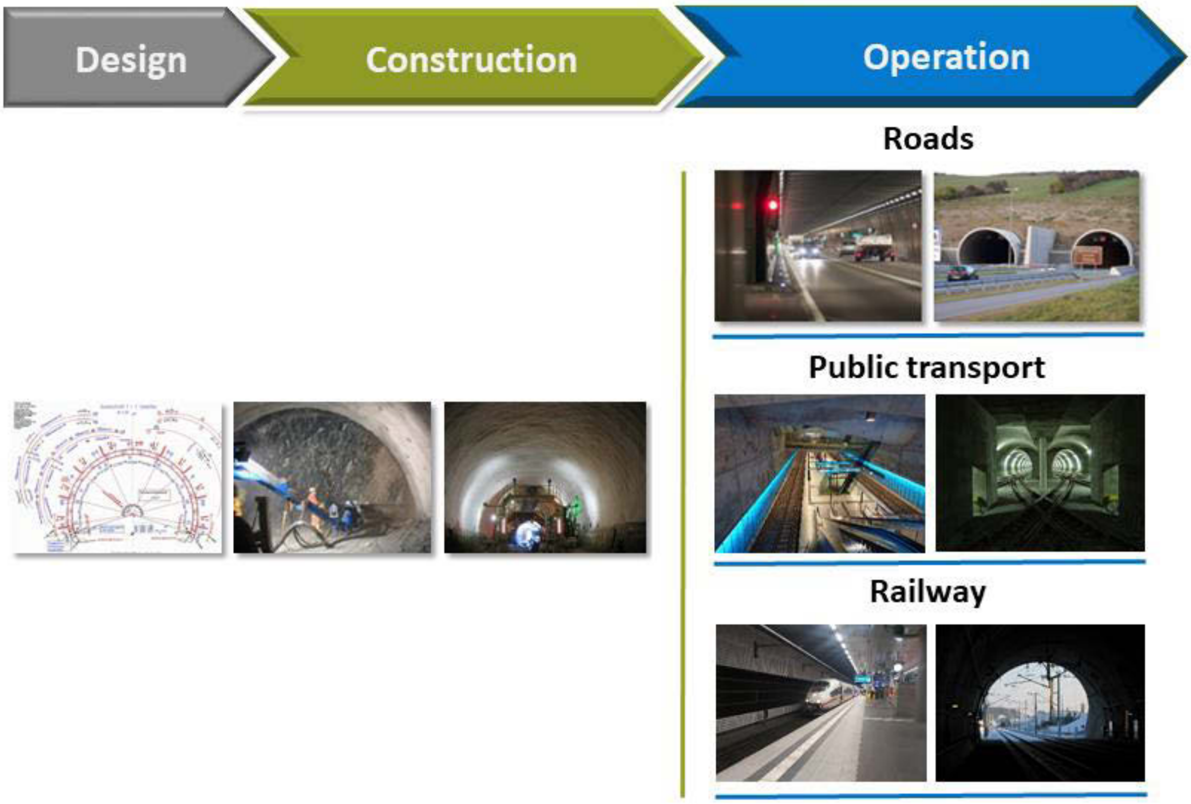
Recommendations for the Determination of Lifecycle Costs for Tunnels



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1 Introduction

1.1 Problem and motivation

The development, construction and operation of structures with the aim of sustainability is a consensus of society. Sustainable buildings are advantageous in economy, ecology and in their social function. Despite this generally recognised objective, civil engineering structures are predominantly designed to minimise construction costs and the aims of sustainability are of no or only subsidiary importance. One reason for this is that procedures are currently only available for the assessment of sustainability in building construction but only the first attempts for civil engineering structures.

One significant pillar of sustainability is the estimation of lifecycle costs, which include not only construction cost but also the costs of operation, maintenance and repair. New research work has been undertaken in this field, in which procedures for the forecasting of lifecycle costs have been further developed for special application to tunnels.

The recommendations of the German Tunnelling Committee (DAUB) published in 2018 addressed this research and provided practical tools, data and sources. In the present revision of 2023, the recommendations for road tunnels are updated. In addition, recommendations for the application of "public transport tunnels" are supplemented. Furthermore, instructions for the application to rail tunnels including high-speed traffic are given.

All costs of a tunnel during its lifecycle are included in the calculation. This comprises the costs for design and construction of the structure as well as the equipment of the tunnel. For the follow-up costs over the lifetime (maintenance and repair as well as operating costs), one significant parameter is the service life of each component. For tunnel construction, a service life of 100 or more years is intended, while service lives for the equipment are significantly shorter and thus demand (repeated) replacement during the lifetime of the overall construction.

All types of cost mentioned here are collected in an overall model for the calculation of lifecycle costs. In this way, the most favourable solution for the overall tunnel can be determined. Variant studies can be performed to compare and evaluate individual components and construction elements.

This recommendation presents a methodology for calculating the lifecycle costs of tunnels, which is now available with application to calculation examples ("example tunnels") for both, road and public transport. For rail tunnels, the application with the described methodology and the indicated references is also directly possible. The method is also generally applicable to infrastructure works. For an improved forecast of service lives, especially of equipment components, and for an extension to a comprehensive evaluation of sustainability, there is a need for further research.

1.2 Intended recipients

The recommendation provides a decision-making aid for client organisations and operators of tunnels and other infrastructure in order to discover the economically most advantageous variant for construction, operation and modernisation. This mostly applies to public sector bodies and their planners. In case of tunnels for urban public transport, this can apply to responsible bodies such as municipalities, districts or special-purpose associations, which are usually also the purchasers of the transport service. Furthermore, this group of addressees includes municipal subsidiaries that plan and build independently. However, the recommendation can also be used to objectify decisions for PPP tunnel projects, since in this case an improved estimation of lifecycle costs, in addition to the most accurate possible forecasting of use volumes for toll systems, are of great economic importance. It also enables the evaluation of alternative proposals in the tendering process. Finally, equipment suppliers can test and demonstrate the advantages of their innovations.

1.3 Structure of the recommendation

In the recommendation, all the necessary basics for the calculating of lifecycle costs are explained in the first four chapters, with references to further reading for more details. The general methodology is explained in seven steps in Chapter 5:

Step I – Initial situation

Step II – Structuring of the building

Step III – Module formation

Step IV – Procedure of cost determination

Step V – Transfer to a cost matrix

Step VI – Lifecycle cost calculation: net present value method

Step VII – Variant comparison and interpretation

For the interpretation of the results, notes are given in Chapter 6. Chapter 7 includes a calculation example for road tunnels, and chapter 8 for public transport tunnels; these examples help to simplify the introduction of the presented methods in future projects.

Using the explanations and working aids, it is possible to carry out a scientific and practically founded calculation of the lifecycle costs of a tunnel. With engineering interpretation of the results, the user then gains forecasts and comparative values for use in decision making for the selection of the most advantageous variant for the construction measure.

2 Lifecycle of tunnels

Analysing the lifecycle of tunnels requires consideration in phases. Based on an average total service life of a tunnel of 90 to 130 years[1], the lifecycle of a structure consists according to ISO/FDIS 15686-5[2] of all phases including construction, operation, and maintenance until the end of serviceability. For this purpose, a distinction is made between the primary phases design, construction, utilisation, and recycling. These phases are in turn assigned to processes, which represent specific activities. The process classifications presented below are not exhaustive, but they are to be understood as examples. Basing the classification on cost codes used in practice or other organisational structures can make the application more practicable.

In order to enable a sufficiently accurate analysis, a differentiated consideration of tunnel structure (Section 2.1) and the necessary tunnel equipment (Section 2.2) is recommended.

2.1 Lifecycle phases of tunnel construction

According to the ASB-ING[3] and RI-WI-BRÜ[4] the phases for tunnel construction can be categorised into construction, maintenance, repair and recycling. Design work should be added to enable the exact determination of costs.

Figure 1 shows a detailed categorisation based on the applicable regulations for infrastructure buildings. Categorisation into the various phases enables better assignment of the costs, which are broken down into initial and follow-up costs. The initial costs comprise the expenses of design, building of the structure, and installation of equipment. The follow-up costs result essentially from the maintenance, upgrading and recycling processes stated in Figure 1.

Figure 1: Lifecycle phases of a tunnel[5]

The design phase includes all costs for service needed for the preparation of a design ready for construction. The construction phase includes all expenses incurred for the construction of the tunnel. The longest and thus most influential phase is maintenance and includes all constructional and operational expenses incurred during utilisation. This includes repair and

[1] Cf. ABBV (2010), p. 865
[2] Cf. ISO (2008)
[3] Cf. ASB-ING (2013)
[4] Cf. RI-WI-BRÜ (2007)
[5] Illustration of the relevant processes for tunnels based on the ASB-ING (2013)

tunnel maintenance, the latter being broken down into constructional and operational maintenance. During this period of many decades, upgrading (modernisation) may have to be undertaken to comply with changing constraints. Should the tunnel no longer fulfil its function, then demolition or recycling is due as the last stage of the lifecycle. This includes expenses incurred for demolition or for alternative use.

2.2 Lifecycle phases of tunnel equipment

In order that continuous and safe tunnel operation is possible, the tunnel structure and the tunnel equipment have similar lifecycle phases. Tunnel equipment, however, generally has a shorter service life, having to be renewed several times during the overall lifecycle of a tunnel. Furthermore, due to the highly technical nature of tunnel equipment and the high safety requirements, the operational and thus cost-relevant extent must be considered in more detail.

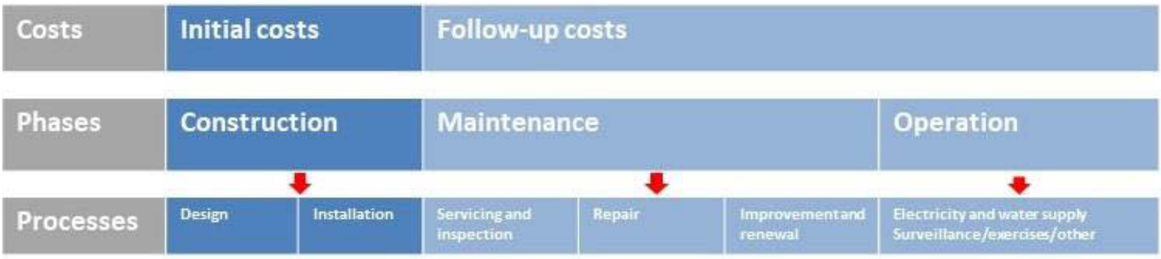

Figure 2: Lifecycle phases of tunnel equipment[6]

Figure 2 shows the corresponding phases and the assigned processes for tunnel equipment. As with the tunnel structure, the design phase also must be placed first here, followed by installation of the equipment in the tunnel. With the transition into tunnel operation, a phase consideration based on DIN 31051[7] and the RABT[8], in combination with the EABT-80/100[9].

The consideration is extended to the field of operation, which includes all activities associated with utilisation – the ongoing operation of the tunnel. Maintenance is the significant phase for tunnel equipment and includes servicing and inspection, repair and improvement. It is recommended to extend the block "Improvement" to include the process of "renewal" (Fig. 2). Renewal is mostly due in cycles and covers complete replacement after a given or appropriate service life and is recorded regularly in the course of lifecycle cost consideration. The operational phase includes tunnel monitoring, energy supply (electricity, water), but also the regular large-scale exercises to be carried out by the emergency services to train hazard prevention and dealing with incidents.

No recycling or reuse phase analogous to the tunnel structure is to be provided compulsorily since after the expiry of the service life the equipment is normally renewed and recycling is not sensible (cf. Chap. 3).

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[6] Illustration of the relevant phases and processes for tunnel equipment based on DIN 31051 (2012) and RABT (2006).

[7] Cf. DIN 31051 (2012)

[8] Cf. RABT (2006)

[9] Cf. EABT 80/100 (2019)

2.3 Lifecycle approach and lifecycle costs

As can be seen in Figure 3, two possible situations mark the changeover to a lifecycle-oriented view of a tunnel: while the first case starts with the start of design work for a new tunnel, the second case applies to a tunnel that is already in operation.

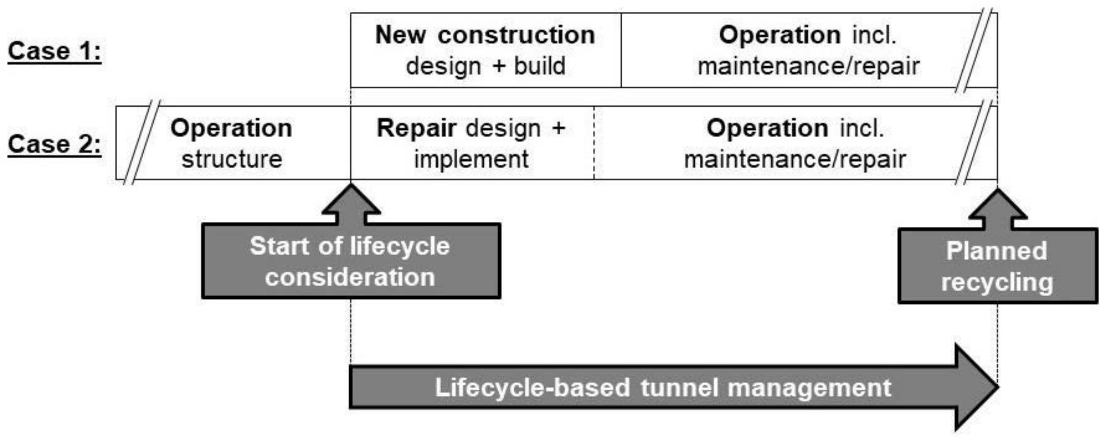

Figure 3: Case-related changeover to lifecycle consideration[10]

The two cases ensure that both new tunnel constructions and existing tunnels in the transport network are included in the concept. In both cases, once the new construction (case 1) has been completed or once any necessary maintenance work on an existing structure (case 2) has been finished, the subsequent tunnel operation is dominated by maintenance and repair measures.

The main criterion for the evaluation of the lifecycle are costs [11]. The preferable design variant, depending on opinion and objectives, is that with the lowest sum of initial and follow-up costs, hereafter described as lifecycle costs. It is characteristic of the investment process that during the construction phase (cf. Fig. 1), high payments[12] are due and, in the maintenance or repair/operating phase (cf. Fig. 3), there are fluctuating payments and perhaps also income. The payments to be considered in a lifecycle cost analysis fluctuate in amount and do not necessarily repeat periodically. Income is relevant, for example, for road tunnel concession projects or when considering ticket revenues for public transport tunnels (see also business management explanations in chapter 4).

Each design variant has the characteristic that it is in competition with other variants. This demand is however only fulfilled if all variants provide the same level of primary tunnel functions. The focus of a lifecycle cost analysis is aimed to determine the most advantageous from several technical design variants. To do this, the previously introduced lifecycle phases are linked to a consideration unit and the necessary preconditions are created to substitute follow-up with initial costs or initial with follow-up costs in the course of variant studies[13].

[10] Cf. THEWES, VOGT (2014).
[11] In the context of this recommendation, life cycle costs are considered as the economic pillar of sustainability. A complete sustainable life cycle assessment must also evaluate the ecology and the social pillar.
[12] The initial costs are referred to as "payouts" in the sense of the net present value method (cf. ch. 4).
[13] Cf. VOGT (2013)

From the described constraints, the conclusion can be drawn that in addition to the technical design of a tunnel, further expert knowledge is needed to evaluate the economic benefits. Both processes, the technical and the financial planning, must be carried out in parallel and produce the economic optimum as the result of evaluating alternatives. A precondition for achieving this objective is the representation of the investigation period of the building in an overall model. The step-by-step procedure and the objectives followed are summarised in Figure 4.

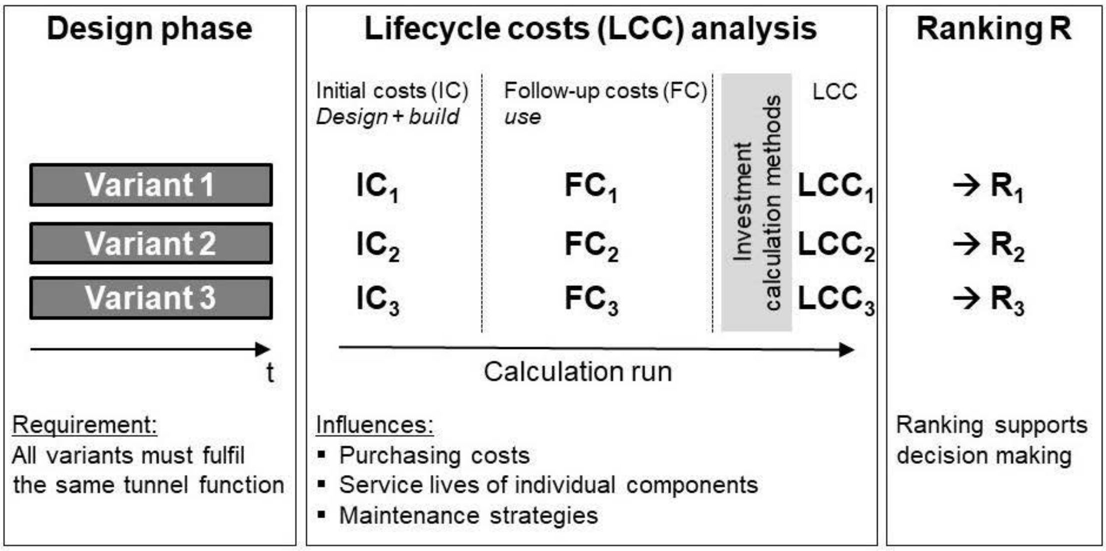

Figure 4: General procedure and objectives of a lifecycle cost analysis

The procedure for the analysis and interpretation of lifecycle costs of tunnels thus must ensure the following features:

- Support in the selection of the necessary building elements and components (called "modules", cf. Chap. 5) and specification of calculation (assumed) service lives and suitable maintenance cycles (cf. Chap. 3),
- A system for the statistical interpretation of building element failures that have already been recorded or are documented in the future, making possible conclusions about the service life of building elements and components (modules),
- Time-dependant assignment of the resulting costs according to amount, type and time of occurrence,
- Specification of the parameters needed for the application of the investment calculation process (cf. Chap. 4),
- Evaluation of uncertainties or risks (cf. Chap. 6).

Considering that a lifecycle cost analysis usually covers several decades, a dynamic procedure of investment calculation – the net present value method – is selected. More detailed explanations of the net present value method can be found in Chapter 4.

3 Service lives

3.1 Influencing factors

As explained in Chapter 2.3, lifecycle costs are composed of initial and follow-up costs for all building elements, from which the tunnel is built. The forecasting of follow-up costs is closely linked to the estimation of appropriate service lives for each component of a building.

It should be pointed out here that the selected calculation process – the net present value method –includes assumptions, which also must be taken into account in the interpretation of the overall result. A corresponding discussion can be found in Chapter 4.

In the design of tunnels and the consideration of lifecycle costs as a decision-making criterion, average values have normally been assumed until now, particularly for the operational and safety equipment (lighting, ventilation, safety system, central plant, etc.), and a theoretical service life has been assumed.

The basis for determinations of lifecycle costs of tunnels until now has been the German “Redemption Payment Calculation Regulation” (German abbreviation: ABBV), which gives as a value from experience a theoretical service duration of 20 years for operational and traffic management equipment[14], or, for urban public transport tunnels, the "Standardized Evaluation of Investments in Transport Infrastructure for Rail-Bound Local Public Transport" [15].

The determination of lifecycle costs for the selection of a variant, particularly for new construction, also uses the statements in the ABBV, as also with the comparison of two or more possible equipment variants (e.g. mitigation measures in the course of risk analyses). During the actual planning of finance for strategic maintenance planning of, for example, owners and operators, such an all-inclusive process can however only be used to a certain degree. In order to determine the costs and maintenance cycles with reasonable accuracy, it is recommended to differentiate the consideration of individual plant components.

According to the requirements of the ABBV, a payment amount repeating every 20 years is to be assumed. Through the dynamic investment calculation, interest is discounted from these payments and their amounts thus differ from the starting point t_0 (see Fig. 5). If it is now assumed that the average service life is reduced in comparison to the ABBV value, then the necessary payment flows shift to an earlier time, which influences the finance required and its provision. With shorter service lives, the number of theoretical replacement and renewal cycles in the overall lifecycle increases. An additional replacement is exemplary shown in the graphic in Figure 5 as a hatched area.

Only through an improved time forecast for costs and their due dates can a strategic maintenance plan be derived for individual tunnels, and also for the entire stock of tunnels.

