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Optimum tunnel system with regard to the entire lifecycle for long rail tunnels

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ABSTRACT: Since more than 30 years long tunnels with a total length of more than 50 kilometres exist. Many of them show a different tunnel system: double track tunnels with service tunnel, two single track tunnels and two single track tunnels with a service tunnel are the existing systems. The decision on the tunnel system of this long tunnels had to be taken at a time when only few information on operation and maintenance costs were available. Today more information on operation and maintenance should be available. The paper shows, how the decision-making process could be adapted today considering the criteria construction, operation and safety and life cycle. Recommendations on the selection of the tunnel system will be given, based on the available operation experience of the long tunnel railway tunnels.

1 MOTIVATION

For more than 100 years railway tunnels with lengths of 10 km and more have been built. To a large extent, these tunnels are still operating today (see Table 1). However, the demands posed on such tunnel systems have increased during the past years. For a long-time, the double track Tunnel without a service tunnel was the most popular system (variant 1A). Due to the higher safety standards such a system, even with an additional service tunnel, is no longer permissible nowadays unless drastic operating restrictions for mixed railway traffic apply (Ehrbar et al., 2016).

Today – similar to modern buildings –tunnel systems are highly developed technical systems with high demands. In order to thrive against competing transportation systems, the modern rail infrastructure must on the one hand, comply with all safety requirements and on the other hand, provide high availability and an economic operation. Thus, in the case of very long tunnels in particular the question arises, which tunnel system will be able to fulfil the large number of needs in an optimal fashion considering the entire lifecycle of the infrastructure.

2 TUNNELLING SYSTEMS

When choosing a system, there are theoretically no limits on the number of tubes and their configuration (see Figure 1). Systems with a pre-investment could also be made. Thus, a third tube could be created, which is not yet fully provided with railway equipment (as e.g. in the Lötschberg Base Tunnel on 40% of the total length the second single track tube is excavated, but no railway equipment has been placed in).

Railway tunnel systems with more than one tube can consist in a system of pure railway tunnels or in a mixed system of railway tubes and service tunnels.

The historic long railway tunnels such as the Mont Cenis Tunnel, the Gotthard Tunnel, the Arlberg Tunnel and the Lötschberg Tunnel were created as pure double track tunnels without

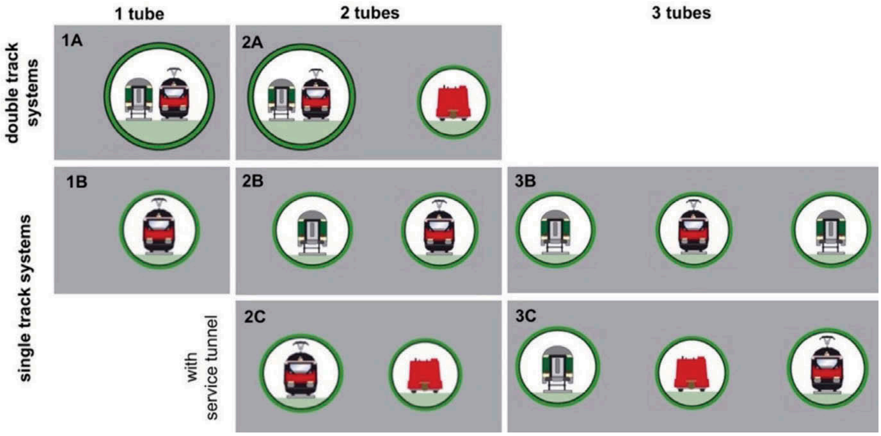

Figure 1. Variants of railway tunnel systems.

a service tunnel. Only the 19.8 kilometres long Simplon Tunnel has a system with two separate traffic tubes. The decision on this system based on economic and logistical reasons (stages of the construction process, ventilation and cooling).

For the first time in history, in 1988 an over 50 km long railway tunnel was commissioned with the 53.8 km long Seikan Tunnel in Japan.

Parallel to this project in Japan the construction work on the 50.4 km long Channel Tunnel was started in 1987 crossing under the English Channel. The safety requirements for this tunnel exceeded all existing ones. The tunnel system was implemented with two single-track tunnels and one service and safety tunnel plus an extra complex ventilation system. The Channel Tunnel was commissioned in 1994.

