Approach for the Life-Cycle Management of Structures including Durability Analysis and Maintenance Planning

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Summary

The paper describes a case study on a highway section in Austria comprising 100 structures conducted for the Austrian Federal Highway Company ASFINAG in 2011. A tailored life cycle model was developed utilizing state-of-the-art information from literature and VCE's experience gained in the course of performing bridge monitoring and bridge inspection worldwide. This knowledge has been incorporated into the assessment procedure that is described in the paper. Probabilistic methods are used for the service life calculations of the whole structure as well as for individual items delivering lower and upper bounds of life expectancy. Based on the available structural information, inspection reports and traffic data maintenance instructions were elaborated in order to ensure the demanded structural service life and operability. Besides cost optimization the main focus was on the minimization of traffic impediment. The case study includes different budget scenarios given by the client over a period of 30 years.

Keywords: life-cycle management, maintenance planning, deterioration & cost analysis, cross-asset optimisation

1. Introduction

Managing assets is about making decisions. Current practices are characterised by methodical diversity and fragmented approaches. In the course of IRIS (European Commission FP7) an integral approach for infrastructure management was developed.

The basis is the consideration of the entire life cycle of engineering structures. The following major aspects are covered:

a) The determination of the DESIGN LIFE OF NEW structures
b) The estimation of the RESIDUAL LIFE OF EXISTING structures
c) Assessment criteria whether the REAL DEGRADATION PROCESS corresponds with the applied life cycle model, in order to take corrective measures
d) MAINTENANCE INSTRUCTIONS to guarantee the original design life and operability

All relevant datasets (Key Performance Indicators) are incorporated into a probabilistic model to cover occurring uncertainties during structural service life. To reflect the common composition of inspection routines even characteristics of individual structural members are considered - making it coherent with civil engineering practice worldwide.

2. Case Study

2.1 Project description and objectives

The purpose was to elaborate a maintenance concept for highway infrastructure (bridges, culverts, gantries, tunnels, flyovers, access ramps, noise barriers) for the upcoming 30 years. This maintenance concept was intended to give a long-term outlook for maintenance measures (heavy & routine maintenance) during the up-coming service life of the analysed structures. To derive tailored maintenance plans for every structure the documented ageing process of structures and structural members was considered.

The cost and availability optimization considering the existing pavement management concept was one of the key issues.

The result can be used as a basis for decision making in the long run.

The calculated lifetime prognosis represents estimations at the time of investigation. This means in further succession it is necessary to periodically update the incorporated ageing curves based on the latest knowledge from on-site inspections and structural assessment.

2.2 Investigated assets – S6 Semmering Schnellstraße

The S6 Semmering Schnellstraße is part of an important North-South-Corridor within the Austrian highway network - linking two major highways (A2 Südautobahn and A9 Pyhrn-Autobahn). Including feeder streets the total length of the S6 Highway is 106 km (including 17 km in tunnels). Since 2009 the Semmering Schnellstraße consists of two lanes for each driving direction throughout its entire length. In case of traffic obstructions at the highway A2 the S6 highway serves as relief road for the North-South traffic.

For the present case study a 25 km long highway section (km 70.142 - 94.005) including 102 structures (see Fig. 1 and Tab. 1) was chosen.

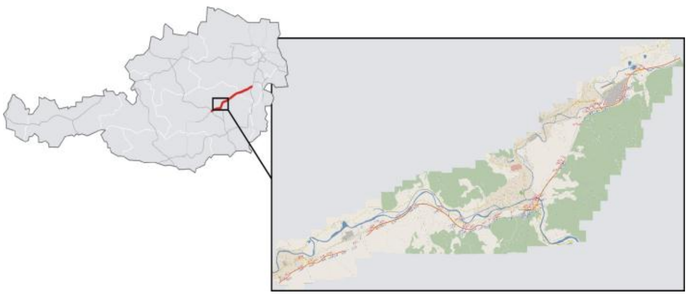

Fig.: 1. Overview S6 Semmering Schnellstraße and chosen highway section

Table 1: Analysed structures S6

Structural Type	Amount
Bridges	76
Tunnels	8
Gantries	18
Total	102

2.3 Provided input data

The input data required for the maintenance concept were based on a pool of information provided by the client:

- Data sheets including main information (geometry, design, year of construction)
- Maintenance condition (rating) for all structures/structural members over time
- Digital archive including latest inspection reports, drawings and photo documentations
- the already existing pavement management concept for the investigated highway section

Additionally, an on-site visit was made due to still missing information on structural specification, geometric properties and types of fabricates of certain structural members.

