SEVENTH FRAMEWORK PROGRAMME

IRIS Final Report

1 Introduction

The structure of this final report gives an overview of the outcome/results of the main innovations developed during the European research project IRIS (Integrated European Industrial Risk Reduction System).

The innovations of the first chapters (from chapter 2 to 6) can be used for all industries, even when it was developed and shown for specific ones. Chapters 7-10 have developed solutions to problems that occur in specific industries.

The most important innovation is the frame to risk assessment for all industries established within WP6. The IRIS Risk Paradigm is a framework for systematic risk identification and risk assessment and leads therefore to either prevention or mitigation of the diverse risks of the different industries.

A fundamental new approach in addition to structural health monitoring assessment routines, that have already been state of the art before this project, has been developed within WP7 and is described in chapter 3.

The standard degradation curve (chapter 4) and the Life Cycle Assessment concept (chapter 5) is another quite comprehensive task, valid for all industries.

In order to be able to have fast decision support systems, an IT platform that can visualize the results in an efficient and intuitive way is also required. Exactly these features have been also developed in the IRIS project and an overview of those is given in chapter 6.

Last chapters (from 7 to 10) describe innovations more related to the specific industries.

In chapter 7 the developed tools for the workers safety are described. This task is related to the construction industry.

Chapter 8 deals with vibration mitigation equipment for the chemical industry.

In chapter 9 the new approach for the mining industry is presented, whereas chapter 10 presents the innovations for the energy industry.

2 IRIS Risk Paradigm (WP6)

The objective of the present description is twofold. The first objective is the schematic presentation of the IRIS Risk Paradigm, highlighting its elements, objectives and architecture. The second objective is the provision of guidelines for implementing risk assessment under the framework of the Risk Paradigm, considering the significance of this module in the risk management. The rest of the elements of the Risk Paradigm are described in detail in the IRIS 2nd Period Progress Report.

The IRIS Risk Paradigm is a comprehensive generic framework/product of risk management substantiated with the use of several interconnected elements/tools. It comprises five major elements; these elements along with their objectives are shown schematically in Figure 2-1. The elements of the Risk Paradigm can form the basis to define specifications/standards for managing risks in the European industry (Risk Management Standard (RMS)), as it is also shown in Figure 2-1.

The architecture of the IRIS Risk Paradigm is shown in Figure 2-2, where the interconnections (synergy) between the several elements of the Risk Paradigm and the connections of these elements with the Risk Knowledge Portal (i.e. Ontology Server (Risk Core Ontology), Database Server) are included. The Portal is Web based and constitutes the User Interface (UI) for the Risk Paradigm System. The variables Factor, Mechanism, Component and Impact included in Figure 2-2 are defined in Table 2-1.

