NON-MONETARY LIFE-CYCLE ANALYSIS OF ROAD PAVEMENTS

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ABSTRACT

Due to the new BOT-contracts (Build-Operate-Transfer) which become increasingly important in Germany, road authorities as well as road construction contractors need a generally accepted method to compare and evaluate road pavement structures over a long term. For this purpose the life-cycle cost analysis provides a useful instrument to assess efficiency of different construction methods and maintenance strategies. Basing on findings of deterioration models of road pavements, maintenance costs and maybe a salvage value are considered in addition to the initial costs.

The research project is divided into two parts. The first step contains the analysis of methodical backgrounds by considering existing national and international used evaluation models. For this, input parameters and boundary conditions need to be realized and their effects on the final outcome have to be examined. Once developed a theoretical model based on the results from the first step, a software tool which allows a uniform evaluation process will be created in the second step.

Comprehensive studies about long-term performance of road pavements already exist basing on results from the periodical condition survey of German national highways. These data provide an important base to evaluate the cost-effectiveness of road infrastructure and give the opportunity to forecast necessary maintenance works. But not only have the direct costs of roadwork to be considered, also indirect costs for road users incurred due to these works.

A first evaluation model therefore combines available information to assess the monetary advantages or disadvantages of a considered variant. In continuation to this model a deterministic nonmonetary method, which will be described in this article, was developed. For this purpose the surface conditions as well as the structural qualities of a pavement are included into the evaluation process. By creating standardised values for these two main properties of a road, the evaluation is done by comparison of the renewed structure and the achieved salvage value.

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Keywords: evaluation, efficiency, pavement, road deterioration

1. INTRODUCTION

The life-cycle analysis represents a useful instrument to evaluate competing project alternatives over their whole (service) life. Primary purpose is to consider not only the initial costs but also all expected follow-up costs.

In this context, aim of the evaluation is to compare different road constructions – mainly bituminous and concrete pavements – by their long-term effectiveness, respecting varying constraints. It's important to point out, that only the road pavement with all bounded and unbounded layers will be considered. Everything else, like road equipment and also the cost-effectiveness of the road itself are not part of the evaluation process.

In many countries, calculation of life-cycle costs is, not at least for high-priced projects, in common use during the design process. For example, the Federal Highway Administration (FHWA) in the US made lot efforts to develop guidelines and recommendations concerning the proper use of life-cycle cost analysis, resulting in the publication of an interim technical bulletin (FHWA, 1998). At least, road authorities in most US-States already developed their own evaluation methods and policies, e.g. Pennsylvania (PENNDOT, 2003) or Colorado (CDOT, 2000).

But not only in the U.S., also are most of European countries as well as Canada and Australia using life-cycle cost analysis (PIARC, 2000), mainly for comparison and selection of different pavement types for new constructions. Another widely-used model represents the HDM-system developed by the World Bank (KERALI, 2000). The level of detail, concerning mainly the considered types of cost and the prognosis of road deterioration, however, varies between the different models.

Although the cost-effectiveness of different road constructions also plays an important role in Germany, there is actually no explicit need and no specification to calculate life-cycle costs. Empirical investigations about road deterioration exist indeed, however they are mainly used for maintenance strategies inside Pavement Management Systems.

The design process of road pavements in Germany is actually based on the guidelines for standardisation of road pavement structures, RStO 01 (FGSV, 2001a). These guidelines provide a limited variety of different construction types for which the evaluation will be performed. Layer thickness thereby depends on the assumed traffic load and is divided into so-called road construction classes. In the following only construction class SV and 1, convenient for (very) high heavy traffic loads, are considered.

Within this project, a monetary evaluation method was firstly developed and enhanced to a deterministic nonmonetary model as described below. Main reason for neglecting cost rates within the evaluation was to avoid them as an additional uncertain input parameter.

But one has also to mention that each prognosis is mainly based on experiences from the past, which means that an evaluation model can never be finalised and needs continuous adjustments. Therefore a model has to be clearly formulated on the one hand but also flexible to allow always changes if necessary.

2. BACKGROUNDS

2.1 Road deterioration models

The long-term performance of road surface can be described either by mechanistic or by empirical deterioration models. As these are the key element in the field of road management and maintenance planning, they are already a long time ago subject of many researches. Very detailed and high-developed deterioration models are used within the HDM-System (N.D. LEA, 1995). However, there are high requirements concerning the level of detail of input parameters and calibration. Other comprehensive studies were done within the PARIS-Project (PARIS, 1999), where road condition data from eleven European countries in so-called Real-Time Loading Tests were combined with data from Accelerated Loading Tests.

