LIFE CYCLE COSTING AS A DECISION-MAKING AID TO THE PLANNING OF UNDERGROUND INFRASTRUCTURE

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INTRODUCTION
Generally, underground infrastructure projects are recognized as technical ambitious and cost-intensive building projects. This relates to the construction, the operation and the maintenance of the project. Since the boundary conditions are determined at an early stage during the project planning, e.g. the method of construction, costs for construction and operation are defined. Subsequent corrections are possible, but only in a restricted dimension. Therefore constructional and security-technical requirements make underground infrastructure projects cost-intensive with increasingly rising follow-up costs. The objective of a study funded by the DBU (German Foundation for Environmental Research), which is carried out by the GSTT Consulting Ltd., Berlin and the Chair for Tunnelling, Pipeline Construction and Construction Management, Ruhr-University Bochum, is the development of a methodology for a practical evaluation procedure, enabling operating authorities to choose an adequate construction method for the respective project. Considering a holistic approach in the planning phase, not only economic aspects can be estimated and included with the help of a life cycle costing analysis, but also ecological and social factors. “Sustainable Construction” regards the three dimensions of sustainability, the ecological, the economical and the social sustainability as equal as possible. In a life cycle consideration, sustainability should act as a constant approach. According to that sustainability in building construction contains the whole life cycle. In this paper possible strategies are indicated for the choice of an environmental friendly and cost-efficient construction method for underground infrastructure. In connection with a short introduction on current life cycle costing models of the classic building sector, the difficulties concerning the definition of the life cycle in the underground construction are presented. In addition the authors evaluate, how costs are quantifiable during and, above all, after the construction of an infrastructure project. In consideration of the newly gained knowledge a multi criteria evaluation process will be introduced, which makes it possible to structure all criteria hierarchically, logically and process-oriented. In the end a comparative consideration of different construction methods will be possible.

LIFE CYCLE COSTING IN THE CONSTRUCTION SECTOR
Life Cycle Costing (LCC) is a concept which identifies the most cost-efficient and competitive solution for a construction project. The concept allows the reproduction, forecast, analysis and the improvement of the whole life cycle costs for a specific system or building. Taking a closer look on the life cycle costs, different result-oriented goals can be formulated. It is possible to capture all life cycle costs in order to deviate the efficiency of a system rather than that of a building. Further particulars, e.g. the returns, can be integrated in the life cycle consideration, resulting for instance in a check of the rentability of a system.
The life cycle of a building

The life cycle of a building comprises changes during the life time of the object. Periodic events are understood by a cycle model. In the context of life cycle costs a distinction is drawn between two different models: life cycle costs in the narrower sense and life cycle costs in the broader sense. The life cycle of a building in the broader sense includes the life cycle of the total object. A project is to be planned and developed, then under construction and operation and finally disposed. As soon as the disposal is concluded, the property can be used again and the life cycle continues, indeed, the life cycle is continued with new cultivation, but still within the same life cycle. The disposal or destruction of the building does not signify the ending of the life cycle at the same time. A possibility for a graphic representation can be made as shown in figure 1 (Bruhnke et al. 2002):

The life cycle in the narrower sense possesses a defined beginning and a defined ending. Unlike the life cycle in the broader sense, the life cycle theoretically does not continue endlessly, since it comes to an end after the expiration of the cycle. Also a life cycle in a narrower sense can be extended by a conversion, so that the cycle cannot continue forever. E.g. the life cycle in the narrower sense ends with the destruction of the building. A possibility for a graphic representation can be made in form of a time bar (figure 2; Bruhnke et al. 2002). With regard to the sectioning of the whole life time of buildings into phases (as well as the description and classification) different views are existing as shown in figure 3 (Herzog, 2005).

<table>
<thead>
<tr>
<th>Standard</th>
<th>Phases in the Life-Cycle of the Building</th>
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Figure-3: Different views (according to Herzog, 2005)

It becomes clear, that ÖNORM A 7000 "Facility Management – Basic Concepts" defines only one operation/use phase, whereas guideline GEFMA 100-1 divides the „operation phase“ into three parts, while ISO 18686-5 defines two different phases within. From figure 3 it is also apparent, that the same “phases“ can have different meanings.
Cost structure in the building construction
The cost structure of a life cycle, in compliance with the German standards DIN 276 (2006) and DIN 18960 (2008), includes costs for the construction of the building, costs for the modification, conversion, maintenance, rehabilitation, and revitalisation as well as costs for the disposal. DIN 18960 (2008) examines the current costs of a building, which result from an intended use of the building. A general view of the cost structure of DIN 276 (2006) and DIN 18960 (2008) is shown in figures 4 and 5.