[14] Cf. ABBV (2010), S. 866
[15] Cf. INTRAPLAN CONSULT (2017)

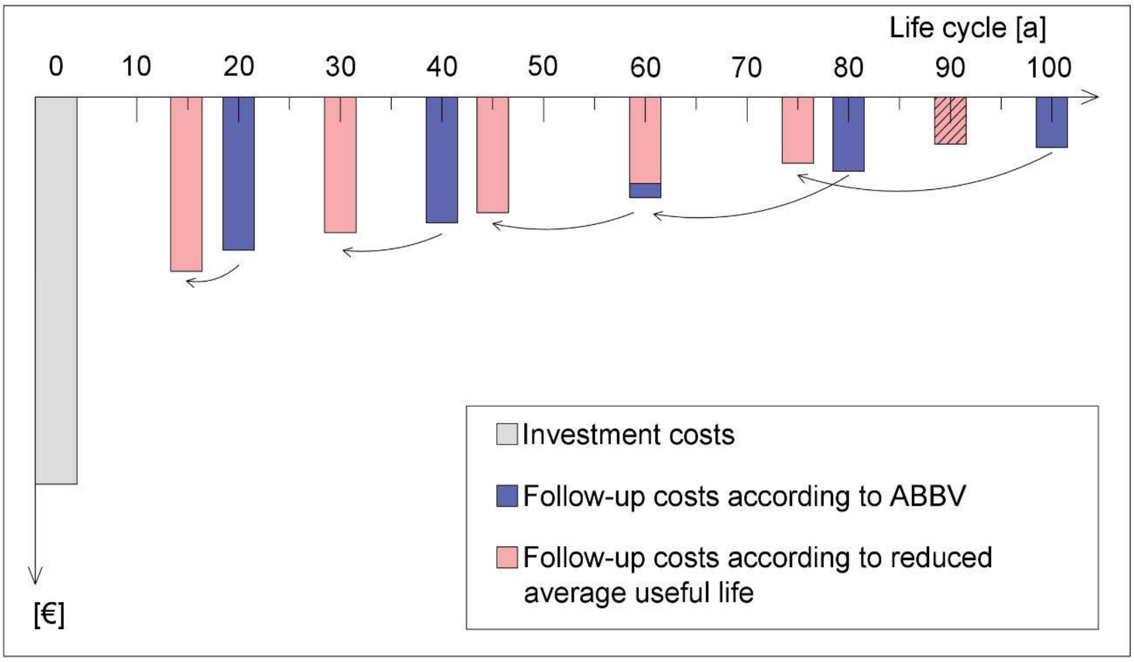

Figure 5: Displacement of the payment flows within the overall lifecycle due to shorter service lives (exemplary)[16]

3.2 Definition of terms

The term "service life" in business management denotes the period, in which the operational use of an asset is possible under typical properties. According to the ABBV, the service life begins with the year of completion ready for traffic of the building. However, it is also explicitly pointed out there that the statement is a value from experience for a possible service life, which is to be used in the calculation of the redemption payment independent of the actual service life.[17]

Also considering the increasing number of PPP projects and an ageing stock of structures, the relevance increases of an economic and above all projectable operation over a longer period, during which the technical equipment in particular will require high operating, maintenance and repair expenses. Knowledge of the level and particularly time point of maintenance expenses thus is significant for the planning and the provision of finance.

Therefore, it is necessary to determine the actual service life. This calls for differentiated consideration of the service lives of the individual operations components taking into account the relevant lifecycle aspects.

3.3 Service life

There are many factors, which can influence the service life. For the operational and safety equipment of tunnels, the technical, economic and socio-economic influences on the service life are of relevance.

[16] Cf. ADDEN, THEWES, LEHAN (2016), p. 10.
[17] Cf. ABBV (2010), p. 862

3.3.1 Technical factors with an influence on the service life

The technical service life denotes the period, during which the corresponding equipment detail is physically available and complies with the required properties. The DIN 31051 describes this unavoidable wear as the reduction of the wear reserve, induced by chemical and/or physical processes.[18] The operational and safety tunnel equipment has, in contrast to the road tunnel, which according to the ABBV has a service life of 90 to 130 years, a short theoretical service life of 20 years, for public transport tunnels 75 years[19], a short theoretical service life of 20 years. The tunnel equipment normally must be replaced several times in the course of the overall lifecycle of the tunnel and thus represents a significant part of the maintenance costs. The technical service life depends on many factors. With reasonable (and proactive) maintenance, the technical service life can exceed the theoretical service life according to the ABBV or deviate from it.

For the assumption of the technical service life, numerous influences must be considered, such as:

- Equipment properties (material fatigue, corrosion),
- Environmental or climatic influences (temperature/water/chloride exposure/pollutant effects/tunnel atmosphere/effects of traffic),
- Type and extent of the maintenance and regular servicing,
- Design/installation errors (observe the state of the technology).

The essential reasons leading to the (early) reaching of the technical service life are wear, expected and unexpected defects, (excessive or particularly laborious) repairs, spare part problems and technical overhauls. The spare part problem is becoming increasingly significant for technical plant since spare parts for older components are only produced and stocked to a limited extent due to rapid technological progress. This not seldom means that an assembly cannot be repaired and must be completely replaced with all associated components since continued operation of the plant is not possible without these components – long before the expiry of the theoretical service life.

For the assumption of a theoretical service life for the determination of lifecycle costs of the various equipment components, it is recommended to use the manufacturer's data with the inclusion of figures from experience, and to consider the influences affecting the equipment. A recommendation for different assumptions of the actual service life of operational and safety equipment can be taken from Table 1.

3.3.2 Economic factors with an influence on the service life

The economic service life indicates how long it is economically sensible to use an asset. This is difficult to forecast for infrastructures since, in contrast to building where the requirements and change of use as well as expected yield are more important than with infrastructure, availability is an essential criterion. The economic service life is shorter than the technical service life (at the most equal).

[18] Cf. DIN 31051 (2012), p. 7
[19] Cf. INTRAPLAN CONSULT (2017): Table A1-17

For the determination of the economic service life, the following influences can be relevant for tunnel equipment:

- Location and surroundings or function of the system,
- Available finance,
- Traffic development,
- Interfaces, interdependencies,
- Synergies and cost savings through the bundling of measures.

Typical reasons for the end of the economic service life are technological change, compatibility problems and technical constraints, adaptations or extensions due to capacity bottlenecks or economic or energy-related optimisation.

While the technical service life can be estimated from manufacturer's data and figures from experience, considering other factors with an influence, this is more difficult for the economic service life. Calculation based on a positive capital value is not appropriate for infrastructure in operation, as already mentioned above. In this case as well, values from experience or a review of the stated influential factors in past years are of significant assistance and should only serve to verify and adapt the assumption of the selected service life.

3.3.3 Socio- economic influencing factors on the service life

Another aspect to be considered is the socio-economic influencing factors on the service life. This applies to the safety level required by society, which leads to revisions of regulations and standards.

As soon as the operational and safety equipment no longer complies with the requirements, it must be adapted to the required conditions. Revisions of the safety conditions thus end the service life of the affected equipment ad hoc. One current example of this is the safety retrofitting programme with a finance volume of altogether 1.2 billion Euros[20] introduced by the German government in 2001 after the fire incidents in European road tunnels, which was largely completed in 2018.

The plan was to classify and prioritise German main road tunnels and adapt them to the revised state of the regulations. In the course of this measure, all tunnels have been retrofitted, even relatively young tunnels built after 2003. Such influences are not predictable because they are event-driven, as in the given example.

For public transport tunnels[21], various influences can also be identified that have led and will lead to research, to new regulations, and to retrofits in the future.

The 2013 amendment to the German Passenger Transportation Act (PBefG) [22] stipulated complete barrier-free accessibility of public transportation by January 1, 2022. This has made it necessary, for example, to retrofit mobility-friendly elevators, tactile guidance systems and barrier-free information systems in subway systems.

[20] Cf. KOSTRZEWA (2015), S. 7
[21] This refers to all underground infrastructure structures of light rail systems.
[22] Cf. PBEFG (2022)

Due to the modification of the Technical Rules for Fire Protection in Underground Transportation Systems TR Strab BS in 2014[23], a fire protection assessment of existing buildings must be carried out. As a rule, fire protection concepts must be prepared and a proof of timely and safe escape must be provided for each subway station.

The EU regulation "Ecodesign requirements for light sources" 2019/2020/EU[24] and the ban of fluorescent tubes from September 2023 require the renewal of all lighting systems in underground railroad facilities and stations.

Society's changed perception of security has a far-reaching influence on surveillance technology in stations by using video cameras and recordings, the deployment of security guards, the deconstruction or reconstruction of obscure areas, niches, pillars, sales facilities in stations, and on color design and lighting to increase subjective security.

3.4 Approaches to service lives

3.4.1 Road tunnel

An elementary requirement for the calculation of life cycle costs is that the points in time at which costs are incurred are approximately known. If the points in time are available, the costs can be used as a cost forecast in the financial mathematical sense. Table 1 collects service lives to be assumed for the operational and safety equipment of road tunnels from various references.[25,26,27,28,29,30,31]

Some sources make detailed statements about the service life of individual equipment and plant components, while others give average service lives to be assumed for an entire module. It should however be considered here that the worldwide equipment and requirement levels vary greatly (especially the statements from PIARC). It should also be noted that when the service life of an individual component of a module expires, e.g. due to a technical defect, the entire function block must/could be replaced, if the economic service life of the overall module is no longer given.

In addition, an analysis was carried out on selected structures for all equipment components to determine the actual service life before replacement. This real-world data was supplemented with information from expert assessments and the literature. The resulting data set was statistically processed in a sub-module for a life cycle cost forecast model using Monte Carlo analysis.[32].

[23] Cf. TRSTRABBS (2014)
[24] EU (2019)
[25] Cf. ABBV (2010)
[26] Cf. VOGT (2013)
[27] Cf. PIARC (2004)
[28] Cf. SIA (2004)
[29] Cf. WELTE (2004)
[30] Cf. FSV (2014)
[31] Cf. DMRB (1999)
[32] Cf. LEHAN (2020)

Table 1: Data from various sources for the service life of operational and safety equipment in road tunnels[33]

Service lives for the equipment of road tunnels					Sources						
					DE		PIARC	CH		AT	UK
	Module				ABBV	Vogt		SN	Welte	RVS	DMRB
Tunnel equipment	Lighting				20		11,2		0-5		
		Entrance lighting								20	
		Inner tunnel lighting				20				20	
		Lamps						25-30			18
		Ballasts						15-20			
		Lighting of cross passages/escape routes				20				20	
		Control/regulation/measurement instrumentation				12		10-15		15	
			Brightness measurement								15
	Ventilation				20		18,2		15-20		
		Mechanical longitudinal ventilation									
			Jet ventilators			35		20-25			18
			Mechanical parts of jet ventilators							20	
			Electro-mechanical parts of jet ventilators							20	
			Extraction through controllable dampers and separate extract duct			35					
			Ventilation dampers					15-20			
			Axial fans					25-30			30
			Mechanical parts of axial fans							30	
			Electro-mechanical parts of axial ventilators							20	10
		Noise dampers						30-40			
		CO measurement				12		20-25		15	13
		Visibility measurement instruments				12		20-25		15	15
		Regulation/control						10-15		15	
			Flow measurement								20
	Traffic management systems				20						
		Static traffic signs				20				10	
		Variable light signals								10	14
		Variable traffic signs									
			Variable signage control							10	14
		Height controls						10-15		10	15
		Traffic data recording								10	
		Barriers (closure barriers)				20					15
		Permanent light signals						20-25		10	14
		Variable direction signs						20-25		15	14
		Measurement equipment							5-10		
			Longitudinal speed measurement							15	
		Induction loops									13
	Safety systems				20		14,8				
		Escape route signage				20				10	
		Orientation lighting								10	
		Guidance systems				15					
		Fire alarm systems						20-25			
			Manual fire alarm system			15					
			Fire detection						5-10		5
			Fire alarm system (cable)			20				20	
			Fire alarm system (control)							10	
		Fire fighting systems									
			Hand fire extinguishers					10-15		20	7
			Extinguishing water supply							20	
				Pressure raising plant		20					
				Hydrant		50		40-50			28
			Stationary firefighting plant								20
			Firefighting and binder stocks							20	
		Communications equipment									
			Emergency call system			20				15	
				Emergency telephone (SOS niches)				20-25			
				Emergency exit doors into the lock		30					
			Video surveillance			15		10-15			
				Video systems						10	
				Camera							15
				Monitor							10
				Control equipment							20
				Cable							20
			Tunnel radio			20		15-20		15	
			Traffic reports/radio						0-5		
				Radio antenna cable							15
			Loudspeaker system			15				20	
			Telephone (landline)					15-20		20	15
	Central plant				20						
		Electricity supply				20	20,1				
			Mains connection/supply					25-30			
			Medium voltage plant							25	
			Low-voltage switchgear					25-30		25	20
			Low-voltage cable						0-5		40
			Emergency power supply (UPS)					20-25	10-15	15	15
				Batteries with acid filling				15			5
				Batteries with gel filling				10			
			Emergency power generators							25	20
		Cables and wiring					25,7		15-20		
			Cu cable					35-40			
		Fibre optic cable						20-25	5-10		
		Transformers						30-40	15-20		30
		Earthing/lightning protection/equipotential bonding								25	
		Control systems (control, automation and surveillance)					10,7				18
			Overall control system					10-15			
			Traffic guidance system					10-15			
			Control centres					15-20			
		Tunnel control									
			Control computers			8					
			Automation							15	
			Process visualisation							10	
			Archiving/data evaluation							10	
		Air conditioning components							0-5		
			Ventilation							15	

Due to the very long forecast period of a life cycle assessment (assumption of new construction or initial equipment), considerations must be made as to the level of detail in which calculations should be carried out. The flat-rate approach according to the ABBV of 20 years only allows for a very rough cost estimate. However, the information in Table 1, which is partly aimed at individual components of functional blocks, could be too detailed in the sense of a forecast. A suitable approach is therefore to look at functional blocks/title group levels[34] or modules.

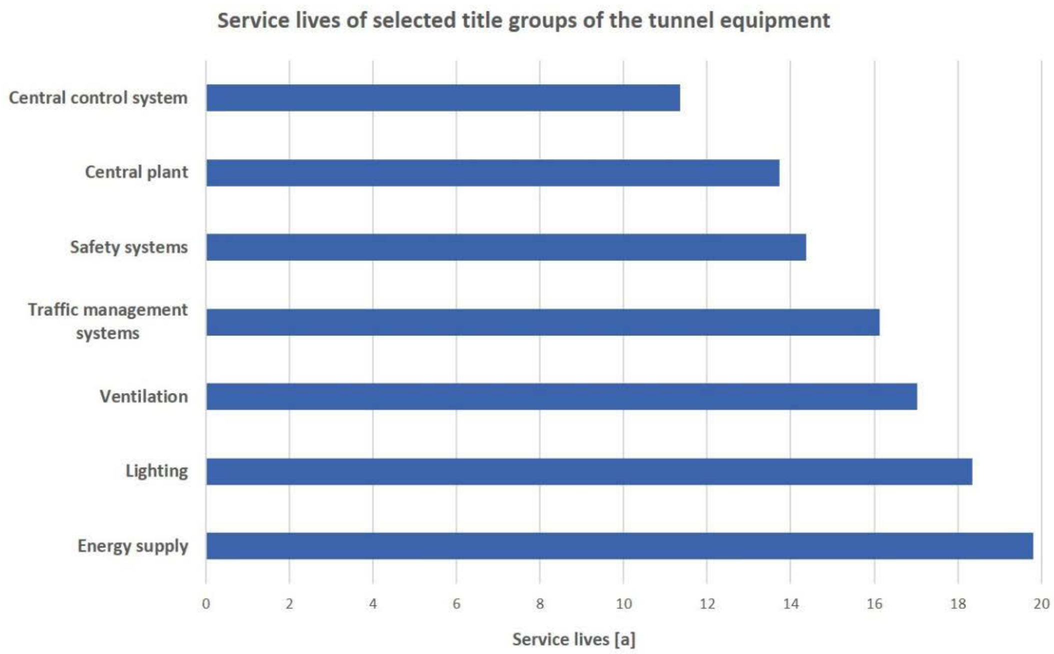

Figure 6: Probability-based service life of tunnel equipment

The service lives shown in Figure 6 were determined on the basis of the data set.[35] It can be seen that no group of titles as a whole has more than 20 years of service life, and the central control technology, at 11.4 years, only reaches slightly more than half the flat-rate number according to ABBV. Components for energy supply can be assessed as particularly robust. [36] To create a more precise planning basis or for shorter forecast periods, it is recommended to look at a more detailed level (e.g. at module level, Figure 16).

Finally, the challenge remains to apply a suitable calculation parameter for the service life of the respective structure under all the influences mentioned, which takes into account all external influences as well as the special features of a structure in the best possible way and reflects the selected repair strategy.

[33] Cf. LEHAN (2017)
[34] Functional blocks according to EABT-80/100 (2019); as part of the analysis, the main equipment elements were grouped into title groups (also referred to as assemblies in subsequent chapters).
[35] Cf. LEHAN (2017)
[36] Cf. LEHAN (2020)

3.4.2 Public Transport Tunnel

Municipal administrations in many cases own public transport facilities, such as underground and light rail tunnels, or are entrusted with the construction and maintenance of these facilities through municipal subsidiaries. For these administrative bodies, the rules of the New Municipal Financial Management (NKF) or comparable regulations were introduced in 2008, which form the basis of today's financial and budgetary system in Germany. Here, investment production costs and renewal costs and consumption maintenance costs, such as maintenance, repair and cleaning costs, and also depreciation and useful lives are defined and recorded.

The service life for the different components of the public transport tunnels are regulated according to the "NKF framework table of the total useful life for municipal assets" in § 36 para. 4 KomHVO[37][38] (Figure 7):

- Shell construction systems (tunnels, ramps, bridges ...): 70 - 80 years
- Station interior fittings (floors, ceilings, cladding, furniture ...): 20 - 30 years
- Technical installations 1 (electrical installations, lighting ...): 20 - 30 years
- Technical installations 2 (IT installations...): 3 - 15 years
- Technical installations 3 (air-conditioning systems ...): 8 - 12 years
- Operational equipment (tracks, overhead line, train protection, ...): 20 - 33 years

The municipal owners have developed their own accounting manuals from these specifications.

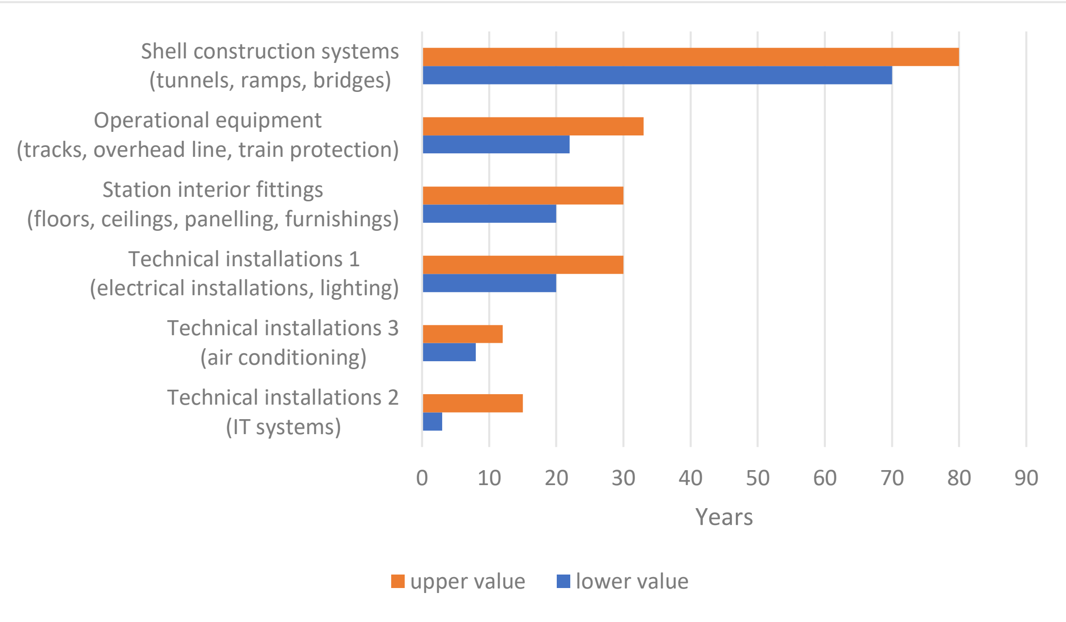

Figure 7: Predetermined service lives of selected components of the public transport tunnels

[37] Cf. KOMHVO (2018)

[38] Cf. MBI NRW (2005)

3.4.3 Service lives of railway tunnels

For the service life of structures and equipment in the field of railway tunnels, there are internal documents, which have not been published.

3.5 Maintenance and repair strategies

According to DIN 31051[39], the wear reserve is successively dissipated through the effects of chemical and/or physical processes under the influence of the use of structural and equipment components (which are assembled to sensible functional units as modules, (cf. Chap. 5). This is countered by regular measures of repair and structural maintenance; these increase the wear reserve through targeted measures in the various phases of the use of a module. Fig. 8 shows in various colours examples of ageing curves and the implementation of various measures to increase the wear reserve.

