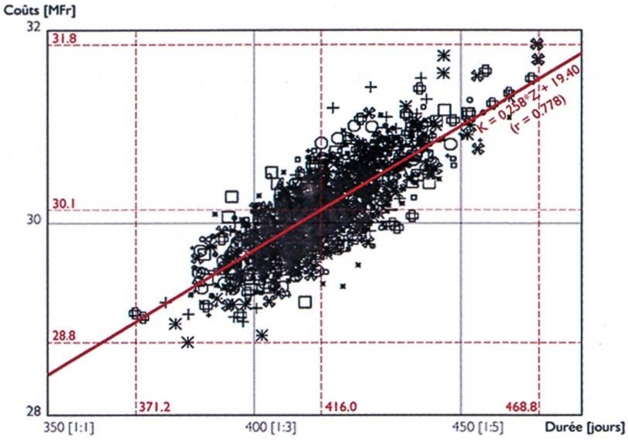

Fig. 2a: LBT Pilot Tunnel Frutigen- Mitholz – Resulting Cost - Time Scattergrams, Based on original estimate.

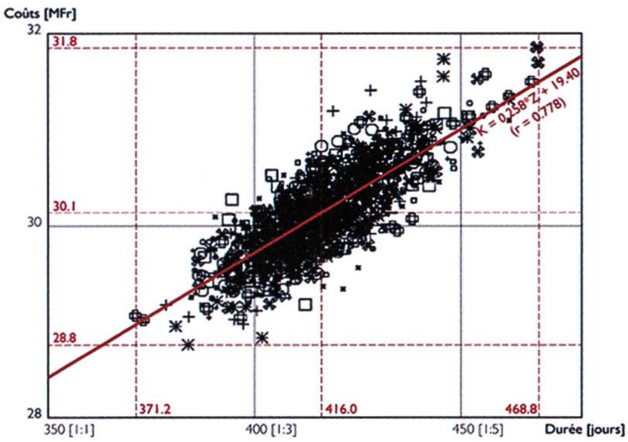

Fig. 2b: LBT Pilot Tunnel Frutigen- Mitholz – Resulting Cost - Time Scattergrams. Based on updated estimate.

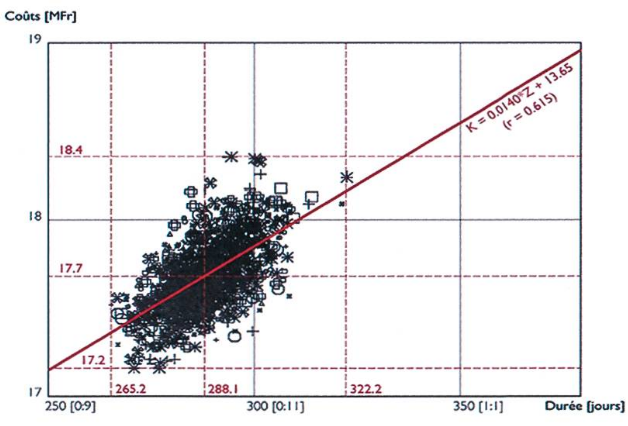

Fig. 2c: LBT Pilot Tunnel Frutigen- Mitholz – Resulting Cost - Time Scattergrams, Based on information from the contractor's bid.

2.2 1997 Study of Construction Cost and Time

This was the same study for the GBT and LBT with the objective to compare the DAT results with those obtained by the project teams. (Please see also Section 3.4. in Part 1). The schematic of tunnel sections that were included for the LBT is shown in Figure 3. Note that although the general layout corresponds to what has been built (two single track tunnels Raron-Ferden, one single track tunnel complete Ferden-Mitholz-North Portal (Frutigen), raw tunnel Ferden - Mitholz, access tunnel Steg); however, the simulated example is using Drilling + Blasting for all sections, while in the realization TBM was used for all South of Ferden. The input regarding geology and construction classes was analogous to that for the GBT and a major problematic zone, the sealing of the Doldenhorn Section was included as well as some smaller disturbed zones. The resulting cost-time distribution is shown in Figure 4a. As was briefly discussed in Part 1 Section 3.4, it makes a difference if the unit time and cost distribution are varied around a known (and thus constant) mean value or if the latter is also uncertain (see Table 12, in Part 1). The result of varying these mean values becomes evident when comparing figures 4a and b. The time - distance diagram for the East-tube (the one which is fully operational) is shown in Figure 5.

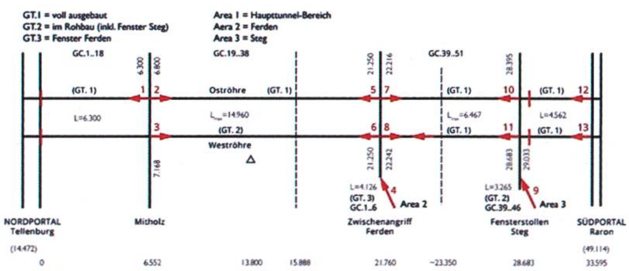

Fig. 3: LBT 1997 Study of Cost and Time – Schematic of Construction Simulation.