![Figure-4: Building Construction Costs](image1)
![Figure-5: Use/Operation Costs](image2)

The focus of the mentioned methodology lies on the economical analysis and the comparison of alternative proposals for solutions beyond the life cycle. This contains the analysis of the primary costs (KG 300), which result from the construction and modification, as well as the follow-up costs (KG 340 and KG 410; DIN 18960 (2008)) and disposal of the building (figure 6: Herzog, 2005).

![Figure-6: Specific life cycle costs (DIN 18960:2008 and DIN 276:2006) (according to Herzog, 2005)](image3)

Ecological considerations in the context of LCC
Presently, the construction phase is only examined from the viewpoint of the planning phase. During that phase, both operation and disposal/destruction phases are considered insufficiently. If taking a look at the life cycle of the building more closely, in consideration of an holistic approach, it is recognizable that costs as well as environmental impacts continue to accrue more in the operation phase than in the construction phase of the building (figure 7; Kohler et. al, 1999). Therefore costs can be influenced more in the phase of the project development and it becomes obvious that one has to turn his attention on the operation phase, so that the project has to be optimized not only during the construction phase, but also in the operation phase. A further analysis, among the identification of the general direct costs, should be taken in the correct definition of ecological costs. The greatest ecological cut takes place during the construction of an object. Also after the completion of a building many impacts occur on the environment, which are defined e.g. as a huge demand for energy. Figure 8 (Kuenzler, 2001) shows that an ecological
assessment is evaluated qualitatively, because the sum of ecological impacts grows larger during the life cycle of a building.

Figure-7: Environmental impacts (according to Kohler et. al, 1999)  
Figure-8: Influence on environment (according to Kuenzler, 2001)

The monetary and qualitative assessment of ecological problems has to be applied, too, if environmental impacts are directly measurable. Compensation measures like the planting of new trees might be given as an example. Therefore it is possible to differentiate between two measurements: The indirect monetary quantification and the approach of the „willingness-to-pay“. The indirect monetary quantification includes the approach of the costs of disposal, prevention or restriction, substitution and recycling, avoiding, defensive, but also financial penalties and reduction in value. In the context of an ecological assessment all necessary measures clients have to carry out to protect and to prevent the environment have to be determined and examined.

"Willingness-to-pay" has to be understood as the „willingness to give s.th. (amount of money) for s.th. other (benefit)“ (Manner, 2006). Theoretically, this means to pay a specific amount of money for the reduction of ecological impacts, e.g. in correspondence to a societal consensus.

BASIC CONSIDERATIONS FOR LCC OF UNDERGROUND CONSTRUCTION

Life time of underground construction

The main problem of LCC-considerations of underground constructions is the correct definition of the life cycle and its length, especially thinking of tunnel constructions. As shown in the previous chapters a life cycle is composed of many phases. Regarding the planning process of an underground facility, such a building has to be considered as an asset with a longer lifespan than typically used in the construction sector for economical estimations. In other words: Clients are planning with a long, not always clearly defined lifespan, anyhow a lifespan of about 100 years is typically applied for an economical assessment of underground facilities. Extensive modernizations and rehabilitations may extend the lifespan several times, for example due to an adjustment to the law or to new rules for regarding safety & security of passengers travelling through the tunnel.

If both areas, the building sector and underground construction sector, are compared on this topic, one has to state that both sectors do include the phases of construction and operation/use in its life cycle but that a huge difference can be found in the durations and therefore in all related considerations as far as economic estimations. Also complete estimation of all occurring costs is almost impossible due to heterogenic boundary conditions of underground facilities and their life cycles.


*Cost types and monetary valuation method*

An economical consideration of a project does not only include the analysis of direct costs, but also of the so-called indirect costs, as far as follow-up costs that result from operation, maintenance and destruction, and also ecological costs. Direct costs can be summed up immediately regarding the specific project e.g. the consumption of electricity, material costs, costs of labor etc. Regarding the whole lifespan of a facility, direct costs are generated during the phase of construction, but also during the operation and destruction phase e.g. regularly arising expenses for maintenance and renovation. Within life cycle costing estimations direct costs therefore have to be accounted for all phases of the life cycle, but can be estimated with a specific certainty before the construction process begins.