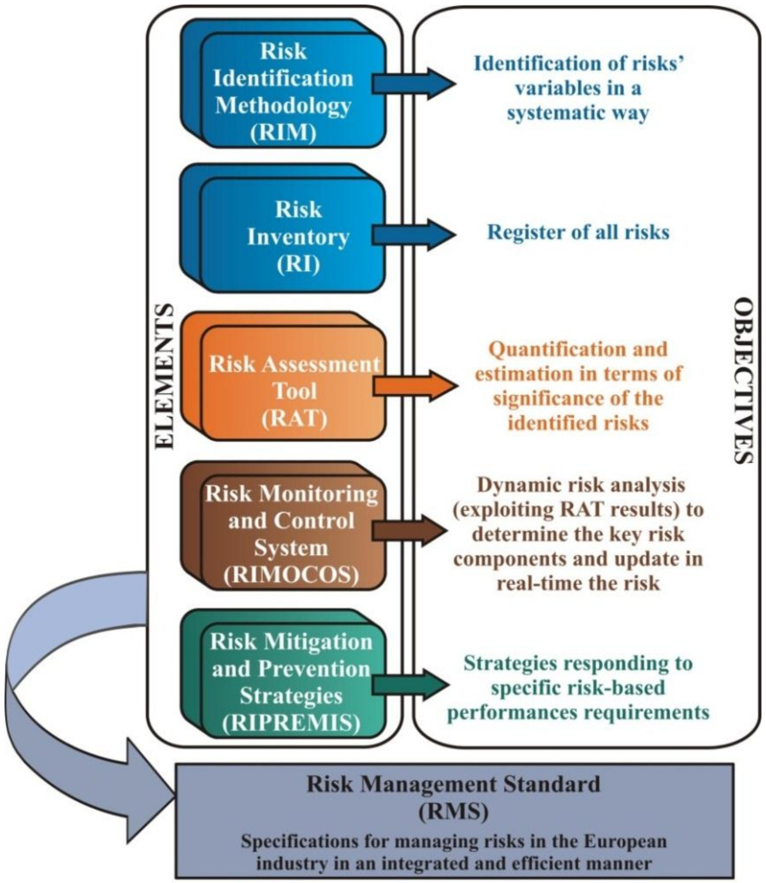

Figure 2-1: IRIS Risk Paradigm elements and their objectives

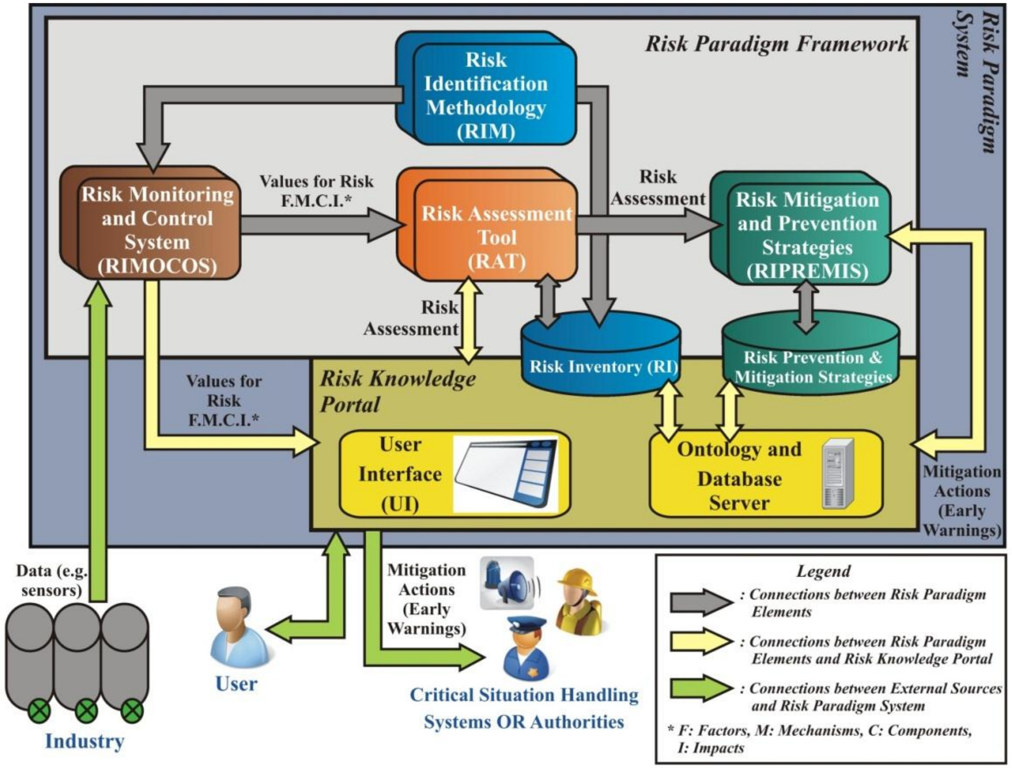

Figure 2-2: IRIS Risk Paradigm System: Architecture of the IRIS Risk Paradigm.

Table 2-1: Risk identification variables according to the RIM element

Variable	Definition
FACTOR	A measurable characteristic, element or variable that can cause a risk to occur.
COMPONENT	A constituent of risk, which is identifiable upon risk occurrence and its presence, denotes the occurrence of the risk.
MECHANISM	The sequence of the driving forces that result to the occurrence of a risk. Risk occurrence is the result of relations of events, processes conditions and system reactions that all together constitute a risk occurrence mechanism.
IMPACT	The negative result or effect of an event. There may be a range of possible impacts associated with an event (only negative effects are considered here).

The Risk Assessment Tool (RAT) presents one of the most significant elements of the Risk Paradigm. Implementation of the RAT is established via the following three steps, also illustrated in Figure 2-3. The aforementioned implementation is based on the modelling/computational approach initially discussed in (Taflanidis and Beck, 2009). Note that though the illustration in Figure 2-3 corresponds to risk assessment for offshore wind turbines, the framework and guidelines presented are generic and can be directly extended to other types of applications.

Step I: System modelling

The first step for the IRIS risk paradigm is the adoption of appropriate, numerical models for the various components of the overall system. These models should be able to provide a detailed, faithful representation of the behaviour of the true system under consideration. They can be based on physics or on empirical approximations. No specific requirements are imposed for them; they can be high-fidelity, computationally intensive numerical models. In most cases (though this is not an absolute necessity) the following sub-systems can be distinguished: excitation, system and performance evaluation models, with model parameters θf (excitation model–"factor"), θm (system model–"mechanism") and θc ("component") and θi (performance evaluation model–"impact"), Figure 2-3.

The excitation model represents the "hazard" (or more generally, risk factor) and ultimately provides an "excitation" to the system, whereas the performance evaluation model assesses the impact to the system and ultimately transforms the system response to quantities meaningful to the stakeholders (distinction between acceptable or unacceptable performance, loss of revenue due to downtime or "performance" degradation, repair costs due to damages, and so forth).

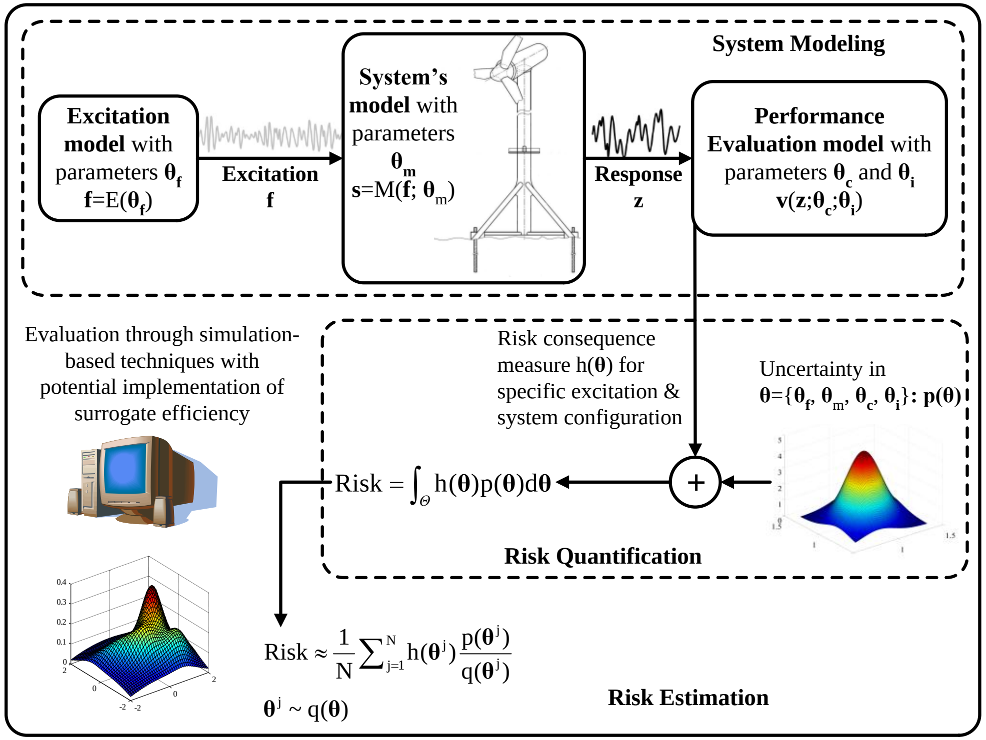

Figure 2-3: Schematic for implementation of IRIS RAT (illustration example corresponds to offshore wind turbine risk assessment).

