THE LIFE-CYCLE COST ANALYSIS FOR ROAD TUNNELS TAKING UNCERTAINTIES INTO ACCOUNT

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1 INTRODUCTION

For almost half a century, the integration of road tunnels has helped to make European road networks considerably more efficient. Beside the design and construction of new tunnels, especially the refurbishment of existing tunnels is gaining importance. Also, private capital participation in infrastructure projects is increasingly being accepted. The previously described influences require the necessity to develop a new perspective on economical aspects of road tunnel design and operation. The life-cycle cost analysis is an appropriate method to illustrate all mandatory expenditures and, if applicable, revenues over the proposed service life of a tunnel. Since costs for planning and construction are referred to as initial investment costs, follow-up costs comprise expenses for operation, maintenance and repair. In order to merge all shares of expenses, investment appraisal methods are applied for the calculation of the life-cycle costs. In conjunction with the number of variables, the net present value method is considered to be most suitable for a life-cycle cost analysis. The methodology for assessing the life-cycle costs of tunnels is mainly dependent on the project phase, i.e. the tunnel is either in planning, under construction or in operation. For the preliminary design stage it is characteristic that alternative project variants exist, but at the same time the level of detail for the planning of each alternative is somewhat low. Consequently, uncertainties arising from theoretical life-cycle times of construction materials and technical components as well as uncertainties associated with cost variables have to be dealt with. It is obvious that the earlier the cost analysis, for example, during the planning phase of a tunnel is being done, the more the input data are subject to uncertainties. Uncertainty concerns both, technical as well as economical input data. This requires that theoretical useful life-times for all relevant materials and components have to be defined. The life-cycle cost model proposed in this paper supports the user by either statistically processing recorded historical data or by implemented average theoretical life-time values. Additionally, appropriate ranges for all different kinds of costs have to be assigned and implemented into the cost model. Finally, the development of the tunnel life-cycle cost model under the influence of technical and financial uncertainties will be presented and explained.

2 STATUS QUO AND FUTURE CHALLENGES WITH RESPECT TO TUNNEL OPERATION

2.1 Age structure and previous amount of investment

In figure 1, the increase in the number of road tunnels in Germany is shown. It is apparent that the portfolio has developed rapidly, particularly during the past 20 years. By the end of December 2010

about one-third of the total of 244 tunnels on federal roads have an age of more than 20 years, whereas about two-third of the tunnels are 20 years or less in operation.
As shown in figure 2, the percentage of expenditures for newly constructed road tunnels in Germany relative to the capital investment in federal roads has steadily increased since the mid 1970s. The data have been derived from several publications, issued by the German Ministry for Transportation.

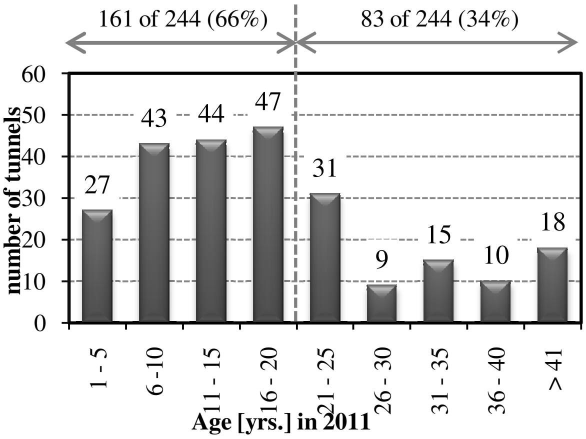

Figure 1. Number and age of tunnels on federal roads in Germany, accord. to Knoll (2011).