However, one has to mention that the long-term behaviour of roads is influenced by a large number of factors and their interactions (Figure 1), which are sometimes not recordable and sometimes even unknown. That’s why empirical evaluations usually show a wide statistical spread. For this reason it seems to be impossible to definitely predict road deterioration, one should always keep in mind the uncertainties.

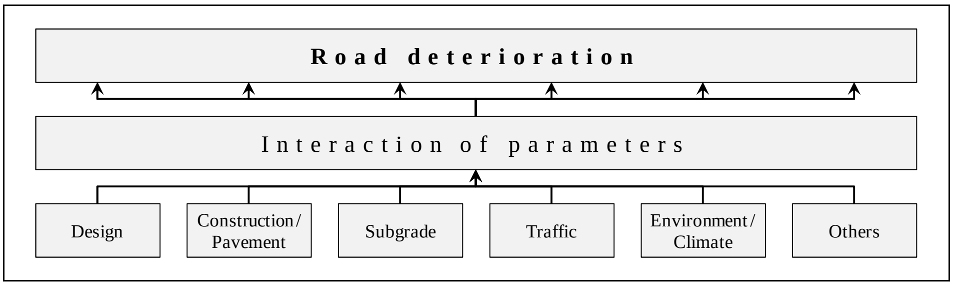

Figure 1 Influences on road deterioration

In Germany, several studies with the main goal to determine deterioration models were also carried out (e.g. RUEBENSAM ET AL., 1994). At least comprehensive findings derived in the last time from the periodical condition survey and evaluation of trunk roads ZEB (FGSV, 2001b), which is held on every four years since 1992. From these survey data, empirical models for different construction types were deduced by statistical evaluation (HINSCH ET AL., 2005). They describe road deterioration depending on traffic load and will be used within this evaluation to predict surface condition (Figure 2). The advantages of these empirical models are that they are easy to use as they require only a small number of input parameters, that the observed road sections underlie all real impacts and that they are basing on a very large population as data come from all German trunk roads.

The evaluation model uses three attributes, which are the main reasons for maintenance works, to describe road condition. It’s the so called AUN-Value [cm³], representing the longitudinal unevenness and comparable to the IRI, the rut depth (RD) [mm] and cracking/surface damages [% damaged area].

For the prediction of all attributes, the common power function is used:

$$y = a + bx^c \qquad \text{(Eq. 1)}$$

Where: y: Predicted condition variable (AUN [cm³], RD [mm], cracking [%])
x: Cum. number of millions of 10t equivalent single axle loads (ESAL)
a, b, c: Parameters

The cumulative ESALs are calculated since construction or last maintenance work until the date of prognosis, usually for every year, according to the method of Germans RStO 01, primarily depending on the average daily truck traffic (ADTT), but also taking in consideration some further matching coefficients. The parameters a, b and c depend on the predicted attribute, the construction type, the wearing course material, the considered lane and the gradient.

Besides the deterioration models, the prediction of maintenance work also requires a definition of intervention criteria for the considered attributes to determine the intervention point. For this purpose, some values already exist. However, researches about this topic are currently still running.