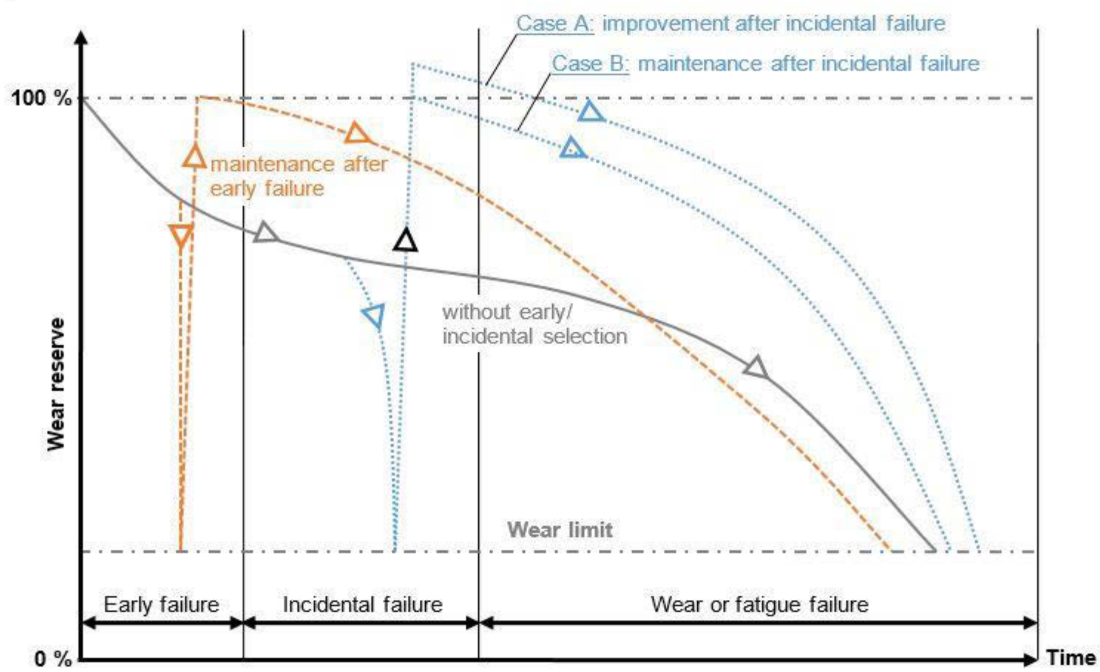

Figure 8: Dissipation of the wear reserve and repair measures[40]

Repair and structural maintenance measures can be based on various strategies. Details are provided in DIN EN 13306[41], which divides repair into preventive and corrective measures (Fig. 9). Preventive maintenance (servicing) is carried out at specified intervals or according to specified criteria with the objective of reducing the probability of failure. Corrective maintenance (repair) is carried out as soon as a defect is detected. Accordingly, the module is repaired so that it can fulfil its function in the future.

[39] Cf. DIN 31051 (2012)
[40] Cf. VOGT (2013).
[41] Cf. DIN EN 13306 (2018)

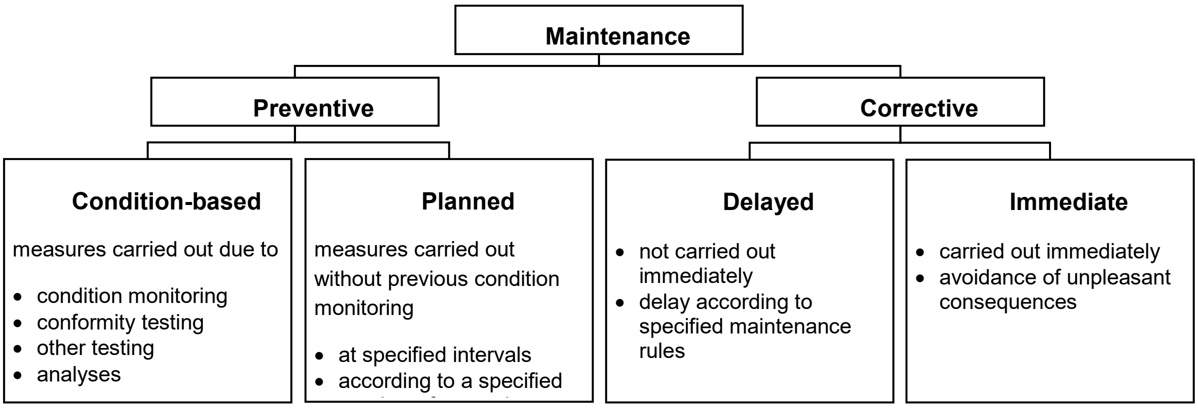

Figure 9: Sub-division of the term maintenance

The primary objective of maintenance is to preserve the intended state of a module and document its actual states during the ageing process.[42] Before reaching the wear limit, maintenance measures are to be carried out to recreate or improve on the intended state (Fig. 9). This can be achieved by intermediate technical development providing better materials than those materials used until the (near-) failure.

The appropriate probability of failure for each module reflects on the one hand the type of functional use and on the other hand its safety relevance. From the safety relevance of a module, conclusions can be drawn whether a module that suffers an irreparable failure has to be replaced with a new module immediately or with a tolerable delay. This depends particularly on whether there are technical redundancies and the lost function can be covered by another element during a transition period.

An element with a high safety relevance can lead to a restriction of tunnel operation if it fails. If the module is of high safety importance, then a difference has to be made whether it is installed in high numbers or only a few are used. Examples of elements installed in high numbers are lighting fixtures, information signs, manual fire extinguishers and the fixings of installed components. For these modules, which belong to Status 1 in Figure 10, it can be assumed that they are permanently stocked as spare parts. Modules with Status 2 in Figure 10, which are installed for example in a road tunnel in smaller numbers and may have to be specially produced, are tunnel fans, smoke extract dampers, visibility measurement instruments or barriers to close vehicle entry to the tunnel. The replacement of these is normally associated with high follow-up costs, and also delivery periods in the magnitude of some weeks.

A method to deal with the already mentioned influences must have the potential to produce a valid estimate of the theoretical service life of the specific module. The basis of such reliability investigations is the documentation of the times when a specific module loses its functionality. If it is assumed that maintenance of the failed module is uneconomical or technically impossible, then it must be replaced. The requirement for the replacement module must be that the function it had before the failure is also ensured after it has been replaced.

[42] Cf. GÄNßMANTEL et al. (2005)

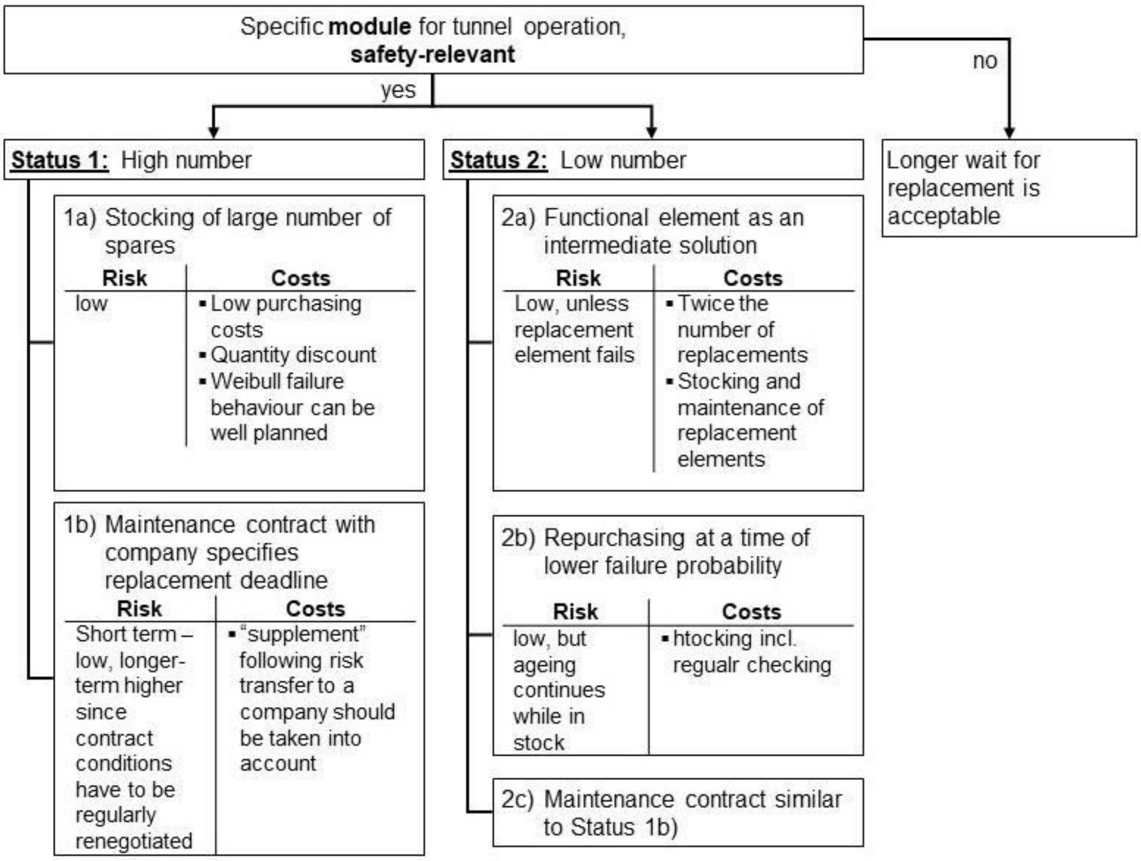

Figure 10: Handling of safety-related tunnel equipment[43]

Categorisation of the safety relevance of modules can lead to various strategies regarding the maintenance of a tunnel. Depending on the selected strategy, particularly the selection of an appropriate failure probability varies. There is a direct dependency between the selected failure probability and the effects on the follow-up costs in the lifecycle cost calculation.

Due to the influences stated above (service life, maintenance strategies, further development and safety requirements), it is necessary to regularly compare the intended and the actual situation in order to be able to determine the further lifecycle with adequate accuracy.

A comprehensive status report on maintenance strategies and rehabilitation procedures for traffic tunnels was published by a STUVA-led working group.[44]

[43] Cf. VOGT (2013).
[44] Cf. STUVA (2018)

4 Net present value method

4.1 Basic statements and assumptions

In the design phase of investment projects, the net present value method is a financial mathematical decision-making method to evaluate the economic advantageousness of individual net present values/investment programmes and is used to select a process in a comparison of variants.[45]

The net present value method can be used in the following decision situations:

- Whether or not to make an investment without consideration of alternative net present value possibilities. The net present value shows whether the investment is economically beneficial.
- Selection of an optimal investment object from a defined quantity of autonomous alternatives, which rule each other out.
- Determination of the optimal service period or the optimal replacement time.
- Determination of the extent and composition of an optimal investment programme, which consists of net present value objects that are independent of each other.

The economic evaluation of alternative investment projects can only be implemented with correct methodology if they are comparable in terms of their objectives, design periods, capital inputs and environmental situations.

The investment is thus a project, which begins with one or more purchase payments and whose use leads to future payments and receipts.

The investment calculation has as input data

- all the payments and receipts associated with the object (payment series),
- the payment dates,
- the uncertainty of the payments.

Further input data with regard to the investor also naturally has to consider his/her

- target system,
- decision-making situation (alternatives, additional constraints),
- attitude to risk and the
- form of the organisation (with regard to liability and taxation consequences)

4.2 Analytical standard model

Economic evaluation of tunnels is normally only concerned with the determination, analysis and optimisation of the accounted initial and follow-up costs; the net present value calculation in this application corresponds to the cash calculation of a series of payments. The net present

[45] Cf. ADDEN, THEWES, LEHAN (2016)

value is thus the sum of all cash inflows and outflows associated with the investment, the tunnel, discounted to the reference point in time

(1) $$NPV = -a_0 + \sum_{t=1}^{n} c_t \cdot q^{-t}$$

with:

NPV	**N**et **P**resent **V**alue, present value of payments at time 0 (end of life cycle phase 1 = design and construction
a_0	Design and construction payments[46] at time 0, also discounting time t
c_t	$c_t = (b_t - a_t)$; Excess of cash inflows (b_t) over outflows (a_t) in the period t
q:	Discounting factor $(1 + i)$ with i = calculation interest rate
n:	Service life of the investment object with t = 1.2,.., n (in years)

With uniform payments, the formula (1) simplifies to

(2) $$NPV = -a_0 + c \cdot RBF_i^n$$

with:

$$RBF_i^n = \frac{q^n - 1}{i \cdot q^n}$$

RBF Net present value factor

Selection criterion:

$$NPV \geq 0$$

The greater the net present value, the more economical a building project is.

4.3 Decision-relevant parameters

Selection of the calculation interest rate

If the payment series associated with a tunnel project is given, then the net present value is solely a quantity dependent on the calculation interest rate. The calculation interest rate, which is kept constant over the service life of the tunnel project, thus has a decisive influence on the evaluation of cost-effectiveness. A high interest rate will favour alternatives with pronounced follow-up costs and low investment costs.

For investment projects with a longer service life, it is recommended to calculate with an interest rate, which is at least based on one of the ministerial examples[47,48,49] (Table 2).

Table 2: Interest rate guidelines of the Federal Ministry of Finance[50]

Year	2005	2007	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Interest-rate (%)	4.3	4.0	3.3	3.4	3.5	3,.1	2.3	1.7	1.3	1.0	0.7	0.6	0.5	0.5	0.7

46 Design- and construction costs are to be used as cash outflows.
47 Cf. BMWSB (2015), BNB Criterion No. 2.1.1, Annex 4
48 Cf. BVWP (2030), Chapter 12.1
49 Cf. ABBV (2010), Chapter 2.4
50 Nominal interest rates in %

Base evaluation 0%

In order to have a sensible reference scale for the quality and sensitivity of the result in practical application, it is necessary to always assume a 0% variant of the net present value function for the calculation of the net present value. With a calculation interest rate of 0%, the net present value is equal to the sum of the future, not discounted payments.

Price level changes and relative price changes

In the usual application cases, the price change rates of the relevant payment quantities differ. They can also, like the general annual inflation/deflation rate, change over time or become due at different dates. These relative price changes are to be considered as follows:

(3) $$NPV = -a_0 + \sum_{t=1}^{n} \frac{\prod_{t=1}^{n} c_t(1+p_{ct})}{\prod_{t=1}^{n}(1+p_t)(1+i_r)^t}$$

with:

p_{ct}: *Price changes of the annual payments*
p_t: *Changes of the inflation/deflation rate with time*
i_r: *Real calculation interest rate*

$$NPV = -a_0 + \sum_{t=1}^{n} \frac{\prod_{t=1}^{n} b_t(1+p_{bt}) - \prod_{t=1}^{n} a_t(1+p_{at})}{\prod_{t=1}^{n}(1+p_t)(1+i_r)^t}$$

p_{at}: *Price changes of the annual cash outflows*
p_{bt}: *Price changes of the annual cash inflows*
p_t: *Changes of the inflation/deflation rate with time*
i_r: *Real calculation interest rate*

The special case of uniform price level changes, i.e. inflation or deflation, leads to uniform changes in all prices in the net present value calculation and therefore does not have to be taken into account. Formula 4 shows that the input and output variables and the calculation interest rate are influenced equally in terms of amount and direction.

(4) $$NPV = -a_0 + \sum_{t=1}^{n} \frac{b_t(1+p)^t - a_t(1+p)^t}{(1+i)^t * (1+p)^t} \quad => \quad NPV = -a_0 + \sum_{t=1}^{n} \frac{b_t - a_t}{(1+i)^t}$$

with:

p: *Uniform inflation/deflation rate*

Risk and uncertainty

The expected future cash inflows and outflows of the investment project are planning values and cannot therefore be calculated with certainty in advance; the net present value to be determined becomes a multi-value target quantity. The degree of uncertainty of the input parameters can generally be considered in the net present value method through deterministic correction processes, sensitivity analyses or stochastic processes of risk analysis (cf. Chap. 6).

4.4 Extension of the standard model

Supplementary investment

If supplementary investment is considered, alternative investment intentions can be made comparable, differing

- in the quantity and distribution with time of the cash inflows and outflows $(b_t. a_t)$
- design- and construction payments (a_0),
- in the length of the service lives (n) and
- in the degree of uncertainty.

If there are no plans at the reference date for the use of the unneeded investment finance or the replacement of the plant after the expiry of the service life, a partially analytical analysis is carried out with a *"neutrality assumption".* The net present value method assumes that the present value of any supplementary investment to be considered may be zero since the fictitious reinvestment of any excess receipts (in the case of concession models) is at the calculation interest rate.

Financing of the investment

The financing side of the investment project is not considered in the standard model. The net present value method assumes that the full amount of the required investment is available to the investor. The financing side can however be integrated into the investment calculation by adding a separate row of figures, which represents the raising of capital with subsequent periodic repayment instalments. Financing and investment only actually differ in the plus or minus sign of the periodic payments.

4.5 Evaluation of the net present value method

The net present value method for the calculated implementation of a lifecycle cost concept is currently without a practical alternative to its methodology. The quality of the results of the calculation for a specific case depends to what extent modifications of the standard model lead to a realistic representation of the definite circumstances of a tunnel construction project.

The standard approach as a partial model is simple and quick to handle. The evaluation of the advantageousness of autonomous investment projects is only based on the target value "optimisation of net present value". Further target dimensions – liquidity, purchasing and/or finance restrictions – are not explicitly considered. The characterisation of an investment object through the series of payments does not initially neglect monetary amounts. Technological, organisational and legal as well as external effects (air pollution, noise nuisance) can be considered for the investigation period by monetising them.

The data basis for the figures for the net present value calculation is the actually incurred costs based on figures from external invoices. The lifecycle cost calculation is systematically assigned to the calculated internal cost and performance calculation. The use of net present value calculation can be implemented when based on actually incurred costs.

5 Calculation of the lifecycle costs

The process to determine the lifecycle costs of a tunnel is shown as a flow chart in Figure 11. The individual steps I to VII are explained in the following Sections 5.1 to 5.7.

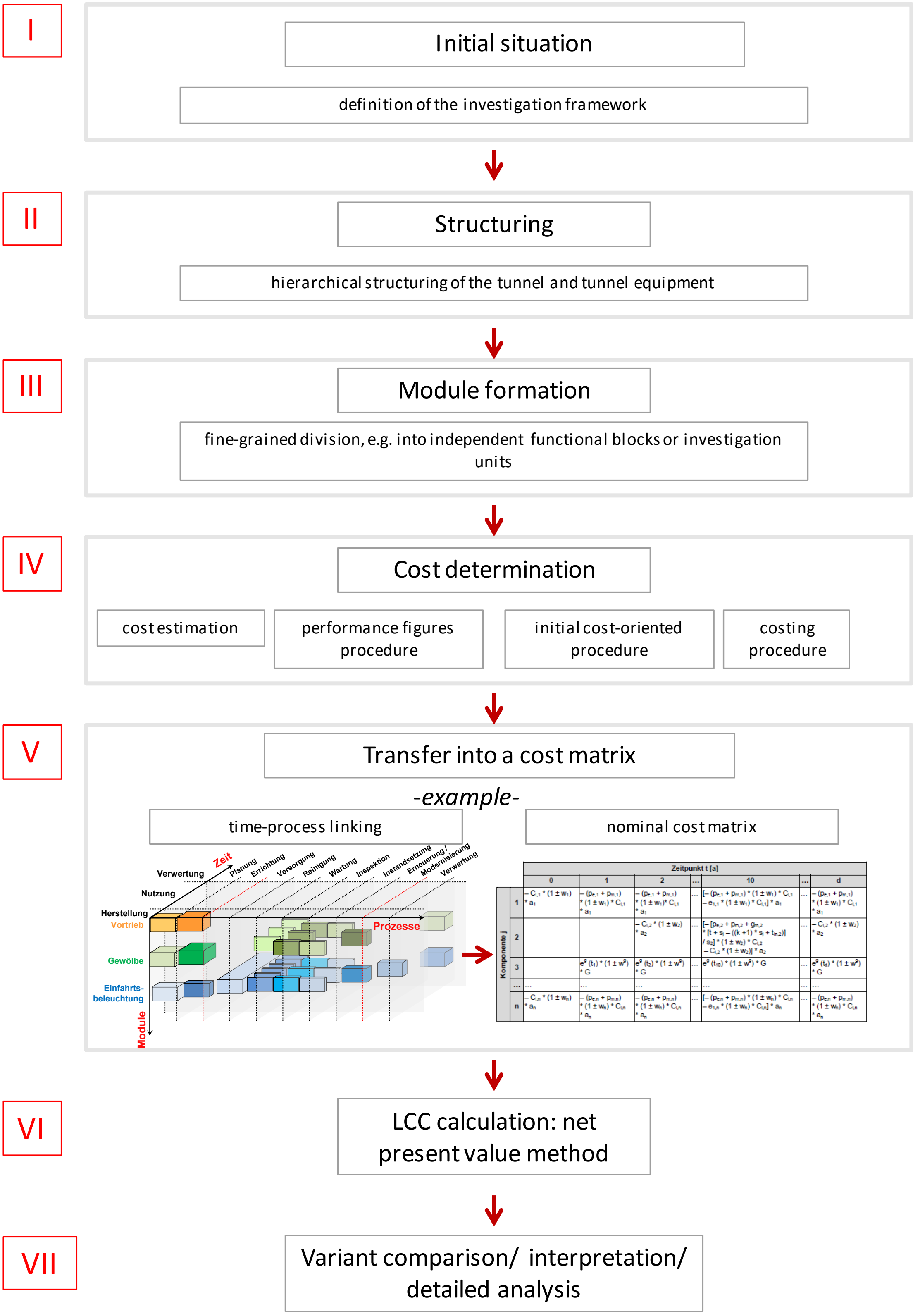

Figure 11: Procedure to determine lifecycle costs

The key to the procedure is the structuring of the tunnel into independent modules and the division of the lifecycle into the processes involved. The determination of the individual cost quantities can be undertaken based on various approaches according to the objective or the current state of knowledge.