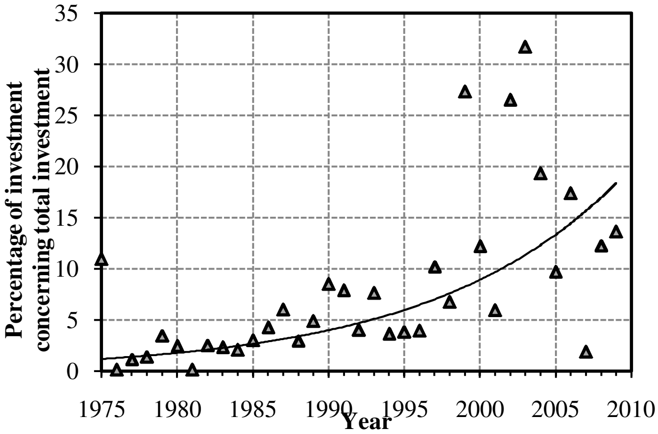

Figure 2. Percentage of construction investment in tunnels in relation to total investment in federal roads on yearly basis.

In figure 2, the fluctuation of percentage rates mirrors the fact that the construction phase of a tunnel usually expands over several years: the total investment for a tunnel project includes operational equipment and is being integrated in figure 2 as soon as the tunnel is complete for operation (i.e. year of invoicing).

2.2 Financial resources for new tunnels vs. tunnel refurbishment

Peil & Hosser (2007) predict that the whole construction industry will be faced with a sustainable change. The reason for this development will firstly be the replacement or reconstruction of aged existing structures, and secondly the advancement of technical standards. Over a period of several decades, the authors expect an explicit shift from an investment in new structures in favor of renovation and maintenance measures. Transferred to the financing of roads, the described trend will also intensify noticeably over the next years. Peil & Hosser (2007) describe the necessary renewal effort as "a serious mortgage of the future". In particular, an improved structural monitoring can help to predict and plan the necessity for follow-up investments more accurately.
As Staudt et al. (1999) and Braschel & Hetzer (1995) have found for the real estate sector, the expenditures spent for operating a building exceed the sum of construction costs after a few decades. If the design engineer is aware of the fact that all major decisions concerning the operation of buildings are being made in the planning phase, the potential for future savings becomes visible. The conclusion drawn by the authors, can qualitatively also be adopted for the operation of tunnels. Taking into account that technical equipment in a road tunnel according to ABBV (2010) has to be replaced on average every 20 years, a high amount of investment into refurbishment measures is apparent. The increase in numbers of tunnels on one hand as well as the need for re-investment in existing tunnels justifies a philosophy change towards the life-cycle concept for road tunnels.

3 THE LIFE-CYCLE COST CONCEPT AND ITS ADAPTION FOR ROAD TUNNELS

3.1 Distinction between initial and follow-up costs

Buildings are no serial products, but rather individually manufactured structures. Except for prefabricated houses, the production of a prototype is unusual and also economically inefficient. Moreover, the configuration of a building has to be adjusted to the client´s specifications and fitted to local environmental conditions, for example in terms of geological or infrastructural circumstances. Under ideal conditions, significant parameters are being made available by the client, such as the investigation of the subsoil or the recording of groundwater levels. Subsequently, it is the task of the design engineer to describe the building and its requirements thoroughly by specifications and drawings. Taking economical aspects into consideration, the best possible implementation strategy is gradually being identified and finally incorporated into a detailed design. Since planning, construction and operation of a facility are based on numerous dependencies, it is necessary to point out the characteristics of the life-cycle theory for buildings. The general definition of the life-cycle concept, which is used in this publication, has been derived from ISO/FDIS 15686-5 (2008) and covers all stages from early planning up to the end of the service-life. Referring to figure 3, the entire life-cycle of a project can be subdivided into four main stages: Development (stage A), construction (stage B), operation (stage C), and disposal (stage D).
More information concerning the characteristics of each stage is included in figure 3. Since the total costs of stages A and B are referred to as the initial costs, expenditures that arise during stage C are defined as the follow-up costs. For the life-cycle of an arbitrary project, the upper chart in figure 3 shows costs and revenues per accounting period – each bar stands for example for one quarter of a year or for the period of an entire year. The summation of all single values yields two cumulative curves, which are plotted in the lower chart. In order to finally evaluate the efficiency of the project, the mathematical difference between both curves – revenues minus costs – reflects the development of the overall profit.