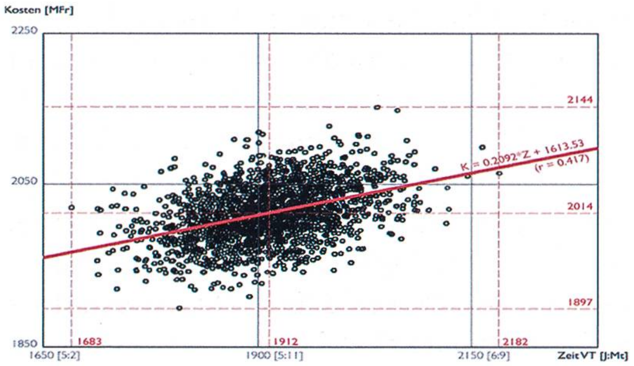

Fig. 4a: LBT 1997 Study of Cost and Time - Resulting Cost - Time Scattergrams, Constant mean unit costs and advance rates.

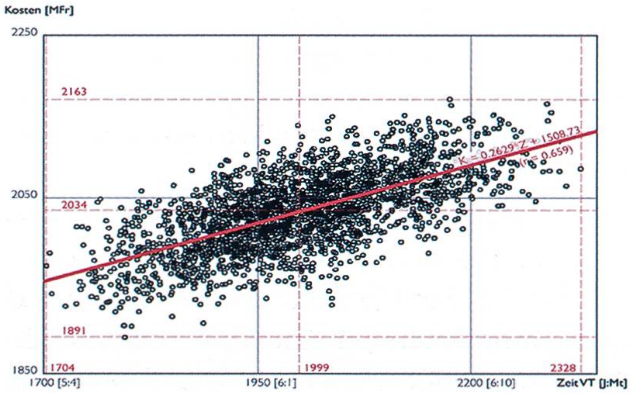

Fig. 4b: LBT 1997 Study of Cost and Time - Resulting Cost - Time Scattergrams, Variable mean unit costs and advance rates.

2.3 Updating the time estimates for the LBT

In 2002 EPFL was charged by BLS Alptransit to review the time estimates and update them based on the actually recorded advance rates. The results are presented in Figure 6, which nicely shows the single lines in the executed part and the fans in the unexcavated ones representing the remaining uncertainties. It also shows that the section between Ferden and Mitholz is essential regarding completion time. In Figure 6a and b one can see that the drive Mitholz-South follows the planned construction progress but that the access Ferden was delayed. The projections (fans) indicate that the pessimistic hole-through may be only in 2007 while it was planned for 2005. Fortunately, the real advance rates were much faster than planned. This then led, still including the same uncertainties, to a much more optimistic performance prediction with an estimated mean hole through in 2004 and a late one

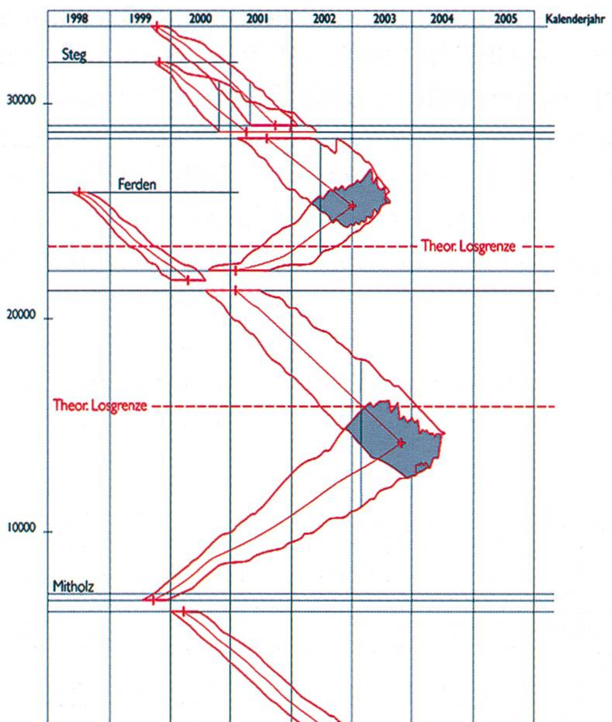

Figure 5: LBT 1997 Study of Cost and Time – Resulting Time-Distance Diagram.

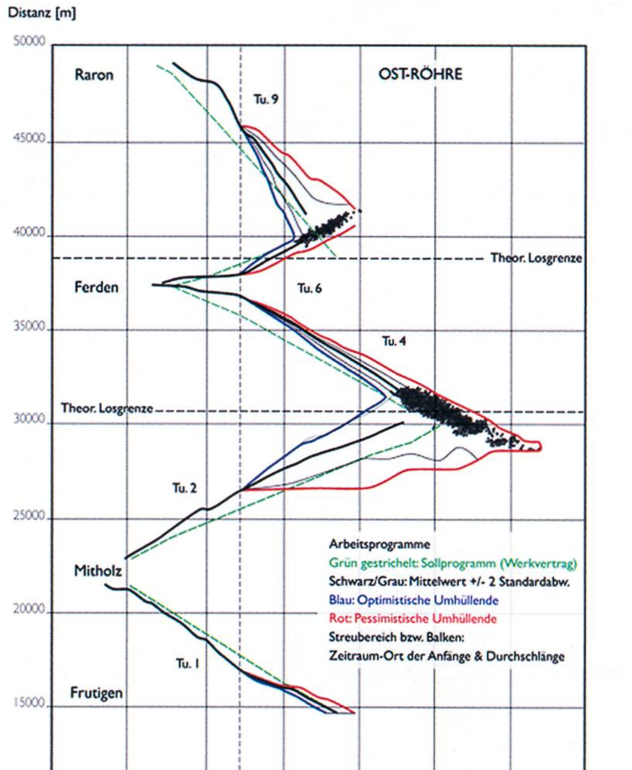

Fig. 6a: LBT Updating of Time Estimates, Estimate May 2002.