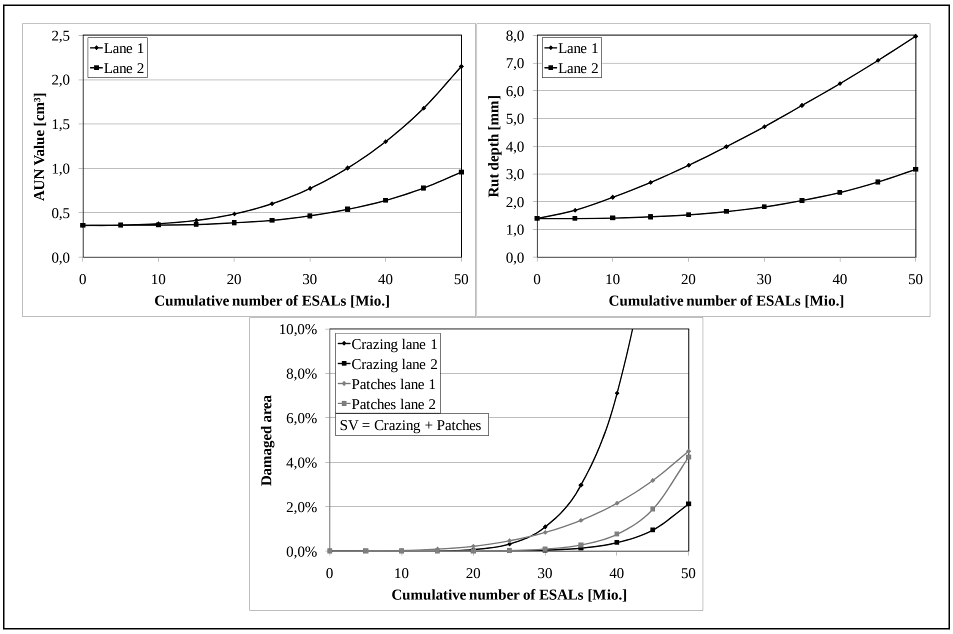

Figure 2 Examples of road deterioration for pavements with stone mastic asphalt wearing course and bituminous road foundation (properly dimensioned, level stretch) (HINSCH ET AL., 2005)

2.2 Structural performance

As the deterioration models are used to predict the condition of roads surfaces depending on traffic load, the structural properties will be respected in the evaluation model by introducing a time-related structural number. This describes the structural loss over the expected structural service life as the equivalent layer strength depending on the age of each layer:

$$SN_n = \sum_{i=1}^{I} \left(Eq_i \times h_i \right) \quad \text{(Eq. 2a)}$$

Where: SN_n: Structural Number in year n
i: Number of layer (Total number of layers = I)
Eq_i: Layer (strength) coefficient for layer i:

$$Eq_i = Min\left(Eq_{i,Max}; Max\left(Eq_{i,Min}; a_i - b_i \times Age\right)\right) \quad \text{(Eq. 2b)}$$

Where: a_i, b_i: Parameter for layer i
h_i: Thickness of layer i

These age-related layer coefficients are only calculated for bounded layers according to OEFNER ET AL., 2000 and FGSV, 2001b. For unbounded layers, no structural loss is assumed therefore the layer coefficient $Eq_{i,unbounded}$ will be constant (Figure 3).

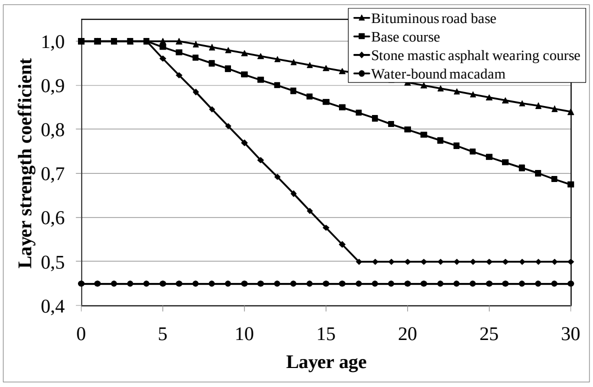

Figure 3 Examples of age-related layer strength coefficients for different layer types (OEFNER ET AL., 2000)

2.3 Maintenance works

Within the evaluation model, different maintenance and rehabilitation works (M/R) are respected (Table 1). In this context, maintenance (M) includes only work which concerns the wearing course (replacement), rehabilitation 1 (R1) concerns wearing and base course and rehabilitation 2 (R2) the whole road foundation (all bounded and unbounded layers).

Table 1 Respected M/Rs within the evaluation model

Cat.	**M/R**
Bituminous pavements	
M	Milling and replacement of wearing course
R1	Replacement of wearing and base course
R2	Replacement of road foundation
Concrete pavements	
R1	Replacement of slabs
R2	Replacement of slabs and road base(s)

Each M/R thereby has different work effects on the road surface as well as the road structure. Changes in road structure are respected by resetting the age of each concerned layer to 0 (Eq. 2b). On the road surface, work effects immediately after M/R match the condition after initial construction. About long-term work effects, however, only few findings exist. But as one can imagine, there are doubtless different effects whether only the wearing course or the road foundation will be renewed. Therefore a work effects coefficient will be defined, depending on the amount of renewed structure.

Smaller maintenance works like patching are not part of the evaluation as the effect of these works on long-time behaviour seems to be marginal. Because the considered constructions are expected to be properly dimensioned, overlays which mean a structural strengthening are also neglected.

3. DETERMINISTIC EVALUATION MODEL

3.1 Basics

Basing on the mentioned backgrounds, a deterministic life-cycle evaluation model was developed. This model is based on the three following principles:

- Non-monetary
- Layer related
- Lane related

The last two points mean that each layer and each lane is considered separately in terms of M/R-planning and work effects.