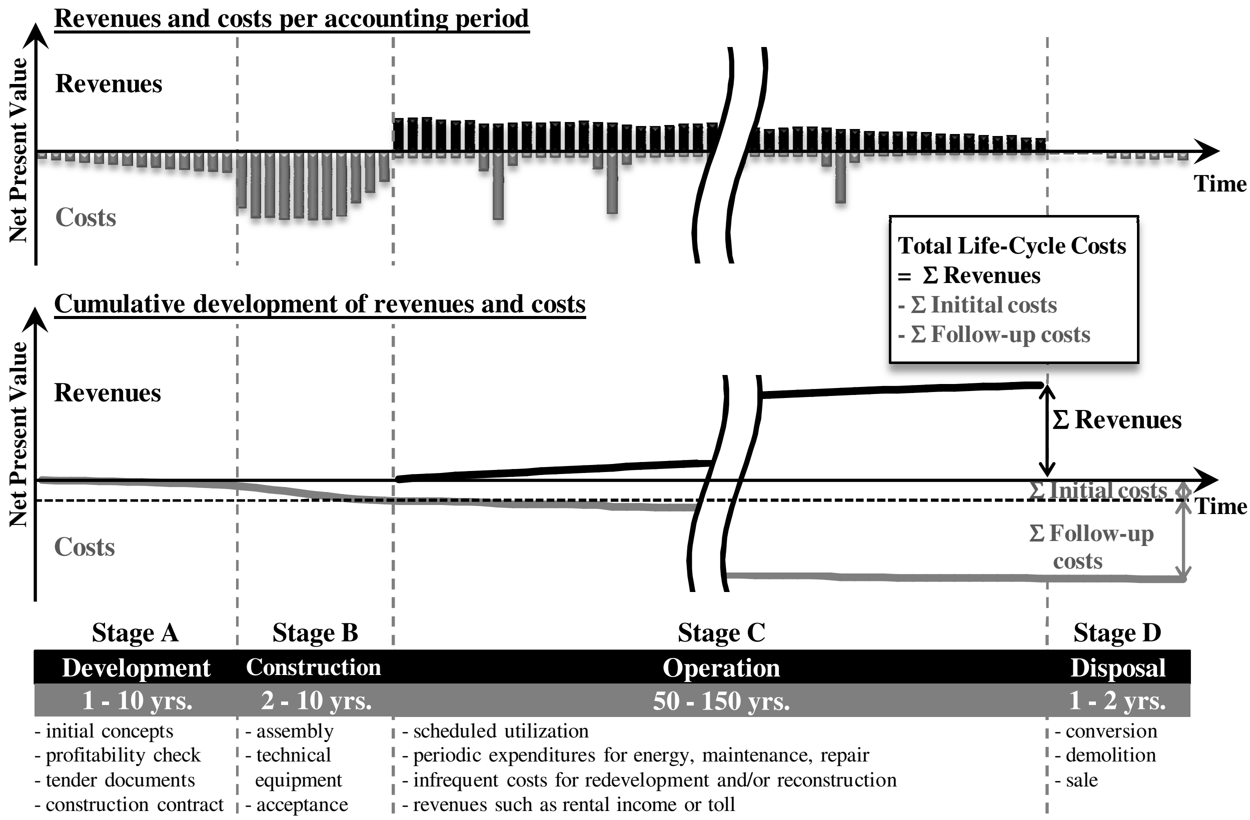

Figure 3. The life-cycle of constructed assets expressed by costs and revenues.

3.2 *Cost influences on tunnel projects*

In public perception, the costs for prestigious, publicly-funded infrastructure projects are usually only associated with the initial costs for designing and construction efforts. However, for the owner or the operator, costs that arise from the long-term management of the facility play an important role.

Provided that the operation of a tunnel is based on the life-cycle concept, decisive key issues have to be stressed in early project stages. For a road tunnel project, the main key issues are shown in figure 4. While some factors either affect initial or follow-up costs, others influence both parts, initial as well as follow-up costs. If the planning of a project is at the very beginning, a substitution of initial by follow-up costs – and vice versa – implies cost savings on a long-term basis. In contrast, if a project is in an advanced stage, the set of mutual dependencies is usually limited to operation, repair and maintenance, whereas the remaining dependencies are to be regarded as fix. In figure 4, mutual dependencies between different factors have been illustrated with the help of arrow links. The shape of arrows indicates whether dependencies exist for projects under planning (straight arrow) or for tunnels in operation (curved arrow).