In 2007 the Lötschberg Base Tunnel started the commercial operation with a mixture of the tunnel systems 2B (on 40% of the length without the installation of the railway installations) and 2C on 20% of the total length according to the definitions of Figure 1. The reasons for the selection of such a system were financial restrictions and political decisions.

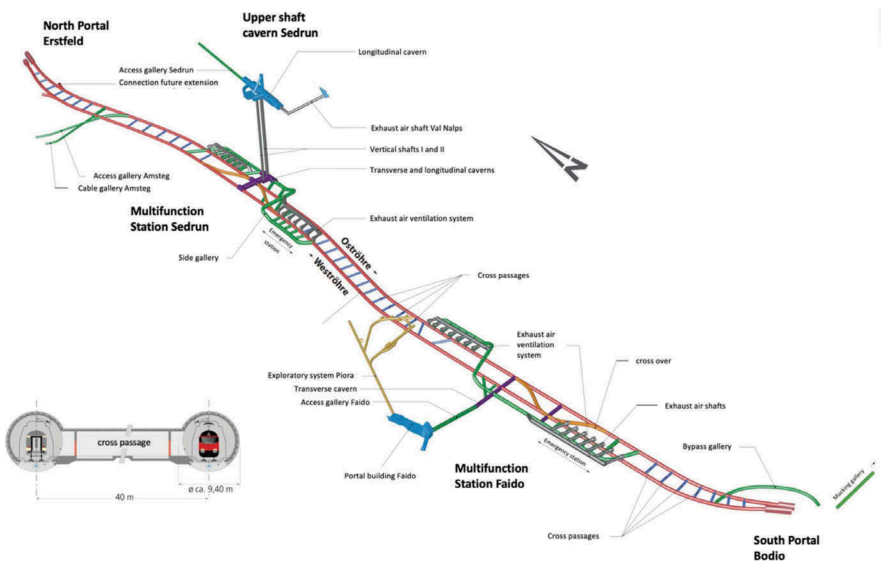

Figure 2. Tunnel System Gotthard Base Tunnel (©Amberg Engineering, STS, 2016).

In 2016 the 57.1 km long Gotthard Base Tunnel (the longest railway tunnel of the world) followed. It was built following the principles of System 2B with two multifunction stations in the third pointes, dividing the tunnel in sections of 20 kilometres in the maximum (see Figure 2).

Other long tunnels following this construction principle are the TELT (Lyon Turin) and the Follow Line Tunnel in Norway (without multifunction station).

Table 1. Overview of operating long railway tunnels in Europe.

Project Name	Country	length (km)	Commissioning	Tunnel System
Mont Cenis Tunnel	France - Italy	12	1871	1A
Gotthard Tunnel	UK - France	14.9	1882	1A
Arlberg Tunnel	Austria	10.6	1884	1A
Lötschberg Tunnel	Switzerland	14.6	1913	1A
Simplon Tunnel	Switzerland – Italy	19.8	1906/1922	2B
Furka Base Tunnel[1]	Switzerland	15.4	1982	1B
Vereina Tunnel[1]	Switzerland	19.0	1999	1B

Table 2. Overview of operating very long railway tunnels (based on Tannò, 2018).

Project Name	Country	length (km)	Commissioning	Tunnel System
Gotthard Base Tunnel	Switzerland	57.0	2016	2B
Eurotunnel	UK – France	50.0	1994	3C
Lötschberg Base Tunnel	Switzerland	34.6	2007	2B 80%, 2C 20%
Guadarrama	Spain	28.4	2007	2B
Pajares	Spain	24.7	2011	2B
Seikan	Japan	54	1988	2A[2]
New Guanjiao-Tunnel	China	32.7	2014	2B
Qinling Tunnel	China	28.2	2016	2B
Taihang	China	27.8	2007	1A
Hakkoda	Japan	26.5	2010	1A
Iwae-Ichinohe	Japan	25.8	2002	1A
Lüliang-Tunnel South	China	23.4	2014	2B
Iyama	Japan	22.2	2015	1A
Dai-Shimizu-Tunnel	Japan	22.2	1982	1A
Wushaoling	China	22.1	2006	1A

Table 3. Overview of very long railway tunnels under construction in Europe (based on Tannò, 2018).