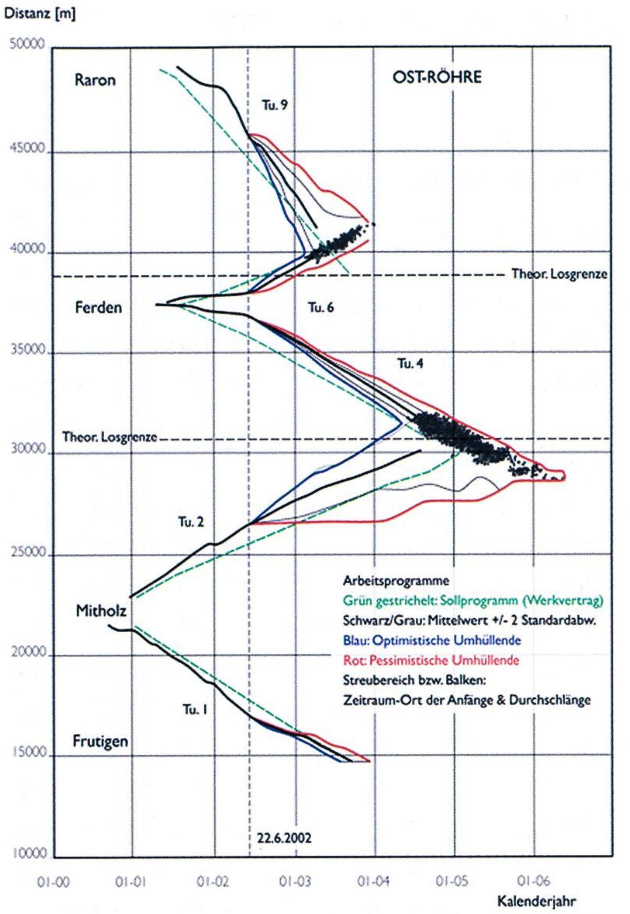

Fig. 6b: LBT Updating of Time Estimates, Estimate June 2002.

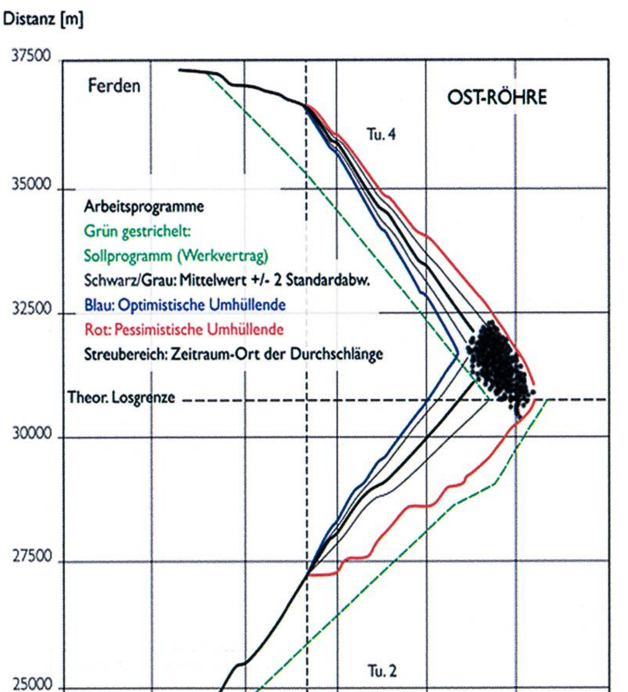

Fig. 6c; LBT Updating of Time Estimates, Estimate September 2002.

in early 2005. The actual hole-throughs were on March 15 / April 28 2005. Quite relevant is the fact that the main problem, the occurrence of the Carbon, which caused a delay of two months was not considered. The Carbon was not included in the geologic prediction since it was thought to only occur at greater depths (see Ziegler, 2004). This attests to a well-known fact that computer models cannot make up for missing input. Fortunately, the actual faster advance rates built up a reserve through which this major delay was somewhat compensated.

2.4 Modeling of Resource Management

The use of the DAT for materials management in the GBT was discussed in Part 1, Section 3.3. For the LBT the DAT were used in a synthetic study in the M.Sc. thesis of Ch. Kollarou (2002) to model the LBT resource management. While the model and its results were not used in the LBT project, the project team made all the necessary information available (and reviewed the results). The DAT modeling was similar to what was done for the GBT but with a difference in material characterization. Table 2 shows the categories used by the LBT management and the refinements introduced by Kollarou. This refinement consisted of a differentiation in categories 1 and 2 distinguishing the origin from drill and blast or TBM excavation, the latter being only usable for shotcrete aggregate. A further differentiation was the consideration of alkali reactive material than can only be

Main muck Categories as initially used by LBT-Management: • Class 1 materials (K1): Good quality materials, relatively homogeneous. Used as aggregate in shotcrete and concrete. • Class 2 materials (K2): Moderate to good quality materials, relatively heterogeneous. Used if necessary as aggregate in shotcrete and concrete production. • Class 3 materials (K3): Poor quality materials, unsuitable for shotcrete and concrete aggregate.
Further subdivisions (as done in the MIT investigation; similar to but not exactly as done in reality): • K1DB and K1TBM (K1DB used for cast in place concrete, K1TBM useable for shotcrete). • K1arDB and K1arTBM (Same usages as above but only with special mix to accommodate alkali reaction). • K2DB and K2TBM (Used if necessary for shotcrete and cast in place concrete). • KuDB and KuTBM. (This includes alkali reactive K2 material produced by TBM or DB and all K3 material independent of the method of excavation.) Needs to be disposed of e.g. in landfills.