5.1 Step I – Initial situation

In order to prepare for a lifecycle analysis, the investigation framework first has to be defined (Figure 10), with the determination of the characteristics of the investigation framework starting from the investigated object (new construction or existing structure). The individual depth of consideration is decided based on the available level of detail of design and information and the objective being followed. Corresponding to the modular structure, the extent of the individual modules up to the complete tunnel can include all characteristics. More detailed investigations can be implemented of occasional areas, while also maintaining a larger-scale consideration.

The definition of the aim of the investigation, for example a lifecycle cost calculation in order to optimise overall costs or for budget planning, has a great influence on further proceedings. Particularly the definition of the relevant time horizon for the investigation framework is decisively influenced by this.

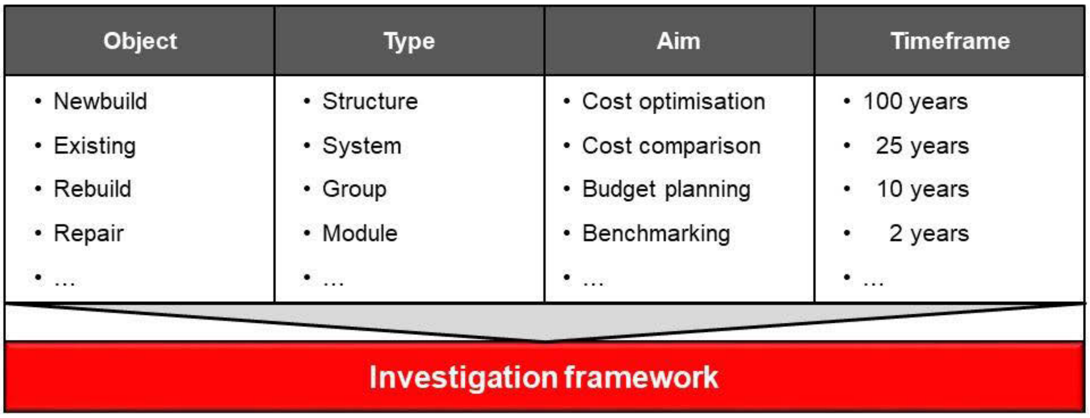

Figure 12: Definition of the investigation framework

For a comparison of construction variants, comparability should be ensured in the definition of the investigation framework. This can be ensured, for example, through an equivalent safety level, identical performance classes, comparable input quantities (e.g. traffic volume, permitted maximum speed etc. for road tunnels or passenger volume, vehicle length, platform length etc. for public transport tunnels) or a comprehensive task fulfilment. When planning public transport tunnels, it must be taken into account that the structure gauge and tunnel cross-section of the largest possible vehicle in the respective network must be used to ensure that the network remains sustainable and that the project is eligible for funding.

5.2 Step II – Structuring of the building

A planned structuring is to be carried out in order to represent the costs of the tunnel in a lifecycle cost model in a clear fashion. A modular model with a hierarchical structure is produced for active arrangement of the overall costs. Modular in this context means that the system is broken down into largely independent units.

This structuring achieves the result that individual elements (modules) can be subjected to isolated analysis due to their independence and considering existing relationships. It is also possible to transfer solution approaches (structure, module, costs etc.) once developed to other projects. The hierarchical structuring also permits the consideration of the existing depth of design to be individually adapted.

Starting from the overall structure, tunnels can be broken down, for example, into the partial systems auxiliary construction measures, construction and equipment. This ensures the assignment of initial and follow-up costs in accordance with their causes. Auxiliary construction measures have a one-off nature and do not normally cause any follow-up costs, although they can, particularly in an urban environment, represent a large part of the initial costs. The differentiation of construction and tunnel equipment reflects their very different characteristics regarding initial and follow-up costs and their design and implementation at different times.

The modules are assembled into construction groups with similar function, purpose, or structure. (Figure 13)

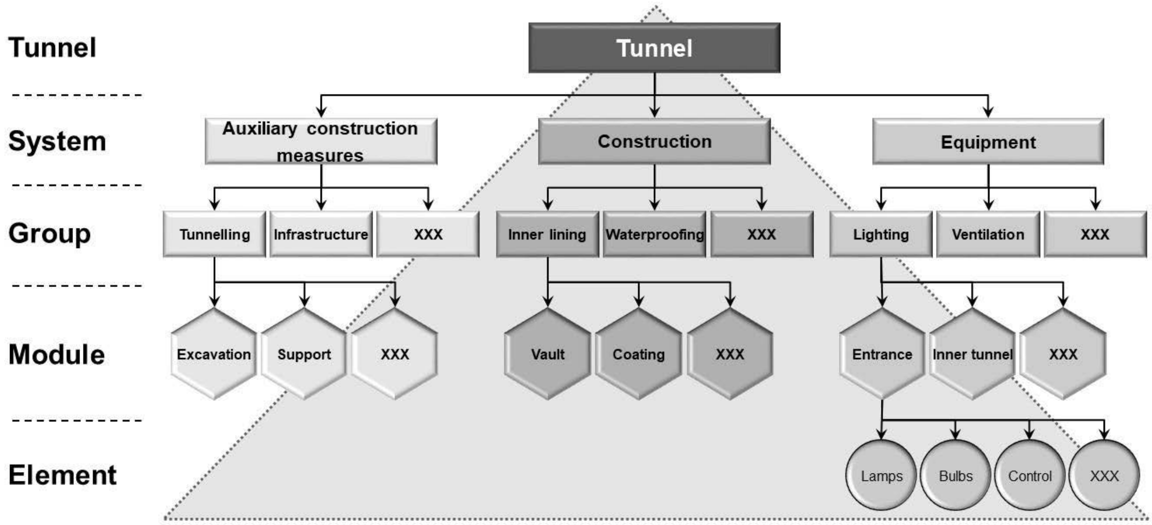

Figure 13: Hierarchic-modular structuring of tunnel construction[51]

5.3 Step III – Module formation

A tunnel construction is divided into modules in accordance with the undertaken structuring. A module itself is defined by the technical and functional tasks it must fulfil and represents a largely independent unit.[52]

[51] Cf. ENGELHARDT (2015)

[52] For the theoretical derivation of modules and their delineation through the criteria independence and integrity, reference is made to ENGELHARDT (2015), pp. 95.

5.3.1 Structuring the modules

In order to ensure transferability or comparability, it is recommended to use modules with a generally valid internal structure (Figure 14). The attributes of the individual modules that are necessary for this purpose should be recorded as completely as possible for the determination of the lifecycle costs.

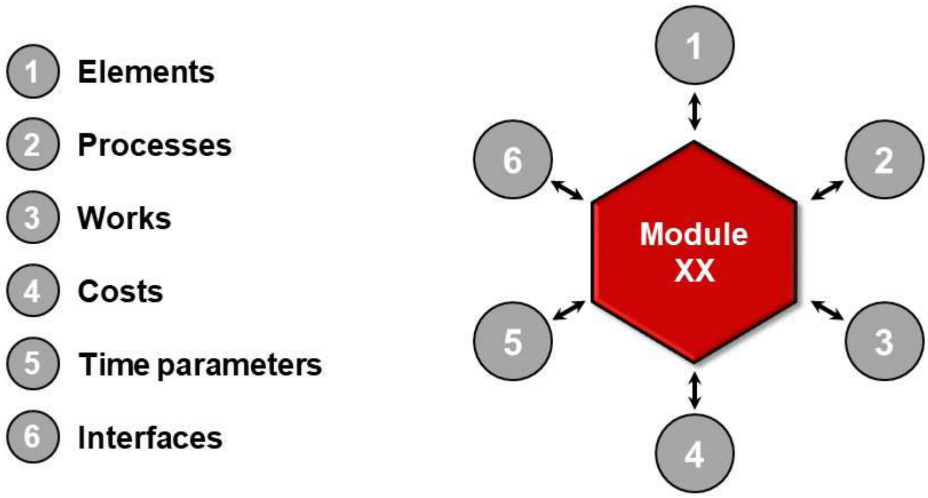

Figure 14: Internal structure of a module[53]

Elements

The essential parts (elements) of a module must be recorded and differentiated from other modules, with all components with a common technical and functional task being summarized. Should an element be intended for several tasks, the predominant task is decisive for the module assignment.

In order to ensure comparability or transferability, the individual elements must be exactly recorded and specified. For the lighting, for example, the types used (fluorescent tubes, high-pressure sodium lamps or LED) should be differentiated. To limit the amount of work recording data, the differentiation can be restricted to the elements with a significant effect on costs.

Processes

The individual modules, as explained in Chapter 2, run through many different processes over their entire lifetime. For each module, the relevant processes must be determined and assigned to the relevant phase according to extent and frequency. The processes can be collected into higher level processes depending on the intended target horizon. For example, it can be useful to aggregate the individual processes cleaning, inspection and servicing to one overall process. Figure 15 shows examples of road tunnels.

[53] Cf. ENGELHARDT (2015)

Tunnel	System	Group	Module	Processes						
			Module	Design	Construction	Operational maintenance	Constructional maintenance	Repair	Modernisation	Recycling
Sample Tunnel	Construction	inner shell	vault	x	x	x	x	x	-	-
			invert	x	x	-	-	-	-	-
			coating	x	x	-	x	-	x	x
			air duct slab	x	x	x	-	x	-	-
		road construction	pavement	x	x	x	x	x	-	-
			substructure	x	x	-	x	x	-	-
		sealing	sealing	x	x	-	-	-	-	-
		dewatering	side drainage	x	x	x	x	x	-	-
			dewatering	x	x	x	x	x	x	-
		operation building	operation centre	x	x	-	x	x	-	-
			niches	x	x	x	x	x	-	-
	Equipment		Module	Design	Installation	Servicing and Inspection		Repair	Improvement and Renewal	Supply / Surveillance
		lighting	entrance lighting	x	x	x		x	x	x
			passage lighting	x	x	x		x	x	x
			breakdown bay lighting	x	x	x		x	x	x
			escape route lighting	x	x	x		x	x	x
		ventilation	ventilation system	x	x	x		x	x	x
		traffic technology	traffic signs	x	x	x		-	x	-
			traffic lights	x	x	x		x	x	x
			variable traffic signs	x	x	x		x	x	x
			variable direction signs	x	x	x		x	x	x
			traffic monitoring	x	x	x		x	x	x
		safety systems	traffic guidance system	x	x	x		x	x	x
			escape route signs	x	x	x		x	x	x
			emergency call system	x	x	x		x	x	x
			fire alarm system	x	x	x		x	x	x
			fire-suppressing system	x	x	x		x	x	x
			tunnel communication	x	x	x		x	x	x
			GSM-technology	x	x	x		x	x	x
			traffic reports / radio	x	x	x		x	x	x
			loudspeaker system	x	x	x		x	x	x
		central facilities	medium-voltage system	x	x	x		x	x	x
			low-voltage system	x	x	x		x	x	x
			transformer	x	x	x		x	x	x
			electrical switchgear	x	x	x		x	x	-
			UPS system	x	x	x		x	x	x

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Figure 15: Exemplary allocation of processes and modules for a road tunnel

Services

In order to create transparency and the necessary understanding for the cost drivers, the services and their extent must be determined for the individual processes. For this purpose, various reference sources can be used, for example:

General

- German Standard Book of Bill Items (STLB-Bau[54])
- Guideline for the maintenance and repair of engineering structures (RI-ERH-ING[55])
- ZTV-ING[56], ABBV[57], RWVZ[58], RWVA[59], DIN 1076[60] etc.

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[54] Cf. STLB (2019)
[55] Cf. RI-ERH-ING (2021)
[56] Cf. ZTV-ING (2022)
[57] Cf. ABBV (2010)
[58] Cf. RVWZ (1997)
[59] Cf. RWVA (1997)
[60] Cf. DIN 1076 (1999)

Road Tunnel

- Bulletin for the control, servicing and care of road tunnels (M KWPT[61])
- Performance booklet for the road operation service on federal trunk roads[62]
- Guidelines for Equipment and Operation of Road Tunnels (RABT[63])
- Recommendations for the equipment and operation of road tunnels with a design speed of 80 km/h or 100 km/h (EABT)[64]

Public transport tunnel

- Building and Operating Regulations for Tramways (BOStrab) [65]
- Technical Rules Tunnel (TR Tunnel) [66]
- Technical Rules for Electrical Installations (TR EA) [67]
- Technical Rules Fire Protection (TR Strab BS) [68]

Railway tunnel, including high speed traffic

- Ril 853 - Design, construction and maintenance of railway tunnels[69]
- VV Construction of the Federal Railway Authority[70]
- General Railway Act [71]

Costs

Costs must be determined for the work to be performed in the processes. For sake of uniformity, these are calculated as net sums. Depending on the state of design and information when the costs are determined, various methods of cost planning can be used (cf. Chap. 5.4).

If costs cannot be directly assigned to a process or a module, for example for servicing and/or cleaning, then the essential process or module is identified and an appropriate cost assigned to it. Alternatively, the processes can be combined or modules in the level above in the structuring (construction assembly or system) are to be taken.

Time parameters

The value of a monetary quantity is influenced by its time of occurrence. Therefore, it is necessary, in addition to the frequency, to consider the relevant time, when the works or

[61] Cf. M KWPT (2015)
[62] Cf. BMVI (2021)
[63] Cf. RABT (2006)
[64] Cf. EABT-80/100 (2019)
[65] Cf. BOSTRAB (2019)
[66] Cf. TRTUNNEL (2015)
[67] Cf. TRSTRABEA (2011)
[68] Cf. TRSTRABBS (2014)
[69] Cf. RIL853 (2018)
[70] Cf. VVBAU (2013)
[71] Cf. AEG (2020)

the costs arise for the individual processes. This is ensured by using the net present value method – cf. Chapter 4.

For cyclical processes, e.g. cleaning or inspection, the time parameters can be securely forecast in many cases due to legal or operational constraints.[72] The determination of the time point of non-cyclical processes is more complex, e.g. for the renewal of individual construction elements. This is explained in Chapter 3.

Interfaces

Although the modules should be independent of each other, reciprocal interactions of the modules or processes should still be considered as attributes. The essential influential parameters, such as the degree of reflection of the inner lining, the lighting brightness in or before the tunnel, the tunnel length etc. should be determined.

5.3.2 Examples of road tunnel modules

Figure 16 shows an example of the hierarchical organisation for road tunnels according to the structure "Structure - System - Assembly - Module".

Tunnel	System	Group	Module
Sample Tunnel	Construction	inner shell	vault
			invert
			coating
			air duct slab
		road construction	pavement
			substructure
		sealing	sealing
		dewatering	side drainage
			dewatering
		operation building	operation centre
			niches
	Equipment	lighting	entrance lighting
			passage ligthing
			breakdown bay ligthing
			escape route ligthing
		ventilation	ventilation system
		traffic technology	traffic signs
			traffic lights
			variable traffic signs
			variable direction signs
			traffic monitoring
		saftey systems	traffic guidance system
			escape route signs
			emergency call system
			fire alarm system
			fire-suppressing system
			tunnel communication
			GSM-technology
			traffic reports / radio
			loudspeaker system
		central facilities	medium-voltage system
			low-voltage system
			transformer
			electrical switchgear
			UPS system

Figure 16: Example for the structure of Modules for road tunnels

[72] For example from the Bulletin for the control, maintenance and care of road tunnels (M KWPT), the Guideline for the equipment and operation of road tunnels (RABT), DIN 1076 (1999) etc.

5.3.3 Examples for Modules of Public Transport Tunnels

Modularisation is based on the typical division of trades in a light rail system. In this way, additional speculative allocations of existing costs are avoided. Firstly, the structure is divided into three systems: the structural systems, the technical systems and the operational systems. In a master's thesis at the Ruhr University Bochum[73], a real object was analysed. The analysed project comprised a total of 81 modules, for which different amounts of cost information were available (Figure 17 to Figure 19).

No.	Assembly	Module	Abbreviation / Synonym / Elements
1	Shell	Earthwork	Excavation
2		Reinforced concrete construction	Bf., ramp, tunnel, emergency exit shaft, concrete repair, waterproofing injection
3		Tunnel construction	excavation, inner lining
4		Steel construction	
5		scaffolding, building aids	
6		Excavation support	Shoring
7		Special civil engineering	
8		Site equipment	BE
9		Dewatering	
10		Waterproofing	Exterior waterproofing, joint sealing
11		Sewer construction	
12		Pipeline construction	Utility lines, public utilities, telecom, Unitymedia, etc.
13		Road construction	Surface restoration
14		Light signal systems	LSA in the course of road construction
15	Expansion	Screed	
16		Tiles	
17		Natural stone works	
18		Drywall and masonry	Interior walls
19		Plastering works	
20		Painting and coating works	
21		FH doors	
22		Door systems	room and building doors (not FH)
23		Metal construction	wall cladding, panel ceilings,handrails, railings, gratings
24		Glass construction	
25		Steel construction	Escape routes in the track area, escape staircase, roof construction
26		Roof waterproofing	Roofing work
27		Elevator enclosure	Elevator enclosure and elevator shaft doors
28		Signage	
29		Furnishing	Locksmith work equipment
30		showcases	
31		Landscaping	Outdoor facilities
32		Final construction cleaning	
33		Line route extension	Wall brackets, cable troughs, cable ducts
34		Pigeon deterrence	
35		Cleaning	Cleaning of stations and equipment
36		graffiti removal	graffiti protection and removal
37		Removal of vandalism damage	
38		guarding	
39		Insurance	

Figure 17: Modules for the structural parts[74]

[73] Cf. FREIMANN (2020)
[74] Cf. FREIMANN (2020)

No.		Module	Abbreviation / Synonym / Elements
40		Electrical through connection	grounding
41		Main distribution	
42		Sub-distribution	electrical works
43		Lighting/electrical maintenance	public lighting in the station (track level, distribution level)
44		Lighting	service room equipment
45		Rolling shutters	
46		Ventilation system	
47		Air conditioning	
48		Heating system	
49		Sanitary system	fresh water, sewage, WCs, building drainage
50		Pumping and lifting equipment	
51		Structural fire protection	fire bulkheads, fire dampers, smoke detectors, fire alarm system,BMZ
52		Smoke aprons / smoke extraction	Smoke retention
53		Escape route signage	
54		Dry extinguishing line	TLL, fire extinguishing pipe
55		Fire department key depot	FSD, key safe

Figure 18: Modules for the technical equipment[75]

No.		Module	Abbreviation / Synonym / Elements
56		Track construction	Tracks, switches, superstructure
57		Overhead line	Catenary system
58		Elevators	
59		Escalators	
60		Train protection	Signaling systems, emergency stop, cabling
61		Power supply	Substations
62		Medium voltage system	
63		Transformers	
64		Uninterruptible power supply	USV, ESV
65		Batteries	
66		Emergency power system	Emergency generator (diesel)
67		Telecommunication system	FM cables, FM cabinets
68		Telephone and emergency call system	
69		Automatic operation control	ABF
70		Telecontrol system	
71		Network control technology	
72		Clock system	
73		TV system with network	Video system
74		Electric public address system	ELA, electro-acoustic system
75		Dynamic passenger information	DFI, train destination indicator
76		Ticket vending machines	FAA, ticket vending machines
77		Ticket validator	FAE, ticket validator
78		Computer-controlled operations control sys.	AVL
79		Operational radio	Digital radio
80		BOS radio	Radio of authorities and organizations with security tasks
81		WLAN / Mobile radio	Customer connection / cell phone networks

Figure 19: Modules of operation-related installations[76]

5.4 Step IV – Procedure of cost determination

In order to determine the costs for the individual modules or the higher system levels, various approaches can be used dependent on the state of design and information or the intended objective.

