# Bridges

22

Helmut Wenzel

Bridges have been the preferred structures where structural health monitoring (SHM) and performance assessment have been developed. Comprehensive methodologies are available already and good reference is provided in the literature (health monitoring of bridges, Wenzel 2008). Practical application started in the 1990s and has developed into a full life cycle engineering approach (LCE) as desired now. Out of the initial desire to detect damage a methodology to optimise and manage the constructed infrastructure has developed and is being applied widely.

The field of technical diagnostics still remains a process of special expertise, becoming more and more integrated into LCE as it shows relevance in most of the stages of the life of a constructed infrastructure.

## 22.1 Life Cycle Engineering of Bridges

Experience has shown that there is a large variation in life cycle cost depending on initial engineering choices and on chosen maintenance concepts. Variation of 150 to 500 % of construction costs over the entire life cycle has been found. This large variation depends on a number of parameters of which the maintenance concept based on technical diagnostics plays a decisive role. In this chapter, the stages of a typical bridge life cycle are explained and the relevance of technical diagnostics is provided. The scheme given below sketches these stages over time (Fig. 22.1).

**Demand**

Our constructed infrastructures comprise a system of systems. Critical nodes, where demand exceeds capacity, normally identify themselves. In this stage the LCE community can contribute to the establishment of good solutions by optimising various performance scenarios. The data of adjacent nodes of the network are used to compute an optimum scenario for the satisfaction of a demand. Yet, such a global infrastructure management system is rarely applied due to missing procedures and due to its complexity.

**Feasibility**

Besides the detailed performance model, feasibility studies have to be conducted to find the relevant constraints and to establish the conditions for the new structure. The results of this feasibility should be fed back to the performance model created at the demand stage.

**Planning**

Performance models also show the demand on availability of bridges. This influences the choice of materials, structural systems and

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construction methods. This choice then considerably influences the life cycle costs to be expected.

**Permits**

Authorities responsible for granting permissions for construction have the opportunity to look at investments also from the standpoints of environmental protection and social compatibility. This can considerably influence the performance model through the conditions imposed on the project. Therefore, a relevant performance model has to contain procedures that enable the introduction of socioeconomic parameters.

**Contracting**

Technical diagnostics and performance assessment should be an integrated part of any construction contract. This not only comprises the necessary quality control which is already sufficiently established. Decisions that influence the life cycle performance are not yet sufficiently considered in project cycles and require different steps of diagnostics and asset management planning in the early stages of a project. On this subject the potential conflict of interest, namely the contractor checking personally, has to be taken care of.

**Design**

The results of the system optimisation performed from the beginning of the project cycle have to be communicated to the detail designer. Depending on the operation, decisions on conditions and the setting of a structure design have to be taken which go beyond simple structural design issues. So far, unfortunately, concepts mainly based on lowest possible construction costs have been introduced. The enormous impact on the entire life cycle costs has been neglected.

**Construction**

Technical diagnostics have a firm role during construction. The desire would be to integrate all these steps from simple material testing to complex performance control into the life cycle process. This is not yet properly done. This information will improve any prognosis in the future providing background information and deterministic input.

**Operation**

The constructed infrastructure has to be maintained. Various maintenance concepts are available and executed depending on the regional strategy. In Europe, preventive maintenance has been successfully applied and has led to infrastructures in very good condition. Due to shrinking budgets this procedure has to be optimised without sacrificing on safety and quality. Experience has shown that visual inspections overestimate risks and have sometimes led to unnecessary costly interventions. A well-established technical diagnostics, SHM and performance assessment procedure, can help to optimise the preventive maintenance process.

In this section on life cycle, all the classical approaches, methodologies and technologies of SHM are applied. Reference is made to the relevant publications. How to model the life cycle of a bridge is described in detail in the following sections. This standard model can be applied as the basis for the desired performance model.

**Upgrade**

The type, size and timing of upgrades of the infrastructure can be optimised in the performance model. This has a major influence on the total life cycle costs. Various scenarios can be established, in addition to introducing availability considerations and also the flow of revenue (i.e. toll collection).

Ideally, the structure should be equipped with a permanent online monitoring system that provides the necessary data for decision making. Warnings in case that critical safety levels are reached should be given well in advance in order to allow planning and execution of upgrade measures. These kind of SHM systems should be used more and more in the long-term planning procedures in order to predict the latest point of action and give a window for execution of the necessary works.

**Intervention**

When technical diagnostics methodologies have calibrated the actual life cycle curve the predictions of performance over a long period of time becomes feasible. When the performance curve reaches critical levels sometimes emergency interventions become necessary. The

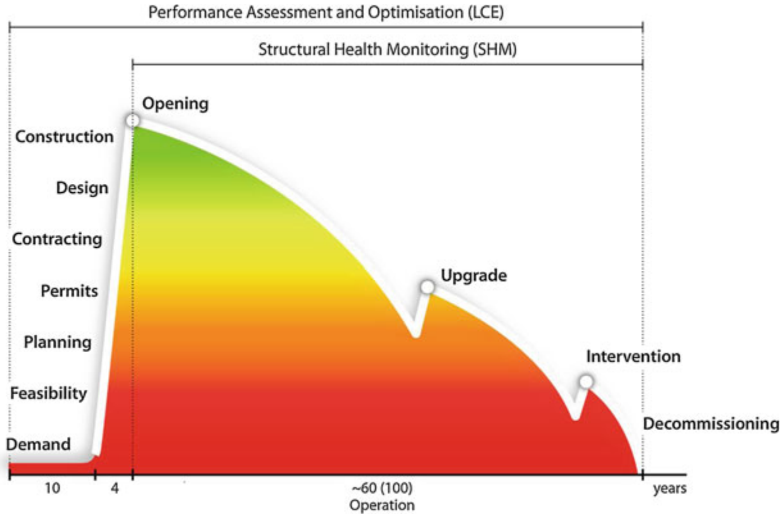


**Fig. 22.1** Typical life cycle of a bridge

diagnostics will enable good decision making on the extent and type of intervention.

**De-commissioning**

Not enough attention is being paid to this issue currently. The help that proper SHM procedures and availability considerations can provide is neglected. It can be expected that in future more attention will be paid to this last element of the life cycle.

The core for the application of this technology is the performance model. In the entire risk management procedure as provided in the new IRIS risk paradigm (result of the European IRIS project), there is a new element together with the assessment of uncertainties that led to a quantitative risk value. Due to the generic definition it produces a figure that allows comparison between projects' assets and structures (Fig. 22.2).

It is to be expected that such approaches will be introduced in the entire sector.

Within the risk management procedure a generic model for the life cycle of bridges has been developed which is described in the subsequent chapters. It has been already introduced into a European standardisation process (CEN—workshop 563) and it can be expected that it finds introduction into EUROCODE with the coming revision.

## 22.2 Life Cycle Methodology and Durability Analysis with Regard to Relevant Heavy-Maintenance Instructions

### 22.2.1 Introduction

Methodologies for the management of the constructed infrastructure have been developed in the **IRIS Project** (CP-IP 213968-2). The basis is the consideration of the entire life cycle of a structure. In bridge management this is performed based on the **BRIMOS**® method developed by VCE, which allows introducing additional quantitative parameters through monitoring techniques.