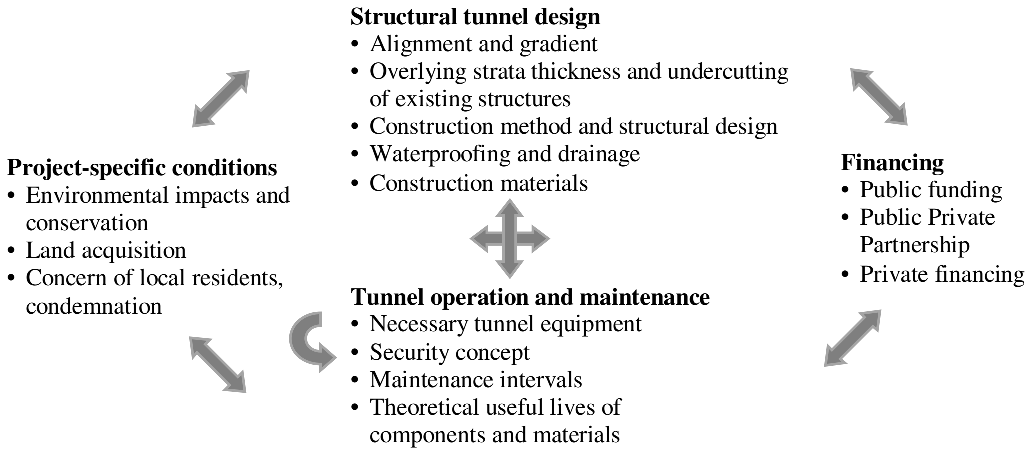

Figure 4. Mutual influences on costs for road tunnels as a function of the project stage.

In a broader sense, the total economic expenditures do not only cover a life-cycle cost analysis, but also a long-term cost and benefit analysis in order to evaluate the economic aspects which are directly related to the project. For a road tunnel project that is in the planning process, these additional costs can be assessed by evaluating travel time reductions or by analyzing the effects resulting from improved commodity flows. But also effects in the immediate environment of the tunnel, such as risks for residents or for tunnel users have to be taken into account. These costs, which are outside the definition of the life-cycle costs, are referred to as indirect costs. For completeness reasons, indirect costs are mentioned here, but they are beyond the scope of this paper.

A stepwise method to assess the boundary conditions of tunnel planning in accordance with the appropriate design stage is given by Thewes & Vogt (2011).

3.3 *Calculation of the life-cycle costs*

The most suitable parameter to describe the characteristics of the life-cycle of buildings is the monetary flow. According to ASTM E 917 (2009) the sum of all relevant costs associated with owning and operating a building system, are the life-cycle costs. Additionally, AS/NZS 4536 (1999) defines the process of life-cycle costing as the methodology to determine the sum of all expenses associated with a project; these expenses include costs for acquisition, installation, operation, maintenance, refurbishment and disposal.

With reference to the description of the life-cycle phases A to D in figure 3, equations (1) and (2) express the key indicators of the life-cycle cost approach; these are the total life-cycle costs (TLCC) and the profitability (P) of a specific project:

$$\mathrm{TLCC}_{\mathrm{A-D}} = \sum_{\mathrm{t=t_A}}^{\mathrm{t_D}} \mathrm{LCC(t)} = \sum_{\mathrm{t=t_A}}^{\mathrm{t_B}} \mathrm{IC(t)} + \sum_{\mathrm{t=t_C}}^{\mathrm{t_D}} \mathrm{FC(t)} \qquad (1)$$

$$\sum_{t=t_{\mathrm{A}}}^{t_{\mathrm{D}}} \mathrm{P}(t) = \sum_{t=t_{\mathrm{C}}}^{t_{\mathrm{D}}} \mathrm{RE}(t) - \sum_{t=t_{\mathrm{A}}}^{t_{\mathrm{D}}} \mathrm{LCC}(t) \qquad (2)$$

where $\mathrm{TLCC}_{\text{A-D}}$ = Total life-cycle costs covering stages A-D; t = time variable; t_{A}, t_{B}, t_{C}, t_{D} = Period length of each stage A-D; LCC (t) = Life-cycle costs as a function of time; IC (t) = Initial costs as a function of time; FC (t) = Follow-up costs as a function of time; P (t) = Profit as a function of time; RE (t) = Revenues as a function of time.