Cost estimation

In the determination of costs for the individual modules, values from experience should be used. It is possible to adapt or update assumptions from existing tunnels, considering the relevant constraints. This procedure is especially appropriate for early project stages, when

[75] Cf. FREIMANN (2020)
[76] Cf. FREIMANN (2020)

only approximate, large-scale knowledge is available about the later characteristics of the tunnel and its use. With the progressing state of knowledge, this should be replaced with other, more detailed procedures.

Performance figures procedure

Procedures based on performance figures rely on cost determination or performance-derived figures from real existing tunnels or processes and their data collection. In this case, absolute and relative performance figures should be differentiated. When using this method, it is essential to know the decisive influential quantities for the performance figure and to derive from this its transferability to the constraints of the case under consideration. As an example for a road tunnel, when a performance figure is used for the annual electricity consumption of the tunnel lighting (e.g. in kWh/m), one decisive point is what brightness or type of lamps were in use in relationship to the case under consideration.

Initial cost-oriented procedure

With the initial cost procedure, the follow-up costs are derived based on percentage proportions of the initial costs. These can derived from reference figures (e.g. ABBV[77]), from performance figures from existing tunnels (e.g. FGSV[78] or in-house documentation of tunnel operators). A detailed collection of tunnel structural and equipment installation costs as well the associated annual operating costs has been collected by the FGSV. From this database, considering the relevant price level, the annual follow-up costs to be expected for various modules can be derived as a factor of the initial costs. This procedure links directly into the substitution principle explained in Chapter 2.3 and makes clear the dependency of follow-up and initial costs at module level.

There is no comparable general data for public transport tunnels and railway tunnels available. In each case, the operators use data which is based on individual experience.

Costing procedure

The costing procedure is based on the usual estimation methods in construction. The costs are the result of the individual costs of partial works and can be sub-divided according to cost types (wages, machines, material, subcontractors etc.) (see example in Chap. 7 and 8). Since the costs are determined starting from the work to be carried out, they can be directly assigned to the cost element (module or process).

In order to determine the calculation approaches, it is recommended to work from known cost figures (e.g. from tender documents, invoices of subcontractors etc.) from comparable projects. The collected costs are to be converted to the reference data and collected to an average quantity.

For services, which cannot be directly represented, research should be undertaken to discover published figures (costs, estimation rates, quantity rates, expense figures etc.) to determine the costs. For services without a valid data basis, it is recommended to determine the costs from the extent of the work and the cost.

[77] Cf. ABBV (2010).
[78] Cf. FGSV (1996).

Considering that not all the required input parameters are available, a combination of various procedures can be used to gain an approximation. However, this demands later detailed consideration or continuous upgrading as soon as more accurate values are available.

5.5 Step V – Development of a cost matrix

The number of all modules, which completely or according to the objectives represent the tunnel in parts, is expressed by the variable *x*. For each module, a number n_j of similarly constructed modules and the value of the theoretical service life d_j are given. From the theoretical service life d_j and the overall period of the lifecycle cost calculation *z*, the number of exchange actions required for each module within a defined period can be determined. The module initial costs $a_{t,j}$ comprise the payments *j*, which have to be made for the production or purchasing of the module ready for operation at the selected time *t*. The initial costs for the module j at time t=0, the reference point for discounting, are expressed in particular by the quantity $a_{0,j}$ (cf. Chap. 4.2). During the next phase, the follow-up costs $c_{t,j}$ arise, depending on the method of function and operation of the module, the follow-up costs include all required measures for operation, maintenance, repair and for the (partial) replacement of the module as soon as the theoretical service life of the module is reached.

Figure 20 shows a summary of the previously mentioned quantities and costs in the context of a lifecycle analysis.

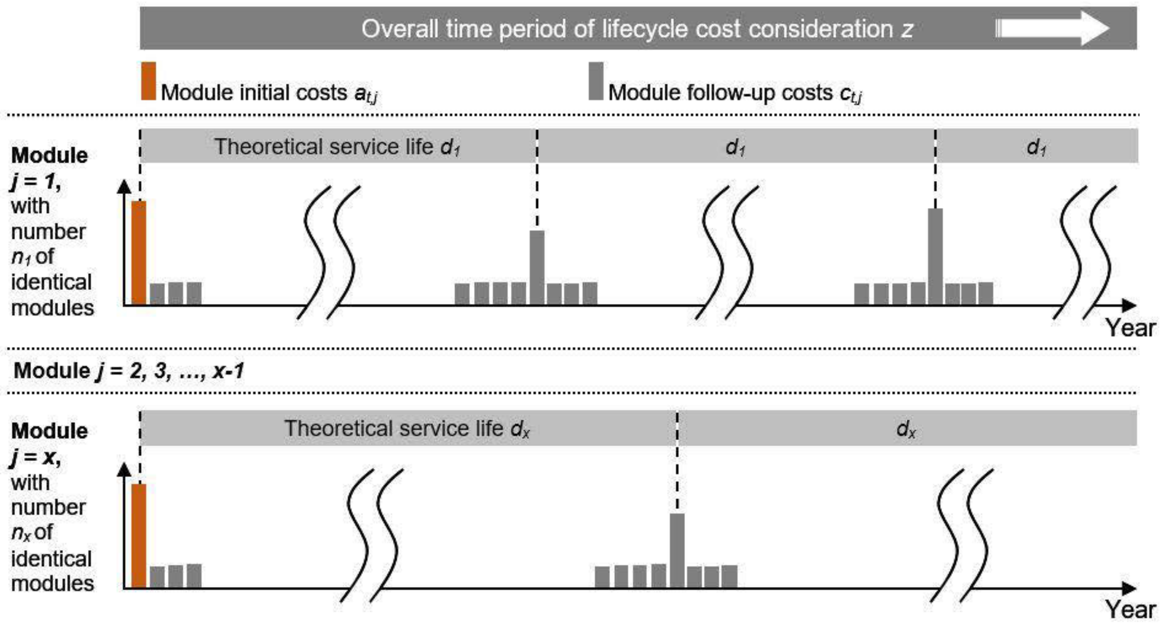

Figure 20: Variables for the recording of a module

In the next step, time, cost and process are linked in three dimensions by assigning the relevant cost quantity to the time of occurrence and arrangement of the investigation framework (Figure 21). The individual quantities here are obtained by adding the individual cost components for the corresponding process.

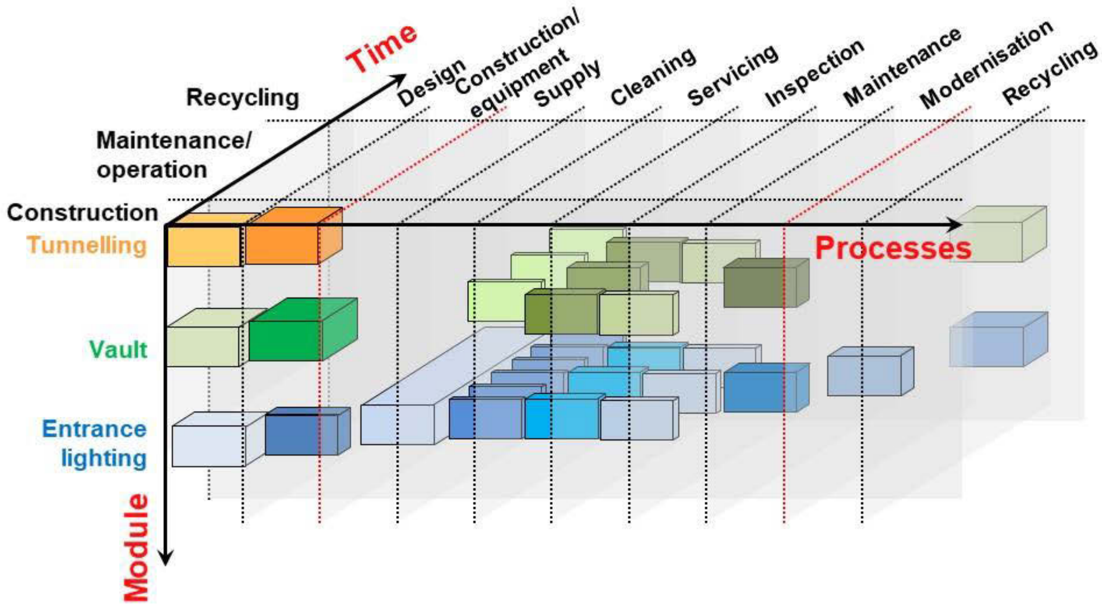

Figure 21: Time-cost-process linking (example arrangement)[79]

In the layout, the costs are planned starting from the point in time under consideration. In order to ensure comparability, price inflation or depreciation of money must be considered. The initial costs $a_{t,j}$ and the follow-up costs $c_{t,j}$ represent nominal costs, as can be gained for example from maturity accounting on the 31/12 of each year. Table 3 shows an example of a nominal time/cost matrix.

Table 3: Nominal time/cost matrix

		Time point *t* [years]						
		0	***1***	***2***	**…**	***10***	**…**	***z***
Module *j*	***1***	Initial costs – $a_{0,1} * n_1$	Follow-up costs – $c_{1,1} * n_1$	Follow-up costs – $c_{2,1} * n_1$	…	Follow-up costs incl. replacement – $c_{10,1} * n_1 – a_{10,1} * n_1$	…	Follow-up costs – $c_{z,1} * n_1$
	2			Initial costs – $a_{2,2} * n_2$	…	Follow-up costs – $c_{10,2} * n_2$	…	Follow-up costs – $c_{z,2} * n_2$
	…	…	…	…	…	…	…	…
	x	Initial costs – $a_{0,x} * n_x$	Follow-up costs – $c_{1,x} * n_x$	Follow-up costs – $c_{2,x} * n_x$	…	Follow-up costs incl. replacement – $c_{10,x} * n_x – a_{10,x} * n_x$	…	Follow-up costs – $c_{z,x} * n_x$

[79] Cf. ENGELHARDT (2015).

5.6 Step VI – Lifecycle cost calculation: net present value method

Starting from the attributes of the individual models collected during the previous sections, the lifecycle costs are now calculated using the net present value method (cf. Chap. 4). The intention is to determine the net present value. The reference time point required for the determination of the net present value is by definition the date of the start of for use. For the initial costs, therefore, no discounting or compounding is undertaken. The follow-up costs on the other hand are discounted to the reference time point.

5.7 Step VII – Variant comparison and interpretation

The result of a lifecycle cost calculation delivers the net present value as a quantity. The net present value, although expressed in EURO, is an abstract figure. Without further investigations or interpretations, findings can only be derived from this to a limited extent, except with a pure variant comparison.

Through the aggregation of the annual discounted cost figures, a curve of the lifecycle costs can be displayed (Figure 22). From this cost curve, significant events and dates can be read off for the investigation period. In years with a significant jump of the costs, increased investments must be activated and thus planned for. Above all improvement and renewal works can be read off from the curve.

In addition to aggregating the costs for the overall structure, the selected structuring also enables system-, assembly- and module-based evaluation. As an extension, process- or phase-related evaluation can be carried out through the collection of similar processes or matching lifecycle phases. This can enable, for example, evaluation of initial and follow-up costs from the entire investigation period down to an individual module (Figure 22).

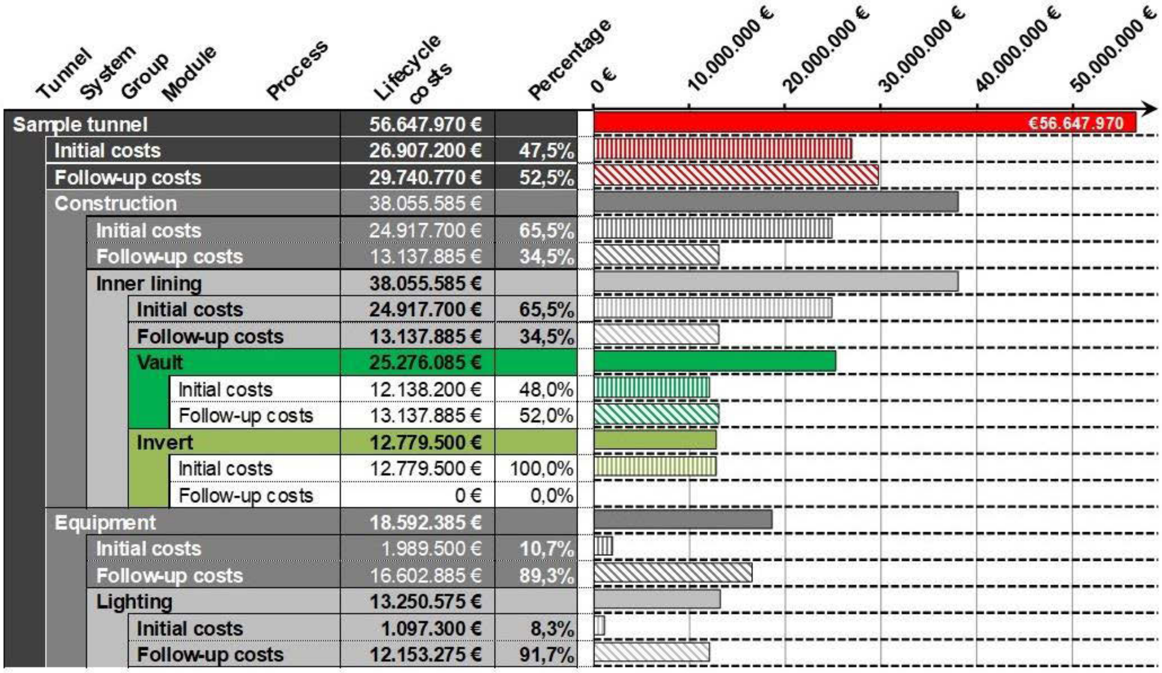

Figure 22: Example for the evaluation of the initial and follow-up costs (excerpt)

Comparison of investigated variants, both in an evaluation of individual quantities (per module or process) and also of the cost curve (overall or in individual quantities), permits further identification of cost drivers or optimisation possibilities.

The influence of the interest rate is made clear by the curve of the lifecycle costs. Figure 23, for example, shows the curves of lifecycle costs based on calculation interest rates of 3.0 % and an interest rate 0.0 % compared.

It is therefore generally recommended to carry out a zero comparison. The forecast of the LCC cannot be determined exactly over this long time period, so the formation of a range is reasonable and shows the limits, within which the costs vary.

In chapter 7 and chapter 8, respectively, a corresponding example calculation is shown for a sample road tunnel and a sample public transport tunnel.

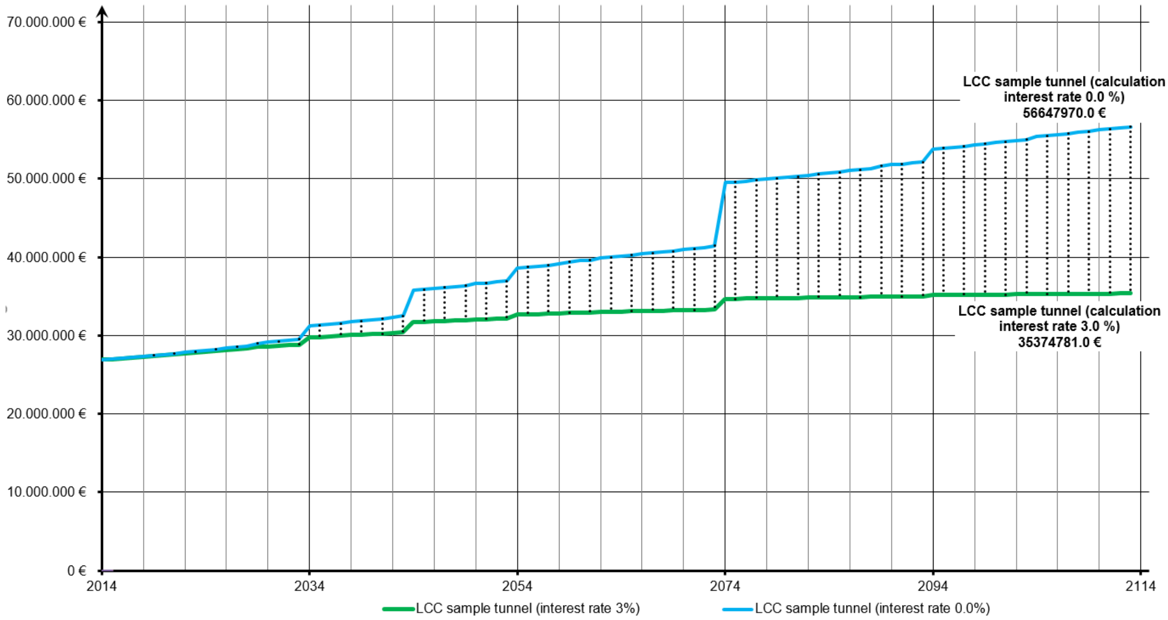

Figure 23: Example curves of lifecycle costs calculated based on interest rates of 3% and 0%

6 Evaluations and analyses

Various procedures are conceivable for further detailed LCC analysis. These make it possible to represent or clearly emphasis uncertainties, risks or also ranges. Primary cost drivers can also be identified, which should then be subjected to detailed consideration in order to limit risks of further optimisation.

6.1 Sensivity analysis

The sensitivity analysis serves to investigate the relationships between the input data of the lifecycle cost analysis and the target values, to identify factors with higher leverage and increase the transparency of the mostly complex dependencies. At the same time, the sensitivity analysis enables an estimation of the risk resulting from the predominantly uncertain input values.

Starting from the determined net present value (lifecycle costs), the analysis investigates how sensitively the calculated result reacts to variation of the actually uncertain input quantities. In order to be able to assign changes in the result to the corresponding input parameter, only one input parameter or group is changed. The variation of the input parameters should be carried out with relevant and realistic features. All further calculation quantities remain unchanged from the initial calculation. This procedure (ceteris paribus) enables the identification of input parameters, which have a particularly strong influence on the target value. Targeted obtaining of information about these data finally leads to a clarification of the uncertain target value.[80]

The result of a sensitivity analysis can be clearly visualised in diagrams. With the form of diagram shown in Figure the gradients of the individual target value curves permit a conclusion about the influence of the relevant input parameter. The steeper the curve of the graph, the greater is the sensitivity of the target value. The elasticity of the variables cannot always be represented by a linear function. Therefore, it is recommended to repeat the individual calculations in the course of a parameter variation.

As an extension of this, scenario analyses, for example in the form of best case or worst caste scenarios, can be carried out to determine the sensitivity. In this case, several parameters are simultaneously changed in their characteristics and their effects investigated. [81] Unfortunately, the transparency and thus the assignability of action and reaction suffer from this.

Knowledge of the stability of the calculation results and the bounding of the relevant input quantities for the lifecycle costs leads to an improvement of the quality of the decision-making basis. This provides the user with the opportunity to intentionally investigate optimisation approaches.[82] The further proceeding can thus be limited to more promising approaches in order to thus keep within bounds the amount of work involved with optimisation.

80 Cf. GÖTZE, BLOECH (1993), BLOHM, LÜDER, SCHAEFER (2012)
81 Cf. FECK (2007)
82 The generation of optimisation potential regarding lifecycle costs is only possible if the relevant input quantities and the decisive relationships have been identified and taken into account. Cf. BECKER (1986)

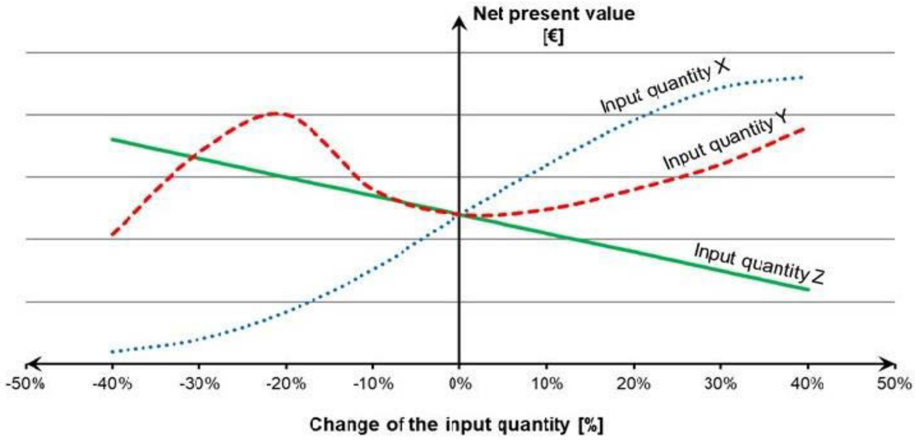

Figure 24: Graph of the results of a sensitivity analysis

6.2 Pareto principle

Starting from the consideration that sensitivity analyses cannot be carried out for all indicators for time and cost reasons, it is recommended to restrict the analysis to those indicators, which

- have a large quantitative influence on the overall result and
- whose actual values are uncertain.