Indirect costs are costs which are resulting from extern impacts. A defined classification and estimation of such costs can be very difficult at times, as shown in the following example: Intra-urban construction sites for underground facilities or pipeline constructions do often result in traffic jams and detours e.g. evolving from the required surface opening for building pits etc. That said, two different cost types are normally occurring for the road user. On one hand higher operational costs for the car itself and on the other hand costs which do result from the extension of the journey duration. The operational costs of a car depend on a velocity related and a non-velocity related part. The minimization of velocity accounts for a higher consumption (higher costs) while a longer journey duration accounts for higher labor costs (GSTT Informationen, 2002).

Coming up with a formula for estimating indirect life cycle cost throughout the whole lifespan seems quite impossible. Durations of lifespans and heterogenic influences on the facilities are complicating such an approach. Also a final and complete list of all arising indirect costs cannot be made due to the extensiveness of such an exercise and the fact that defining boundary conditions do vary from construction site to construction site. Furthermore, a consideration of inflationary effects or variable interest rates at a late point in time has to be recognized as complicated at best. As a result a qualitative evaluation of indirect costs, depending on different construction methods, seems mandatory for a correct choice of an adequate method.

Providing explicit informations for the planned project adds up to the specific complexity of cost assessments of direct and indirect costs in the construction sector. The greater part of relevant informations refers to future impacts exclusively, which are often unknown and therefore cannot be evaluated on a resilient basis. This problem is also known as „The problem of total cost visibility“ (Fabrycky et al., 1991).

That said it is important to identify all cost-critical life cycle phases during the planning process and to concretise the relationship between actions and costs. With the help of relative comparisons indirect costs from present and future impacts are becoming measureable without further ado especially regarding comparisons of different construction methods and their future impacts. For indentifying cost-intensive phases of the facility’s life cycle it is meaningful to create a so-called “Cost Breakdown Structucure” (CBS). The CBS is an effective appliance for calculating and controlling of Life Cycle Costs. In figure 9 a possible CBS is shown for direct costs of underground construction projects (Fabrycky et al., 1991):
Referring to that a development of a cost model has to be carried out (Cost Estimating Relationship (CER)), wherein the relationships between actions and impacts on the one hand and costs on the other hand are devised mathematically. Regarding the different phases of a typical life cycle methods for estimating or calculating costs may vary. With a continuous persecution of Life Cycle Costs during the construction phase the impacts of serious technical alterations are evaluated in a better way than just with a unique procedure of the scoping (Fabrycky et al., 1991).

As soon as the cost model is developed, the cost profile of the system has to be characterized. Thereby the costs of actions and impacts are assigned to the individual cost categories of the CBS and have to be discounted on the day of decision.

Finally the results of the informational data mining have to be analysed for evaluating the appropriate construction method. The finance sector offers a huge number of methods and systems on this field of application. Thereby the capital value method is considered as the method with the highest validity in these cases. It measures the present value $C_0$ of paybacks in the future, depending on the agreed interest rate $r$ (formula 1).

\[
C_0 = - \sum_{n=0}^{N} \frac{a_n}{(1 + r)^n}
\]

The present value criterion defines that one option of an investment has to be preferred, if its capital value is higher than the value of the alternative option. Also, if the capital value offers a value less than zero, the investment should be canceled.

**Conclusions**

Building and underground construction projects do not only vary in boundary conditions, construction methods and operational concepts but especially in the length of usage and the itemization of costs. For underground facilities a projection of costs throughout the life cycle is very difficult due to the enormous grade of complexity and the period of time that has to be considered. Therefore a holistic integration of cost structures into a LCC-model that on its part leads up to decision making about concepts and methods, comes up with a very complex and difficult effort for operating authorities. In this case, when talking about a decision making process for the selection of an appropriate construction method, such an effort doesn’t seem to be feasible by far, especially from an economical point of view. The required estimations would result in a negative cost-benefit ratio.

Another approach can be regarded as conducive, when the combined estimation of qualitative and quantitative criterions leads up to a more manageable task. As soon as direct costs can be calculated

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*Figure-9: CBS combined with LCC*
for underground construction projects, e.g. with the help of German building construction standards (DIN 276; DIN 18096) throughout the life cycle, indirect costs should be evaluated by relative comparisons in a qualitative way. Considering qualitative and quantitative cost structures a further assessment model is required. The determined qualitative and quantitative Life Cycle Costs have to be integrated in a Multi-Criteria Decision Making Method (MCDM). A holistic consideration of that problem, as shown as in the following chapter, is not only carried out for the estimation and evaluation of Life Cycle Costs, but it considers further qualitative and quantitative criterions as mentioned above and therefore can be of a helpful assistance considering LCC-aspects of underground constructions.