Project Name	Country	length (km)	Commissioning	Tunnel System
Brenner Base Tunnel	Austria – Italy	56	2026	3C
TELT Lyon – Turin	France - Italy	53	2026	2B
Koralm	Austria	32.8	2024	2B
Semmering Base Tunnel	Austria	27.3	2026	2B
Follo Line Tunnel	Norway	20.0	2021	2B

Table 4. Overview of very long railway tunnels for mixed traffic under design (based on Tannò, 2018).

Project Name	Country	length (km)	Location	Tunnel System
Finest-Link	Finland - Estland	100	subsea	3C
Gibraltar	Spain – Morocco	37.7	subsea	3C
Erzgebirgtunnel	Czech Rep. - Germany	24.7	mountain	2B
Bohai Tunnel	China	120	subsea	3C

The Brenner Base Tunnel follows the principles of System 3C, whereas the final use of the service tunnel, which is driven as exploratory and drainage gallery, is not yet fixed finally.

The Tables 1 to 4 show a trend from one tube systems to actually two tube systems and to tube systems for the future. What might be the reasons for this trend? Only the fact that most of them are subsea tunnels?

3 PROJECT REQUIEREMENTS AND STAKEHOLDERS INTERESTS

In order to explain the high variability of the tunnel systems of long railway tunnels one has to give a closer look on the project requirements of long railway tunnels.

The main goal of the implementation of a tunnelling project is to meet all project requirements within the agreed level of quality, design life and operational requirements (functionality) such as safety, operating (type of traffic, timetable, flexibility, costs) and maintenance etc. Other important requirements are the realization of the project within the fixed milestones and within the given cost budget, respecting the environmental aspects and the interest of the different stakeholders (see Figure 3). All these requirements are the boundary conditions for the definition of the tunnel system of a long railway tunnel.

Many stakeholders are involved in the processes for the realisation of a major tunnel project. Each stakeholder plays a different role and has his individual interests (see Figure 3).

3.1 *Financier*

An early stable financing of major tunnelling projects is crucial for a later successful realization. The railway operators usually are not able to create sufficient revenues with their transport services to payback the initial investment. The revenues should at least cover the operation costs. Therefore, almost all the projects get a public funding. Only the Eurotunnel was privately funded, with all the well-known financing problems 10 years after starting the commercial operation (Table 5).

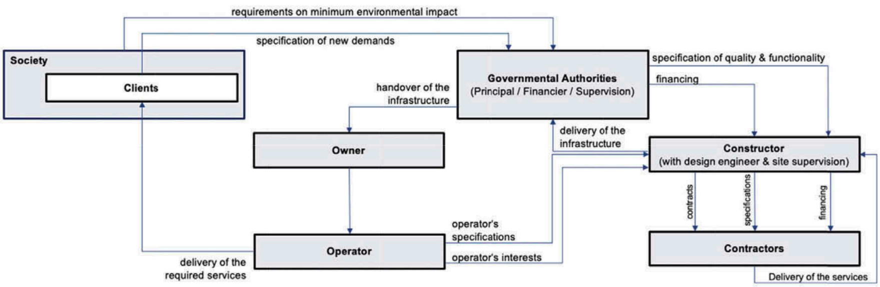

Figure 3. Possible constellation of stakeholders for a public financed long rail tunnel project.

Table 5. Overview on the total costs of selected very large tunnels (based on Tannò, 2018).

Project Name	Country	Total Costs [Bn EUR]	Prices from	Type of financing
Gotthard – Base Tunnel	Switzerland	7,0	1998	public
Lötschberg – Base Tunnel	Switzerland	4,3	1998	public
Seikan	Japan	4,7	1988	public
Eurotunnel	UK – France	4,7 Bn £	1994	private
Guadarrama	Spain	1,4	2007	public
Brenner– Base Tunnel	Austria – Italy	10	2018	public
Lyon – Turin	France – Italy	8,0	2018	public

3.2 *Principal*

The key interest of the principal is the implementation of his order within the required quality and functionality, on time and on budget (minim investment costs), considering the interests of the society. Often the principal is not the operator as he hands over infrastructure to a dedicated operator.