For this purpose, the Pareto principle was developed. This describes the statistical phenomenon that a significant part of the overall result (e.g. 80 %) is determined by a small part of the expenses (e.g. 20 %).

For the lifecycle cost calculation, this means that both for effective risk evaluation and for targeted optimisation of the lifecycle costs, the gathering of detailed information can be restricted to the significant cost factors.

For this reason, the individual components are ordered according to magnitude for the evaluation of costs. A modular structure of the lifecycle costs enables unhindered identification of the significant cost drivers (Figure 25). The resulting processes identified as leading factors are then investigated for their risk and optimisation potential. For suitable parameters, a sensitivity analysis is then carried out to further delineate the existing risks or optimisation potential.

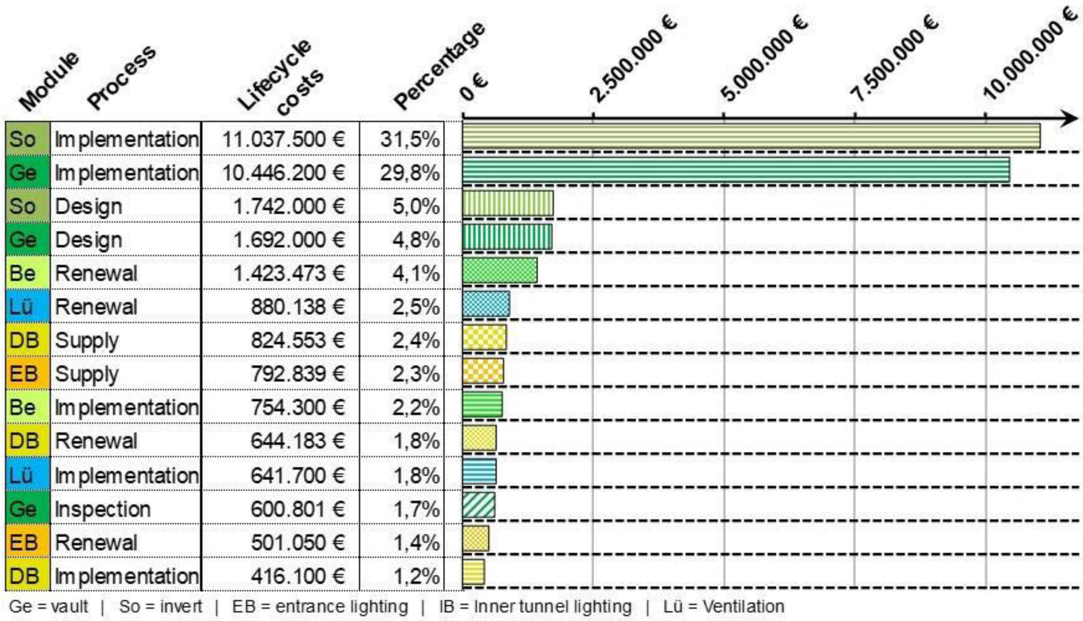

Figure 25: Ordering to identify significant processes (excerpt)[83]

6.3 Creation of an ABC categorisation

In the ABC analysis of the overall costs, the priority items with the largest share of the lifecycle costs are collected in category A. For a reliable lifecycle cost calculation, these modules must be included in the investigation framework. Elements of category B have much less relevance for the overall cost of a tunnel. Modules of category C have only a minor effect, so considering the amount of work in data collection, it is recommended to use or derive only generalised sums. This enables the analysis of the cost estimate to consider only those items that have a significant influence on the overall result. For an assessment of the relevance of modules, a categorization is made from the evaluation of a real existing project (example road tunnel) with regard to the influence on the total costs (Figure 26).

[83] Exemplary extract from the calculation of a road tunnel.

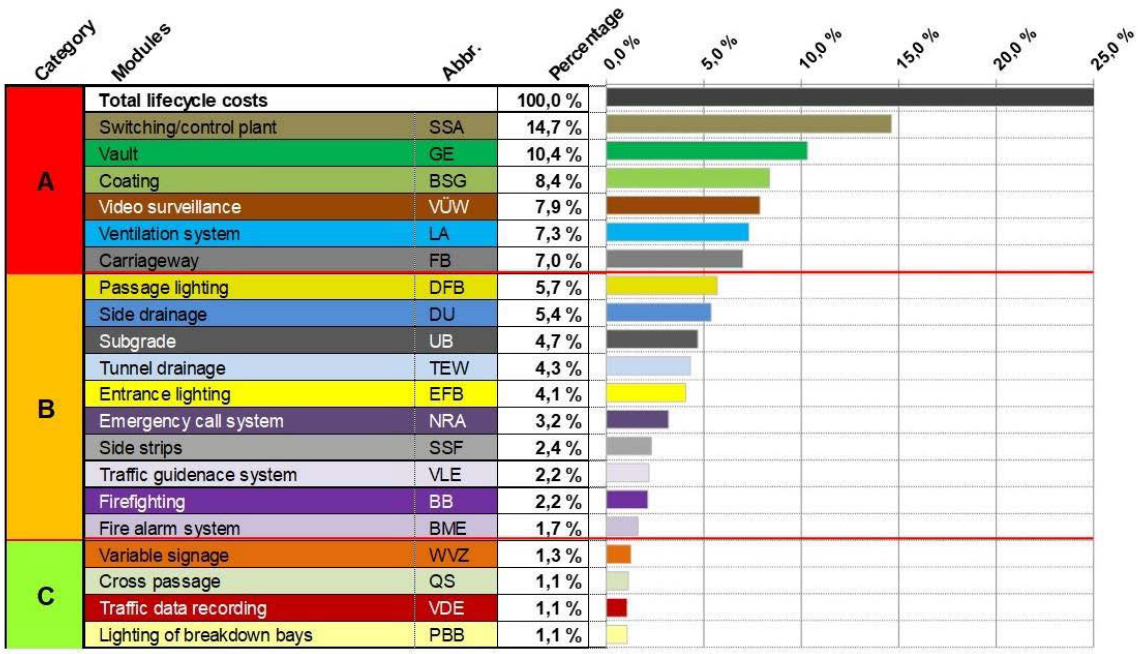

Figure 26: Evaluation to determine the relevance of modules (excerpt)[84]

6.4 Risk analysis for the consideration of uncertainties

In the investigations until now, all calculation quantities (payments, due dates and interest rate) were assumed as deterministic quantities. However, a lifecycle cost calculation is a modelled representation of future events. The data used and the resulting occurrence of the assumed environmental conditions can thus not be predicted with certainty.

The effects of possible changes can however be made visible by integrating a risk analysis. From this, probabilities can be determined, within which limits the target value will actually occur.

The risk analysis is integrated into the methodology described so far using a Monte Carlo simulation.[85] Therefore, deterministic calculation models can be used – without further adaptation. The deterministic input quantities are replaced by probabilistic calculation quantities (Figure 27).

The determination of the probabilistic input quantities is the essential step to considering uncertainties in the lifecycle cost calculation. First the uncertain input quantities must be described using discrete or continuous distribution functions. In order to limit the amount of work here, only quantities with an effect on the result, according to the result of a sensitivity analysis or an ABC categorisation (Sections 6.1 and 6.3), are used.

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[84] Exemplary extract from the calculation of a road tunnel

[85] The term "Monte Carlo simulation" covers various simulation procedures, in which random numbers are used to determine target figures. Detailed explanations of Monte Carlo simulation can be found for example in BOUSSABAINE, KIRKHAM (2006); COTTIN, DÖHLER (2013), FISHMAN (1996) or ENGELHARDT (2015).

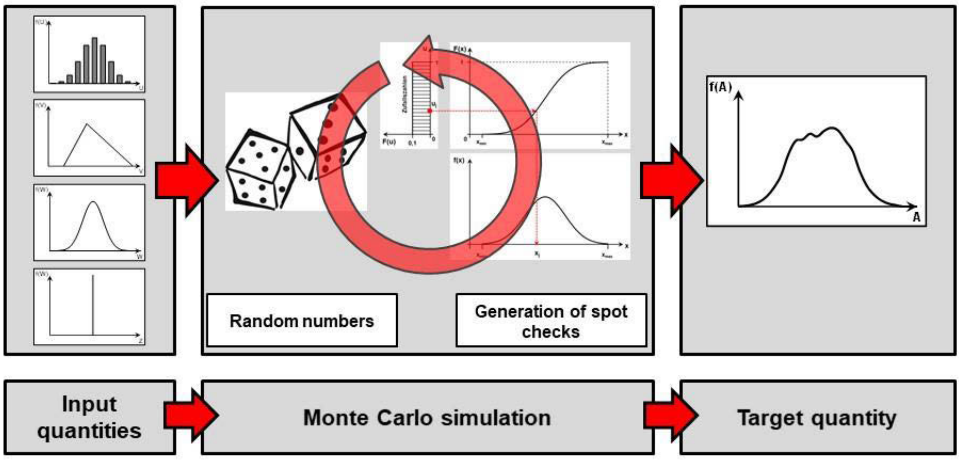

Figure 27: Integration of a Monte Carlo simulation for lifecycle cost calculation[86]

The result of the Monte Carlo simulation comprises a range of possible result occurrences according to the number of simulation runs. From this, conclusions can be drawn about the actual probability distribution of the lifecycle costs and the resulting risk magnitude can be derived. In contrast to deterministic determination, the unclear, probability-based result of the overall costs requires its own analysis and evaluation. In order to obtain the most advantageous situation from the economic point of view, the risk readiness attitude (negative, neutral, positive) of the decision maker must be included. A corresponding approach for the consideration of cost uncertainties by means of the Monte Carlo simulation was explicitly chosen in a project for the determination of the manufacturing costs of tunnel structures[87] and conceptually also transferred to life cycle cost forecasts[88].

6.5 Benchmarking

The procedure until now to optimise the costs of tunnels essentially concentrated on the design phase for new construction or thorough refurbishment of existing tunnels. Instead of this singularity, it is more effective to implement this option for cost reduction permanently in all phases in the form of a continuous optimisation process. The concept of benchmarking, which is already widely established in other fields, permits such a continuous generation of optimisation and improvement potentials.

The advantage of benchmarking is, in addition to the gaining of operating figures, the consideration of the services and processes responsible for the operating figures. This raises awareness of the internal structure and the real working processes. With this continuous recording of data, the tunnel operator gains an overview of the running costs and the overall condition of the tunnel. From these, the relevance of the individual cost quantities can be derived, and the presence of gaps or deviations is made clear. This simplifies the strategic planning of maintenance (e.g. structural management) and supports the decision-making process for future investments.

86 Cf. ENGELHARDT (2015)
87 Cf THEWES (2019) und THEWES (2020)
88 Cf. RUB (2018)

Benchmarking is not only aimed at the lifecycle costs but also enables, through the identification of the relevant individual parameters or processes, a comparison of the existing figures with those to be generated.

7 Application example for sample Road Tunnel

7.1 Introduction and project description of the sample tunnel

The procedure explained in the recommendation for the determination of the lifecycle costs of road tunnels is presented below through the example of a sample tunnel.

It should be noted that the data used is not based on a real tunnel structure and can only be transferred to other tunnels after modification. Extensive simplifications and estimations have been undertaken, based on actual costs, references and empirical values. The sample tunnel under consideration is an inner-city road tunnel with the data shown in Table 4.

Table 4: Features of sample tunnel road

Parameter	Sample tunnel
Tunnel length	550 m
Completion	2007
Number of tunnel tubes	1 tunnel tube
Number of lanes	1 lane in each direction
Operating type	Two-way traffic
Construction type	150 + 100 m cut-and-cover 300 m mined tunnel
Standard cross-section	RQ 11 t
Equipment	including 2 emergency exits, jet fans, fire alarm system, video surveillance system

7.2 Procedure

The procedure for the determination of the lifecycle costs of a tunnel is presented as a structured sequence (Figure 11) and is implemented as follows for the processing of this example:

1. Initial situation: determination of the data of the investigation period
   (Consideration period, relevant structural data, focus of consideration etc.)
2. Structuring: production of the basic framework of the modules
3. Module formation
4. Cost determination
   - 4.1 Checking, what data is at hand or will have to be queried or determined
   - 4.2 Derivation of regularities (costs and time intervals)
   - 4.3 Filling out the module forms
5. Transfer into a cost matrix
6. LCC calculation
7. Interpretation

7.3 Step I: Initial situation

For the analysis of the lifecycle costs, the main phases design, construction and use until the end of serviceability are considered. This is a new tunnel, for which the investigation period is assumed to be 100 years, based on the average total service life in accordance with the ABBV[89]

The following description covers the determination of the lifecycle costs for the described tunnel. In order to explain the methodology, the entire tunnel is considered, which limits the number of modules examined in more detail.

In the present example, the procedure is shown as an example for one equipment variant; comparisons with other variants are omitted. The determination of the net present value for each comparison variant would be carried out accordingly and can also be carried out specifically for individual modules.

7.4 Step II: Structuring and Step III: Module formation

The modules are formed in accordance with the desired level of detail or existing data structure. In the present case, seven independent modules are chosen for each of the systems tunnel construction and tunnel equipment and these are the focus of further consideration. A rest item is also created, in which costs that are not considered in detail are collected.

Tunnel construction

- Vault of mined tunnel
- Invert of mined tunnel
- Invert of cut-and-cover
- Walls of cut-and-cover
- Slab of cut-and-cover
- Drainage (structure)
- Carriageway
- "Residual" tunnel structure

Tunnel equipment

- Tunnel automation
- Video surveillance
- Ventilation system
- Lighting
- Fire alarm system
- Tunnel closure system
- Drainage (equipment)
- "Residual" tunnel equipment

7.5 Step IV: Cost determination

7.5.1 Initial costs

The construction costs are, as in the present case, understandably documented or can be well estimated empirically. The usual division into items of a bill of quantities makes it possible to assign the costs to the corresponding modules.

Construction costs, which cannot be unambiguously assigned to one of the stated modules, were either distributed into several modules with related objects or assigned to the general modules "Residual tunnel structure" or "Residual tunnel equipment".

[89] Cf. ABBV (2010)

Design costs, on the other hand, are not normally at hand related to modules. A division in proportion to the construction costs would be based on the principles of the HOAI[90] (German regulations for the payment of architects and engineers); it can however also be sensible to undertake a content-based percentage distribution.

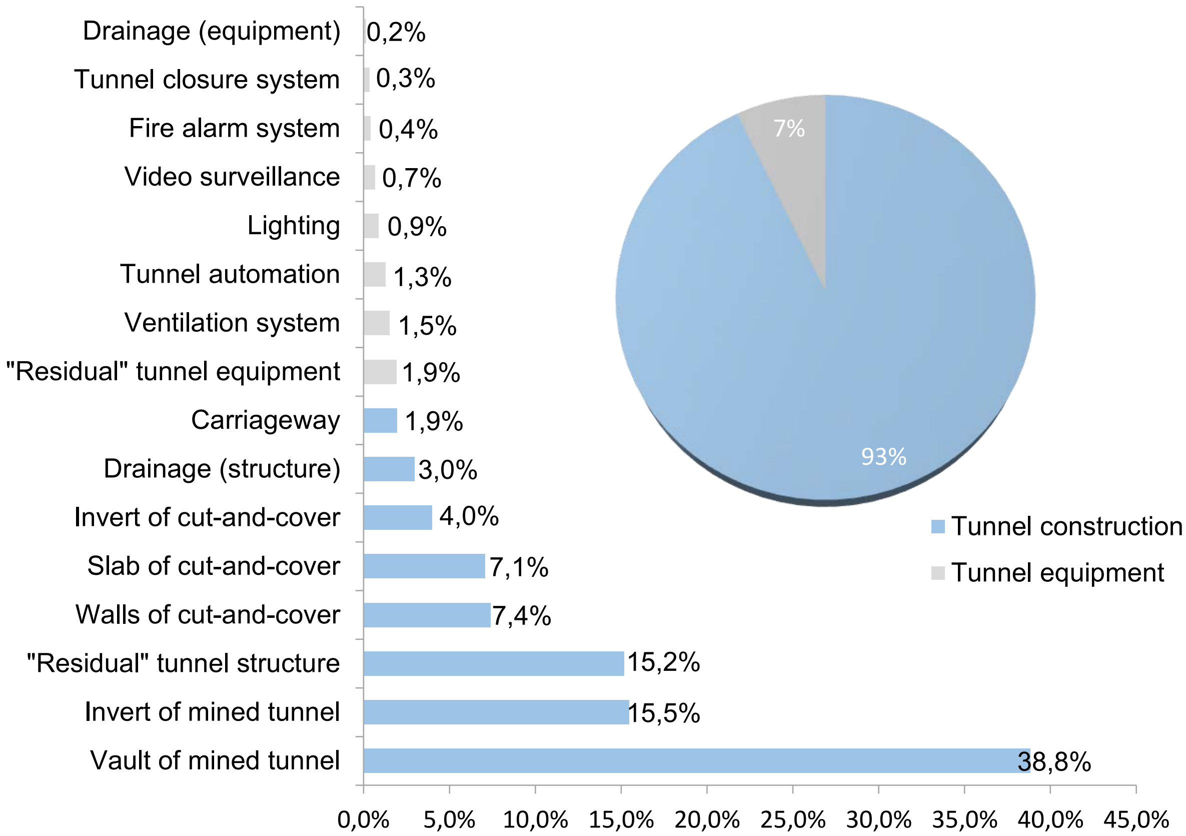

Figure 28: Distribution of initial costs (design + construction/equipment)

7.5.2 Follow-up costs

The determination of the follow-up costs represents the greatest challenge. Definite empirical values for the required data like service lives and maintenance cycles with the associated costs are only available to a limited extent or vary widely. It is recommended here to make use of service lives from experience; maintenance contracts can provide the basis for maintenance for maintenance costs.

The forecast costs and their future dates of occurrence, which mostly lie far in the future, can only be predicted with uncertainty (see Chap. 6.4).

If, as in this example, existing data from tunnel operators are used, these are mostly documented according to cost types, but not always related to individual structural elements and equipment components. So, electricity costs can be recorded as a sum for the entire tunnel, but not be available broken down to the individual consumers. Therefore, assumptions will

[90] Cf. HOAI (2021)

have to be made about the percentage distribution to the individual modules. In the present case, this division is made using the relative power of the electricity consumers in the tunnel.

The costs for renewal include demolition, new design and the installation of new construction elements and equipment elements. Since future price changes, considering also technical progress, can only be predicted with uncertainty, the costs have been estimated based on the initial costs.

7.5.3 Module forms

For the clear collection of the determined data sets, module forms have been created, which record all the initial and follow-up costs of a module.

Range	**Equipment**		
Module	**Ventilation plant**	**Code: LUF**	
Process	Services	Costs [€]	Time factor [in years]
Initial costs			
	Design	45.000,00 €	-
	Equipment (construction)	450.000,00 €	-
Follow-up costs			
Electricity and water supply/ monitoring/ exercises/other	Electricity, rest	30.000,00 €	1
	Insurances	115,00 €	1
	…		…
Maintenance/ inspection/ repair	Construction - external contracts	4.500,00 €	3
	Maintenance	10.000,00 €	1
	Maintenance, additional	7.000,00 €	2
	Maintenance, internal	500,00 €	1
	…	…	…
Improvement/renewal	Complete replacement	500.000,00 €	15
	Partial replacement (sensors)	35.000,00 €	8
	...		…

Table 5: Excerpt from a module form for tunnel equipment

7.6 Step V: Transfer into a cost matrix

The filled-in module forms are then transferred into a cost matrix. The cost figures for each module are assigned to a time point and collected for each year over the investigation period. According to the objective of the evaluation, all services in a module could also have been considered together.

Code	Module j	Time point t [years]						
		Sum	0	1	2	3	4	5
	…	…		…	…	…	…	…
LUF	Design	45.000,00 €	45.000,00 €					
LUF	Equipment - (construction)	450.000,00 €	450.000,00 €					
LUF	Electricity	300.000,00 €		30.000,00 €	30.000,00 €	30.000,00 €	30.000,00 €	…
LUF	Insurances	1.150,00 €		115,00 €	115,00 €	115,00 €	115,00 €	…
LUF	Construction - outside contracts	148.500,00 €		0,00 €	0,00 €	4.500,00 €	0,00 €	…
	…	…		…	…	…	…	…

Table 6: Excerpt from an example time/cost matrix for a module (here LUF)

7.7 Step VI: LCC calculation with application of the net present value method

The net present value serves in the design phase as a method of assessing the cost-effectiveness of an investment or comparing various construction and equipment variants.

There are no receipts for the example under consideration. Degrees of uncertainty of payments and price increases are also not taken into account for the sake of simplicity.

The time of putting into operation is set as the start of the lifecycle cost calculation and simultaneously reference time point t=0. Initial costs until time point=0 (design, construction and equipment costs) are therefore to discount all follow-up costs.

The calculation interest rate was assumed in line with the nominal interest rate of 1.75% specified in the 2030 Federal Transport Infrastructure Plan.