The overall system performance is assessed through the risk consequence measure h(θ) which can be calculated numerically as a function of the augmented model parameter vector θ={θf, θm, θc, θi} composed of all individual subsystem parameters. Any modelling or numerical-approximation error (for example because of use of surrogate models as discussed in Step III later) should be also augmented in vector θ.

Step II: Risk quantification

Foundation of the IRIS paradigm is characterization of the uncertainty in the model parameter vector θ, through appropriate probability model p(θ), once a faithful model description is developed (in Step I). Selection of the specific probability model p(θ) will depend on the application considered; it can be based on regional measured data (for example for the statistical distribution of the environmental conditions), on engineering judgment or on real-time measurements obtained during the life-cycle of the system. For most applications, the most important source of uncertainty corresponds to the excitation model, since significant variability is anticipated for it during the life-cycle of the system. But the uncertainty in the other subsystems needs to be also carefully considered as it can have an important impact on the overall performance. Ultimately risk is expressed as the expected value of the risk consequence measure over the established probability models

$$\text{Risk} = \text{H} \equiv \int_{\Theta} \text{h}(\boldsymbol{\theta})\text{p}(\boldsymbol{\theta})\text{d}\boldsymbol{\theta} \qquad \textbf{(2.1)}$$

Different definitions for the risk consequence measure will lead to different characterizations for risk. For example if h(θ)=Cin(θ)+Clif(θ), where Cin(θ) corresponds to the initial cost and Clif(θ) to the additional cost over the lifetime of the system, then Risk corresponds to life-cycle cost. If h(θ)=IF(θ), where IF(θ) is the indicator function against some event F (0 if F does not occur and 1 if it does), then risk corresponds to the failure probability against F.

Step III: Risk estimation

For estimation of risk according to Eq. (2.1) the multi-dimensional integral representing risk needs to be estimated. An efficient approach to perform this estimation is though stochastic simulation (Taflanidis and Beck, 2009); an estimate for risk is given by ()

$$\text{Risk} \approx \hat{\text{H}} \equiv \frac{1}{\text{N}}\sum_{\text{j}=1}^{\text{N}} \text{h}(\boldsymbol{\theta}^{\text{j}})\frac{\text{p}(\boldsymbol{\theta}^{\text{j}})}{\text{q}(\boldsymbol{\theta}^{\text{j}})}$$
$$\boldsymbol{\theta}^{\text{j}} \sim \text{q}(\boldsymbol{\theta}) \qquad \textbf{(2.2)}$$

when using a finite number, N, of samples of θ simulated from some importance sampling density q(θ). In Eq. (2.2) vector θj denotes the sample of the uncertain parameters used in the jth simulation. As N→∞, then $\hat{\text{H}} \rightarrow \text{H}$ but even for finite, large enough N, Eq.(2.2) gives a good approximation for Eq.(2.1). The quality of this approximation is assessed through its coefficient of variation, δ. An estimate for δ may be obtained through the information already available for the risk assessment using the following expression:

$$\delta \approx \frac{1}{\sqrt{\text{N}}}\sqrt{\frac{\frac{1}{\text{N}}\sum_{\text{j}=1}^{\text{N}}\left(\text{h}(\boldsymbol{\theta}^{\text{j}})\frac{\text{p}(\boldsymbol{\theta}^{\text{j}})}{\text{q}(\boldsymbol{\theta}^{\text{j}})}\right)^2}{\hat{\text{H}}^2}-1} \qquad \textbf{(2.3)}$$

Thus, the simulation-based risk assessment provides not only with an estimate for the risk integral, but simultaneously with a measure for the accuracy of that estimate. The importance sampling density q(θ) may be used to improve this accuracy and, ultimately, the efficiency of the estimation of Eq. (2.2). This is established by focusing the computational effort on regions of the Θ space that contribute more to the integrand of the risk integral in Eq. (2.1) (Taflanidis and Beck, 2008). The simplest selection is to use q(θ)=p(θ), then the evaluation in Eq. (2.2) corresponds to direct Monte Carlo analysis.
This simulation-based approach for the risk estimation creates no constraints for the numerical or probability models adopted, thus facilitating a detailed description of system risk. It is though computationally intensive since a large number of evaluations of the model response is typically required to approximate risk according to Eq. (2.2) while establishing good accuracy [small coefficient of variation according to Eq.(2.3). For problems involving high-fidelity, computationally demanding models, approaches for alleviating the associated computational burden are required. A common solution for this problem is to rely on surrogate models for the system-model evaluations needed for estimation of Eq. (2.2) (Taflanidis et al., 2011). Such surrogate models can be developed using a relatively small number of evaluations of the real system model, and then used for all subsequent evaluations of the system response needed for estimation of the risk integral.

3 Accumulated Energy Function for SHM (WP7)

The dynamic characteristic of a structure is changed with the presence of damage. These changes follow patterns that can be detected from the signals.

The involved indicators are (Figure 3-1):

- Eigenfrequencies representing the global stiffness of the structure
- Mode shapes indicating the dynamic behaviour of the structure
- Vibration intensities showing how much energy is absorbed by the structure as an indicator for lifetime consumption
- Local damping values as an indication were energy is consumed locally which indicates a potential failure mechanism
- The changes of the structural behaviour, the trend that shows irregularities by comparing to other measurement data either in time or position. In these trends usually the frequency spectrum was plotted against time or position.