All the given and collected information was evaluated concerning completeness and usability with regard to the remaining uncertainties of the lifetime prognosis.

3. Methodology

3.1 Framework

The BRIMOS® Life Cycle Methodology is based on three main categories of evaluation:

- Visual Inspection
- Design safety according to the applied code
- Field Measurements (Structural Health Monitoring, Non Destructive Testing etc.)

In the course of an initial prognosis loop a theoretical curve is computed as a mean result derived from benchmark data based on experience with a large number of structures. It is correlated with the following most relevant influence parameters on structural ageing:

- Year of construction
- Cross-section design
- Static system
- Type of material used

For the determination of a methodically refined prediction of the lifecycle curve any additional information which is able to contribute to a better understanding of a structure is used. These are:

- Original static calculation (Safety level according to the applied design code)
- Numerical simulations
- History of already performed maintenance and rehabilitation measures
- Loading history (historical traffic data)
- Material tests (Chloride intrusion, compressive strength, carbonation etc.)
- Data on the environmental conditions
- Judgments/ratings from bridge inspections (reports)
- Results from performed monitoring campaigns

From these key parameters the structures' Health Index is calculated which is used as reference point for the life expectancy calculation.

3.2 Prognosis Model

The starting point for the lifecycle calculation is the rating of the bridge according to the Austrian national guideline for visual inspections (RVS 13.03.11). Both the total rating and the rating of the individual structural members (superstructure, substructure, expansion joints, bearings, pavement, edge beam, guard rail and railings, dewatering and miscellaneous facilities) are used.

These ratings are converted into so called Health Indices. The transformation is done by calibrating the local condition with regard to the total capacity available for the analysed component – depending on the type of structural member, material and product type.
The applied ageing models (Fig. 2) are based on literature, bridge owner databases of structures and VCEs' 50 years of experience in the field of bridge inspections and structural health monitoring.
Based on the calculated health index for each bridge component, its year of construction and the current traffic loading/chemical exposure a first deterministic lifeline prognosis is performed (Fig. 3). This lifeline considers all available information at the time of investigation and assumes the so-called "do-nothing-strategy" (unrestricted deterioration) in full succession. Furthermore, this lifecycle curve is used as the basis for the elaboration of the maintenance schedules.