The curve of the lifecycle costs can be given as a summary of the annual discounted costs.

7.8 Step VII: Interpretation

The initial costs of the tunnel and the follow-up costs of the tunnel equipment determine the lifecycle costs. In the following figures it becomes clear that the selected calculation interest rate has a large effect on the ratio of the follow-up costs to the initial costs. In order to be able to estimate the significance of the follow-up costs, a comparative evaluation was thus carried out with a calculation interest rate of 0%.

If correspondingly differentiated costs are available, the proportions of each module can be investigated more decidedly, and strategies and optimisations can be derived (e.g. conversion to LED).

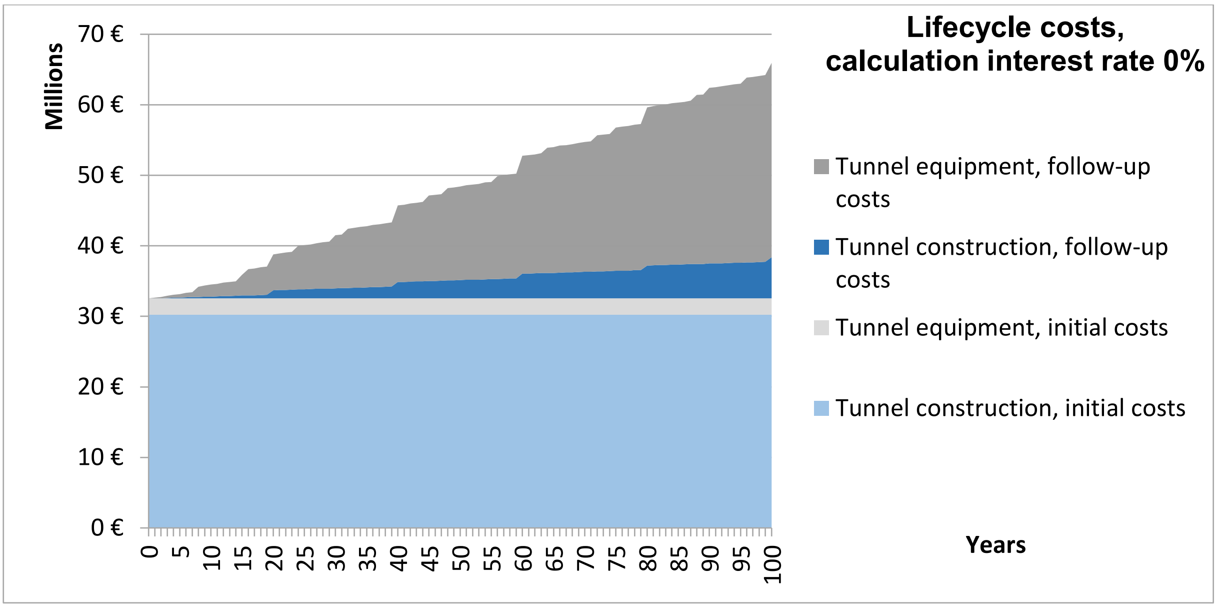

Figure 29: Curve of lifecycle costs (calculation interest rate 0%)

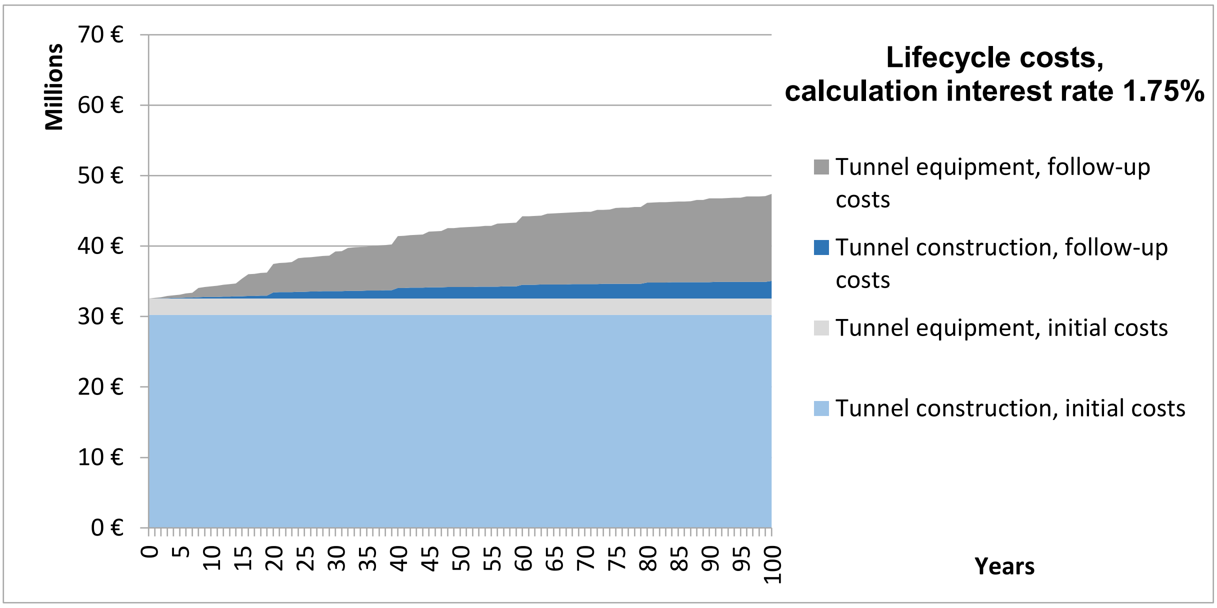

Figure 30: Curve of lifecycle costs (calculation interest rate 1.75%)

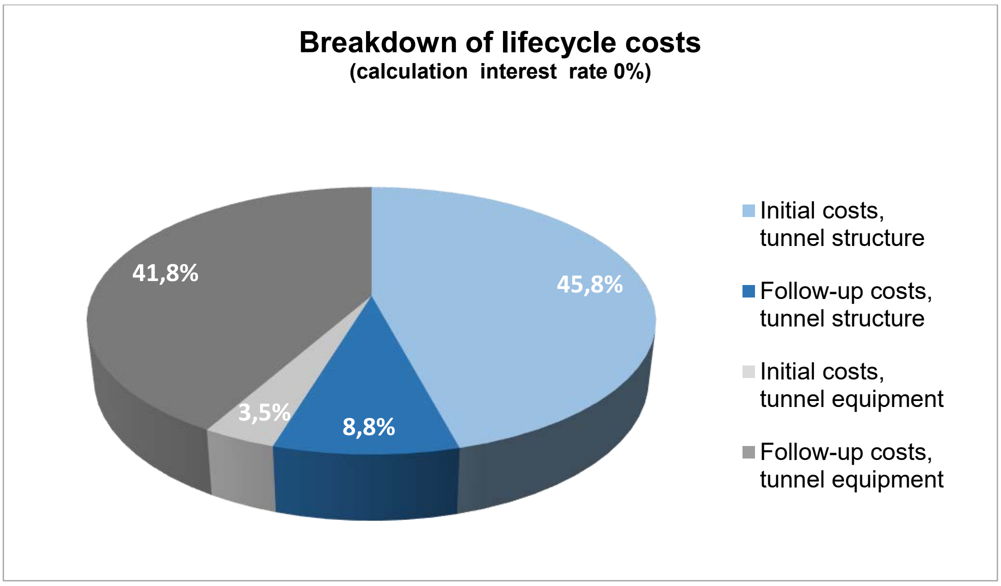

Figure 31: Breakdown of lifecycle costs (calculation interest rate 0%)

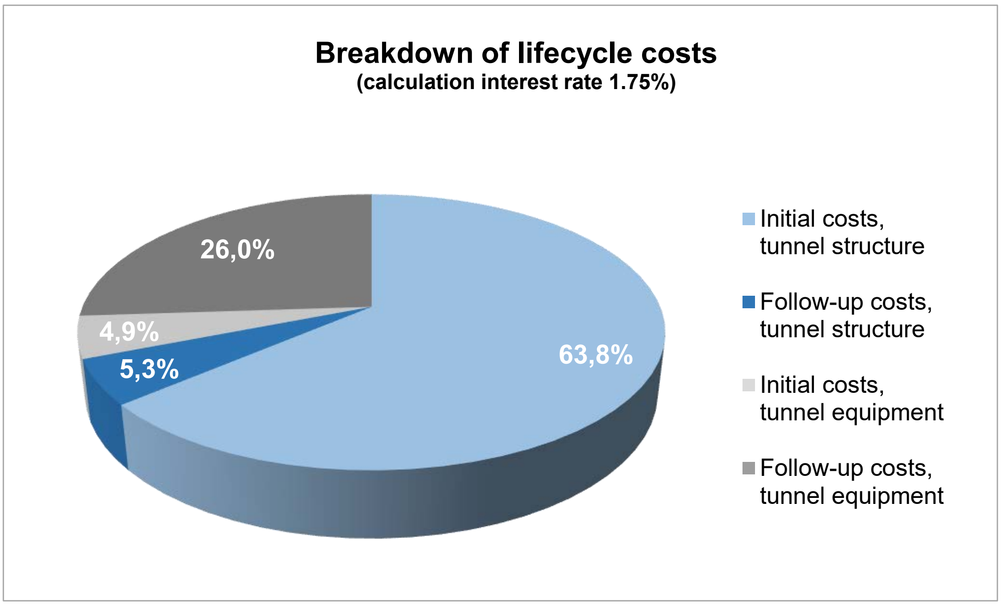

Figure 32: Breakdown of lifecycle costs (calculation interest rate 1,75%)

8 Application example for a sample tunnel of the local public transport

8.1 Step I: Initial situation and project description of the sample tunnel

In order to validate the theoretical principles described in the preceding sections and the application example of the sample road tunnel, it will be shown how the procedure for determining life cycle costs for road tunnels can also be applied to underground light rail systems. [91] Similar to Chapter 7, the procedure shown in Figure 33 was selected.

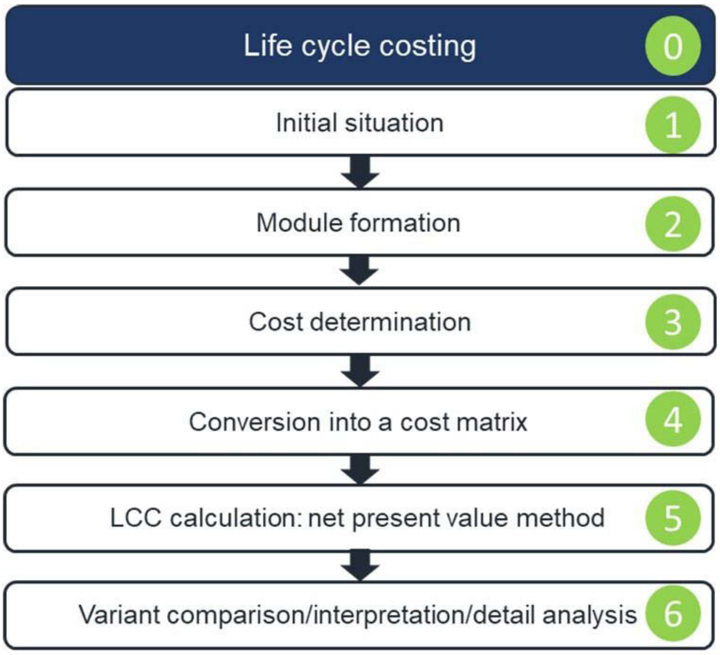

Figure 33: Procedure for the determination of the LCC for light rail systems

The data used are based on an existing underground section of a light rail line and can be transferred in modified form to other comparable structures. The quality of the calculation results in the respective specific application depends on the extent to which modifications of the presented standard model lead to a realistic representation of the specific conditions of the light rail system under investigation. As in the case of the example for a road tunnel, the calculations had to be simplified on the basis of actual costs, literature or experience values due to the partially incomplete data situation.

The evaluation of the underground light rail system is limited to the determination of economic efficiency based on the target value "net present value maximization". Technological, organizational and legal as well as external effects (air pollution, noise pollution) and the consideration of revenues can be taken into account in the future through appropriate monetization in the ongoing cash inflows and outflow.

[91] Cf. FREIMANN (2020) and DAHOUD (2023)

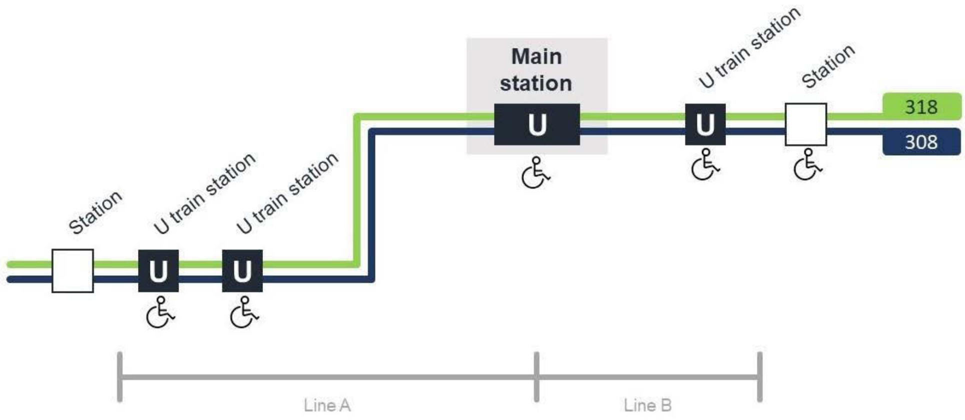

Figure 34: Underground sections of the light rail systems

Life cycle cost calculations are based on an existing urban subway tunnel with the following characteristics and data according to Figure 34 and Table 7.

Table 7: Features of the underground pattern light rail system

Parameter	Sample light rail system
Start of con-struction	1971
Commissioning of line	Line A: 1979 Line B: 1981
Length of line	3.300 m
Construction method	New Austrian tunnel construction Method (NATM), cut and cover
Tubes	One tube, only one section 2-tubed
Equipment	4 stations, 9 elevators, 40 escalators with 2 emergency exits, ventilators, fire alarm system, video surveillance system

8.2 Steps II, III and IV: structuring, module formation and basic cost information

The starting point and core of the subsequent cost determination is the structuring of the overall structure into independent modules and the subdivision of the life cycle into the processes involved. The individual cost parameters are determined on the basis of different process approaches, depending on the objective and the available state of knowledge.

The modularization of the structure was carried out on the basis of the structuring carried out by the responsible municipal civil engineering department. The structure was divided into the systems "structural plants", "technical plants" and "operational plants".

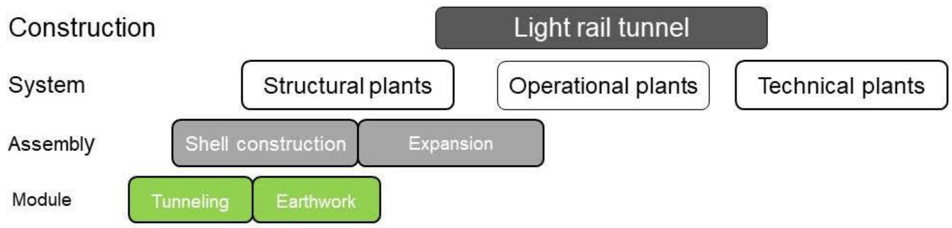

Figure35 Exemplary trade division of a municipal operator

Based on the breakdown of different lots, a total of 81 modules resulted for the project under review, for which cost information is available in varying degrees of detail.

Building	81 Modules
Structural plants	39
Technical plants	16
Operational plants	26

Basis of the cost calculation of the initial and follow-up costs:
- For the Modules
- Lines A +B

with different respective cost information:	
▪ Cost data	None, stable, fluctuating
▪ None	---
▪ stable	Cleaning, insurance
▪ fluctuating	Vandalism, graffiti removal
▪ Special modules	
▪ Initial costs, no follow-up costs	Site equipment
▪ follow-up costs, no initial costs	Cleaning, security, insurance

Figure 36: Modularization of the structure and cost information

The structural facilities were divided in 39 modules (Figure 17 in Section 5.3.3) and were again differentiated into the systems of "lining" and "equipment" for both, the line and the stations, respectively. The modules in this system are mostly modules with high acquisition costs, longer service lives and lower follow-up costs than technical or operational facilities.

The "Technical installations" system is made up of 16 modules (Figure 18 in Section 5.3.3). These are generally characterized by high renewal costs due to high replacement costs and a short service life.

The operational equipment is divided into a total of 26 modules (Figure 19 in Section 5.3.3). As with the modules of the "technical equipment" system, high follow-up costs are incurred by operation and maintenance or replacement due to the short service life and high replacement costs.

The data bases shown in Figure 37 and Table 7 were used to determine the initial and follow-up costs:

Table 8: Cost data/basis of sample tunnel of the local public transport

System	Initial costs	Follow-up costs
Structural plants (incl. special modules)	Actual costs, otherwise - Critical Allocation[92] - Estimate based on construction lot of a comparable light rail system - Expert estimate	Excluding energy costs 2015-2018, partly 1997-2018
Technical plants	Actual costs, otherwise - Critical allocation	Excluding energy costs 2015-2018, partly 1997-2018
Operational plants	Estimated costs from the last years (consider technical progress)	Average values 2017-2018

While the initial costs for the structural and technical facilities were available on the basis of a final invoice, empirical values from expert surveys had to be used in part for the initial costs of the operational facilities.

The planning costs are not available by module. However, a percentage distribution can be made here based on the initial costs.

The follow-up costs are of great importance for life cycle costing. They can exceed the manufacturing costs after only a few years[93]. Specific empirical values for the required data such as service lives and maintenance cycles with the associated costs were available only to a limited extent, but varied greatly. Here, empirical values for service lives were used. Maintenance contracts were used as the cost approach for maintenance.

It proved difficult to determine the energy costs, which were only available as a total value for the building, but not broken down by module. Here, the power balance of the electricity consumers was used or a percentage breakdown was made.

8.3 Step V: Conversion into a cost matrix

The transfer of the data into a cost matrix was carried out according to the methodology described in chapter 5.5.

8.4 Step VI: LCC calculation with application of the net present value method

The net present value method is used to determine the economic efficiency of the entire light rail system, as well as to compare the economic efficiency of different design and equipment variants.

Degrees of uncertainty in the payments are not taken into account in the actual application, but relative price increases are included in the calculations. Different values are assumed for the calculation interest rate.

[92] Cost allocation in case of missing information by experts.
[93] With a capital interest rate of 0%.

The time of commissioning is taken for the start of the life cycle calculation and also for the reference time t=0. Apart from the initial costs at time t=0 (planning, construction and equipment costs), all follow-up costs must be discounted.

8.5 Step VII: Comparison of variants, interpretation, detailed analysis

The initial and the follow-up costs determine the life cycle costs. Based on the module-oriented initial cost distribution of the entire infrastructure structure, it is clear from the following figures that the calculation interest rate selected in each case and assumed to be constant for the entire service life, as well as the service lives applied to the individual component groups, have a major impact on the development of the ratio of follow-up costs to initial costs.

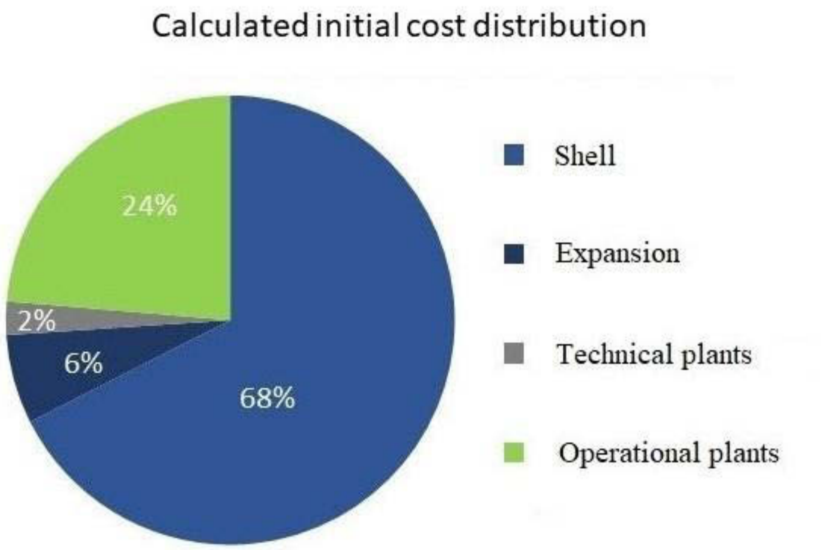

Figure 37: Calculated initial cost distribution

The significance of the interest rate for the development of follow-up costs over the service life is particularly evident when a comparative analysis is based on the reference calculation interest rate of 0% (Figure 39 to Figure 42).