This paper covers all aspects of the appropriate life cycle analysis for engineering structures. In order to meet the governing requirements regarding integral life cycle analysis, durability, the real degradation process and residual lifetime considerations, the following major aspects are considered for life cycle modelling [4]:

(a) The determination/estimation of the **design life of new** structures

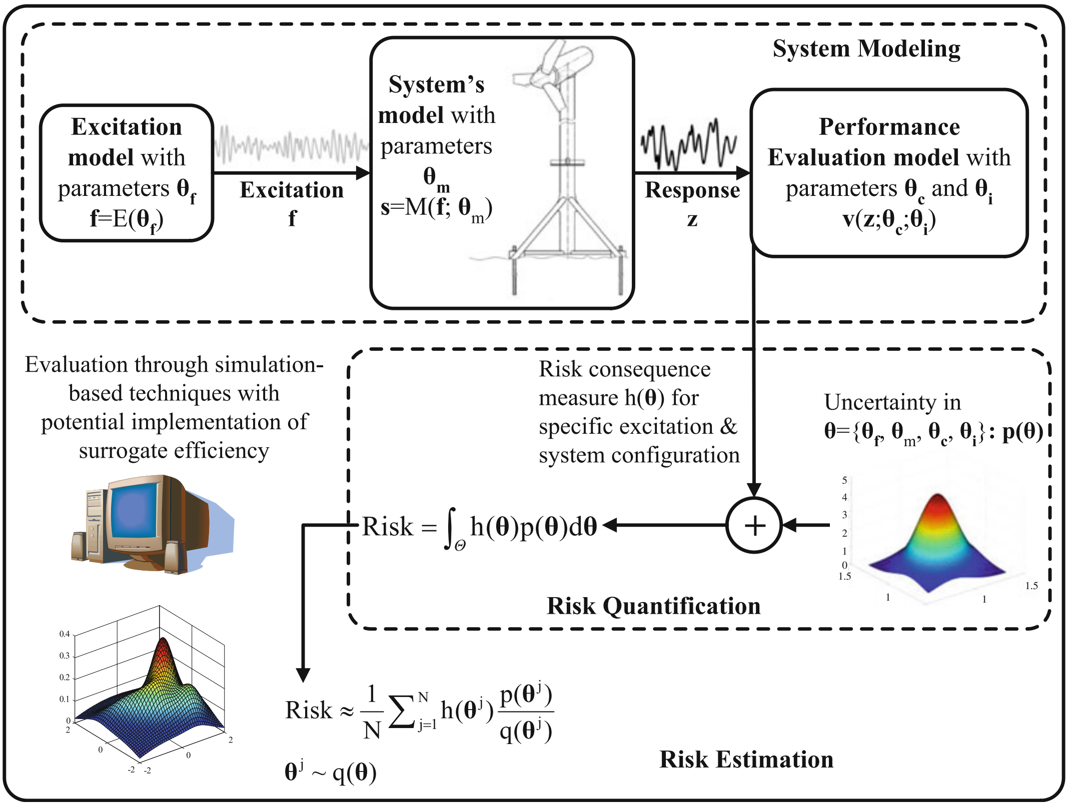
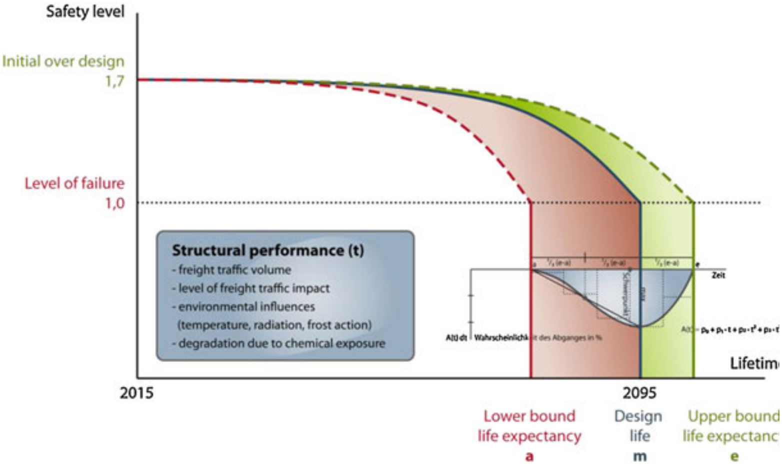


**Fig. 22.2** The IRIS risk paradigm

**Fig. 22.3** Expected (analytical) lifeline of new structures



(b) The determination/estimation of the **residual life of existing** structures

(c) Assessment criteria, whether the **real degradation process**—determined by

- Dynamic Bridge Monitoring
- Visual Bridge Inspection
- Material tests assessing chloride intrusion, compressive strength, carbonaisation

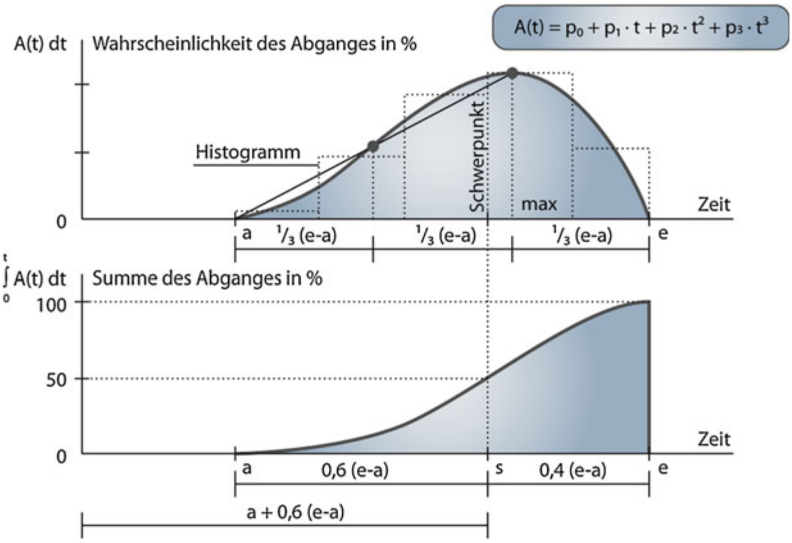


**Fig. 22.4** Failure probability and sum of the failure

(***Durability***) correspond with the assumed and applied life cycle model, in order to take corrective measures in cases of accelerated ageing

(d) Maintenance instructions to guarantee the original design life and preservation of functions.

## 22.2.2 The Determination/Estimation of the Design Life of New Structures

### 22.2.2.1 Primary Load Bearing Structure

Conventional life cycle models are based on the information provided by the respective databases. In order to introduce objective values for assessment, a tailor-made model was developed, which utilised state-of-the-art information from the literature (European, American and Asian) as well 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 following:

All important key performance parameters (KPIs) which influence the life cycle of a structure are acquired. These datasets are implemented into a probabilistic model for service life calculations of the individual items. The reason is to cover occurring uncertainties which have to be also implemented into the established maintenance plan in terms of lower and upper bounds of life expectancy.

The starting point of the bridge's service life—in terms of the safety level—is according to the initial overdesign and depends on the applied design code and certain safety consideration in the course of the static calculations (Fig. 22.3).

#### A **Basic model—Initial and adapted range of lifetime**

To estimate the range of lifetime in the first step, statistic analyses using probability density functions are applied. A basic model covering the operational lifetime of every investigated structure is composed from the followingparameters [5] (Table 22.1):

- Year of construction
- Static system
- Material
- Typical cross section.

Exemplified for the primary loads bearing structure (Fig. 22.4):

a = 45 years…lower bound life expectancy

e = 120 years…upper bound life expectancy

$a' = a{*}k_1{*}k_2{*}k_3\ {*}k_4\ldots$ adapted lower bound life expectancy

**Table 22.1** Parameters which influence the lifetime of a bridge [5]

| Year of construction | $k_1$ | Static system | $k_3$ |
|---|---|---|---|
| <1970 | 0,667 | Vault | 1,2 |
| 1971–1985 | 0,9 | Frames and arches | 1,05 |
| >1986 | 1 | Girder/beam, slab and others | 1 |

| Cross-section design | $k_2$ | Material | $k_4$ |
|---|---|---|---|
| Solid cross-section | 1,05 | Stone | 1,2 |
| Box girder | 1 | Concrete and reinforced concrete | 1,1 |
| T-beam, composite section, etc. | 0,95 | Prestressed concrete, steel–concrete composite | 1 |
| Corrugated profile | 0,8 | Wood | 0,8 |

$e' = e{*}k_1{*}k_2{*}k_3{*}k_4$ adapted upper bound life expectancy

Average design life $= a' + 0{,}6{*}(e' - a')$

To guarantee these stated ranges of theoretical design life of new structures, the assessment is refined by the consideration of the following additional aspects regarding individual minimum requirements:

- Concrete cover
- Concrete quality
- Environment influences
- Maintenance history
- Monitoring activities.

B **Second step—Service lifetime**

To address the deterioration process properly, the following sources of impact affecting the structural performance (t) are to be considered in detail:

- Freight traffic volume
- Level of freight traffic impact
- Environmental influences
- (Temperature, radiation and frost action)
- Degradation due to chemical exposure.

For demonstration purposes, a well-established approach (suggested by A. Miyamoto (Japan) [1] and D. Frangopol (USA) [2]) is described briefly, which covers all the major sources of deterioration impact. For the present demands these suggestions will necessarily have to be broadened and refined due to each of the listed major issues.