Damage detection in civil engineering has long been concentrated on the change of stiffness with increasing damage. This indicator, however, has often been proven to be not sensitive enough to satisfy the practical requirements. VCE experience is that a more sensitive indicator could be observed when the measured frequencies of higher order are carefully examined. While the lower fundamental frequencies appear not much affected by the stiffness changes, the higher frequencies can indicate much earlier signs of it. It was found that actually an energy transfer process is taking place from lower to higher frequency range with increasing damage. The reduction of eigenfrequencies and the transfer of energy are both observed in this case.

This phenomenon has never been described in the literature yet except it was briefly mentioned in an earlier article by VCE after the first observation of this kind.

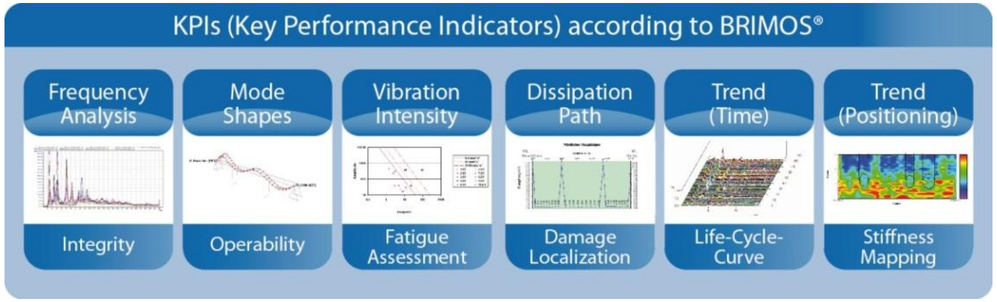

Figure 3-1: Key Performance Indicators (KPIs): Parameters for dynamic system identification.

Meanwhile it is also identified that the increase of damping goes along with a drop of spectral peaks caused by increasing damage. It is obvious that this is not the modal damping and it needs to be described by a system behaviour parameter. The physical concept, the mathematical modelling and a clear simulation of the phenomena are not available yet.

Related to this is the energy cascading phenomenon.

Energy cascading is well known in dynamic systems with a change of conditions for a wave in the medium. These processes have been described by Kolmogorov and Richardson long time ago; targeted laboratory tests (SAFE PIPES Project FP6 STRP-013898) showed this phenomenon with the increasing non-linearity of the dynamic system. An example from the damage test at the S101 Bridge in Austria is provided below. It shows the results of above described algorithms for the 2 damages introduced during this demonstration within the IRIS Project (FP7 CP-IP 213968-2).

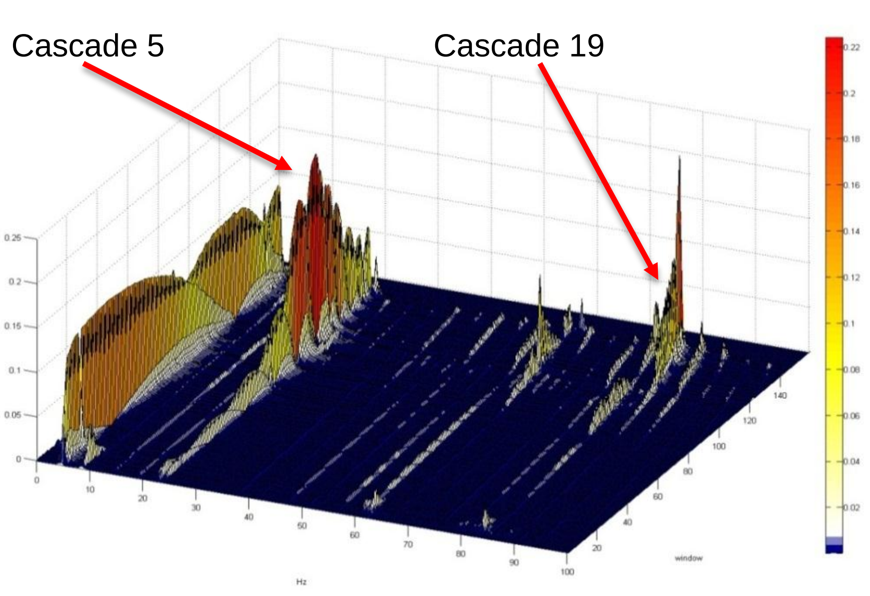

Figure 3-2: Energy cascading with damage (SAFEPIPES test at MPA Stuttgart)

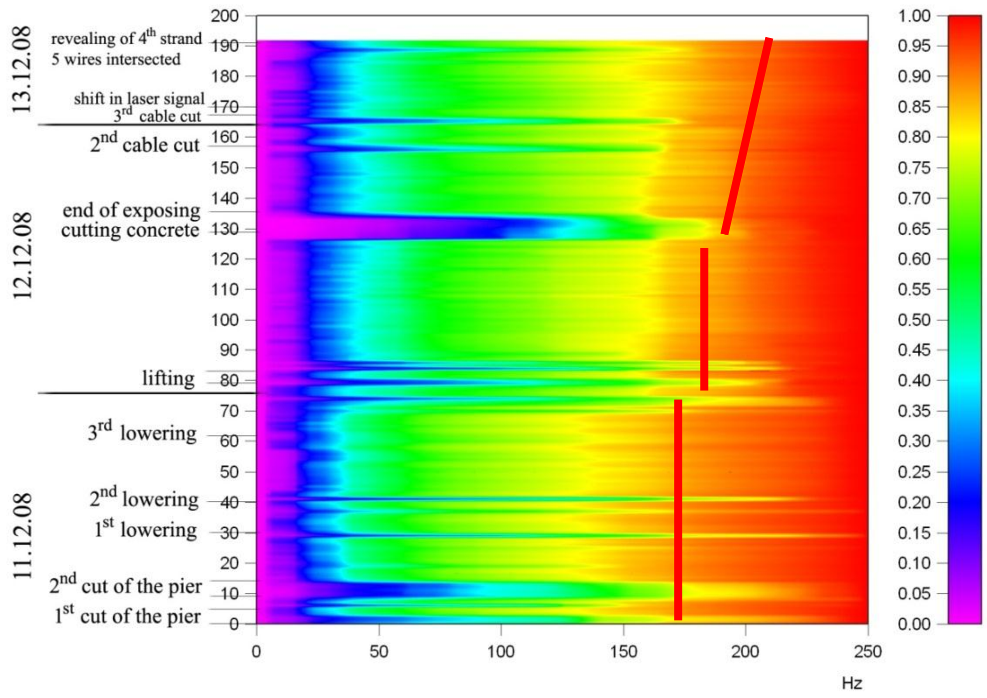

Figure 3-3: Simulation S101 with damage (IRIS test at A1, Austria)