3.3 *Constructor*

The creation of a very long railway tunnel is often a project outside the field of action of the principal's organization. The long project duration allows to build up a specific, temporary organization for design, construction and commissioning. The constructor is the creator of the project, the overall project leader. The role of the creator is very demanding, as the existing worldwide knowledge is small. The creator has a pioneering role. A large number of processes have to be defined as usually structures and processes cannot be copied directly from other projects.

3.4 *Operator*

The operator takes over the responsibility for the operation of the infrastructure after completion of the construction work (commissioning process). Maintaining deadlines and the delivery of the mutually agreed quality are important to the operator. He has a high interest in a quick and smooth integration of the new infrastructure into the existing network. Finally, he interested in creating high profits. Therefore, the operator has a high interest on a high availability of the infrastructure, while minimizing the operation and maintenance costs. This requirement is usually in a direct contrast to the requirement of the minimization of investments.

3.5 *Authorities*

The authorities define the legal boundaries for the project by issuing the technical specifications and the approvals for construction and operation. The authorities check the compliance with the legal requirements. Since such centennial projects sometimes go beyond the current legal framework, it must be expanded or adapted.

3.6 *Designers*

The main interest of the designer is the utilisation of his resources, creating good references and financial profits. The designers are already involved in the very early project phases. They have a great influence on the project.

3.7 *Contractors and Suppliers*

The contractors' and suppliers' demand on the project are the utilisation of their resources or the delivery of their products (suppliers), to generate a reasonable profit and to receive a contribution for a good reputation. The constructability of the project should be confirmed already during the design phase in order to avoid time consuming and expensive changes during construction. Contractors knowhow should be used already in the design phase in such a way that conflicts on the procurement process can be avoided.

3.8 *Experts*

Experts bring an independent view on the project on special aspects, such as e.g. tunnelling, environmental and safety aspects. The expert's main interest is his good reputation.

3.9 *Society*

Large tunnel projects often affect also large regions and many people due to the environmental impact during construction and operation. Acceptance of the project by the public, politicians, industry and associations is important. A lack of acceptance can cause important delays in financing or in getting legal approvals.

3.10 *Customers*

The end customers are particularly interested in a high availability of the infrastructure and in cheap, comfortable and reliable transport services.

4 DECISION MAKING PROCESS

All the different interests of the various stakeholders create a complex situation for the decision-making process. Therefore, the decision-making process is highly depending on the complexity of the problem statement.

Several methods are available for taking decisions (see Figure 4). As long as costs are the only main target value, static (cost comparison studies, benefit comparison studies) and dynamic cost calculation methods (amortization studies, net present value studies) are helpful tools to create the information needed for the decision on different variants.

Often, the projects have to fulfil more than only one target value (usually costs), but also target values on construction, operation and safety (see Chap. 5) which cannot be measured only by cost elements. For such cases the value-benefit analysis is among other options an often-used powerful tool.

In the context of this paper, only the value-benefit analysis and the net present value method will be considered.

5 REVIEW OF THE DECISION-MAKING PROCESS FOR THE SWISS NRLA PROJECT

In the early seventies of the last century, when the Gotthard Road Tunnel was under construction, Swiss Federal Railway (SBB) elaborated the final design for a 46 km long Gotthard Base Tunnel with one double track tube and a service tunnel. The project was postponed by the political authorities but created the basis for the political decision on the New Railway Line through the Alps (NRLA) by a public vote in 1992. The preliminary design work started