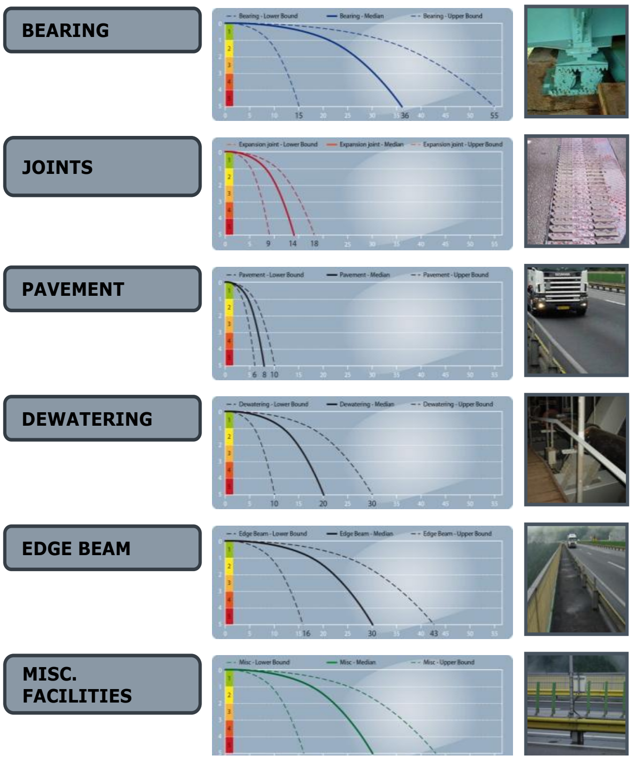

Fig.: 2. Standard degradation curves for certain structural members

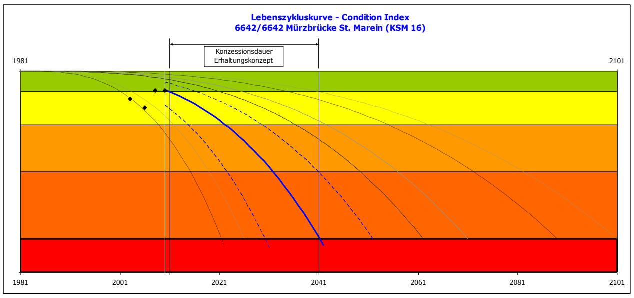

Fig.: 3. Global Lifecycle curve – "Do nothing" strategy serving as basis for the maintenance concept

During the progression of the analyzed lifelines (annual analysis variables) both routine maintenance interventions and in the end the replacement of the structural member are triggered and scheduled in the maintenance plan. In this process the inspection/maintenance history is considered as well as those time intervals until the structural member are appearing in the range of rating 3 (maintenance works) or in the range of rating 4 (retrofit, replacement).

Depending on the quality of information received a confidence level is introduced to determine the upper and lower bound of the theoretical performance curve. In other words the degree of completeness and reliability of the initial information results in a statistical dispersion of every individual lifeline. Thus, the aim of optimization is to find the most applicable combination of maintenance and replacement measures for each bridge element in all the computed, possible strategies.
At the end of the process a weighted lifecycle curve for the whole structure is calculated (Fig. 4). This global lifeline represents the superposition of all the individual curves - the relevance of the bridge element within the whole structure is reflected by its weighting. This final step is used for demonstration purposes only - the trigger mechanism, deciding about maintenance and replacement is made due to deterioration analysis on every single structural component.

3.3 Cost model

To get reliable total cost estimations for the maintenance measures the following aspects had to be considered:

For all possible maintenance and replacement measures unit prices were determined. The assumptions for the prices are principally based on VCEs' 50 years of experience in the field of bridge construction and maintenance planning.

At first so called present values linked to the starting year of analysis (2011) were derived. Due to the fact that the cost estimation covered 30 years of service life future values were computed based on the historical progression of the construction price index for civil engineering in Austria. For the entire analysis period of 30 years the average construction price index between 1977 and 2010 was applied - leading to an average assumed price increase of 2.39% per year (Fig. 5).

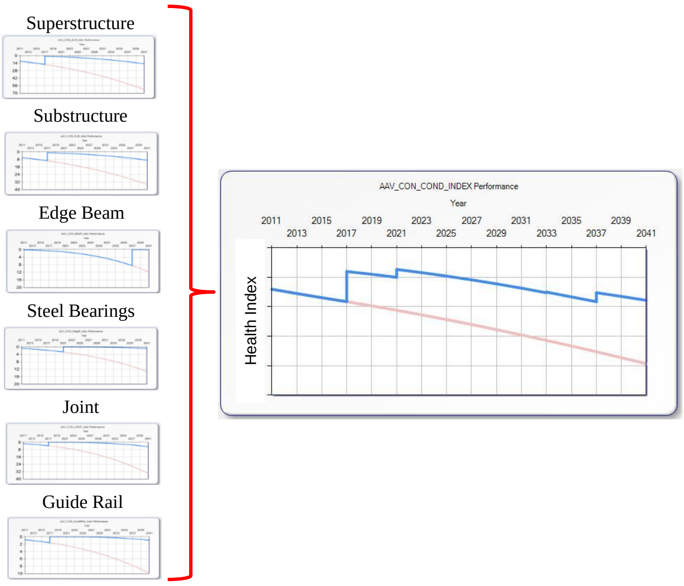

Fig.: 4. Local lifelines (exemplarily) and superposition to global lifeline – "Do nothing" strategy vs. minimize-cost maintenance strategy

To estimate the possible total financial demand the annual sum of future values was discounted to present values applying varying discount rates (3%, 5%, 7.5% and 10%) with regard to different financing models.