Effect of maintenance action on deterioration curve

Initial consideration (NEW Structures)

Soundness (vertical axis) $h_n(t)$:

$h_n(t) = b_n - a_n(t - t_n)^c$

Where:

- t: is the year of service life ending
- n: the number of times a remedial action was taken by year t Index
- $a_n$: the slope of the deterioration curve at the time the nth remedial action has been taken
- $b_n$: the soundness of the existing bridge at the time the nth remedial action has been taken, which changes according to the effectiveness of the remedial action taken
- c: is the power exponent of the deterioration equation

Updating consideration (Existing structures)

The parameters a and b are updated every time repair or strengthening is carried out by using the following equations:

$$b_n = h_n(t_n) = h_n - 1(t_n) + R * \rho$$

$$R = (h_n - 1(t_n - 1) - h_n - 1(t_n))$$

$$a_n = a_0 * \eta_n$$

In the equations, $\rho$ is a parameter for reducing soundness recovery; $a_0$, the slope of the initial

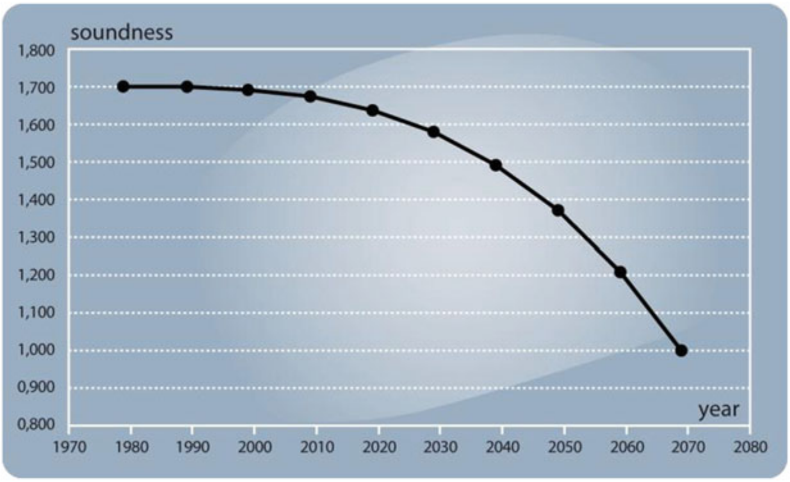


**Fig. 22.5** Example of the calculated graph of the bridge soundness over the time (bridge performance)

deterioration curve; and $\eta$, a parameter for increasing the rate of deterioration (Fig. 22.5).

Example:

$$h_n(t) = 1.5 - 9,766E - 07 * (2059 - 1979)^3$$

### 22.2.2.2 Secondary Load Bearing Structure (Structural Members) and Bridge Equipment

A structure usually consists of a number of components which interact. For each of the components individual performance curves are determined. The structural life cycle curve is the combination of the individual component curves.

Exemplary target values for the life expectation (replacement intervals) are provided in Tables 22.2 and 22.3).

To demonstrate the need and the individual character of maintenance measures for different structural members, their typical lifelines are visualised as a single event on the one hand (Fig. 22.6), and as a repeated event causing several points of intervention during service life of the whole bridge structure (Fig. 22.7).

**Table 22.2** Influence of average daily truck traffic on the mean value of certain structural members' lifetime

| Average daily truck traffic | Pavement (years) | Expansion joint (years) |
|---|---|---|
| >7.000 | 7.5 | 9 |
| ≤7.000<br>>4.000 | 10 | 12 |
| ≤4.000<br>>1.000 | 15 | 18 |
| ≤1.000 | 20 | 24 |

**Table 22.3** Lifetime of particular bridge elements

| Element | Start of failure (years) | Average life span (years) | End of failure (years) |
|---|---|---|---|
| Sealing | 10 | 20 | 30 |
| Edge beam | 16 | 30 | 43 |
| Bearings | 15 | 36.5 | 55 |

## 22.2.3 Determination/Estimation of the Residual Life of Existing Structures

Basically, for primary and secondary load bearing members the same methodology and the same sources of impact are utilised. What makes

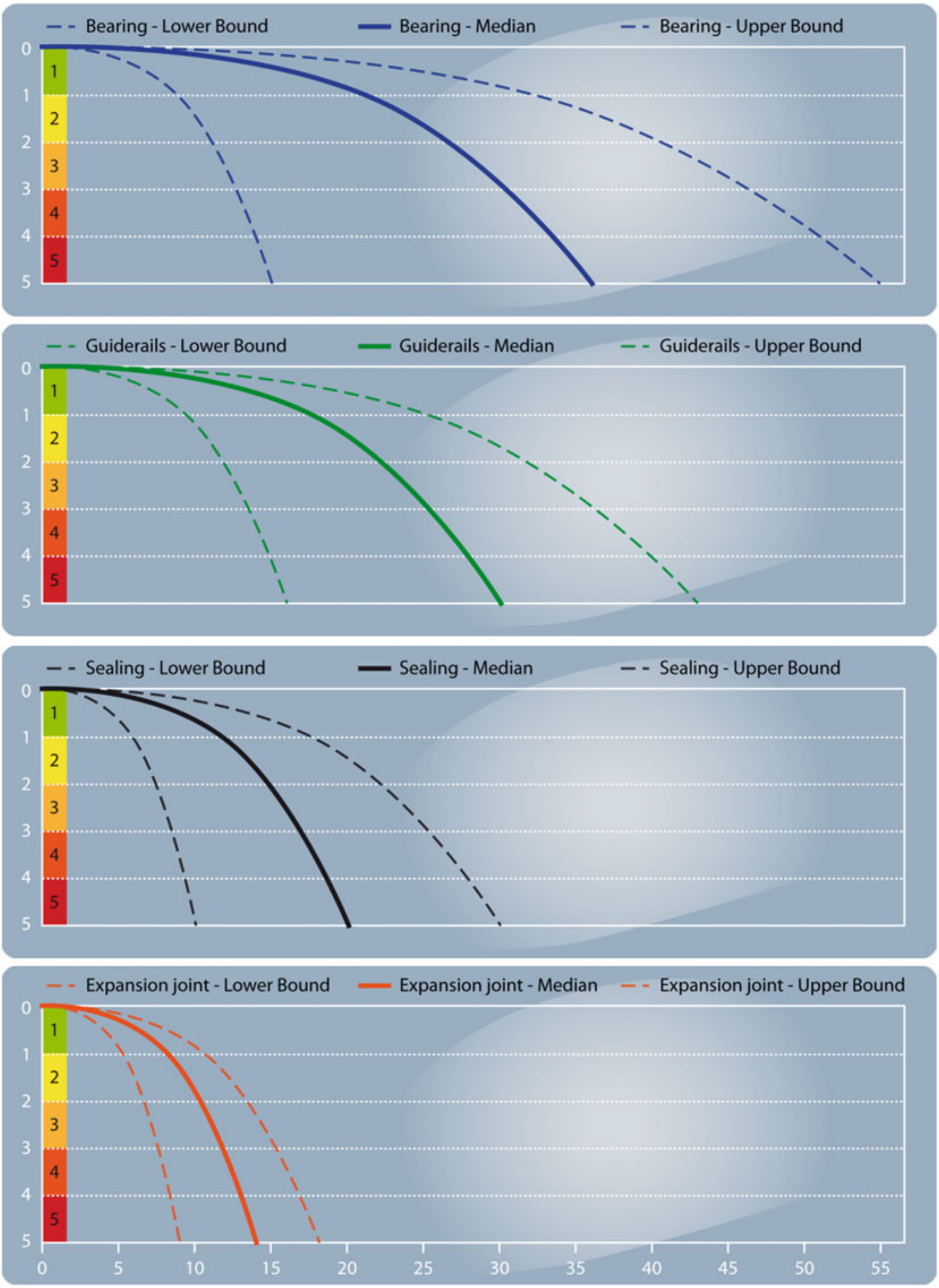


**Fig. 22.6** Comparison of a representative set of individual lifelines for the following succession of structural members: BEARINGS/GUIDERAILS/SEALING and EXPANSION JOINTS

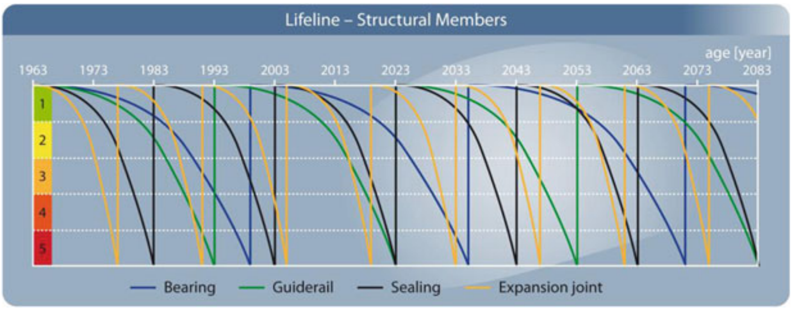


**Fig. 22.7** Telescoping of the individual structural members' lifelines in the course of the whole timeframe of service life of the bridge itself—causing numerous theoretical points of intervention (shown again for BEARINGS/GUIDERAILS/SEALING and EXPANSION JOINTS)

the difference for the analysis itself is the fact that design assumptions are replaced as well as possible by everything, supporting a deeper understanding about the previous lifeline of the investigated structure.

