The economic optimization of tunnels by applying the life-cycle cost analysis

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Abstract
The reduction of costs throughout all life-cycle stages of a tunnel increasingly gains importance under the condition that security and availability requirements of a tunnel are not influenced negatively. The development of a comprehensive approach for determining and optimizing the life-cycle costs of tunnels is part of a cooperative collaboration of Ruhr University Bochum, Bundeswehr University Munich and University of Applied Sciences (HRW) in Mulheim. The starting point of the life-cycle cost calculation represents the net present value method, which is adapted for tunnels by establishing the Modular Process Model. After having identified all interdependencies among various cost components, cost types can be substituted and reduced with respect to its number and its volume. Having illustrated the mutual dependencies of cost parameters, a foundation has been laid to develop a holistic perspective to realize economic potential for optimizing and reducing life-cycle costs of tunnels.

1. The life-cycle analysis for tunnels
Tunnels are integral elements of contemporary infrastructure networks. During the past twenty years, the number of road tunnels in Germany has more than tripled [17]. In comparison to road alignments in open terrain, tunnels generate higher construction costs as well as increased operational costs. In practice, the initial costs represent the primary decision criterion in the planning phase of tunnels [15], whereas the subsequent or follow-up costs, respectively, are only estimated roughly.

By applying the life-cycle perspective to all phases of an underground facility, the costs are optimized holistically. While this approach has gained wide acceptance for the assessment of long-term returns in the real estate sector, the transfer to engineering structures is not yet very common. Consequently, the adaptation of the life-cycle concept to the characteristics of tunnels is stressed in the following.

1.1 The life-cycle
A general definition of the term “building life-cycle” does not exist yet. Furthermore, the meaning of the term varies in national and international guidelines ([1], [9]). According to the opinion of the authors of this article, the life-cycle of tunnels begins in the very early planning stage and ends with the decommissioning of the structure [18]. Beyond that, the life-cycle oriented perspective can either be started along with the planning of a new tunnel or it might be initiated when the refurbishment of a tunnel in operation becomes apparent. Upon completion of planning and construction, the following phase is dominated by regular operation. Periodic maintenance as well as the planning and execution of repair works are
important elements of this phase. The end of the life-cycle is reached when a tunnel no longer performs its intended purpose.

The overall criterion for evaluating the life-cycle of a certain project is the cost performance. Nonetheless, alternative projects can only be compared to each other if their functions are the same. The preferable design variant depends on the operators’ perspectives and targets and possesses the most efficient life-cycle costs.

1.2 The life-cycle cost analysis

In addition to technical knowledge concerning the design of a tunnel, the life-cycle cost analysis needs further expertise in order to evaluate economic indicators. Both processes, i.e. the technical and the monetary planning, have to be carried out at the same time, so that the evaluation of alternatives yields the economic optimum. It is mandatory, to implement the entire operational stage into a model. This approach links the methods of investment appraisal with the theory of the product-life-cycle.

The development of an algorithm capable of analyzing and visualizing the life-cycle-costs of road tunnels needs to be in compliance with the following conditions [16], [17]:

- compilation of the necessary parts and components of a road tunnel as well as their average useful lives and necessary maintenance cycles,
- a statistical analysis of recorded component failures,
- outlining of resulting costs by type, amount and date of origin,
- determination of parameters to be implemented into the net present value calculation,
- specifying ranges of variation for individual parameters in order to evaluate uncertainties and risks.

For investment activities of constructed assets it is characteristic that the construction phase is dominated by high cash flows, whereas after the date of commissioning, payments are fluctuating around a typical average value, interrupted by non-periodic payments. Particularly bearing in mind that a life-cycle cost analysis usually comprises several decades, the net present value method, which is part of dynamic investment calculation methods, has been chosen.

\[
\text{NPV}_0 + \sum_{t=1}^{N} \left[ (1+i)^{t} \cdot (\text{PV}_t - \text{IC}_t) \right] + \left[ (1+i)^{N} \cdot \text{SV} \right]
\]

\[
(1 + i)^{(t_2 - t_0)} (1 + i)^{(t_1 - t_0)} (1 + i)^{(t_2 - t_1)} (1 + i)^{(t_1 - t_0)}
\]

\[
\text{Compounding} \quad \text{Discounting}
\]

\[
\text{NPV}_0 \quad \text{NPV}_1 \quad \text{NPV}_2
\]

\[
\text{t_0} \quad \text{t_1} \quad \text{t_2}
\]

\[
\text{t} \quad \text{time} \quad \text{t} \quad \text{time}
\]

\[
\text{NV} \quad \text{nominal value} \quad \text{NPV} \quad \text{net present value}
\]

\[
i \quad \text{interest rate}
\]

**Figure 1:** The net present value method [16]
By applying the net present value method, the present value of each payment is being determined. The net present value method is based on the assumption that future payments possess a lower value today. Therefore, two parameters, e.g. the due date and the associated interest rate have to be fixed [7]. Referring to figure 1, future payments are discounted and past payments are compounded. This method was integrated into a practical calculation model for road tunnels including an associated software tool [16].