In the end the maintenance and replacement costs were summarized for every individual structure, for all assets belonging to certain construction zones, for every structural category within these construction zones and finally for the whole analysed highway section.

4. Results

The lifetime prognosis in 2011 represents the "do-nothing"-strategy from that time on and incorporates the most relevant influence parameters on the structural ageing.

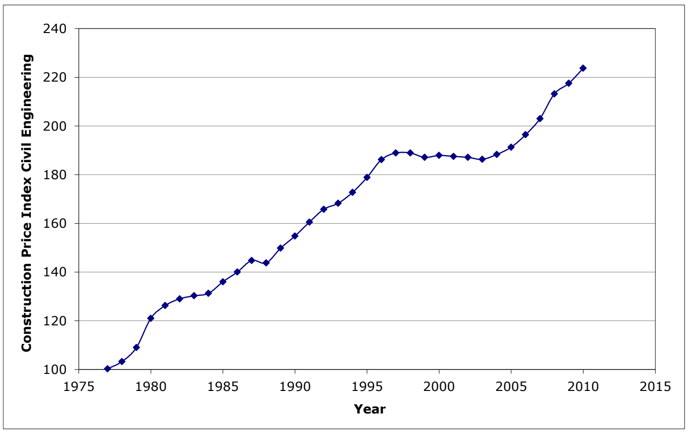

Fig.: 5. Construction Price Index Civil Engineering (bridge construction); time period 1977-2010

4.1 Main aspects (elaborated)

- Amount of derived replacement interventions (per structural member)
- Traffic impediment due to replacement measures (amount of affected lanes)
- Amount of derived heavy maintenance interventions (per structural member)
- Traffic impediment due to maintenance measures (amount of affected lanes)

For further optimization the following influence parameters are considered:

- A defined ceiling price for the whole infrastructure maintenance concept
- Sectioning into construction sites
- Feasibility in terms of time
- Traffic management (two reference solutions A and B were conducted)

4.2 Evaluation on ageing velocity

To evaluate the real deterioration process the field-based ageing velocity was compared to the expectations from the applied ageing model before applying the elaborated maintenance interventions. In general it can be stated, that the deterioration velocity meets the overall expectations, although several structural members tend to remain in better condition under the exposed loading history. At the same time it confirms the underlying, tailored ageing models being appropriate for the present case study.

4.3 Construction zones

To provide a dense scheduling of the necessary construction works on the one hand and minimal traffic impediment on the other hand maintenance measures were merged over certain highway sections. In that step maintenance interventions for highway bridges, for access and exit roads, for culverts and highway crossings and for tunnels and gantries are to be conducted together – demanding reasonable harmonization rules.

The following basic concept for the two reference solution was prepared:

The entire highway section was divided into 3 construction sections of almost equal length for every driving direction (R North / R Centre / R South and L North / R Centre / R South). The length of all construction sections is smaller than the maximum allowable length of 10 km.

In consequence of harmonizing the derived maintenance measures for engineering structures with the pavement maintenance concept the relevant maintenance activities were merged in 2-year-lasting blocks every ten years (2012 & 2013, 2022 & 2023, 2032 & 2033 and finally 2040 & 2041). Of course this block building in full 10-year periods already considers the requirements regarding maintenance condition of the pavement due to the occurring AADT trucks.