The life cycle curve of a structure is determined from the superposition of the individual curves of its components and elements. The following categories are considered:

- Superstructure
- Substructure
- Expansion joints
- Bearings
- Wearing surface
- Sidewalk
- Railings and guidance
- Other bridge equipment
- Drainage and dewatering system
- Other (spare).

The assessment according to a conventional visual inspection is part of the present life cycle model. A typical assessment sheet according to the Austrian RVS 13.03.11 [6] is provided in tabular form. The individual elements are individually assessed (Table 22.4).

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

(a) Orginal static calculation (structural design)
- Possible reduction of safety level reflecting a paradigm changes from previous binding codes to the current ones

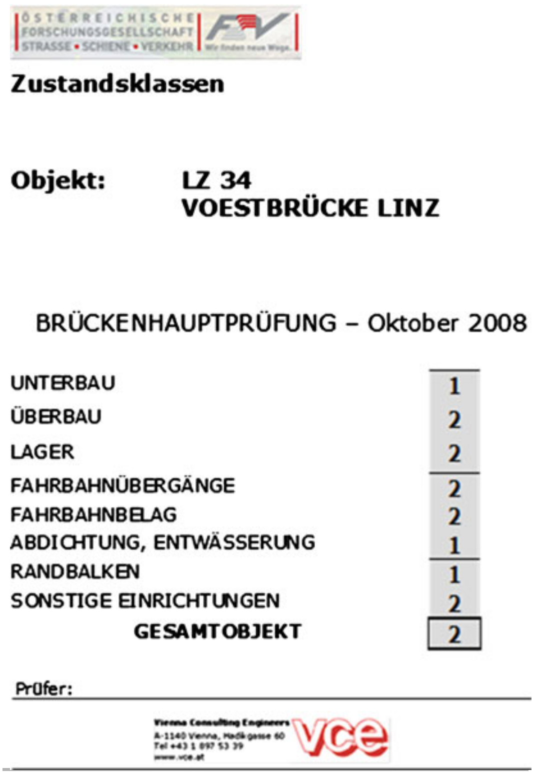
(b) Judgement/rating from bridge inspections (reports)
(c) Performed monitoring campaigns
(d) Schedule of performed maintenance and rehabilitation measures
(e) Loading history (historical traffic data)
(f) Material tests (chloride intrusion/compressive strength, carbonisation, etc.)
(g) Data on the environmental conditions.

These datasets are merged via maintenance condition matrix as provided below (Fig. 22.8) in order to determine the respective life cycle curve analytically. The corresponding safety level is defined as the offset between the initial safety level in the year of construction until the present date of judgement.

Any change in assessment, for every element separately, generates a new assessment routine and changes the character of the life curve. The continuative progression is derived in a similar way to a new structure—but of course this depends on the former impact. Eventual improvements through upgrade or repair works are also considered.

The use of the established maintenance condition matrix supports the individual determination of the current remaining structural resistance and the present risk level by means of a comprehensive weighting function (Fig. 22.9).

**Table 22.4** Visual inspection results from Austrian RVS 13.03.11 [6]



**Zustandsklassen**

**Objekt:** **LZ 34**
**VOESTBRÜCKE LINZ**

BRÜCKENHAUPTPRÜFUNG – Oktober 2008

| | |
|---|---|
| UNTERBAU | 1 |
| ÜBERBAU | 2 |
| LAGER | 2 |
| FAHRBAHNÜBERGÄNGE | 2 |
| FAHRBAHNBELAG | 2 |
| ABDICHTUNG, ENTWÄSSERUNG | 1 |
| RANDBALKEN | 1 |
| SONSTIGE EINRICHTUNGEN | 2 |
| **GESAMTOBJEKT** | 2 |

Prüfer:

- Spread of remaining lifetime 16/30/40 years

The model is constructed in a fully dynamic manner and runs the life cycle curve processing anytime after a parameter update is received. Depending on the quality of the received information the standard deviation is increased or decreased, respectively.

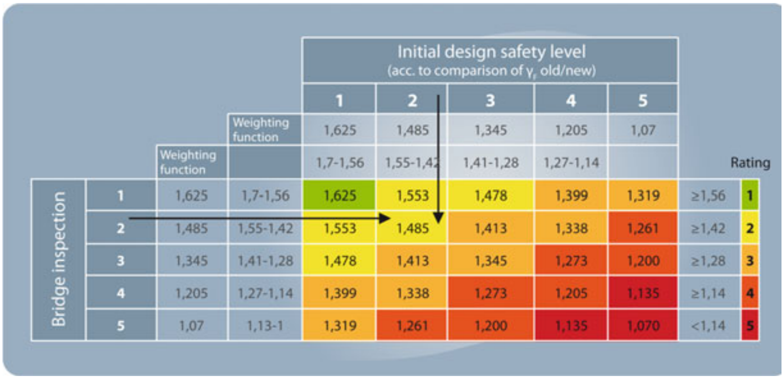
The theoretical–analytical life cycle curve starts with the year of construction. Whenever new information becomes available an update is computed. The example shows three curves which are:

- Theoretical life cycle curve showing the desire over design and expected lifetime of 90 years
- Assessment of the actual life cycle curve after construction considering inspection results (lifetime reduced to 77 years)
- Remaining lifetime assessment at a specific date (i.e. 30 years after construction) derived from a detailed assessment campaign. Life expectation is reduced to 58 years.

It may be mentioned here that in most of the detail campaigns additional capacities are detected rather than reductions as shown in the above example.

### 22.2.4 Assessment Criteria Whether the Real Degradation Process (Determined by Bridge Diagnosis) Corresponds to the Assumed and Applied Life Cycle Model in Order to Take Corrective Measures in Cases of Accelerated Ageing

Continuous condition assessment is a basic prerequisite for an adjusted maintenance planning within the upcoming service life. In the course of being exposed to operational service life new structures are becoming existing



| | | | | Initial design safety level (acc. to comparison of $\gamma_f$ old/new) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | | |
| | | | Weighting function | 1,625 | 1,485 | 1,345 | 1,205 | 1,07 | | |
| | | Weighting function | | 1,7-1,56 | 1,55-1,42 | 1,41-1,28 | 1,27-1,14 | | | Rating |
| Bridge inspection | 1 | 1,625 | 1,7-1,56 | 1,625 | 1,553 | 1,478 | 1,399 | 1,319 | ≥1,56 | 1 |
| | 2 | 1,485 | 1,55-1,42 | 1,553 | 1,485 | 1,413 | 1,338 | 1,261 | ≥1,42 | 2 |
| | 3 | 1,345 | 1,41-1,28 | 1,478 | 1,413 | 1,345 | 1,273 | 1,200 | ≥1,28 | 3 |
| | 4 | 1,205 | 1,27-1,14 | 1,399 | 1,338 | 1,273 | 1,205 | 1,135 | ≥1,14 | 4 |
| | 5 | 1,07 | 1,13-1 | 1,319 | 1,261 | 1,200 | 1,135 | 1,070 | <1,14 | 5 |

**Fig. 22.8** Maintenance condition matrix—assessment scheme

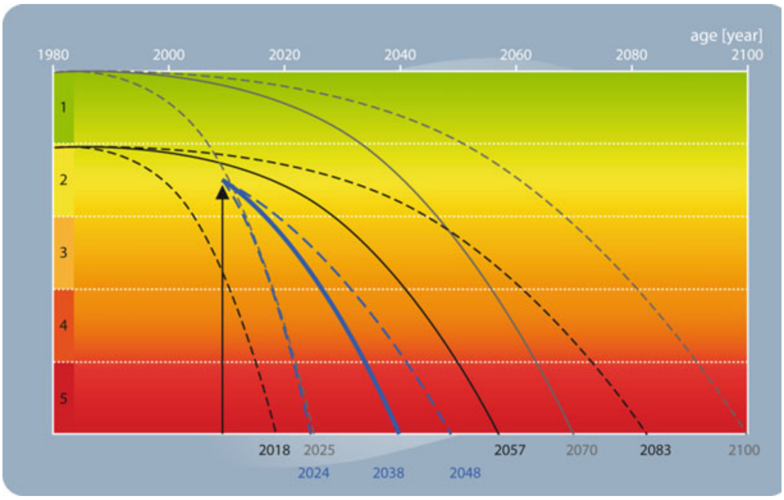


**Fig. 22.9** Enhanced lifetime prognosis of an existing bridge by means of visual inspection 2008 and static safety evaluation—reflecting a paradigm change from previous binding design code to Eurocode

structures. Thus, the methodological approach based on the determination of the design life of new structures must necessarily be used and adapted due to the determination of residual lifetime of the existing structures.