Due to the long-lasting durability of building structures and the unequal distribution of payments along the whole life-cycle, it is reasonable to introduce a factor which takes account of the point in time at which each single cost or revenue arises. Literally speaking, payments with the same nominal amount, which are due at different times – from today´s point of view – possess unequal cash values. For a dynamic life-cycle cost calculation, methods of investment analyses, such as the net present value method, are being applied. When this method is used, all predicted life-cycle payments are being discounted on a common reference time point. The chosen discount rate (i) reflects an appropriate interest rate as well as inflation effects. Based on Kishk et al. (2003), the sum of all discounted payments represents the net present value (NPV), to be calculated from equation (3):

$$\mathrm{NPV}(t) = \sum_{t=t_{\mathrm{A}}}^{t_{\mathrm{B}}} \frac{\mathrm{IC}(t)}{(1+i)^t} + \sum_{t=t_{\mathrm{C}}}^{t_{\mathrm{D}}} \frac{\mathrm{FC}(t)}{(1+i)^t} - \sum_{t=t_{\mathrm{C}}}^{t_{\mathrm{D}}} \frac{\mathrm{RE}(t)}{(1+i)^t} \qquad (3)$$

where NPV (t) = Net present value as a function of time; i = Interest rate (in decimal notation).

For example, if the reference time of the calculation, i.e. $t = 0$, is equal to the time of the completion of the building (i.e. the end of stage B), the time-variable (t) is negative for any time during stages A and B and positive for stages C and D, respectively.

3.4 Financial and technical imprecision

In principle, the prognosis of future developments, such as the time-dependent forecast of revenues and expenses during the operation of a facility or the estimation of advancement rates during the construction of a tunnel, is associated with imprecision. Imprecision can be expressed in two ways, either by implementing theories of probability or by using imprecise and vague formulations. Decisive parameters that influence the assessment of a future state must be assessed in detail and identified carefully.

For the operation of a road tunnel, the subsequent aspects should be considered:

- The extent of a data sample that has been used to determine the failure probability of a technical component,

- The impact of environmental influences that act on a component or a material permanently or on a short term basis,
- The wealth of experience of a facility operator.

Since the topic of imprecision has a considerable significance, further specifications concerning the definition of the terms ‘uncertainty’ and ‘fuzziness’ have to be made.

Concerning Ocker (2010) uncertainty is given, when in a decision situation an observer does not possess adequate information with respect to its quantity and quality. This lack of information leads to the fact, that a (decision-)system cannot be described thoroughly, neither deterministically nor numerically. According to Hauptmanns & Werner (1991) and Knetsch (2003) there are two kinds of uncertainties that affect (decision-)systems: Those uncertainties might be differentiated into aleatory (random-based) or epistemic (knowledge-based) systems. Aleatory uncertainties arise from randomly occurring processes or events and are subjected to stochastic variation. With regard to the operation of a road tunnel, the failure of a technical component – for example, the failing of the device for the measurement of turbidity – is associated with aleatory uncertainties because the time of functional failure has to be regarded as a random process. In contrast, epistemic uncertainties result from incomplete knowledge. If the measurement of air turbidity fails and the tunnel operator has already been informed about it, the reason for the failure is unknown and therefore connected with epistemic uncertainty. The subsequent identification of the failure reason provides the opportunity to gather sustainable information: As Straub (2010) describes, the failure analysis represents an efficient tool for the manufacturer to technically redevelop a component and to reduce the degree of uncertainty about future failures.