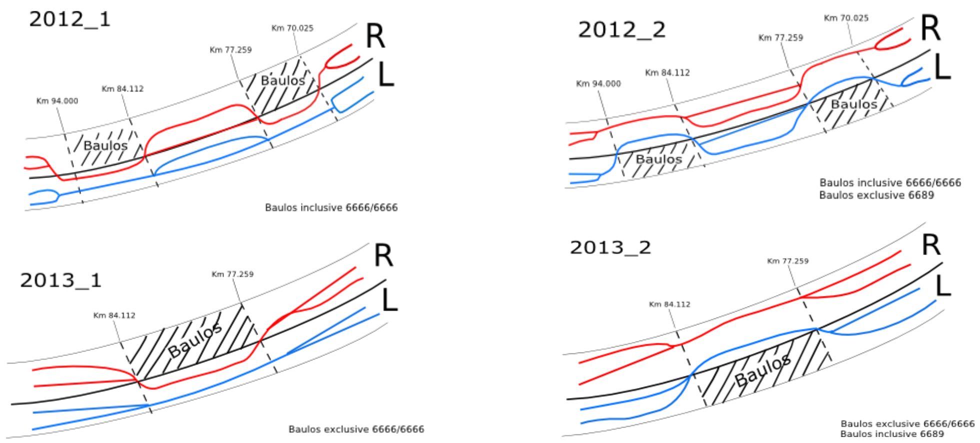

Fig.: 6. Construction zones for blockbuilding

For every construction section a construction period of approximately half a year is scheduled. As not every structure is going to require extensive retrofit measures in the listed timeframes this constraint seems to be realistic (in every 2-year maintenance block certain structures will need selective interventions only). The latter fact can also be taken into account in the course of the detailed planning for the traffic management.

In the first half-year the sections R North and R South will undergo the planned construction activities simultaneously. At the same time the sections R Centre and L Centre serve as the compulsory relief zones (≥ 6 km) between two work zones. In the following half year section construction activities will be moved to L North and L South while the sections R Centre and L Centre act as relief zone again. In the third half-year section R Centre and finally section L Centre (fourth half-year) are addressed.

In consequence of the elaborated solution approximately 2/3 of all merged construction activities are completed in the first year of the stated 2-year block of interventions. In the second year the traffic impediment is focused on the middle of the chosen highway section and therefore already significantly reduced. For further details see Figure 6.

4.4 Reference solution A

Reference solution A simply results from a superposition of the maintenance plans assuming individual maintenance activities on every single structure (Fig. 7).

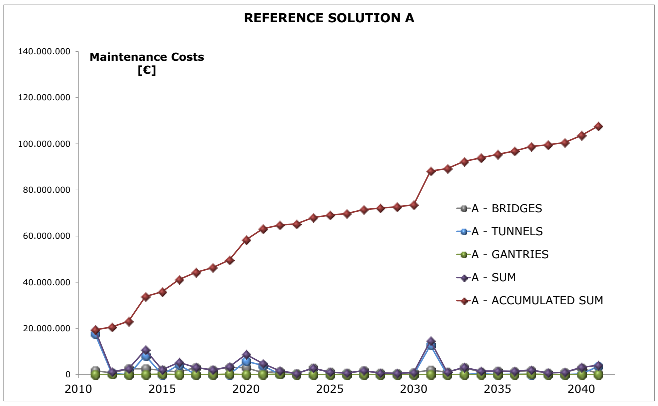

Fig.: 7. Structural type based and accumulated costs – Reference Solution A (individual)

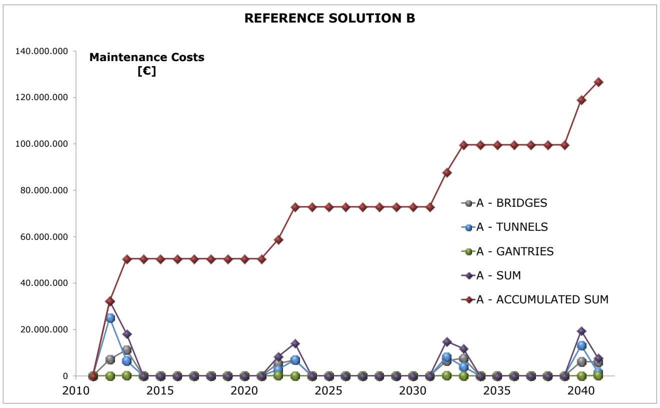

Fig.: 8. Structural type based and accumulated costs – Reference Solution B (blocked)

4.5 Reference solution B

In the course of PPP projects it is common practice that the maintenance concept for engineering structures closely follows the maintenance concept for the pavement. Consequently, certain restrictions concerning resulting block building for maintenance measures are given.

As a pavement management concept was available for the investigated highway section it was used to harmonize the necessary maintenance measures for the assessed engineering structures (bridges, culverts, gantries, tunnels). In other words, the derived maintenance measures were synchronized assigned into appropriate time frames given by the intended maintenance measures from the pavement. Based on that, four time frames at intervals of 10 years (see chapter 4.3) were allocated for maintenance measures during the entire prognosis period of 30 years (Fig. 8).