To cover this certain demand, a strong emphasis is to be put on in situ investigations. The following three major components of structural assessment are to be incorporated in order to be aware of the real ageing process of bridge structures and structural members:

- Dynamic Bridge Monitoring
- Visual Bridge Inspection
- Material tests assessing chloride intrusion/ compressive strength, carbonatisation (*Durability*).

#### 22.2.4.1 Bridge Assessment Based on Dynamic Measurements by Means of BRIMOS®

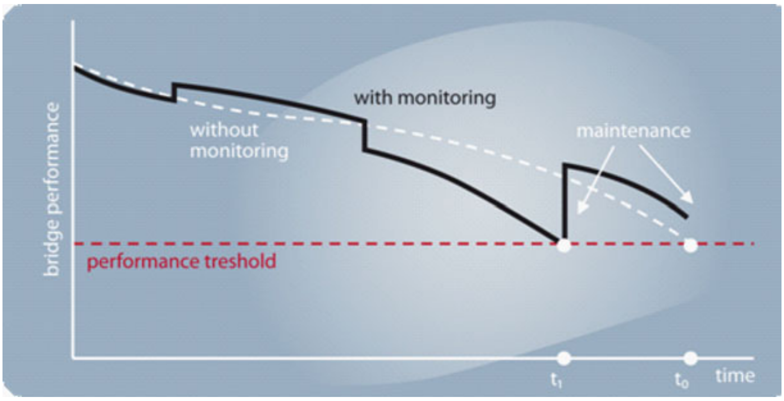
Complementary to visual bridge inspection from common practice full-scale dynamic monitoring turned out to be a powerful evaluation tool that reflects structural resistance and load bearing capacity in a most suitable manner (Fig. 22.10).

SHM is the implementation of damage identification strategies to civil engineering structures such as bridges. Damage is defined as changes to the material and/or geometric properties of the structures, including changes to the boundary conditions (e.g. settlements) and system connectivity. Appropriate SHM by measuring the structural behaviour with various kinds of sensors allows an objective assessment of the structures condition and actual performance. This is the basis for reliable damage detection, the prediction of the future performance and precise maintenance planning. SHM allows increasing the regular visual inspection intervals for bridges, and therefore a reduction of inspection caused traffic impediment. The BRIMOS® SHM concept knows different levels of investigation depths. The appropriate investigation type has to be chosen for each bridge individually according to its size, age, condition, building type, load level and accessibility for a suitable investigation concept. SHM helps to avoid unnecessary repair works and to minimise maintenance caused traffic impediment.

(1) Spot Observation—The **BRIMOS®** Recorder
(2) Periodic Monitoring—The **BRIMOS®** Measurement System
(3) Permanent Monitoring with **BRIMOS®**

A constant comparison between expected and measured structural integrity (multi-level assessment of the investigated Lifeline) is done to be aware of the velocity of *structural ageing*. Figure 22.11 provides an example for a structure which has been assessed in case of the application of successive periodic or permanent monitoring.

**Fig. 22.10** Bridge performance (soundness) over time



Thus, system constantly determines the current safety level in order to refine and calibrate the demanded prognosis about residual lifetime.

By means of the present approach, the need for maintenance measures can be evaluated in a timely manner in order to avoid costly and unnecessary rehabilitation measures on the one hand or already inappropriate measures on the other hand (Fig. 22.12).

BRIMOS® [7] offers a well-defined rating system for investigated structures. This classification allows a fast identification on the structure's integrity as well as the corresponding risk level based on measured dynamic parameters, visual inspection, Finite Element Model-update and reference data (BRIMOS® Database). By merging these sources of information, the major task of determining the exact present position of the analysed structure on its lifeline is covered. Furthermore, the result is a classification which is related to a predefined risk level. The experience of about 1,000 investigated structures worldwide has been incorporated into the assessment procedure.

#### 22.2.4.2 Summarising Emphasis on Life Cycle Analysis

Based on the VCE's experience in the field of structural bridge assessment (about 1,000 structures worldwide have been investigated), it has to be stated that life cycle considerations depend on much more than just the task of chloride-induced corrosion (covered with the Model Code for Service Life Design [3] that is used in many countries in context with residual lifetime calculations.

Even if the latter reflects the degradation process of secondary load bearing members quite well, the deterioration process for Primary Load Bearing members necessarily considers the following sources of impact—affecting the Structural Performance (t):

- Freight traffic volume
- Level of freight traffic impact
- Environmental influences (temperature, radiation, frost action)
- Degradation due to chemical exposure.
 Parameters like
- Cross-section design
- Static system
- Material
- Concrete cover
- Concrete quality (concrete grade).

Providing structural redundancy leads to a lifeline differing very much from the one that observes only chloride impact in terms of its qualitative (progression of the ageing function) and quantitative (resulting time span) consequences. This fact is evident when comparing Figs. 22.13 and 22.14.

It is clearly evident that the real degradation process can only be sufficiently covered with in situ investigations, especially full-scale dynamic monitoring, which reflect structural resistance

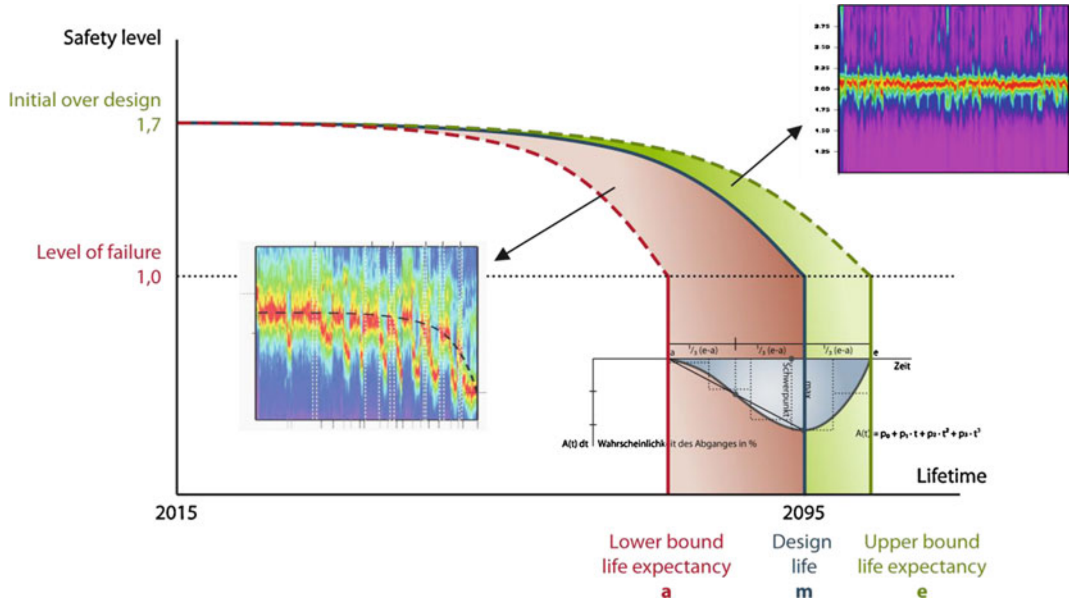
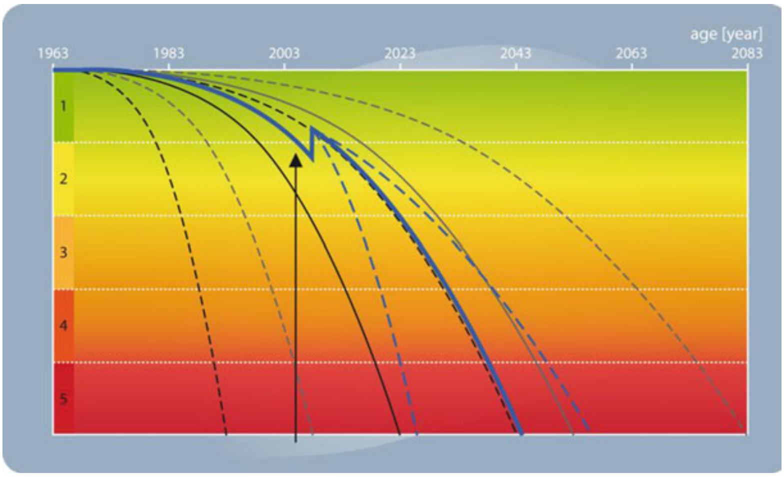