According to Ocker (2010) fuzziness is apparent in a decision situation, if an observer is not able to give quantitative and qualitative information about a (decision-)system. Therefore, it is impossible to describe and predict the system, its behavior or other of its properties precisely and clearly. Fuzziness is expressed through verbal descriptions, for example that the useful life of a turbidity detector which is placed close to the tunnel portal and under the influence of freezing and rapidly changing air humidity is poor compared to an installation well inside the tunnel. The verbal assessment, which is given by the adjective "poor" is not quantifiable at first, but if it would be neglected significant economic consequences arise.

Based on the explanations given above, it can be concluded that the probability of a component failure is "1" in any case, but the time and the extent of the failure is uncertain. Moreover, uncertainty is related with the question of how identical components behave under varying environmental conditions. As exemplarily shown for components, the cost values which have to be implemented into the life-cycle cost model are also subjected to uncertainty and fuzziness. In order to summarize the previously stated relationship, table 1 contains examples of imprecision for the two parameters ‘components’ and ‘costs’. For the purpose of a comprehensive life-cycle cost analysis, influences from uncertainty and fuzziness have to be stressed.

Table 1. Imprecision to be considered in a life-cycle cost analysis.

	Technical component	**Costs**
Uncertainty – based on the empirical truth of information	<u>Aleatory uncertainty</u> • date when component damage occurs <u>Epistemic uncertainty</u> • type of component damage • extent of component damage • availability of spare parts	<u>Aleatory uncertainty</u> • timing and amount of costs for maintenance and component replacement • energy costs <u>Epistemic uncertainty</u> • inflation influences • time value of money
Fuzziness – based on the content and the accuracy of information	• with respect to different (environmental-) influences, identical components possess higher or lower lifetimes	• competing products result in lower costs

Uncertainty and fuzziness are to be considered as two complementary aspects in a decision situation. Informative imprecision is given if the information regarding a decision system is uncertain, fuzzy or both at the same time. When a process or an event is subject to uncertainty and fuzziness, the consequence is referred to as risk.

4 APPLICATION OF THE TUNNEL LIFE-CYCLE COST TOOL

4.1 General outline

A life-cycle cost tool for road tunnels, which is based on a spreadsheet analysis, has been developed by the authors. The approach makes use of the cost breakdown structure by applying full cost accounting. Costs associated with all materials and components necessary for the operation of a tunnel are to be assigned to their appropriate time of occurrence.

The subsequent description of the life-cycle cost analysis follows the chronological order a user of the tool is confronted with. First, the project has to be defined by some key-characteristics. These include the project name, the length of the tunnel, the traffic mode as well as the anticipated duration of the entire life-cycle. Afterwards, a complete listing of materials and components has to be established. For each element, basic values like the average expected useful life, its initial costs and a list concerning the follow-up costs has to be completed.

The tool offers the possibility to define maintenance and replacement intervals individually for every element and with different kinds of comprehensiveness. As soon as the useful life for a specific element has been defined, the tool computes the number of all necessary replacement cycles within the previously specified life-cycle period of the tunnel. The entire service life of the tunnel is usually governed by its structural integrity and the duration might be in the range of one century. In contrast to that, the useful life of a technical component is commonly less than 20 years (ABBV, 2010). The characteristics of technical components obey the principles of the product life-cycle concept as explained by Thewes & Vogt (2011).

4.2 Identification of materials and technical components

The design and the operation of a road tunnel are characterized by process-specific properties and require the application of various materials and technical components. A road tunnel, which is in compliance with the latest issue of the German guideline for the equipment and the operation of road tunnels (RABT, 2006) forms the basis for the subsequent considerations. All materials and components that are to be processed during the construction phase can be divided into two main groups: The first group comprises components and materials for assembling the shell construction of the tunnel (table 2), whereas operational components and technical devices are to be assigned to the second group (table 3).

When all necessary materials and components for a particular tunnel project have been identified, specific exposure to degeneration for all elements has to be considered. Right after installation, materials and components possess a maximum resistance against wear. Under the influence of tunnel operation, dynamic loading, temperature variation as well as chemical substances from de-icing or combustion engines drive the degeneration processes. Depending on the location in the tunnel, identical elements might behave differently and require particular maintenance procedures.