Tab. 2. Materials Management Lötschberg Base Tunnel – Specifics.

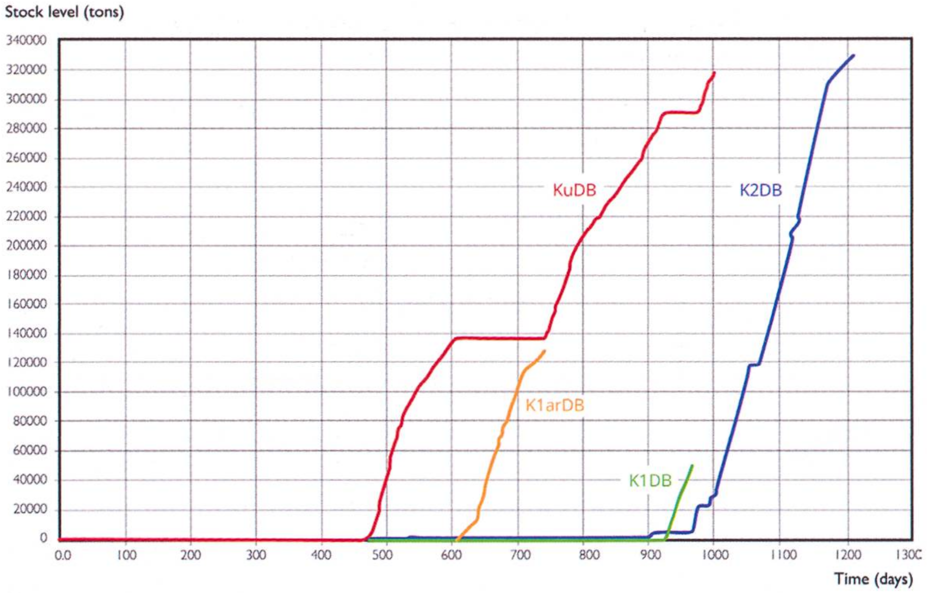

Figure 7: LBT Synthetic Resource Management Study. Material at Raron Repository – Volume- Time Diagram as seen on a Computer Screen: Ku = Not useable; K 1 ar = Class 1 Alkali Reactive; K1, K2 = Classes 1, 2; DB = Drilling and Blasting.

used in a special mix. The latter turned out to be important as shown in Figure 7 for the repository at Raron.

3. Other Tunnels

The DAT were and are used in many tunnels worldwide. Here, applications to the other major transalpine tunnels are briefly mentioned as well as a study of freight tube systems under cities.

3.1 Transalpine Tunnels – Monte Ceneri, Mt Ambin and Brenner

Alptransit Gotthard requested a time study, similar to the one for the LBT, for the Monte Ceneri Base tunnel when the geologic predictions indicated worse than anticipated conditions. Since this study included the use of TBM, which then did not apply in reality, it is not further discussed here.

Fig. 8 a, b, and c are schematic time-distance diagrams prepared by Geodata for the Mt. Ambin Tunnel. Particularly interesting are Figures 8b and c, the former showing the effect of exploration and the latter different time spreads depending on the construction method.

The structure of the resource management (muck reuse) system was shown in Figure 6, Part 1. This was used to assess the muck production and reuse in a section of the Brenner Basetunnel. Analogous to Figures 20 Part 1 and Figure 7, this Part 2, the volume-time diagram of produced and required concrete aggregate is shown in Figure 9.

3.2 Freight Tubes under Cities

In 1994 the US Federal Highway Administration (FHWA) charged MIT with the study of so-called «freight tube systems». These systems consist of tunnels under densely populated cities through which freight originating from truck- or rail terminals is distributed. The MIT work included the study of tunnel-construction as well as the conceptualization of the transport technology; only the former is discussed here. Regarding tunnel construction FHWA wanted to have cost estimates as well as an investigation of the effect of technological improvements on tunnel cost. Specifically, this was done for three scenarios in four different locations as listed in Table 3.

The scenarios represent small diameter tubes for transport of packages, intermediate diameter tubes for transport of standard pal-

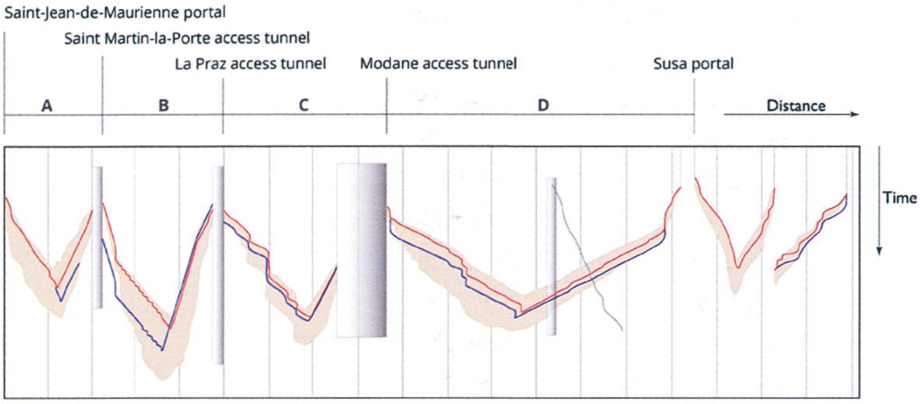

Fig. 8a: Mt Ambin Base Tunnel Schematic Time-Distance Diagram (Figure after Geodata, Turin) - Entire Tunnel with Uncertainties. Tunneling will start at both ends and at several intermediate locations. The diagram shows the deterministic prediction (red line) and «fans» (beige) with mean (blue line) representing time uncertainty.