Structural Nonlinearity and Energy Transfer

Cascading energy transfer in a dynamical system could be caused by the development of nonlinear characteristics of the structural response caused by various reasons. A development of nonlinear mechanism in both damping and stiffness of the structure is often associated with the progress of a structural damage. In the description of structural vibration, it can be typically represented by additional nonlinear correction terms introduced to damping and stiffness terms. It implies that if a simple harmonic oscillation of the structure takes place with certain frequency, whatever the reason is, the vibration will soon become mixed with higher frequency components generally expressed by the multiples of the original frequency. This process will be repeated as time allows and, as a result, a part of the system's dynamic energy will be gradually distributed to higher and higher frequency range. Where would this process end? For the case of damage-caused nonlinearity, the high-frequency energy components dissipate as heat or noise and, if not, the destruction or rupture of the structure would play a roll. Even if it does not reach the destruction point, the mechanism of structural response will change largely when damage progressed that far.

Nonlinear Damping

Energy cascading, such as the one described above, can be associated with various types of nonlinear physical phenomena. Another example of it is typically observed in dynamics of turbulent fluid flow. In fact, the case of fully developed turbulence, the energy cascading process is one of the most central issues. Relationship of energy cascading with nonlinearity of dynamical systems is therefore evident in these two different phenomena.

A very interesting aspect of this point is that the detection of energy cascading could be potentially utilized as a tool for the structural health monitoring. As mentioned earlier, the traditional idea of knowledge-based structural health monitoring is by identifying the reduction of stiffness, which has been proved to be far less sensitive than desired for practical purposes. In contrast to that, by finding the transfer of dynamic energy to higher frequencies through spectral analysis of the ambient vibration survey, it may be possible to detect the damage development in a structure at its earlier stage. Any extent of structural damage can of course change the local structural damping or energy dissipation and stiffness. As a consequence, the global dynamic properties of the structure, i.e., the eigenfrequencies, mode shapes and modal damping would be all somewhat influenced.

It needs to be kept in mind that structural nonlinearity is attributed, however, not only to developing damages. Field experience indicates that the magnitude of modal damping is often amplitude dependent. Increase of damping, when the vibration amplitude is significant, is due to energy consumption at increased friction at bearings, bending action of piers, behaviour of the bridge outfitting and also the structure-vehicle interaction. Admittedly the present method would also detect the developing structural nonlinearity due to large motion. However, if there is a development of structural damage as its consequence, the nonlinear characteristics will remain with the structure after the large amplitude motion disappeared and should be thus detected.

Progress in the Proposed Project

The method described above has been experimentally applied to some bridges to investigate how effectively it can be employed for identifying the existence of structural damages.

Sample structures chosen for this experimental project include ordinary healthy bridges, bridges with progressive deterioration, and also some bridges that were to be demolished. For the case of the last category, the structure was given artificial damages before their demolition and its influence on their dynamic behaviour was examined. The identification of the energy cascading phenomena was performed by time-limited spectral analysis of acceleration data obtained by a standard BRIMOS ambient vibration survey, which has been established by VCE. An ideal condition for this measurement would be when the structure is excited by micro tremors, which can be regarded as white noise excitation. It would be even better if the measurement was continued for a while under the same conditions. However, the reality is often not under such conditions.

Spectral analysis of the vibration record has clearly indicated that dynamic energy tends to be gradually transferred to higher frequency range when structural damages exist. The most fundamental principle of this measurement has been thus confirmed. This was evidenced particularly clear when the structure was artificially damaged and measurement was carried out under rather ideal conditions, namely without being disturbed by the on-going traffic loads directly on the structure.

When the vibration was measured with the structures under service conditions, on the other hand, the measured data were much contaminated, as expected, by direct excitation due to normal surrounding loads. The energy transfer due to possible structural nonlinearity, hence, needs to be carefully concluded by taking into account the effects of load excitations. Also not all changes or damages in structures lead to a nonlinear behaviour. Nevertheless additional information can be extracted from the measurements (ambient vibration monitoring) with this method, which has been proven on different systems, such as the piping mock-up, the dome of NPP Kozloduy and several bridge structures.

4 Standard Degradation Curve (WP7)

Construction industry is a primary activity playing a paramount role in nearly all the sectors relevant to the economy of industrialized countries and is a very important economic activity itself.

In the European Union, the overall turnover of the construction industry represents an average of 10% of the aggregate GDP. It is covering building and maintenance of housing facilities and infrastructure, including transportation infrastructure, lifelines, services and industrial facilities. Construction activity interacts with the environment and provides shelter to human life and goods, thus allowing the development of all human activities under safety and security conditions. In addition, it is not subjected to delocalization and on the other hand it is an important source of revenues from international markets. The share of the overall turnover that is produced outside the European Union by European constructors is very significant and also represents a way to promote export of industrial products to non-European countries.

Failure of structural components in construction is one of the major sources of risk in all industrial sectors. Failures may be produced by errors or lack of knowledge in design or construction or from ageing and obsolescence of structural materials and components, so that improving knowledge and design, construction and maintenance technologies is a key aspect in the reduction of industrial risks.

Today the construction industry necessitates of a profound innovation in the construction sector and in the management of infrastructure and to this aim, the European Construction Technology Platform[1] individuated the following research fields:

- Modelling the performance of the infrastructure,
- Monitoring the performance of the network,
- Improving the performance of the infrastructure: materials and construction techniques,
- Enhanced management.
- The work performed is intended to provide improvements in the construction industry.