All information extracted from tables 2 and 3 combined with its characteristics resulting from wear, have to be analyzed according to their influences on costs. As it is apparent from the previous descriptions, the costs to be applied into the life-cycle cost analysis are subject to uncertainties.

Table 2. Main construction elements of road tunnels.

Construction element	Function	Main construction materials
Temporary lining	Support installation during construction	Shotcrete, steel, fibers
Waterproofing	Prevention of leakage	Thermoplastics
Inner lining (mining technique) or frame-structure (cut-and-cover method)	permanently dimensioned structure	Concrete, shotcrete, steel, fibers
Annular gap grouting	Friction locked connection between inner lining and soil/rock	Mortar
Pipes	Drainage/cable duct	Synthetic materials
Intermediate ceiling	Exhaust duct	Concrete, steel
Cantilever or anchor bar	Rigidly connection for fixing of technical installations	Concrete, steel
Protection lining	Fire or collision protection	Concrete, steel, fibers
Pavement	Surface of roadways and escape routes	Asphalt, concrete
Building	Service and operation facility	Concrete, masonry, steel

Table 3. Operational components of road tunnels.

Component	Function	Main materials
Emergency facilities	Detection of incidents in the tunnel (reported by tunnel users or automatically)	Electronic devices, plastic materials, steel, glass
Fire extinction	Fire-fighting by tunnel user or fire brigade	Steel, electronic devices
Smoke vent	Selective withdrawal of smoke (located in intermediate ceiling)	Steel, electronic devices
Radio circuit	Communication with tunnel users and rescuers	Steel, electronic devices, plastic materials
Illumination	Visibility, orientation	Illuminants, steel, electronic devices, glass
Measurement and control technology	Monitoring of operational conditions, computerized process control	Steel, electronic devices
Ventilation	Fresh-air supply, smoke removal	Steel, electronic devices
Signs	Traffic control	Steel, electronic devices, glass
Roadway drainage	Prevention of liquid spreading	Concrete, steel
Power supply	Redundant power supply for operation	Steel, electronic devices, plastic materials

4.3 Uncertainty and its influence on costs

Uncertainties in the life-cycle cost analysis are influenced by several parameters. Each parameter can at least be assigned to one group (table 4):

- Group 1 considers the theoretical service life-span of building materials and components,
- Group 2 contains cost estimates for the installation and maintenance of building materials and components,
- Group 3 includes the definition of the framework that enables the application of investment appraisals.

Table 4. Uncertain input variables in a life-cycle cost analysis.

	Uncertain input variable	Influence parameters
Group 1	Theoretical useful life of a component / building material	• Technical failure early, random or late (wear, corrosion, deterioration) • Unscheduled-early failure destruction (accident, terrorism, natural disaster)
Group 2	Costs	• Procurement, installation, replacement • Maintenance and inspection • Utilities (energy, gas, water) • Inflation
Group 3	Financial market	• Time values of money • Interest rates and amortization periods for borrowed capital

The user of the life-cycle cost analysis tool decides what kinds of uncertainties are relevant for the considered project. Since the specification of technical failure rates is commonly based on statistical analyses, cost uncertainties consider effects from technical developments or the progress of price indices. Since methods of investment appraisals are being used for the life-cycle cost analysis, the choice of an appropriate interest rate is of major importance. For the detailed modeling of uncertainties, which is beyond the scope of this paper, refer to Vogt (2012).

4.4 Calculation procedure and evaluation of results

The procedure for calculating life-cycle costs is based on the scheme shown in figure 5. The flow-chart visualized in figure 5 is repeated as often until all necessary components are being included in the analysis. All costs to be implemented in the model are valid for one specific reference date. Usually, the reference date is similar to the beginning of the life-cycle analysis. This date mirrors either the completion of a tunnel after construction or the beginning of a philosophy-change for an existing tunnel. Consequently, the costs are real costs and are applied with cost indices in order to allow for the time value of money. The resulting time-dependent costs are referred to as nominal costs.