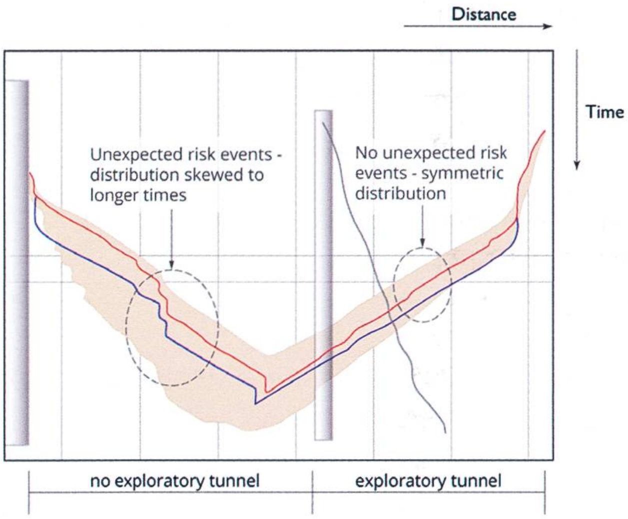

Fig. 8b: Mt Ambin Base Tunnel Schematic Time-Distance Diagram (Figure after Geodata, Turin) - Section D Effect of Information from Exploratory Tunnel (brown, single diagonal line on right side). The diagram shows the deterministic prediction (red line) and «fans» (beige) with mean (blue line) representing time uncertainty.

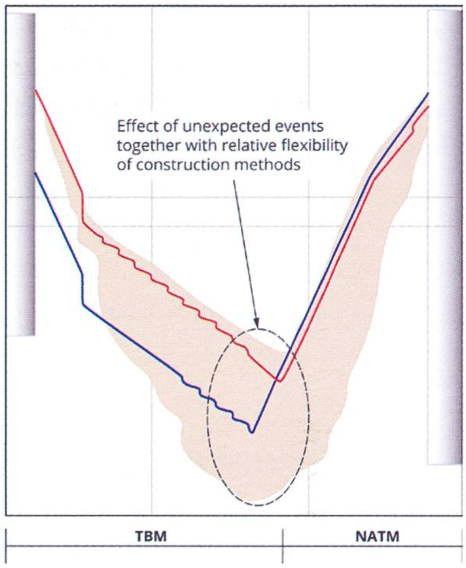

Fig. 8c: Mt Ambin Base Tunnel Schematic Time-Distance Diagram (after of Geodata, Turin) - Section B (note effect of different construction methods) The diagram shows the deterministic prediction (red line) and «fans» (beige) with mean (blue line) representing time uncertainty.

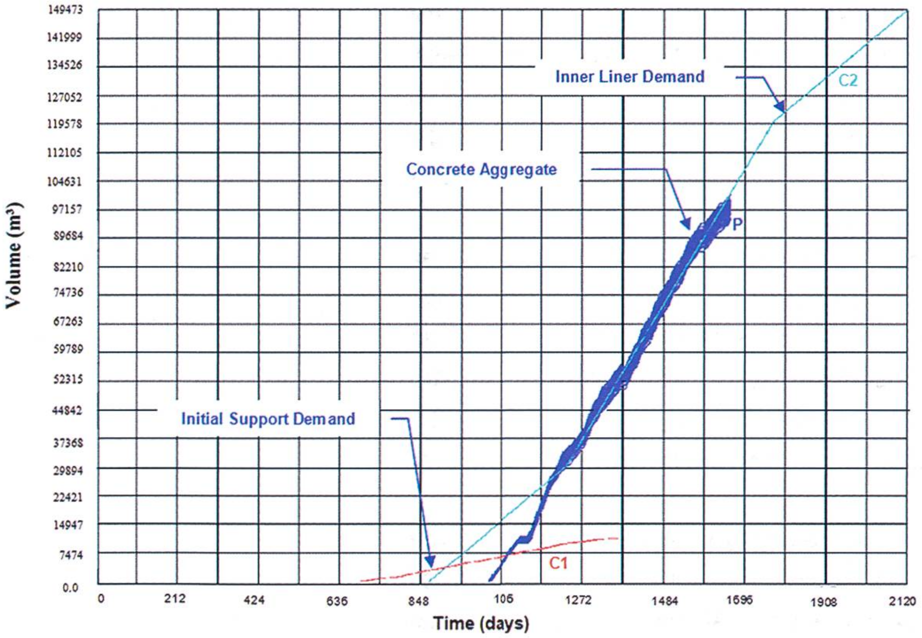

Fig. 9: Materials Management Brenner Base Tunnel (from Ritter et al., 2013) P: Produced material; C 1,2 Re-used as concrete aggregate.