**Fig. 22.11** Expected (analytical) lifeline of structure, validated with dynamic measurements (BRIMOS®)

**Fig. 22.12** Life cycle curve with regard to global safety: The enhanced prognosis is based on the visual inspection in 2005, the dynamic safety evaluation in 2006/2007 and the successive rehabilitation and strengthening in 2008. A narrow spread of remaining lifetime (16/30/40 years) is the result



and load bearing capacity in a most suitable manner.

Relying exclusively on the Model Code for Service Life Design [3] based, chloride analysis-driven approach seems to be very conservative—reflecting only parts of reality, especially when dealing with the primary load bearing structure. The present suggestions are stated with regard to unnecessary repair works and to minimisation of maintenance caused traffic impediment.

Extensive case studies using a huge amount of available data from chloride intrusion measurements along certain highway projects were done. These results were also compared to results from the present, integral Life Cycle Analysis—this comparison fully confirms the chosen methodological approach.

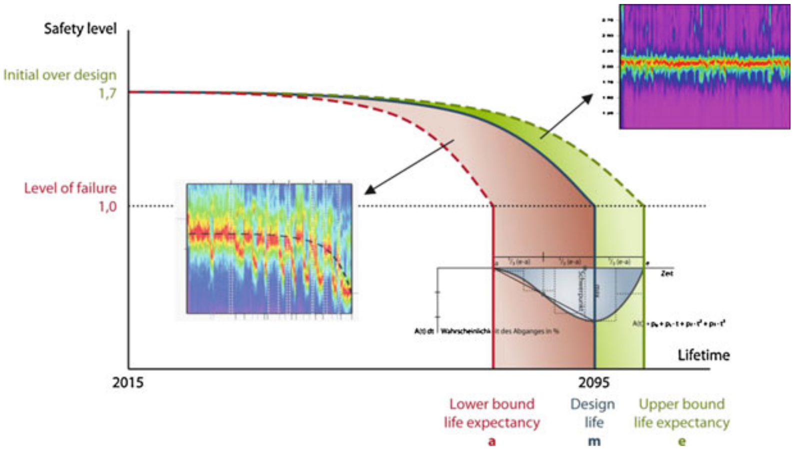


**Fig. 22.13** Expected (analytical) lifeline of structure, validated with dynamic measurements (BRIMOS®) and bridge inspection

## 22.2.5 Maintenance Instructions to Guarantee the Original Design Life and Preservation of Functions

Regarding Life Cycle and Maintenance projects, the contractor is usually obliged to supply principal maintenance instructions for the RWS investigated infrastructure to guarantee that the original design life of the structures can be achieved.

In the course of the life cycle analysis, maintenance plans by means of intervention schedules and by means of corresponding bill of quantities are prepared for the existing and new structures.

### 22.2.5.1 Structural Members Considered in the Maintenance Instructions

To guarantee the functional capability of a bridge object during the entire contract period (of course considering the overall design life) the individual service life of the bridge's structural members has to be considered. Thus, the elaborated maintenance plans deliver all necessary measures for each single bridge element. The following, chosen categorisation reflects the common composition of available inspection reports as well as the aspired maintenance plans:

- Superstructure
- Substructure
- Bearing
- Edge beam
- Expansion joints
- Guide rail
- Railing
- Drainage.

The used categorisation is coherent with the common practice all over Europe.

These basis intervals are adjusted using functions of failure probability (see (Fig. 22.4) and (Table 22.3) in this chapter), considering the general conditions and sources of impact during the operating phase, which can be variable over the years, such as:

- Freight traffic volume
- Level of freight traffic impact
- Environmental influences (temperature, radiation and frost action)
- Degradation due to chemical exposure (a main factor in these considerations is the chloride initiated reinforcement corrosion)
- Bridge inspections (assessment/rating).

As a result of the developed methodology, expected mean values for the operational lifetime and upper and lower bounds of the life expectancy for the single bridge elements are determined, which support the operator's

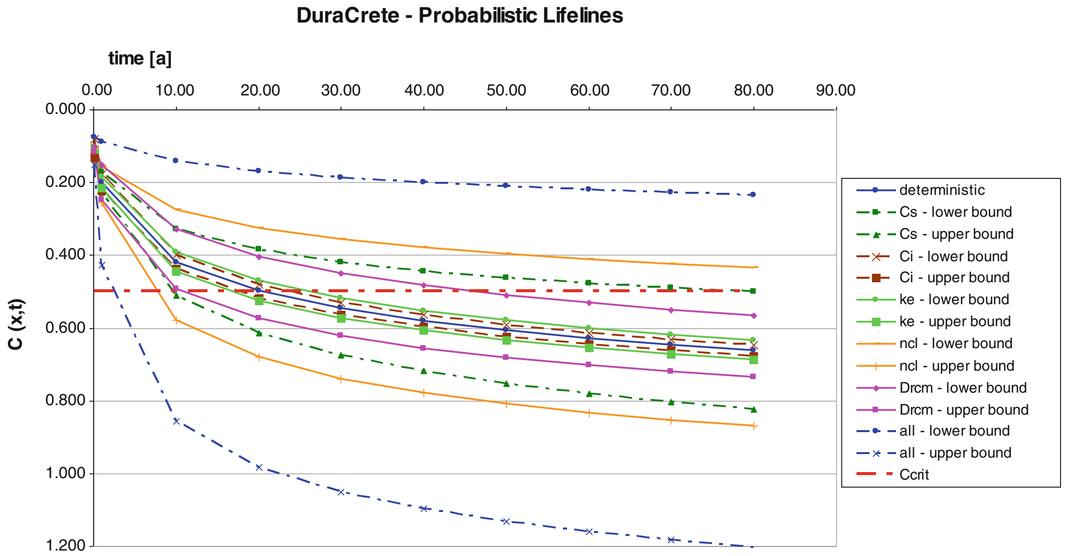


**Fig. 22.14** Lifelines taken from chloride penetration measurements—analysis over time

decision process in the course of maintenance planning as it enables the scheduling of appropriate maintenance instructions.

### 22.2.5.2 Harmonised Maintenance Intervals and Specification of Services

Based on the knowledge about the average duration of operational life and the individual rating from site-inspection, an updated ageing function of all the structural members during the contract period can be derived.

The previous table (Table 22.5) gives an overview about service life **regarding replacement and heavy maintenance for the introduced categories of structural components**—taken from relevant references. Finally, all the possibilities regarding periods of replacement and maintenance are to be harmonised to meet the demands of the certain investigation (see Table 22.5 final column).

To clarify the utilisation of the listed figures, they are exemplified based on the Life Cycle of a single edge beam:

In the Inspection Reports replacement is scheduled for every 33 years. Additionally, there is a probabilistic envelope regarding replacement of ±16 years. In order to ensure a prolongation of 33+16 = 49 years, a relatively late maintenance measure after 25 years is necessary.

While Table 22.5 differentiates only between replacement and maintenance, Table 22.6 specifies different services in the course of a maintenance measure relating to the decisive structural members.

### 22.2.5.3 Application on the Structures of a Certain PPP-Project

In the case of the EXISTING STRUCTURES, a multi-stage concept was developed to provide a comprehensive maintenance plan for the contract period. In the first stage, a maintenance schedule—starting from the year of construction and using the harmonised maintenance intervals only—is developed, considering the whole service life of the object. This stage can be understood as an elaboration stage of **expected (theoretical) maintenance plans** according to common practice.