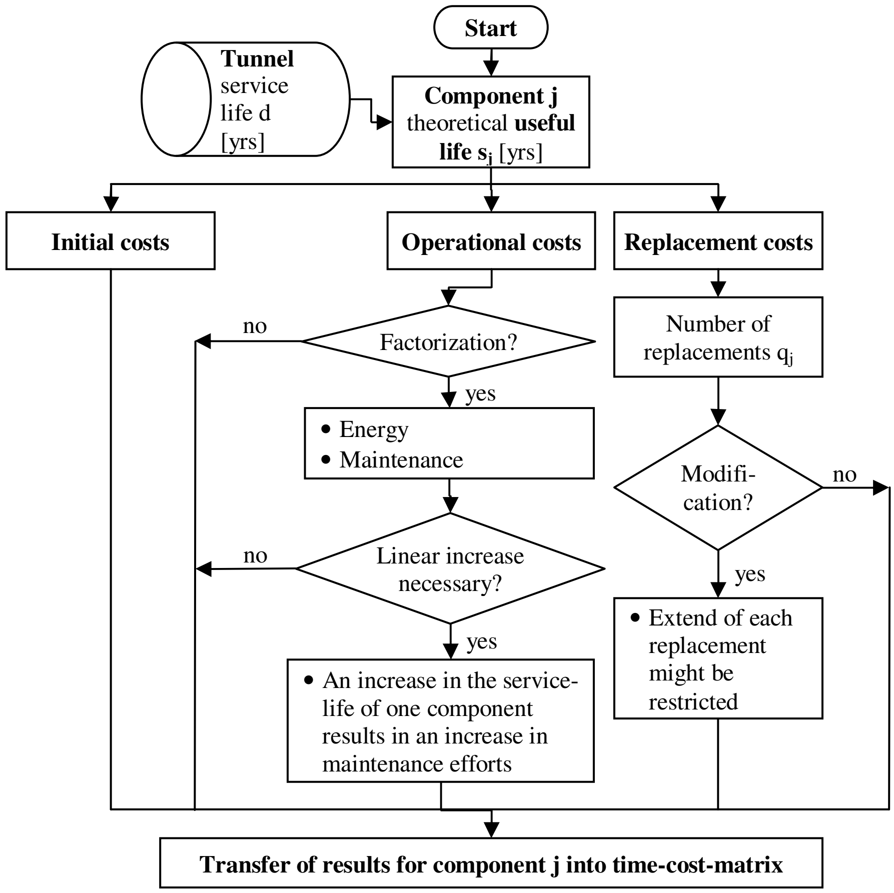

Figure 5. Flow-chart for the component-wise calculation of the life-cylce costs.

For each component, all nominal costs for installation, maintenance, operation etc. are integrated into a time-cost matrix. In the next step, the net present value according to equation (3) is determined. Among all considered alternatives, the net present value of the highest magnitude is the one to be considered for further evaluation.

The user has the opportunity to examine alternative construction configurations as well as to consider influences resulting from uncertainties. Therefore, the whole life-cycle calculation might be repeated under the variation of various variables.

5 CONCLUSIONS

As it has been shown for the age structure of tunnels on federal roads in Germany, the number of tunnels has significantly increased during the past twenty years; moreover, it is expected, that the number will still grow. Due to a limited service life of materials and components, which are used in road tunnels, a high demand for tunnel refurbishment and redevelopment is obvious.

Since public finances are under considerable strain, a more detailed view has to be placed on future tunnel financing. A life-cycle cost model in order to keep track of all monetary flows has been developed. It is based on the cost breakdown structure and uses methods of investment appraisal. Usually, the service life of tunnels lasts for about one century, so that all input parameters have to be examined with respect to uncertainties.

Finally, the user of the life-cycle cost model is able to compare alternative project solutions on a long term basis. Since initial costs and follow-up costs are regarded simultaneously and thoroughly, the described approach is comprehensive and offers a basis for a sustainable financing concept of road tunnels.

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