Scenarios	Excavated Diameter		Services Loop		Access Distance	
	Feet	(m)	Miles	(km)	Feet	(m)
Small Diameter - High Density	4	(1.2)	<2	(~3)	450	(125)
Intermediate Diameter - Moderate Dens	8	(2.4)	2 – 4	(~3-6)	1320	(400)
Large Diameter - Low Density	14	(5.2)	5 - 6	(~8-10)	3200	(1000)

Locations: Cambridge, Downtown Boston, Midtown Manhattan, Downtown Manhattan

Tab.3. Freight Tubes Under Cities - Studied Scenarios.

lets and large diameter tubes for transport of standard containers; the densities of the tube networks vary correspondingly. How this might look is shown in Figure 10 for Midtown Manhattan. Figure 11 shows the results of the other part of the study, namely the effect of technological changes. Readers interested in details are referred to Sinfield and Einstein (1996). This study is mentioned here since freight tube projects in or between cities are under serious discussion at present.

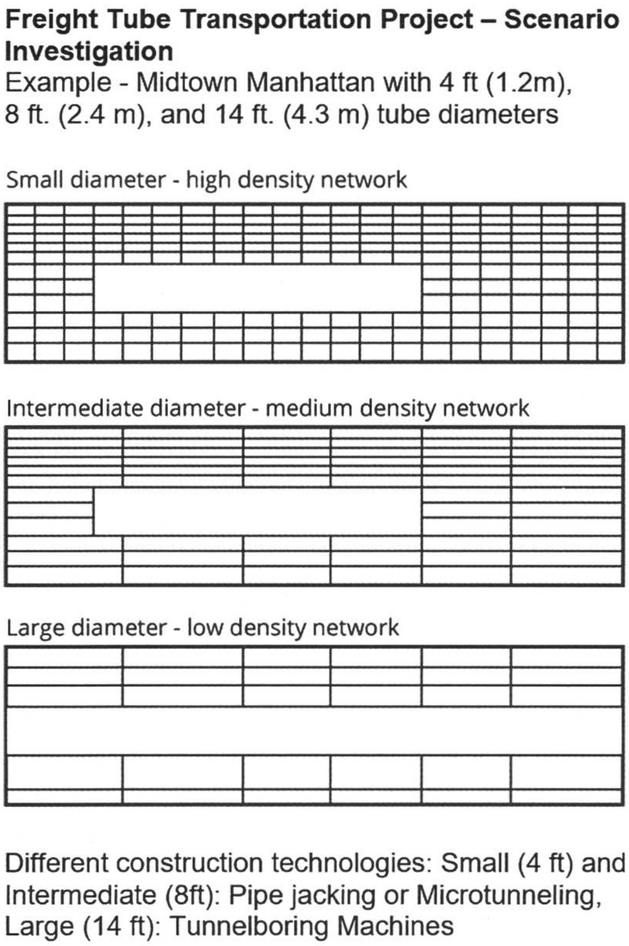

Figure 10: Freight Tube Tunnel Study for the Federal Highway Administration Different Tube Networks in Midtown Manhattan (Around Central Park).

4 Other Applications and Developments

The DAT were extended to cost/time estimation of other types of projects as was described in Einstein et al. (2017) and summarized below.

4.1 Extension to Linear/Networked Infrastructure and Other Uncertainties

Moret (Moret, 2011; Moret and Einstein, 2012, 2016) extended the DAT to include viaducts (bridges), cuts and embankments in addition to tunnels, which makes it possible to determine cost- and time distributions of linear infrastructure projects and in-frastructure networks. The underlying logic of the DAT with geologic profiles (where applicable), with construction activity networks and cost- and time distributions remains. Very important is that, in addition to the random geologic and construction variability considered so far, correlations and disruptive events were included in the DAT.

The extended DAT were applied to a section of the planned high-speed rail line (RAVE) in Portugal. Cost correlation increases the range of cost distribution by a factor of five to ten compared to only considering random variability. Figure 12 shows the range of combined variability and cost correlation (black clouds), and the effect of disruptive events (grey clouds) on the cost-time scatter.