All compounded or discounted payments have in common that they relate to one single reference time point. By this means, the time structure of an investment is taken into account. Finally, the sum of all compounded and discounted payments represents the net present value.

2. **Modular Process Model for the life-cycle cost analysis**

Road tunnels need challenging civil engineering constructive works, in addition they include numerous and high tech facilities [13]. To estimate the life-cycle costs of such complex and diversified structures an appropriate model is required.

The segmentation of structures with the method of modularization gives a breakdown and the transparency for life-cycle cost analysis. The modules as part of the tunnel (construction and facility) are connected with several processes during the life-cycle. These processes are essential to guarantee the safety and the function of the modules. The necessary maintenance, its frequency and time duration – at least the total cost – depends on the individual module and its function.

Considering the time dependence we have developed the Modular Process Model, which is able to estimate the life-cycle costs in transparent and structured way. An additional application is the optimizing of the life-cycle costs: Project alternatives can be compared according to the total costs, as well as single modules and their processes. This is possible because the dependencies and influences of the modules and their interdependencies are included in the model (fig. 2).

![Figure 2: Modular Process Model for the life-cycle cost analysis of tunnels [10]](image-url)
2.1 The modular structure of tunnels

To create the modular process model a hierarchic structure of the tunnel is necessary. According to the well-known Work-Break-Down-Structure (WBS) the top-down view is chosen: The system “tunnel” is divided in sub-systems, assemblies, modules and elements (fig. 3). In addition, several processes are assigned to the single components.

**Figure 3:** Hierarchic structure of the tunnel

The design engineer needs a tool for the active cost control to optimize the costs holistically. For this mean the construction costs and the operational costs must be related to their origin. As shown in [13] and [14] the indirect construction costs, as “route deviations” or a “temporary building pit”, do not create any operational costs. The direct construction costs, as “concrete works for the tunnel wall”, are higher than the costs of the technical facilities (e.g. lighting, ventilation). The relation is contrary in the operation phase, caused by the shorter life expectancy of the facilities and the numerous processes to ensure safe operation.

As shown above, the system “tunnel” is divided in sub-systems (support measures, construction and equipment), assemblies (system units with the same function), modules, elements and their processes (fig. 3). The processes of modules and elements are allocated to defined life phases (fig.4). The estimation of the life-cycle costs is carried out for each module and then summed up for the whole tunnel. The aggregation of the same processes or phases opens up the possibility for a specified process-wise or phase-wise cost analysis. The selective application on elements of different tunnels compares the cost effectiveness of the objects in a transparent way.

2.2 Processes during the life-cycle of a tunnel

Beginning with design and construction, furthermore during operation, numerous activities are necessary. Especially, to guarantee the safety of users at every time during the operation phase [6]. The structural elements of the activities are the processes. During the life-cycle, every module runs through different, partly repeating, processes. The main-processes are the life-phases:
- Construction,
- Operation and
- Recycling.

The main-processes are subdivided in part-processes.

**Construction**
The model contains only the two part-processes „design“ and „construction“. The different steps of the construction process are, according to the modularization, discrete modules.

**Operation**
During operation several different processes take place. They are repeating and / or parallel-processes (fig 4).

![Process diagram](image)

**Figure 4**: Processes during life-cycle (according to [6])

Some of the processes and services during the operation phase can be found in the relevant rules and norms, e.g. DIN 30151 (Principles for maintenance with processes of service operation, inspection, repair, replacement and modernization) [4]. DIN 1076 gives indications for inspection and examination of tunnels. The high tech facilities need additional processes. In Germany, there are “Guidelines for Equipment and Operation of Road Tunnels (RABT)” [6] and a “Recommendation for Inspection and Maintenance of Road Tunnels” [5], which are a suitable basis to estimate these processes. These sources help to define the relevant operational processes.