The calculated maintenance measures from Reference Solution A were now merged in the defined blocks by preponing all measures that would have been scheduled within the following six years. This six year interval is in full accordance to the interval of compulsory visual inspection which is given by the national guideline.

The measures scheduled in the remaining three years before the next block of intervention were necessarily postponed.

Both scenarios utilize the statistic variation of ageing velocity in the course of optimizing the possible strategies.

5 Interpretation

5.1 General

The derived maintenance costs for the different sections are mainly corresponding with the underlying bill of quantities and with regard to structural type and geometrical properties.

An impact due to singularities in the maintenance condition distribution was not identified. There is a uniform distribution of maintenance condition all over the analysed highway section. This statement incorporates the two driving directions (R vs. L) as well as every category of analysed structures (bridges, culverts, access ramps, gantries, tunnels).

The central maintenance sections (L_Mitte & R_Mitte) turned out to be the most cost-intensive ones. The reason is the higher bridge ratio to be maintained (traffic junction Bruck/Mur).

5.2 Details on bridges

In addition to the elaborated maintenance plans and cost calculations further aspects which are relevant for the lifecycle of a structure were analysed and summarized below:

- The average rating of the analysed bridge structures is 2.7. The derived average total life expectancy is 47 years and the corresponding already consumed service life is about 27 years. So far the majority of the analysed structures have already consumed the first third of their total service life. While this time frame up to now tends to be less maintenance- and cost-intensive a high amount of required retrofit measures can be expected in the following 30 years. In general 30-40 % of the replacement value is necessary if the structures should be operated beyond the given analysis period (2011-2041).
- When analyzing the impact of the cross-section design on the calculated life expectancy the corrugated steel turns out to be the most beneficial one while t-beams and composite cross-sections are the most disadvantageous ones. With regard to the life cycle costs again the corrugated steel has to most beneficial (lowest) maintenance costs while the solid cross-section is the most cost-intensive one.
- When analyzing the impact of the static system on the calculated life expectancy the vaults show the most sustainable performance whereas beams and slabs seem to cause the shortest lifelines. The same relations can be observed when analyzing the impact of the static system on the maintenance costs.
- Considering the impact of the material no clear tendency can be observed – neither on the life expectancy nor on the costs.
- Figure 9 gives an insight into the composition of the total maintenance costs depending on the incorporated structural components.

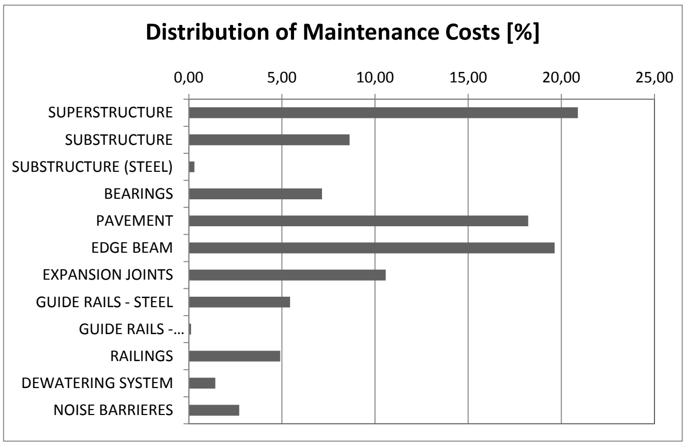

Fig.: 9. Distribution of total maintenance costs

5.3 Impact of block building

Blockbuilding (=Reference solution B) increases maintenance costs by almost 18% compared to individual treatments on every single structure (= Reference solution A). This fact is caused by the tendency to prepone the scheduled maintenance measures in order to ensure that every structural member fulfills the requirements regarding structural safety and operability at every time within the analysis period.

At the same time several treatment measures which would have supposed to be outside the 30-year time frame were preponed into the last block of interventions (2040 & 2041) - to remain consistent with the applied rules on maintenance planning within the analysis period. Thus additional costs arise, that were not considered in Reference Solution A (minimize cost scenario).

6 ACKNOWLEDGMENTS

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