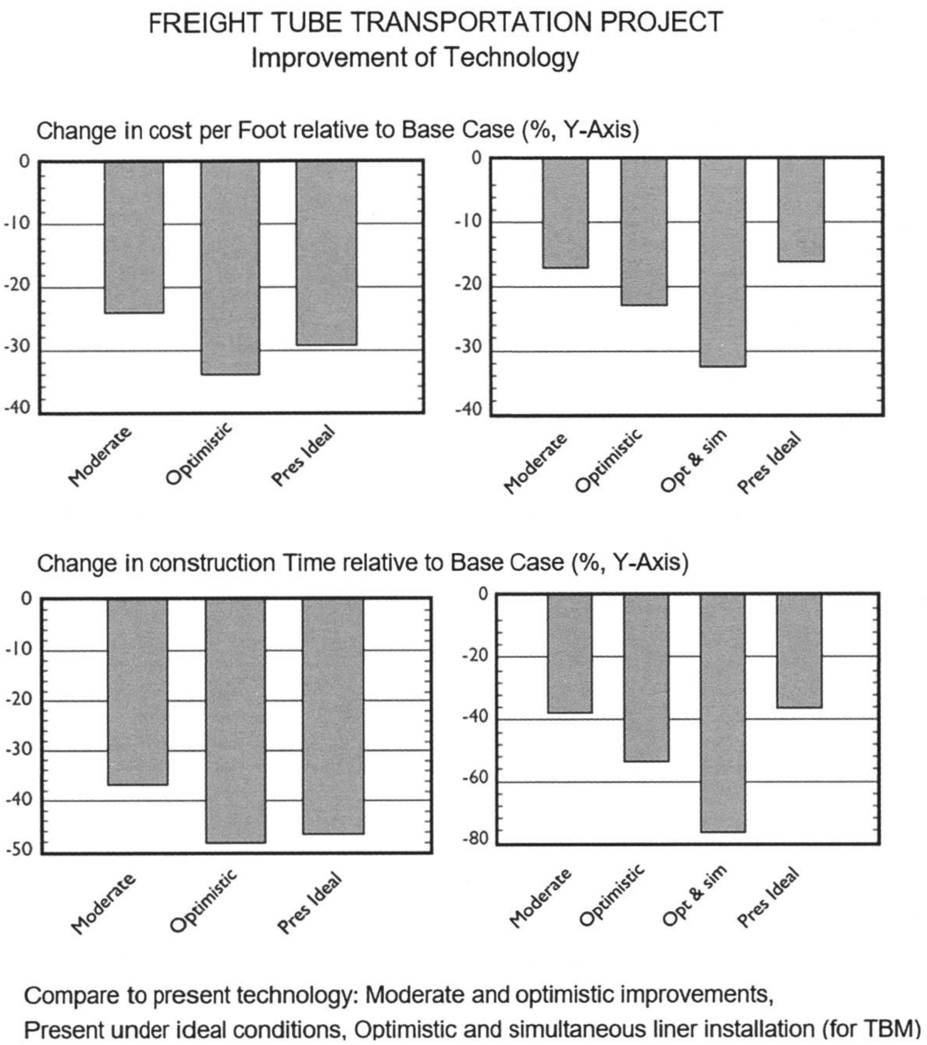

Fig. 11: Freight Tube Tunnel Study for the Federal Highway Administration, Comparison of Technology Improvements.

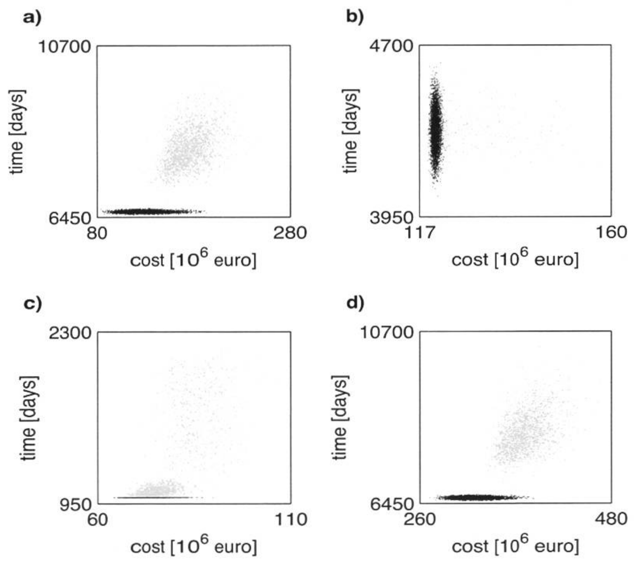

Fig. 12: Extension of the DAT to Linear and Networked Infrastructure (From Moret and Einstein. 2016); Cost-time Scattergrams showing the effect of variability and correlation (black clouds), and the additional effect of disruptive events (gray clouds) for; a Tunnels, b Viaducts, c Cuts/Embankments, d All Combined.

4.2 Extension to Deep Well Boring

Engineered Geothermal Systems require drill holes (wells) reaching depths to 6 km to reach the 200°C temperature needed for electric power production (see e.g. Tester, 2006). Such well borings are subject to geologic and construction uncertainties analogous to those encountered in tunneling but also somewhat different because of the elevated temperature. Yost (Yost, 2012; Yost et al., 2015) modified the DAT to model well boring cost and -time subject to uncertainties and applied them to a synthetic typical well hole (Fig 13). The uncertainty factors are: Component cost, drilling cost and time, fluid usage, trouble costs, geology, temperature effects (affecting logging, fluid loss, cementation). The simulation is analogous to that for tunnels and results in the cost-time scattergram shown in Figure 14. Very interesting is the fact that considering these factors and their uncertainties leads to a cost/time distribution much beyond the deterministic estimate.

4.3 Including Optimization

Looking at different alignments of tunnels or other infrastructure projects and comparing the resulting time/cost distributions is easily possible with the DAT. However, selecting the optimum alignment so far had to be done «by hand», i.e. repeating the simulations for different alignments and comparing them externally. Costa (Costa, et al., 2013, 2016) developed an optimization process based on simulated annealing with which rail line alignments can be optimized regarding economic, environmental and traveler demands as well as considering the potential effects of natural hazards. This tool has now been combined with the DAT, following the process schematically shown in Figure 15, and has been applied to a subway line in Abu Dhabi (Al Kaabi et al.; 2015).