**Recycling**
The recycling is the end of the life-cycle, it follows the operation phase. Three different possibilities can be chosen:
- Conversion,
- Deconstruction and
- Refurbishment

The most relevant is the refurbishment, where highly relevant building elements and technical components are totally reconstructed or replaced. A new life-cycle begins (fig. 4).
2.1 Influences, parameters and dependencies

The modularization is a way to estimate and to predict the life-cycle costs. For the additional purposes as optimizing and identifying substitution potentials (see 3.1) further steps are needed: The relevant influences, parameters and the interdependencies of the modules and processes are introduced in the model and create a modular network. Examples are:

- The geology and groundwater conditions are very important for the construction, but have no relevance for the operation phase.
- The construction costs of a road tunnel do not depend on the allowable traffic speed in the operation phase. This parameter, however, is one of the most important for the lighting costs of the tunnel.

Parameters with importance in all phases, as cross section or tunnel length, are integrated in the model.

In priority the parameters and influences with the highest impact are considered. Different studies are necessary to identify these important parameters. One example is the energy consumption of the tunnel lighting: The result of a simulation process was that the traffic speed and the category of the asphalt decking have the highest relevance, not the reflection of the tunnel walls (fig. 5).

![Sensitivity analysis: Energy consumption for the tunnel lighting](image)

**Figure 5:** Sensitivity analysis: Energy consumption for the tunnel lighting

3. Economic optimization potentials

Provided that during the planning stage for a tunnel all modular elements have been identified, the results of sensitivity analyses might be used to examine different design and equipment concepts.
3.1 Substitution principle

The application of the substitution principle purposefully offers the possibility to optimize the overall costs of tunnels. According to [12], in economic sciences the term substitution describes the replacement of an economic asset by another, usually cheaper one. It has to be differentiated among four possible substitution combinations [16]:

- Case 1: Initial costs replaced by initial costs,
- Case 2: Initial costs replaced by follow-up costs,
- Case 3: Follow-up replaced costs by initial costs, and
- Case 4: Follow-up replaced costs by follow-up costs.

As stated previously, the philosophy of life-cycle costs is not solely restricted on the initial and follow-up costs. Rather, the holistic view enables to specifically influence the two cost components in order to obtain an economically optimized structure [15]. For a proactive optimization, the developed process model supports by pointing out mutual interdependencies of initial and follow-up costs and vice versa.

Case 1, for example, requires a detailed preliminary design in order to achieve cost-effective design alternatives, but causes higher costs for executional alternatives. A substitution of initial costs by follow-up costs (case 2) applies, for instance, if less durable steel components will be installed instead of components made of stainless steel. As a consequence, the installation costs are reduced, but at the same time, due to an increase in maintenance works, the follow-up costs will rise. The follow-up costs for energy for the tunnel lighting can be reduced by additional initial investments for a bright surface coating (case 3). A more frequent cleaning of the tunnel wall surfaces and the pavement might help to achieve the required brightness by reducing the energy demand. In this last case, follow-up costs are substituted by follow-up costs (case 4).

In order to ensure that a substitution is resting on a sound basis, the client must specify the functional requirements of a facility as early as possible.

3.2 Economical optimization

The flow chart (figure 6) illustrates the linking of the variables and all steps to be run through in a life-cycle cost analysis. Either the analysis is carried out for a reference time point corresponding to the completion of the tunnel or it marks the beginning of a strategy change for a tunnel under operation. Generally, all costs to be implemented into the analysis are real values. Indices allow to incorporate the development of the purchasing power with regard to the reference time. Thus, the resulting costs are time-dependent and nominal values.

Finally, the costs for all components are transferred into a time-cost matrix. Depending on the time the costs occur, compounding and discounting, respectively, are carried out. The calculated present values are summed up and represent the capital value. The life-cycle assessment can be repeated for varying parameters under uncertainty, so that the resulting capital values form the basis for decision making among all considered alternatives [16].
4. Conclusions

With the application of the Modular Process Model, essential costs can be identified early, so that the composition of the modules helps to optimize the life-cycle costs. For facilities under operation, an exchange of existing or the integration of new modules yields specific dependencies of existing modules. The implementation of newly developed components can be evaluated explicitly in terms of their influence on the life-cycle costs.

Consequently, the described methodology for the calculation of the life-cycle costs needs to be applied in the project work. A permanent recording of field data generates values, which allow a comparison of similar modules or sub-processes and thus result in a direct evaluation of the economic performance. The benchmarking technique, which has been developed and approved in business economics, will help to identify and resolve weak points for existing buildings as well as to avoid them for new ones.

Instead of applying the net present value method, the payments during the life-cycle of a tunnel might also be implemented into a complete finance plan, allowing the introduction of varying interest rates. Tunnel projects based on a Public Private Partnership represent the field scope of application, because they need to generate revenues in order to repay loans.
5. References