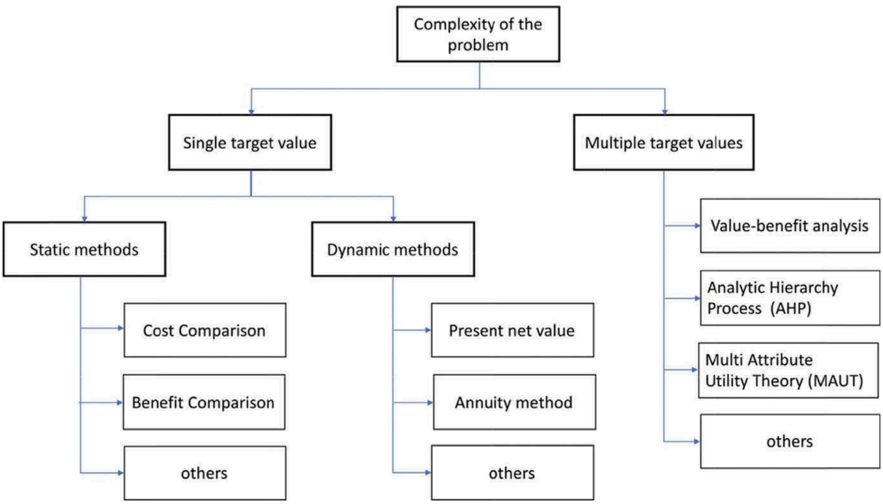

Figure 4. Overview of the various tools for decision-making (Tannò, 2018).

immediately after the positive decision by the swiss voters. Strategic decisions had to be taken on the alignment, the type and number of intermediate accesses and the tunnel system.

An expert committee of swiss and international experts was organised under the leadership of the Swiss Federal Office of Transport office (SFOT) to prepare the forthcoming decision on the basis of objective criteria.

Four alternatives were analysed in this process:

- **Variant 2A**: twin-track tunnel with service tunnel, derived from the 1975 project of Swiss Federal Railway (SBB) and most long railway tunnels built until then,
- **Variant 2B**: two single-track tunnels without a service tunnel but with two underground emergency stations at the third points.
- **Solution 3B:** three single-track tunnels in order to be able to keep two running tunnels open during maintenance,
- **Solution 3C:** tunnel system with two single-track tunnels and a service tunnel, similar to the Eurotunnel solution. The decision whether the service tunnel should be positioned in the middle or at the side, was not decided at this phase. For the cost calculation a lateral service tunnel was assumed.

A value-benefit analysis (point-scoring model) was used for decision making. This process has advantages when the target values are mostly difficult to be represented only by costs.

Table 6 shows, that construction costs were the objectives with the highest weight. This fact is determined by the political situation at that time, which was characterized by the fact that the cost budget of EUR 9 billion for both NRLA-axes should not be exceeded. Reductions in meeting the deadlines were accepted.

It is therefore not surprising that the system with the most favourable construction volume (tunnel system 2B) always achieved the highest score in the value-benefit analysis, also when

Table 6. Objective system for the value-benefit analyses of the swiss NRLA base tunnels (Ehrbar et al., 2016).

Overall Target	Objective	Weighting	Detailed Objective	Weighting
Construction	Costs, Cost risks	0,70	Construction Costs	0,80
			Cost risks	0,20
	Project schedule	0,20	Construction time	0,80
			Time risks	0,20
	Environmental Impact	0,10	Management of spoil	0,80
			Impact on landscape at portal zones	0,10
			Material for embankments	0,10
Operation	Requirements of operation	0,30	Quality of production (timetable, travel time, comfort)	0,40
			Quantity of production (Capacity, complete blockings)	0,40
			Productivity (Energy, rolling stock, etc.)	0,20
	Maintenance & refurbishment	0,60	Operating impairment incidents	0,20
			Effort for maintenance	0,50
			Attractive workplaces	0,30
	Aero-/Thermodynamics	0,10	Effort for ventilation	0,80
Safety	Acceptance	0,30	Passengers	0,20
			Employees	0,80
	Risks	0,70	Train accident	0,20
			Fire	0,25
			Dangerous goods	0,30
			Accidents of persons	0,05
			Accidents at work	0,20

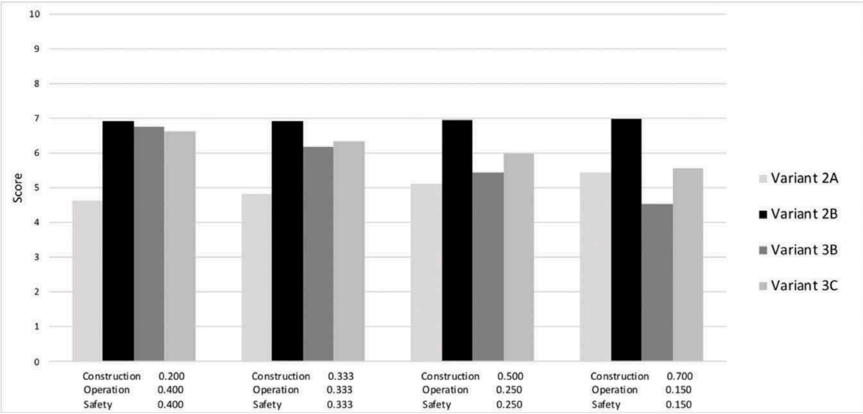

Figure 5. Scores in value-benefit analysis for the Swiss NRLA-base-tunnels (based on EBP, 1993).