The evaluation of different construction types bases on a comparison of required structural supply by M/Rs during the evaluation period, which represents the cost component, and the achieved salvage value as benefit. Everything indicated as costs in the following thereby don’t mean monetary costs but nonmonetary costs in terms of structural supply.

Within the prognosis the three evaluation parameters:

- Structural Index (SI, road structure)
- Structural Value (SV, surface condition, cracking) and
- Condition Value (CV, surface condition, unevenness and rut depth)

as described below are calculated for each year (Figure 4). By comparing the annual SV/CV, basing on the deterioration models, and the defined intervention criteria, the year of necessary M/Rs can be identified. The sequence of M/Rs (M, R1 or R2) thereby is a fixed input parameter, e.g. “Work 1: M”, “Work 2: R1” and “Work 3: R2”.

As one can see, M/Rs are only caused by poor road surface conditions and not by structural deficiency. That’s because according to RStO 01 (FGSV, 2001a), on properly dimensioned sections, no structural deficiencies will occur during the service life which is scheduled 30 years for all types of construction. One more assumption basing on RStO 01 is the technical and structural equality of all construction types within one road construction class. I.e., as the cost component is expressed as the structural quality, initial cost equality for the standardized construction types.

If all M/Rs during the evaluation period, caused by poor surface conditions, are identified, the amount of supplied structure by these M/Rs (cost) for the considered construction type and M/R-sequence can be calculated as well as the salvage value with reference to road structure and surface condition (benefit). By comparing cost and benefit, a ranking list for all evaluated alternatives can be created which indicates the most effective construction type.

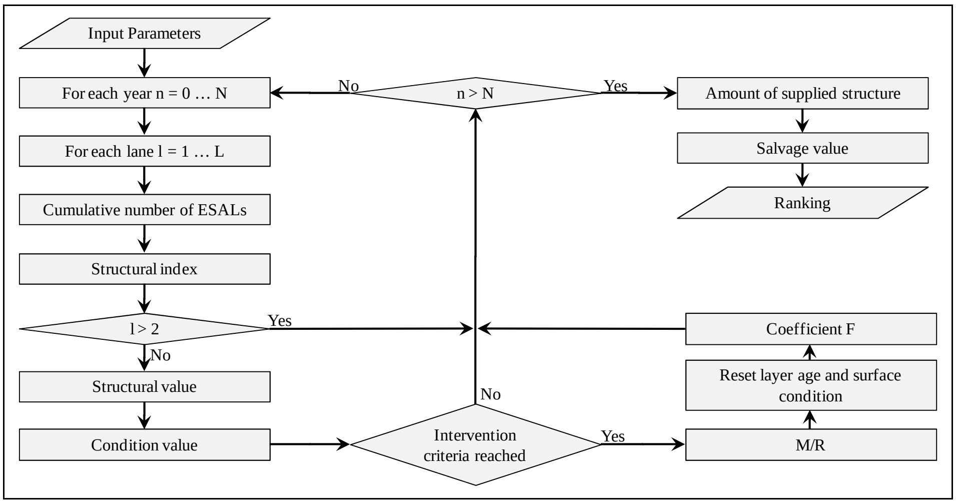

Figure 4 Flowchart of evaluation procedure

3.2 Evaluation parameters

3.2.1 Structural Index

The Structural Index describes the ratio between the existent equivalent layer strength for every year n and the equivalent layer strength immediately after initial construction:

$$SI_n = \frac{SN_n}{SN_0} \qquad \text{(Eq. 3)}$$

Where: SI_n: Structural Index in year n
SN_n: Structural Number in year n (Eq. 2a)
SN_0: Structural Number after initial construction (year 0)

Furthermore, the Structural Index represents the background to calculate the cost component within the evaluation. The total costs thereby can be calculated as the sum of all differences in SI_n due to M/Rs ($\Sigma\Delta SI_k$) multiplied by the total number of M/Rs. Figure 5 (left) shows an example of the chronological sequence of the SI as well as the influence of M/Rs on the SI. For each M/R the layer strength coefficient of the concerned layer(s) is reset to age = 0 (Figure 5 right). So, each layer is considered on its own and the age of the road foundation is variable, depending on the kind of M/Rs and the concerned layers. As the SI is only age-related and independent from traffic load, it will be calculated for each lane of the considered section separately.

According to the agreement above, no structural deficiencies during the evaluation period will occur. Therefore, the definition of intervention criteria for SI is not necessary.