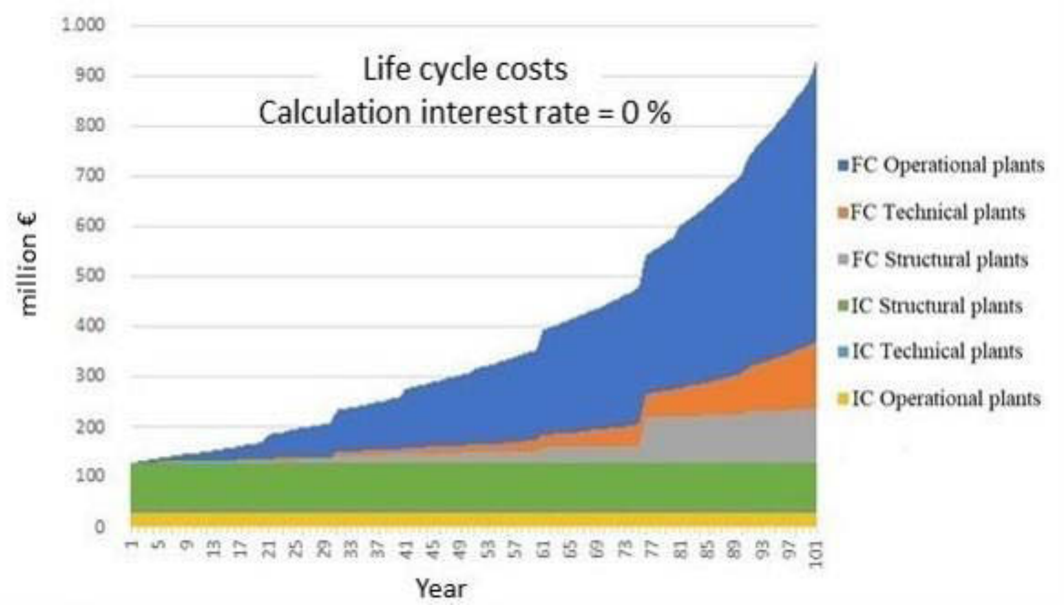

Figure 38: Development of life cycle costs as a function of the discount rate (discount rate 0%)

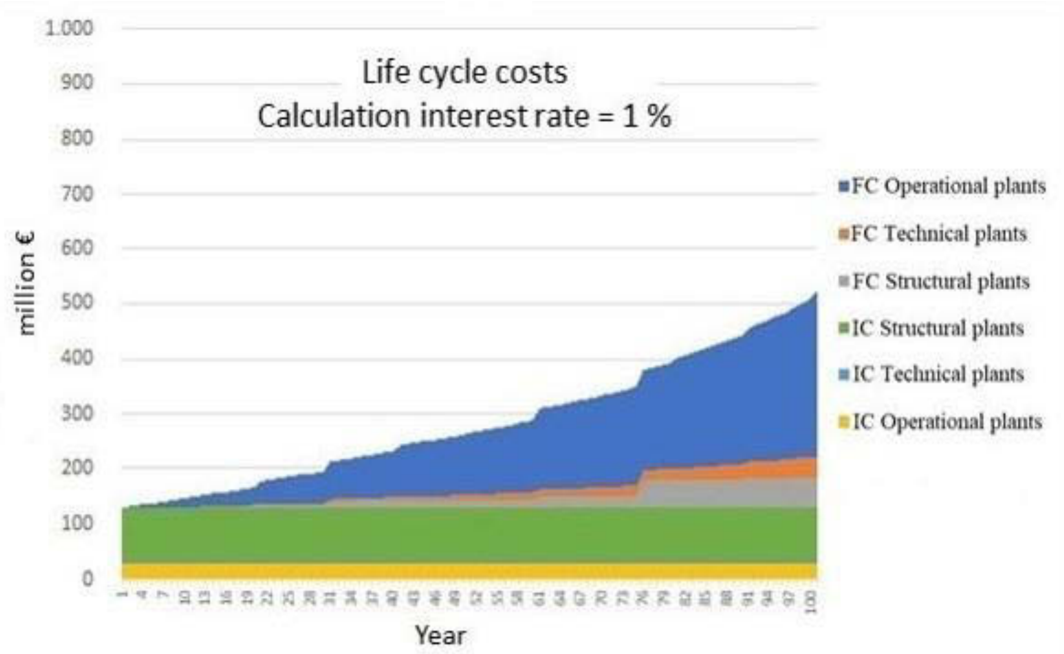

Figure 39: Development of life cycle costs as a function of the discount rate (discount rate 1%)

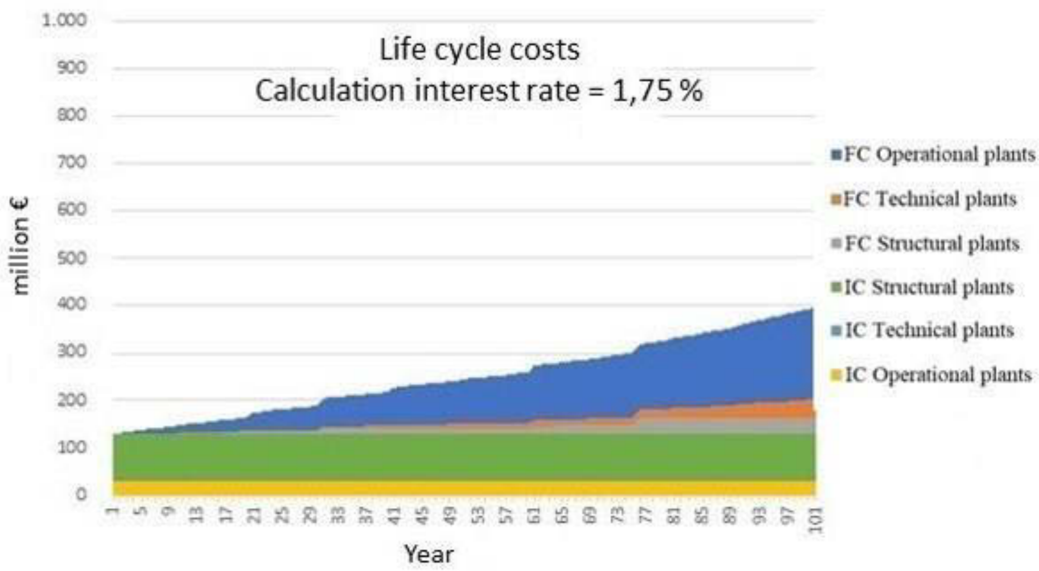

Figure 40: Development of life cycle costs as a function of the discount rate (discount rate 1,75%)

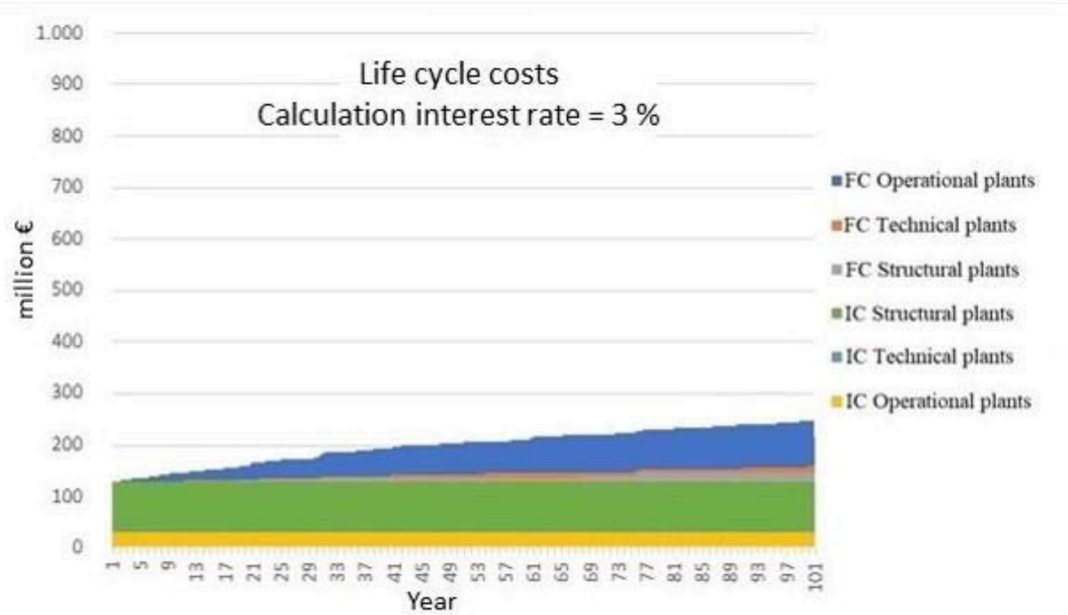

Figure 41: Development of life cycle costs as a function of the discount rate (discount rate 3%)

The extensive evaluation options of the once collected and standardized data documents offer the possibility to perform further extensive detailed analyses and to derive (module-related) strategies and optimizations from them.

This can be exemplified by the following figures.

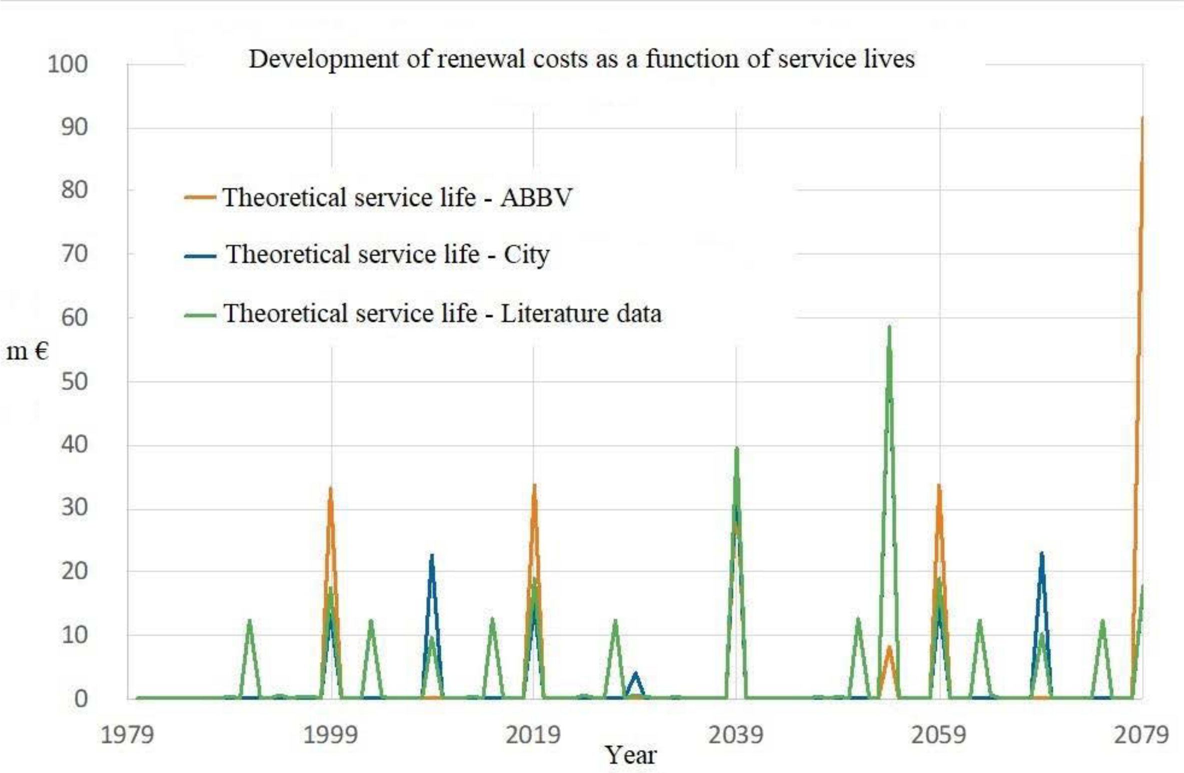

Figure 42: Development of renewal costs depending on different service life approaches

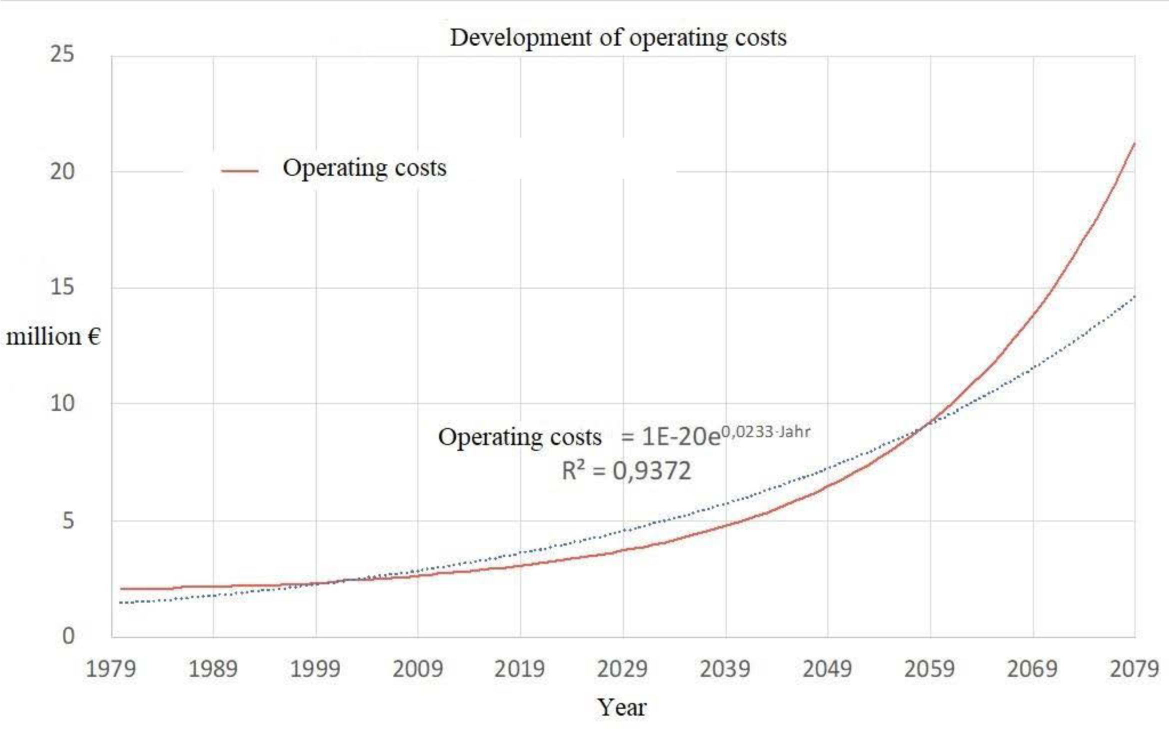

Figure 43: Development of operating costs

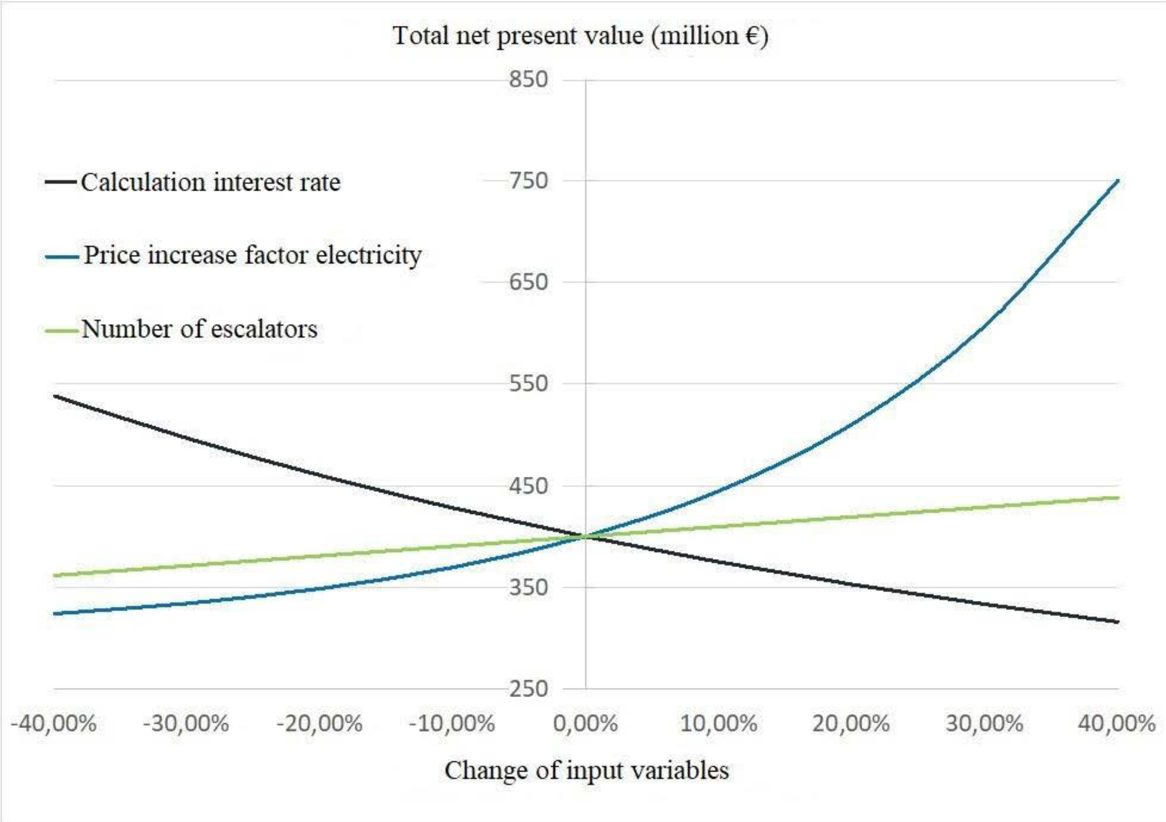

Figure 44: Sensitivity analysis

8.6 Conclusion

The procedure for determining life cycle costs for road tunnels can be conceptually transferred to corresponding calculations and comparative analyses for underground light rail systems. Necessary prerequisites are deeply subdivided modules for components and equipment elements and comprehensive data approaches for costs and utilization periods. More extensive as well as comparative analyses require standardized subdivisions of the structures on the basis of corresponding bills of quantities with assigned costs and service lives.

Due to the flexibility and expandability of the net present value method, there are extensive possibilities to approximate the practical conditions on site. Technical progress, especially in technical and operational equipment, can be taken into account in the lifecycle cost model by appropriate modernization factors. In particular, module dependencies would have to be modeled; the failure or maintenance of a module can inevitably lead to the functional failure of a technically connected module.

For the operator of light rail systems, there are usually not only outgoing payments but also incoming payments in the form of fare revenues. Since the net present value method allows for the consideration of payments (cf. chapter 4), this can be integrated into the life cycle cost models.

9 Summary and conclusion

This recommendation presents a procedure for evaluating and comparing the economic efficiency of future investments in tunnelling projects with regard to the entire lifecycle. The basis for this is knowledge of the construction elements and equipment in the tunnel and comprehensive data sets for costs and service lives.

If the construction costs are already known in the early design phase, the determination of follow-up costs is associated with a cost estimate or with research into available empirical data. These are not yet extensively available in the early design phase and need to be at the focus further development. Future data recording should therefore aim to facilitate the idea of lifecycle costs and to build up a data pool with the corresponding costs and service life durations.

Here, road tunnels and public transport tunnels are considered in detail, which are presented with calculation approaches, data and with the calculation of sample tunnel structures. This provides building owners and operators with a tool for comprehensive life cycle cost calculation.

The methodology is also directly applicable to railway tunnels. The most important regulations are summarised and specific features are also addressed. On the part of DB Netz AG as the owner and operator responsible for Germany, the detailing and the necessary data background can be worked out internally.

Application to other tunnelling structures and to infrastructure structures in general is recommended. For all applications, future data collection should be specifically oriented towards the idea of life cycle costs, and a data pool with the corresponding costs and service lives should be built up as a basis.

The recommendation provides the basis for determining life cycle costs as an essential pillar of sustainability, namely its economic side. Sustainable buildings are also beneficial in terms of ecology and in their social function. For the evaluation of sustainability, ecological and social impacts must be determined for all components, just as the monetary values are determined for the life cycle costs. This can be done for economy and social impact after modularization of the building. The particular target values are to be determined and evaluated. As an example, the CO_2 footprint can be mentioned: After the definition of the evaluation framework and the modularization of the building, the CO_2 equivalents are determined and summed up for all defined processes, just like the monetary outgoing and incoming payments in the life cycle cost calculation.

The overall sustainability can be assessed using certification systems, in which the object to be evaluated is compared with reference values with regard to various criteria. There is a need for research in this area, as there are currently no reference values for infrastructure buildings available. A direct evaluation, including a comparison of variants, would be possible if all influences were monetarized and then summed up.[94]

[94] Procedures for monetization can be found, for example, in the work of LISSON (2014)

Modularization is ideal for linking to a BIM model. The modules are defined as objects of the model, to which the processes and their effects are assigned as attributes. Ultimately, this would simplify and automate the calculation of life cycle costs, using the same methodology described here.

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