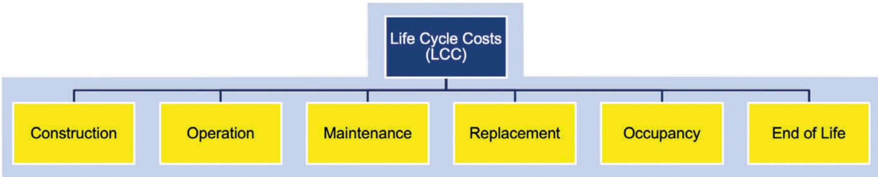

Figure 6. Generic Structure for lifecycle benefit and costs.

the weighting among the overall goals construction, operation and safety was widely variated in the sensitivity analysis (see Figure 5).

The other cost elements of the lifecycle costs (operation, maintenance, replacement and dismantling) were at that time not considered as cost elements (see Figure 6).

6 ADDITIONAL STUDIES 2018

The question whether the changes in the boundary conditions within the last 20 years would have had an effect on the selection of the tunnel system arose the latest during the commissioning phase at the Gotthard Base Tunnel in 2015. The question was asked, not to question the system decision of 1993, which had a very stable basis, but to keep future owner's organisations of long tunnels away of copy paste approaches and to highlight the importance of a detailed study on the selection of the future tunnel system in the earliest design phases.

Various additional considerations were made during a master's thesis in 2018 at ETH Zurich (Tannó, 2018). In a first step the analysis of decision-making process for the projects Euro Tunnel, Gotthard Base Tunnel and Brenner Base Tunnel showed the high importance of this design step, showing also the changes of the selection of tunnel system due to an in-depth planning. At the Brenner Base Tunnel, the tunnel system of the Gotthard Base Tunnel (system 2B) was which copied first and later switched on a tree tube solution (system 3C) (see Figure 7).

In a second step a pure lifecycle cost analysis was tried to carry out, assuming that in the meantime since 1993 a lot information on operation costs should have been produced at the Lötschberg Base Tunnel and at the Eurotunnel. As maintenance budgets not compellingly correspond to the cost structure of the early design phase the usable information content of the provided data was lower than expected. It would be helpful to adapt the operators cost structure in a future digital world in order to create the information needed for such optimization studies.

But not only the lack of cost information limited the validity of such an analysis, but also the fact that the net present values to be determined in such an analysis depend to a very large

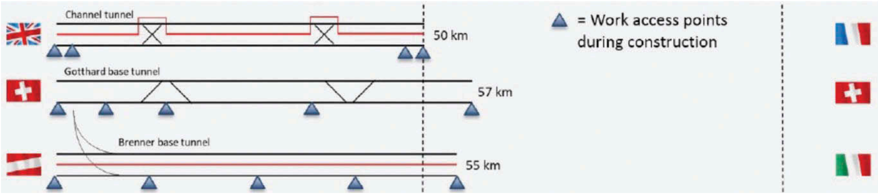

Figure 7. Systems layout of long tunnels in Europe with work access points during construction (FINEST LINK, 2018).

extent on the assumptions of interest rates and inflation rate (see Figure 8). Furthermore, a pure cost comparison study assumes the same benefit for all tunnel systems. This assumption is not correct as the availability of a system with three single track tubes is higher than with two single track tubes, creation also different earnings. Therefore, a pure cost analysis does not allow any compelling conclusions about the system selection and should not be used as a unique tool for the decision-making process.

Therefore, an adapted benefit-value-analysis was carried out with the following assumptions:

– Pure long double track tunnels are not approvable (see Technical Specifications for Interoperability, TSI, EU). Therefore, such tunnels were not part of the thesis anymore.
– The level of safety of the remaining systems was considered as more or less equal for all remaining systems.
– The overall target "safety" was therefore replaced by a new overall target "refurbishment" (see Table 7).
– A simplified scoring model was used with a maximum of 3 points instead of 10 points.