The Structural Index after a specific M/R (SI_{afterk}) also influences the further road deterioration with regard to the road surface, expressed as the work effects coefficient F. F is the ratio between the allowed ESALs after the M/R and the allowed ESALs after initial construction until the intervention criteria will be reached again (Figure 6). E.g. the value F = 0.75 means that the possible amount of ESALs after the M/R is only 75% of the possible amount after initial construction. F depends on the amount of supplied structure:

$$F = (-1) + 2 \times SI_{afterk} \qquad \text{(Eq. 4)}$$

As one can see, if SI_{afterk} becomes 1, which means structural qualities like after initial construction, F also becomes 1. The minimum of SI_{afterk} is 0.5, where F becomes 0.

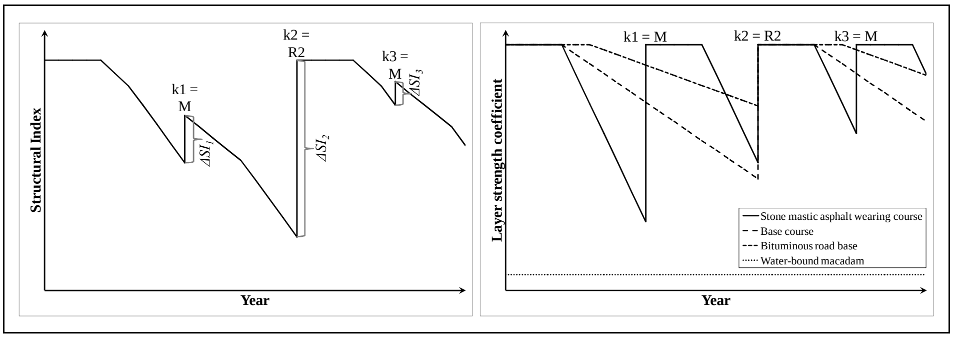

Figure 5 Example of work effects on structural index SI and layer strength coefficients

3.2.2 Structural Value

The structural value describes the condition of road surface as the sum of percentages damaged area by different types of cracking and surface damages. For bituminous pavements SV is calculated as:

$$SV = C + P \quad \text{(Eq. 5a)}$$

Where: C: Crazing [% damaged area]
P: Patches [% patched area]

And for concrete pavements:

$$SV = LTC + S1 + S2 \quad \text{(Eq. 5b)}$$

Where: LTC: Longitudinal and transversal cracking [% damaged area]
S1: Spalling at the slab edges [% damaged area]
S2: Spalling at the slab corners [% damaged area]

The single condition variables (C, P or LTC, S1, S2) are calculated with the empirical deterioration equation (Eq. 1) modified by the coefficient F (Figure 6):

$$y = a + \frac{b}{F^c} \times ESAL_{Cum}^c \quad \text{(Eq. 6)}$$

As the SV depends on the cumulative heavy traffic loads, it will be calculated separately only for lane 1 and lane 2 (right lane and first overtaking lane) by using different parameters a, b and c. Further lanes are not supposed to carry heavy traffic whereby M/Rs on these lanes are not considered. M/Rs on lane 1 and 2 are carried out if intervention criteria are reached or exceeded.

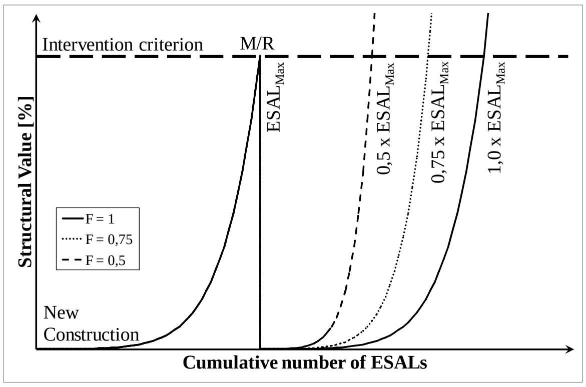

Figure 6 Example of structural value SV depending on cumulative number of ESALs and the influence of coefficient F

3.2.3 Condition Value

While the SV describes the road surface condition concerning the structural quality, the Condition Value provides information about riding comfort. Therefore the CV consists of two separated values for longitudinal unevenness (CV_{AUN}) and for rut depth (CV_{RD}). These two values are also calculated with the empirical deterioration equation (Eq. 1):

$$CV_{AUN/RD} = a + \frac{b}{F^c} \times ESAL^c_{Cum} \qquad \text{(Eq. 7)}$$

Equally to the SV, the CVs are only available for lane 1 and 2. M/Rs also become necessary if reaching or exceeding intervention criteria for AUN and rut depth.