MCDM-Methods for the choice of an adequate construction method in consideration of LCC-Methods

The Analytic Hierarchy Process – An example for multi-criteria decision making (MCDM)

A decision is a sensible choice between alternatives or between different versions of a topic or object, based on defined preferences of one or various deciders. The decision happens spontaneous, emotional, incidental or rational. The decision is made by the decider with the help of objective and subjective decision criterions. The main goal of MCDM is to describe the alternatives with criterions, to compare them and to choose right alternative at last. With the help of MCDM it is also possible to have a higher data transparency for the decider.

One of many decision making methods currently available is known as the Analytic-Hierarchy-Process (AHP), which was developed by Thomas Saaty in the USA in the 1970s. With a prime goal in mind so-called goal attributes are verbalized, which allow a transformation of the decision problem into a hierarchical structure (figure 10: Saaty 1990). Thereby, the strict and formalized distribution and order of the decision situation into hierarchy ranks is carried out, wherein the adaptation and presentation of the chosen approach will always take place.

The appliance of AHP always results in a fixed procedural progress (figure 11: Saaty, 1990). The starting point of further advisements is a correct definition of an overall goal, from which the goal hierarchy is transferred. The achievement of goal-related objectives is accomplished by alternatives and arrangements throughout the hierarchical structure, while all elements of each rank are provided with a priority within their ranks. The specification of the relative priority of any criterion is carried out by comparison of each to one another. By doing this, specific weights of all criterions are calculated and integrated into a pair comparison matrix (Saaty, 1990).

Different aspects have to be evaluated, so that they can be included in a decision hierarchy. Very important seems to be the simultaneous handling of qualitative and quantitative data. The AHP-Method especially is provided for decisions of high complexity which include objective as well as
subjective factors for the decision making. As mentioned above the planning of an underground facility combines many technical, ecological, economical and socio-cultural interests, so that a multi dimensional goal system is already in place. Considering the already shown Life Cycle Costing-methods and their structural complexity regarding underground facilities, the AHP occurs as an appropriate decision making method which can be extended by a life cycle criterion easily.

**LCC as an AHP-criterion for underground construction**

Using an AHP-adapted goal system aims to choosing the best possible construction method, especially regarding maintenance and repair strategies and hereupon related costs during all phases of the life cycle. Therefore all requirements of the specific infrastructure, regarding its performance and availability throughout its lifespan, need to be known, to be defined and to be determined. An example: Scale deposits of drainage pipes of drained buildings often result in large expenses for maintenance and repair, to remove such deposits and to renovate the specific pipes. Regarding the whole life span of a drained tunnel those expenses account for an extensive part of whole-life maintenance and repair costs. Tunnels with a permanent and all around waterproofing do not generated any maintenance for drainage systems but require higher expenses for construction and the proofing itself. Therefore drained tunnels are normally classified as the best economical solution but regarding the whole life cycle waterproofed facilities could become more economical due to massive scale deposits and/or bad maintenance procedures. That said the implementation of a valid sustainable maintenance strategy has to be considered as a positive influence in the context of LCC-considerations. With the help of the CBS and CER methods such a positive influence can be displayed qualitatively in a few steps. After the definition of the cost structures the planer/constructor can get a general idea over the prognosticated life cycle costs with simultaneous consideration of all known informations (figures 12 and 13).

Back to the example: An existing german directive (Federal Highway Research Institute of Germany, 2007) gives detailed informations for the planning, construction and operation of water drainage systems for tunnels, with the purpose to reduce maintenance and repair costs of the drainage systems itself. Guidelines for the maintenance and repair are given for an economically optimized operation of future and existing tunnel structures. Specifications such as this have to be implemented cost-cuttingly in the CBS/CER. Finally Life Cycle Costs can be defined as a criterion for the Analytic Hierarchy Process. With previously examined points of interest the goal and the hierarchy system can be extended with the usage of the criterion “economy”, and thereby a holistic and environmental approach of the tunnelling construction choice can be reached.
CONCLUSION
Within the scope of this publication it was shown how important a life-cycle oriented consideration concerning the choice of the right tunnelling construction method can be, while the difficulties realizing such an approach seem quite obvious. That is why a sustainable maintenance strategy should be implemented which keeps impacts on the specific system and its environment transparent and assessable. By starting up a multi-criteria decision making procedure the planner is able to structure his decision hierarchically, so that with the consideration of technical, economical and ecological aspects picking a sustainable tunnelling method can be realised.
Since our researches on this topic are not yet finished it can be said that an even more detailed cost analysis has still to be carried out in dependence on the different tunnelling procedures and methods. Furthermore the development and estimation of all technical, economical and ecological assessment criterions has to be carried out to complete the already drawn picture.

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