Complementary to this first stage the maintenance plan in the second stage reflects **probably the already existing, officially scheduled maintenance measures** of the latest inspection reports only (Fig. 22.15 at the bottom). For structures, where no official maintenance plans

**Table 22.5** Maintenance intervals due to different kind of references and harmonised intervals

| Intervention | Maintenance interval [years] | | | | |
|---|---|---|---|---|---|
| | OBR | DISK | MIOK | Literature | ALanes 15 Harmonisation |
| Superstructure | | | | | |
| Concrete | | | | | |
| Replacement | | 90 | 90 | 90 | 90 |
| Maintenance | 30 | 30 | 30 | | 30 |
| Anti-chloride measures existing structures | – | – | – | – | if required |
| Anti-chloride measures new structures | – | – | – | – | if required |
| Steel | | | | | |
| Replacement | | 90 | | | 90 |
| Maintenance | | 20 | | | 25 |
| | | | | | |
| Substructure | | | | | |
| Concrete | | | | | |
| Replacement | | 90 | | 90 | 90 |
| Maintenance | – | 30−60 | | | 30 |
| Anti-chloride measures existing structures | – | – | – | – | 12 |
| Anti-chloride measures new structures | – | – | – | – | if required |
| | | | | | |
| Guide rail | | | | | |
| Replacement | – | 50 | 60 | 30 (−14/+13) | 30 |
| Maintenance | – | – | 25 | | – |
| | | | | | |
| Bearing, support | | | | | |
| Rubber | | | | | |
| Replacement | 50 | 50 | 45 | | 50 (±20) |
| Maintenance | – | – | – | | – |
| Steel, teflon and rubber | | | | | |
| Replacement | 50 | 50 | | 36 (−16/+19) | 50 (±20) |
| Maintenance | | 30 | | | 30 |
| | | | | | |
| Edge beam | | | | | |
| Replacement | – | 33 | 33 | 30 (−14/+13) | 33 (±16) |
| Maintenance | – | 25 | 25 | 20 | 25 |
| Anti-chloride measures existing structures | – | – | – | – | 12 |
| Anti-chloride measures new structures | – | – | – | – | if required |
| | | | | | |
| Expansion Joints | | | | | |
| Steel—heavy traffic | | | | | |
| Replacement | 30 | 25−35 | | 14 (−5/+4) | 30 |
| Maintenance | 10 | 10−15 | | | 10 |
| Steel—light traffic | | | | | |
| Replacement | 30 | 25−35 | | 45 (−15/+15) | 30 |
| Maintenance | 10 | 10−15 | | | 10 |

(continued)

**Table 22.5** (continued)

| Intervention | Maintenance interval [years] | | | | |
|---|---|---|---|---|---|
| | OBR | DISK | MIOK | Literature | ALanes 15 Harmonisation |
| Steel profile, synthetic resin concrete and rubber | | | | | |
| Replacement | 15–20 | 12 | 30 | | 30 |
| Maintenance | 5–10 | 4 | 20 | | 10 |
| Special construction for lifting bridge | | | | | |
| Replacement | | | | | 40 |
| Maintenance | | | | | 10 |
| | | | | | |
| Guide rail | | | | | |
| Concrete | | | | | |
| Replacement | – | 50 | 60 | 30 (−14/+13) | 30 |
| Maintenance | – | – | 25 | | – |
| Steel | | | | | |
| Replacement | 20 | 50 | 62 | 30 (−14/+ 13) | 30 |
| Maintenance | – | 20 | 12 | 15 | – |
| Steel—“(middle) stijf” | | | | | |
| Replacement | | 25 | | | 30 |
| Maintenance | | | | | – |
| | | | | | |
| Railing | | | | | |
| Replacement | 20 | 50 | 62 | 30 (−14/+13) | 30 |
| Maintenance | – | 20 | 12 | 15 | – |
| | | | | | |
| Guide rail | | | | | |
| Steel | | | | | |
| Replacement | – | 50 | 50 | | 50 |
| Maintenance | – | 11 | | | 11 |

are available the dates of intervention according to the standard intervals are assumed.

To get a comprehensive individual maintenance plan for every structure based on the introduced life cycle methodology the two previous plans have to be merged (=> from Fig. 22.15 to Table 22.7).

Know-how gained in a large number of projects in the field of bridge engineering and health monitoring strongly supported this merging process which is mainly composed by means of:

- The structure’s individual maintenance history during the previous service life (if a documentation is available) => **key indicator** “**latest intervention**”,
- The **latest rating** of the respective structural member (**bridge inspection**),
- **Probably already scheduled upcoming maintenance measures**—as a manner of principle the latest versions are considered, occasionally also the previous ones are of relevance (including complementary information),
- **Harmonised standard intervals** regarding replacement and heavy maintenance of structural members (Table 22.5).

**Table 22.6** Services in the course of a maintenance measure

| Structural members | Material | Intervention | Services |
|---|---|---|---|
| Superstructures | Concrete | Maintenance | Deep injection of cracks |
| | | | Repair of spallings, holes and concrete pockets as well as removal of contamination of the concrete surface |
| | | Anti-chloride measures | Renewal of the concrete surface coating to protect structural members from chemical exposure—esp. hydrochloride impact (if required) |
| | Steel | Maintenance | Coating of steel surfaces to prevent corrosion processes |
| | | | Local maintenance of corrosion and defective coating |
| Substructure | Concrete | Maintenance | Deep injection of cracks |
| | | | Repair of spallings, holes and concrete pockets as well as removal of contamination of the concrete surface |
| | | Anti-chloride measures | Renewal of the concrete surface coating to protect structural members from chemical exposure—esp. hydrochloride impact |
| Bearings | Rubber | Replacement | Maintenance-free elastomeric bearings |
| | Steel, rubber | Replacement | |
| | | Maintenance | Replacement of single components (e.g. protective covering) |
| | | | Removing of contaminations affecting the structural member's operability |
| | | | Local repair of corrosion and defective coating |
| Edge beam | Concrete | Replacement | |
| | | Maintenance | Deep injection of cracks |
| | | | Repair of spallings, holes and concrete pockets as well as removal of contamination of the concrete surface |
| | | | Repair of the joint between pavement and edge beam |
| | | Anti-chloride measures | Renewal of the concrete surface coating to protect structural members from chemical exposure—esp. hydrochloride impact |
| Expansion joint | see specification | Replacement | |
| | | Maintenance | Pouring of cracks and joints along expansion joints |
| | | | Removing of contaminations affecting the structural member's operability |
| | | | Replacement of the sealing profile |
| Guide rail | Steel | Replacement | |
| | Concrete | Replacement | |
| Railing | Steel | Replacement | |
| Drainage | | Replacement | Local renewal of the piping system |

In the case of the NEW STRUCTURES, the individual maintenance plans are again based on the established life cycle methodology, starting from the year of construction and again using the harmonised maintenance intervals. In the first step a maintenance plan for the whole service life is created, in the second step the detailed maintenance schedule focuses already on the contract period.

After all maintenance schedules have been stated by means of points of interventions so far, the refined maintenance plans are already linked with the individual bills of quantities for every structure, which are necessarily accumulated