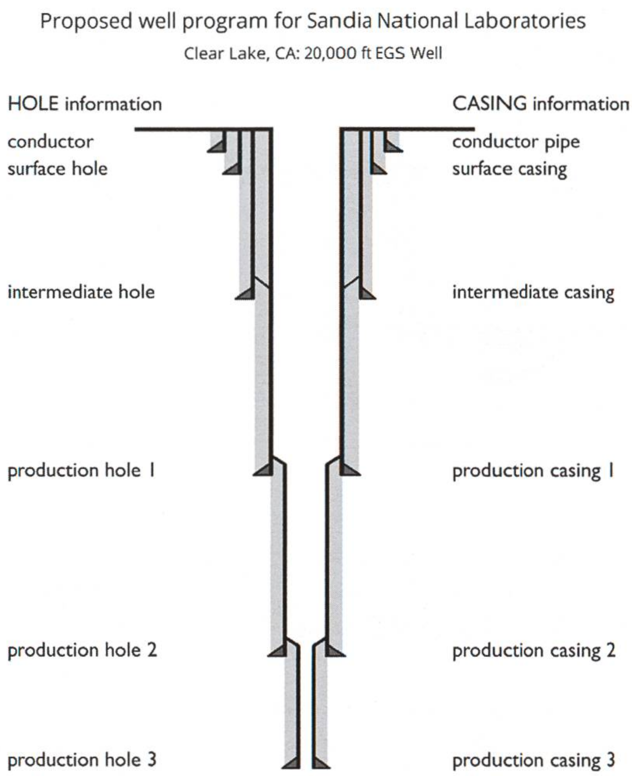

Fig. 13: Application of the DAT for Deep Well Borings – «Synthetic» Well from Sandia National Laboratories (after Polsky et al., 2008).

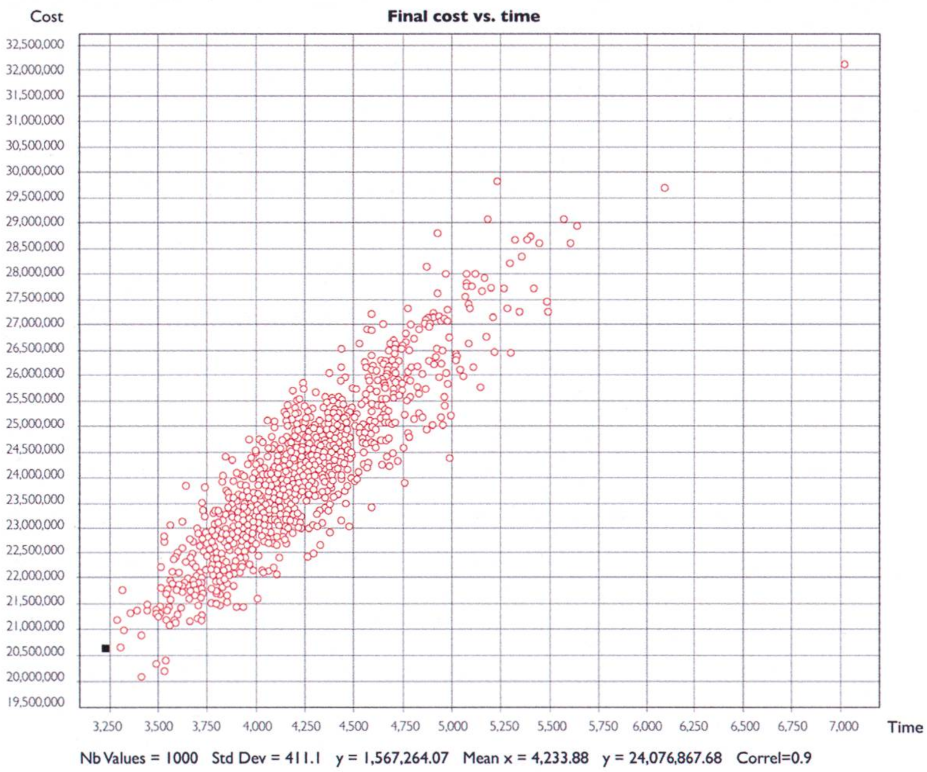

Fig. 14: Application of the DAT for Deep Well Borings - Cost-Time Scattergram Considering Component Cost Uncertainty, Trouble Events, Geological Variation and Drilling Fluid Usage Rates. Dot on Bottom left: Deterministic Case with Original Data (from Yost et al., 2015).

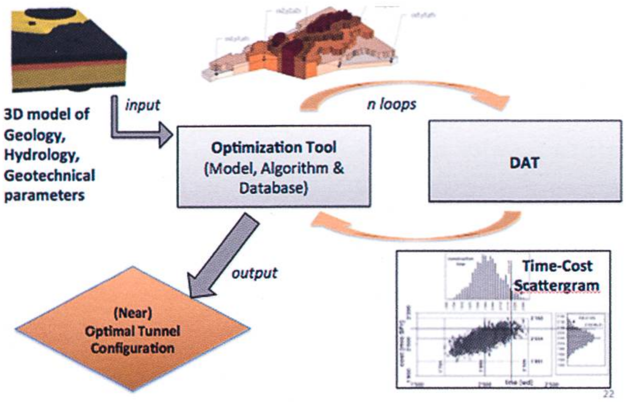

Fig. 15: Combination of DAT and Optimization (from Al-Kaabi, et al., 2015).

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.

5. Concluding Remarks

This concludes the Part 2 of the articles describing the use of the Decision Aids for Tunneling (DAT) mostly in the context of their development and application for the two Base Tunnels, Gotthard and Lötschberg, in Switzerland. These applications but also the others that were briefly mentioned and the new developments show that tunnels but large construction projects, in general, are subject to a variety of uncertainties that affect risk. Considering these uncertainties i.e. «Decision Making under Uncertainty» in the planning, design and construction stages is necessary for technical, economic, social and political reasons. The decision makers in the projects described in the two articles 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.

Acknowledgements

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 as well as in some of the other applications they were mentioned in Part 1 and are now mentioned again:

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