The standard degradation curve allows to describe the reliability of a structural system and of its components within their service life by representing its process of deterioration. Deterioration is actually what is assessed by structural health monitoring. This helps to predict failures and brings also insight into the mechanisms of degradation.

Within the IRIS project the framework of degradation curves for engineering structures has been recently developed (Veit-Egerer and Widmann (2010)).

The degradation curve model represents the deterioration process of an infrastructure over its service life time in combination with inspection, monitoring and maintenance information facilitating decision support for e.g. highway authorities and operators. Furthermore, the degradation curve model can be flexibly adjusted to the user requirements as it can be e.g. empirically based or based on the structural reliability of the infrastructure. For the empirical basis the framework facilitates to apply databases of the individual owner and infrastructure facility management authorities.

The framework can be applied to new structures and existing structures. For existing structures the amount of information which is and can be made available is much higher. Therefore the framework facilitates to integrate all information available comprising loading history and structural health monitoring information, inspection information and the information of damage detection procedures.

[1] ECTP, Networking Europe: VisIon 2030 and strategic research agenda – Focus Area networks, 4.11.2005

An example of a degradation curve for a bridge structure is depicted in Figure 4-1 (Veit-Egerer and Widmann (2010)). Here, the special case of an empirical determined degradation curve on the basis of a generic database is shown. The y-axis thus contains the safety level and with a threshold of 1,0 the bounds of the service life are determined probabilistically.

A lot of work has been performed with respect to monitoring based risk assessment, starting with monitoring based bridge and landslide risk assessment, system identification, damage detection, large scale identification, examples for very different kinds of structures like masonry arch bridges and offshore wind turbines as well as various damage tests.

Modal identification with model updating is included in the procedure and the uncertainty quantification in general, as well as the reliability of the damage detection algorithms in particular has been treated.

New methods were developed in the Operational Modal Analysis context, which are more robust, adapted to unmeasured and changing ambient excitation and faster. Moreover, memory efficient approaches are used to handle a large number of sensors and high model orders in the investigated systems. Established methods for Structural Health Monitoring (SHM) are enhanced to be reliably usable on civil engineering structures, where all parts of the IRIS risk paradigm are considered.

Furthermore the detailed examination of the specific technique of Stochastic Subspace-based Damage Detection (SSDD) as well as the analysis of its applicability within Structural Health Monitoring (SHM) concepts for civil engineering structures has been investigated and tested for different kinds of structures, each of different structural type and material: (a) a road bridge out of pre-stressed concrete, (b) a laboratory test structure from structural steel, modelling a part of the foundation of an offshore wind energy converter and (c) a test rotor blade of a wind energy converter.

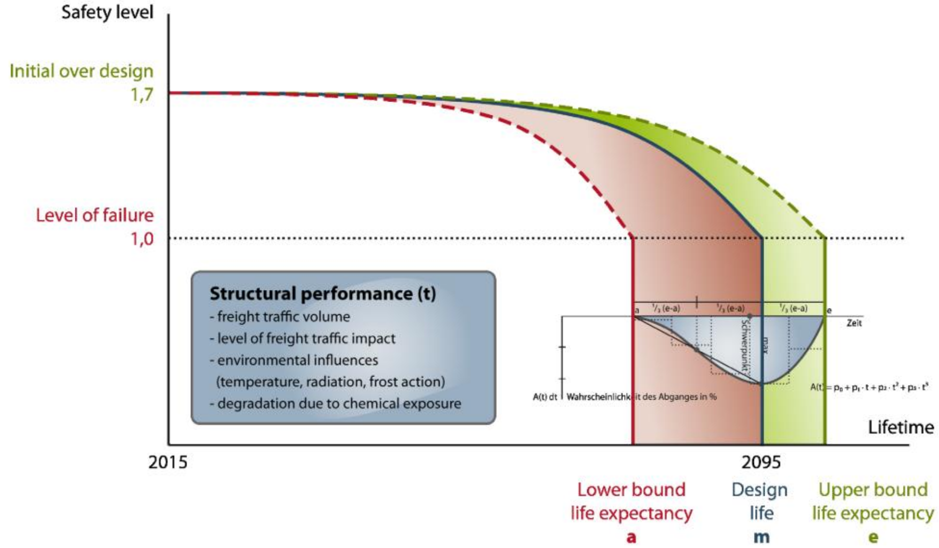

Figure 4-1: Life cycle line of a structure (Veit-Egerer and Widmann (2010))

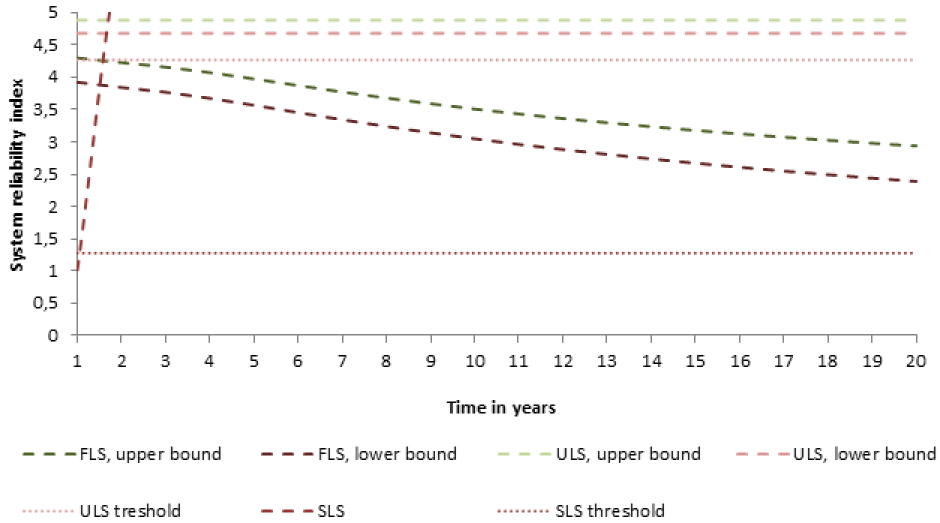

Figure 4-2: Structural reliability based degradation curves and thresholds for the ultimate, the fatigue and the serviceability limit state