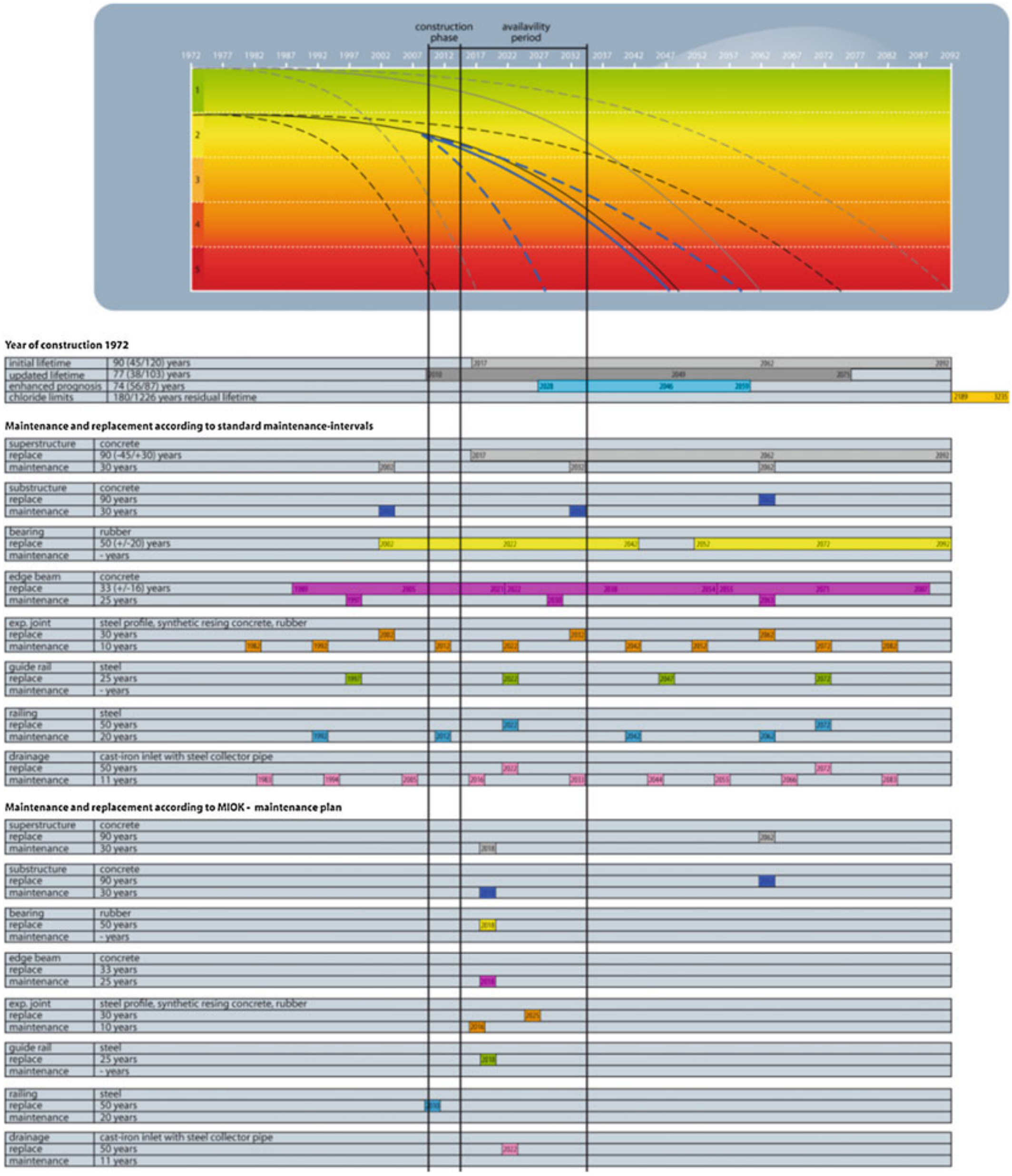


**Fig. 22.15** Maintenance plan—first and second stage

over the whole contract period. This is done for every single object (Fig. 22.15).

Afterwards maintenance plans for the existing structures and for new structures for each traffic junction are merged and harmonised. To avoid unnecessary individual repair works and to minimise maintenance caused traffic impediment these formerly derived accumulated maintenance schedules of one traffic junction are adapted and combined ultimately (in case of doubt the shifting of maintenance measures into the determined "blocks of intervention" follows a conservative tendency.

This final life cycle methodology output follows the demands of civil engineering feasibility.

**Table 22.7** Example for a comprehensive—but still individual—maintenance plan during the contract period—existing structure

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Superstructure (concrete) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Maintenance | 1<br>9<br>7<br>2 | x | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Maintenance – anti chloride measures | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Superstructure (steel) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Maintenance | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Substructure (concrete) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Maintenance | 1<br>9<br>7<br>2 | x | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Maintenance – anti chloride measures | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Bearing (elastomer) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | 1<br>9<br>7<br>2 | | | | | | | | x | | | | | | | | | | | | | | | | | | 1 |
| Bearing (elastomer with steel retainment) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Maintenance | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Bearing (pot bearings) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Maintenance | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Edge beam (concrete) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | 1<br>9<br>7<br>2 | x | | | | | | | | | | | | | | | | | | | | | | | | | 1 |

(continued)

**Table 22.7** (continued)

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maintenance | 1972 | | | | | | | | | | | | | | | | | | | | x | | | | | | 1 |
| Exp. joint (steel profile/concrete/rubber) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | 1972 | x | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Maintenance | 1972 | | | | | | | | | | | x | | | | | | | | | | x | | | | | 2 |
| Exp. joint (finger joints) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Maintenance | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Guide rail (concrete) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | 1972 | x | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Maintenance | – | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | 1972 | x | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Maintenance | 1972 | | | | | | | | | | | | | | | | | | | | | x | | | | | 1 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Replacement | 1972 | | | | | | | | | | | | x | | | | | | | | | | | | | | 1 |

All Bill of Quantities listed within the present tables are to be understood in terms of the total mass for maintenance measures per component. A certain percentage for individual structural members cannot be determined directly. For the existing structures, the inspection reports do not give detailed information regarding the extent of affected degradation. Consequently, it is again difficult to predict this extent of affected degradation for new structures.

This task has necessarily to be solved in the course of price calculation on the one hand and risk considerations on the other hand.

#### 22.2.5.4 Review of Maintenance Instructions and Update of Maintenance Plans

The prognosis of the structural condition, especially of the condition of secondary structural elements is a complicated process. As the prognosis period is relatively long, considerable deviations are not unlikely figure

In the end, the real maintenance plans of the engineering structures have to be coordinated with the pavement maintenance which also can differ from the current predictions—mainly due to varying traffic load intensity.

Therefore, a continuous review and adaptation of the maintenance instructions during the contract period is necessary. It is proposed to implement this updating process in a semi-automatic way. This means that all the acquired condition data from the structures and from the pavement are collected by a Management Information System automatically. The results of the visual inspection are also imported.

The system software automatically updates the life cycle curves of all structures and structural elements and suggests an adapted maintenance plan for the rest of the contract period. This maintenance plan has to be proved and adapted manually in agreement with the pavement maintenance and the operational requirements. This continuous review of the maintenance plans for the structures in coordination with the pavement maintenance allows a minimisation of the traffic impediment and a maximisation of the availability.

#### 22.2.5.5 Cost Model

The life cycle curves of each single element of a structure are connected to typical cost factors. For that purpose the respective unit costs per element are to be assigned to each structure individually. The computed financial demand is automatically computed for the remaining life period. It can be provided as demand for preventive maintenance or as required retrofit investment expected for a specific date. A connection to the actual provided maintenance investment over the history is possible, enabling this model to be used for the optimisation of costs. Parameter studies can be easily performed through variation of individual parameters.

### 22.2.6 Major Remaining Risks

In cases a so-called **major structure strategy** is followed, where only a set of bridges is chosen in order to investigate these in detail and extrapolate the output to all other bridges, this has to be done very carefully. The reason is that huge deviations between the existing structures can arise, while new structures can be treated in this manner without any problem.

Heterogeneous structural documentation (does the evaluation of the existing object really reflect the latest maintenance condition state?)

Available documentation can lack in:

- Completeness of information (drawings, consideration of structural details also)
- Documentation about maintenance history
- Up-to-date aspects
- Well-defined judgements (varying quality of elaborated reports).

## References

1. Miyamoto, A., Ishida, J.: Bridge Maintenance, Safety, Management, Health Monitoring and Informatics - Koh & Frangopol (eds), Taylor & Francis Group, London, ISBN 978-0-415-46844-2, (2008)
2. Dan M. Frangopol, Jung S. Kong, and Emhaidy S. Gharaibeh Journal of Computing in Civil Engineering, (2001)

3. fib Model Code for Service Life Design -bulletin 34 prepared byTask Group 5.6,Lausanne, Switzerland,ISBN 2-88394-074-6,(2006)
4. Veit-Egerer, R., Widmann, M.: Life cycle methodology and durability analysis with regard to relevant heavy-maintenance instructions. VCE-WD 220; IRIS (Integrated European industrial risk reduction system—IP: SP3 and 7); European commission FP7; Project No. FP7-NMP-2007-LARGE-1, (2010)
5. Wicke, M., Kirsch, P., Straninger, W., Scharitzer, B.: Kostenmodell für den Funktionserhalt von Straßenbrücken. Bauingenieur Band 76, (2001)
6. Forschungsgesellschaft für das Verkehrs- und Straßenwesen: RVS 13.03.11 Überwachung, Kontrolle und Überprüfung von Kunstbauten—Straßenbrücken. Wien, (1995)
7. Wenzel H.: Health monitoring of bridges. Wiley, Chichester England, ISBN0470031735; (2009)