Similar to the benefit-value-analysis of 1993 the most recent studies showed also a clear favourite system, this time the system 3C instead of system 2B (see Figure 9).

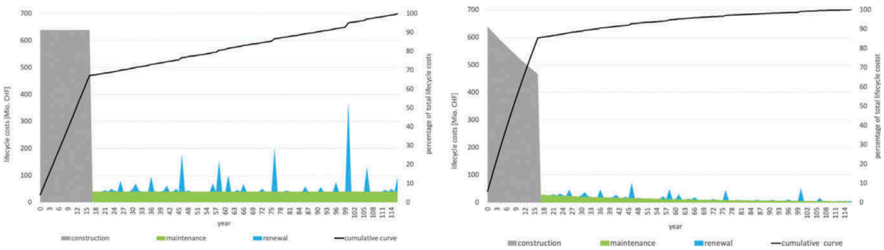

Figure 8. Life cycle cost (17 years construction time, 100 years of operation) without interests and inflation (left) and with (3% interests, 1% inflation (right) (Tannò, 2018).

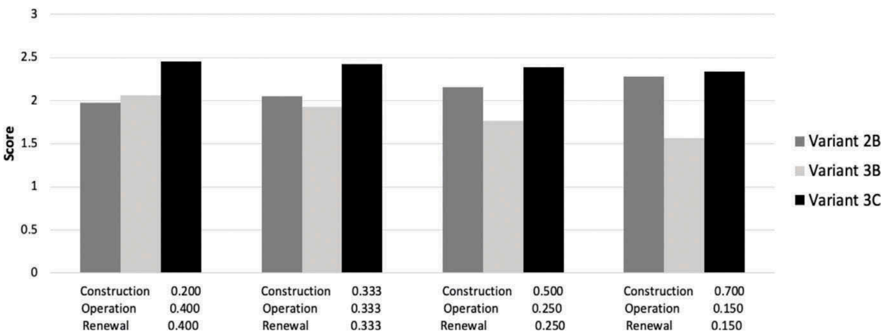

Figure 9. Scores in an updated value-benefit analysis for very long tunnels (Tannò, 2018).

Table 7. Objective system for the value-benefit analyses of the swiss NRLA base tunnels (Tannó, 2018).

Overall Target	Objective	Weighting	Detailed Objective	Weighting
Construction	Costs, Cost risks	0,70	Construction Costs	0,70
			Cost risks	0,30
	Project schedule	0,20	Construction time	0,70
			Time risks	0,30
	Environmental Impact	0,10		
Operation	Quantity of production	0,20		
	Maintenance	0,40	Maintenance effort	0,60
			Attractive workplaces	0,40
	Disruption of normal operation	0,30	Operating impairment	0,40
			Organization of the remedy	0,30
			Accessibility of the defect	0,30
	Effort for artificial ventilation	0,10		
Renewal	Renewal expenses	0,30	Major renovations	0,40
			Minor renovations	0,60
	Complexity of renewals	0,30	Major renovations	0,40
			Minor renovations	0,60
	Loss of capacity	0,30	Major renovations	0,40
			Minor renovations	0,60
	Working place conditions	0.1	Major renovations	0,50
			Minor renovations	0,50

This result is created by the fact that a third tube can contain parts of railway equipment which has to be placed in the driving tube for the solutions 2B and 3B. Solution 3C allows an independent access for tire vehicles which creates many benefits (fewer operating impairment, shorter intervention times).

Such a service tunnel should be placed below the railway tubes, in order to create a spatial separation of traffic and safety infrastructure and operation utilities. Therefore, it is very understandable, that the Brenner Base Tunnel switched to such a system which is from the authors point of view highly recommendable also for other future very long tunnels as long as the service tunnel is used also during operation.

If the boundary conditions do not allow the construction of an additional service tunnel, it should be considered to use also intermediate accesses as independent service accesses during operation. However, only the system with three single track tubes a complete separation of operation and maintenance for bigger renewal work.

NOTES

1 Narrow gauge railway (1‘000 mm)

2 For the first time with an underground multifunction station, subsea tunnel

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