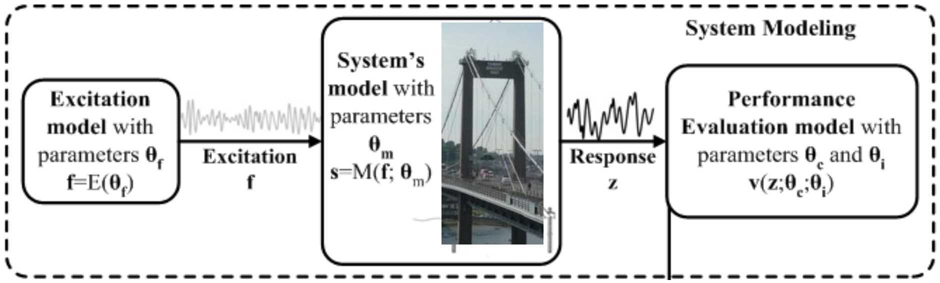

Figure 4-3: System modelling implementation by USFD for Tamar bridge.

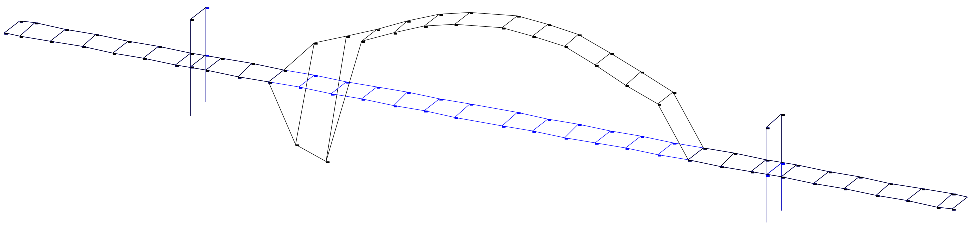

Figure 4-4: piece of first torsional mode for Tamar bridge obtained by means of Operational Modal Analysis.

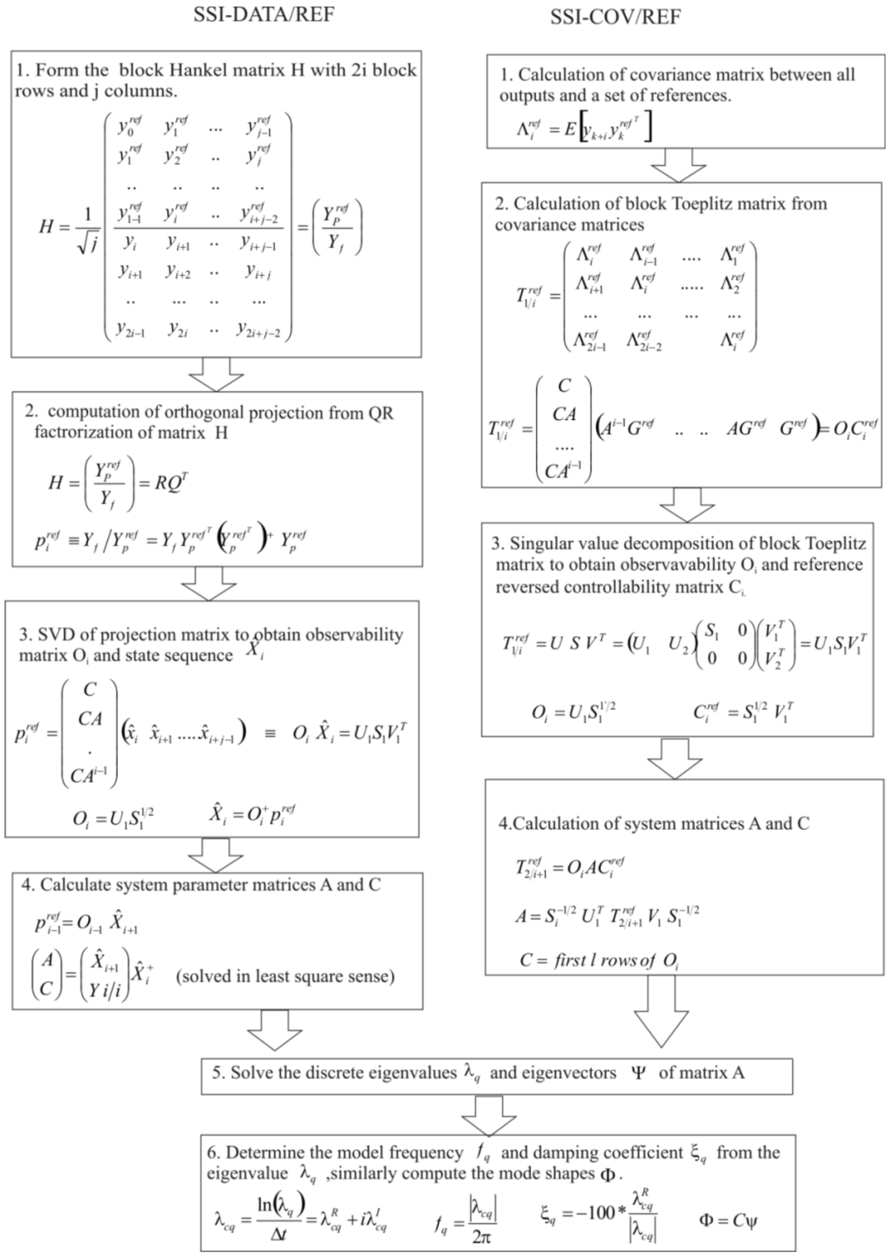

Figure 4-5: Flow chart showing the main steps of SSI algorithms

Another primary objective was to collect existing knowledge on damping values and to describe their use for design assumptions as well as for studies of existing buildings as well as a reliability-based approach to inspection planning for welded steel structures.