3.3 Salvage Value

The achieved salvage value of a considered construction type, which describes the benefit, respects the road structure as well as the surface condition. Therefore, the four evaluation parameters SI, SV, CV_{AUN} and CV_{RD} in year N = 30 have to be standardised to unique values.

According to the ZEB-procedure, the standardised values are between 1.0 and 5.0, whereas 1.0 indicates the ideal condition and 5.0 the worst condition. Thus, for SV and CV, 1.0 is the new condition and 5.0 the intervention criteria. Between these values will be linearly interpolated. For the SI, the standardisation according to FGSV, 2001b is currently used, also with standardised values from 1.0 to 5.0.

The standardised values are subsequently combined to two fractional values (FV). The SI and SV thereby results in the FV_{Struc}, describing the structural salvage value and the CV_{AUN} and CV_{RD} in the FV_{Cond}, describing the surface condition salvage value, calculated as follows:

$$FV_{Struc} = 5 - \left((5 - SI_{Std})^{w_1} \times (5 - SV_{Std})^{w_2} \right) \qquad \text{(Eq. 8a)}$$

$$FV_{Cond} = w_3 \times CV_{AUN,Std} + w_4 \times CV_{RD,Std} \qquad \text{(Eq. 8b)}$$

Where: SI_{Std}, SV_{Std}, $CV_{AUN,Std}$, $CV_{RD,Std}$: Standardised evaluation parameters in year N = 30

w_1, w_2, w_3, w_4: Weighting coefficient with $(w_1 + w_2) = 1$ and $(w_3 + w_4) = 1$

For each lane, the total value (TV_l) is determined as the maximum of the two fractional values. The total value for the whole section (TV) at least is the average over the single values for all lanes. The TV represents the benefit within the evaluation, expressed as standardised salvage value.

3.4 Costs and benefits

As mentioned before, the costs are the structural supply over the whole evaluation period for all lanes with respect to the number of M/Rs. They result due to the exceeding of the defined intervention criteria as M/Rs are immediately necessary when a poor surface condition is reached:

$$C = \left(\sum_{k=1}^{K} \sum_{l=1}^{2} \Delta SI_k \right) \times K \qquad \text{(Eq. 9a)}$$

Where: C: Costs
k: Number of M/R
K: Total number of M/Rs during the evaluation period
l: Number of lane
ΔSI_k: Difference between the SI before the M/R and after the M/R (supplied structure):

$$\Delta SI_k = SI_{afterk} - SI_{beforek} \qquad \text{(Eq. 9b)}$$

E.g., the total costs in Figure 5 (left) can be calculated as:

$$C = \left(\Delta SI_1 + \Delta SI_2 + \Delta SI_3 \right) \times 3$$

On the other hand, benefits for each alternative are calculated as the salvage value respectively total value TV. Benefits thereby are influenced by the costs. The higher the structural supply, the higher can be the achieved salvage value. At the same time, higher structural supply can also improve the long-term behaviour after M/Rs as this depends from the coefficient F.

At least, the evaluation bases on the principle to achieve the best salvage value with a minimum of M/Rs which have a minimal extent.

The decision about the most effective construction type bases on a cost-benefit equation. One can see that as a result of the nonmonetary evaluation, costs as well as benefits are only fictitious values. For this reason, the result provides only ordinal scaled information if more than one alternative is considered. For the comparison therefore a ranking list with costs and benefits of different construction types is created.

4. CONCLUSION AND OUTLOOK

Currently, the theoretical basics for a nonmonetary life-cycle evaluation are established and statements about profitability of compared construction types under different constraints are possible. However the disadvantage is that the fictitious evaluation parameters don't allow conclusions on the relative cost-effectiveness of one construction type. On the other hand, cost units as an additional uncertain input parameter are neglected. Furthermore the evaluation model can always be extended to consider other construction types on condition that deterioration models are known.

In the next step, the evaluation model needs to be calibrated by adjusting weight coefficients to real conditions, mainly basing on further empirical researches.

In addition, one possibility could be to consider also a monetary component. As the kind and date of M/Rs are already known, it will be easy to calculate life-cycle costs by respecting some cost rates. Thereby in addition to the costs of road authorities it will also be possible to consider road user costs, for which calculation methods already exist (e.g. RESSEL, 1994). Due to the uncertainty of most input parameters, one more enhancement could be to develop a probabilistic evaluation by using Monte-Carlo simulation methods.

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