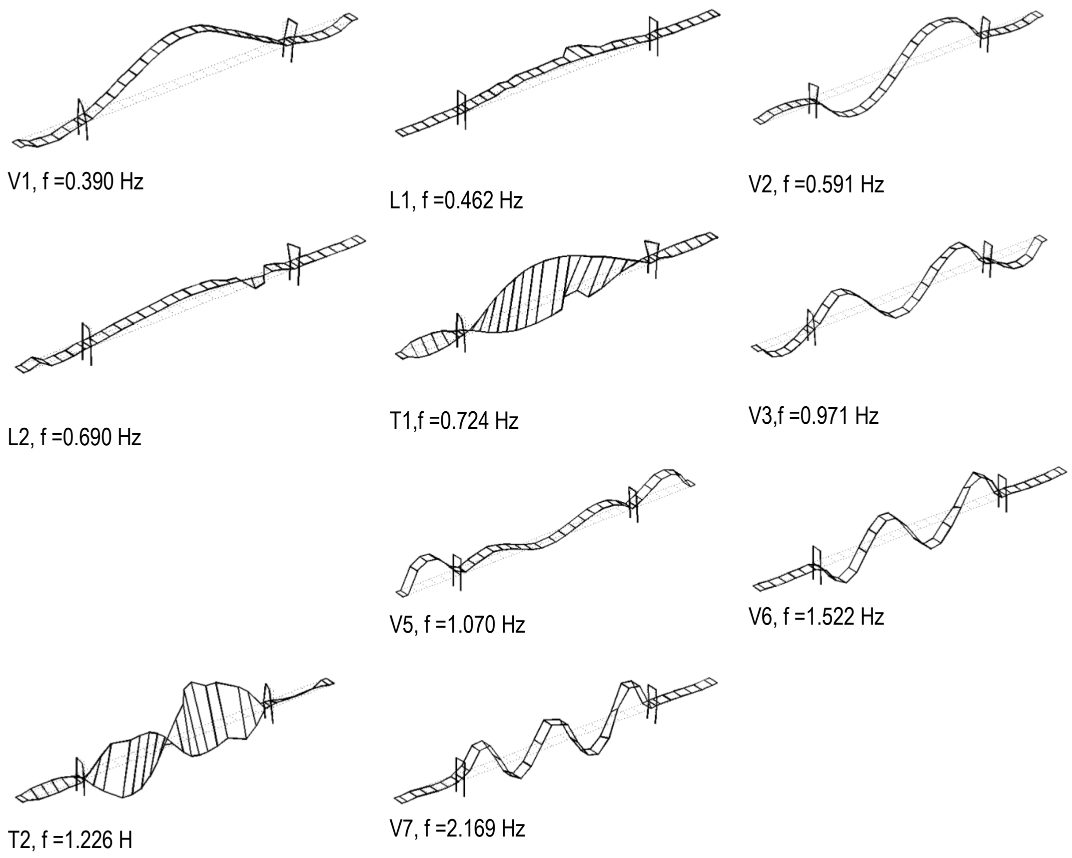

Figure 4-6: Vibration mode shape of Tamar road bridge identified using SSI-DATA method

5 LCA safety assessments concept

Methodologies for the management of the constructed infrastructure are developed in the IRIS Project (CP-IP 213968-2). The basis is the consideration of the entire lifecycle 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 methodology covers all aspects of appropriate lifecycle 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 to be considered for life cycle modelling:

a) The determination/estimation of the design life 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, carbonatisation (Durability)

corresponds 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

The determination/estimation of the design life of new structures

Primary load bearing structure

The starting point of a structure'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.

Basic model – Initial and adapted range of lifetime

To estimate the range of lifetime in the first step, statistical analyses using probability density functions are applied. A basic model covering the operational lifetime of every investigated structure is composed out of the following parameters:

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

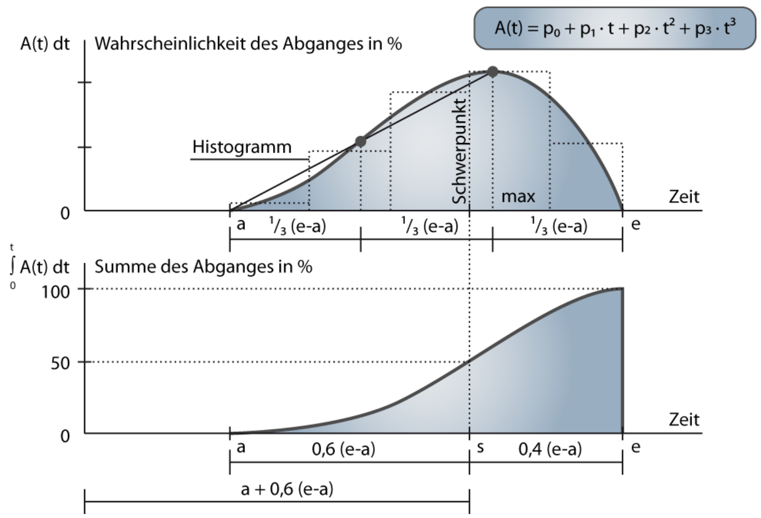

Figure 5-1: Failure probability and sum of the failure

The lower and the upper bound life expectancy can be calculated including the above mentioned parameters.

Exemplified for the primary loads bearing structure:

a=45 years……lower bound life expectancy

e= 120 years…upper bound life expectancy

a'=a*k1*k2*k3 *k4….adapted lower bound life expectancy

e'=e*k1*k2*k3*k4 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

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, frost action)
- degradation due to chemical exposure

For demonstration purposes, a well-established approach (suggested by (Miyamoto 2008) and (Frangopol 2001)) is applied. It covers all the major sources of deterioration impact.

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 lifecycle curve is the combination of the individual component curves.

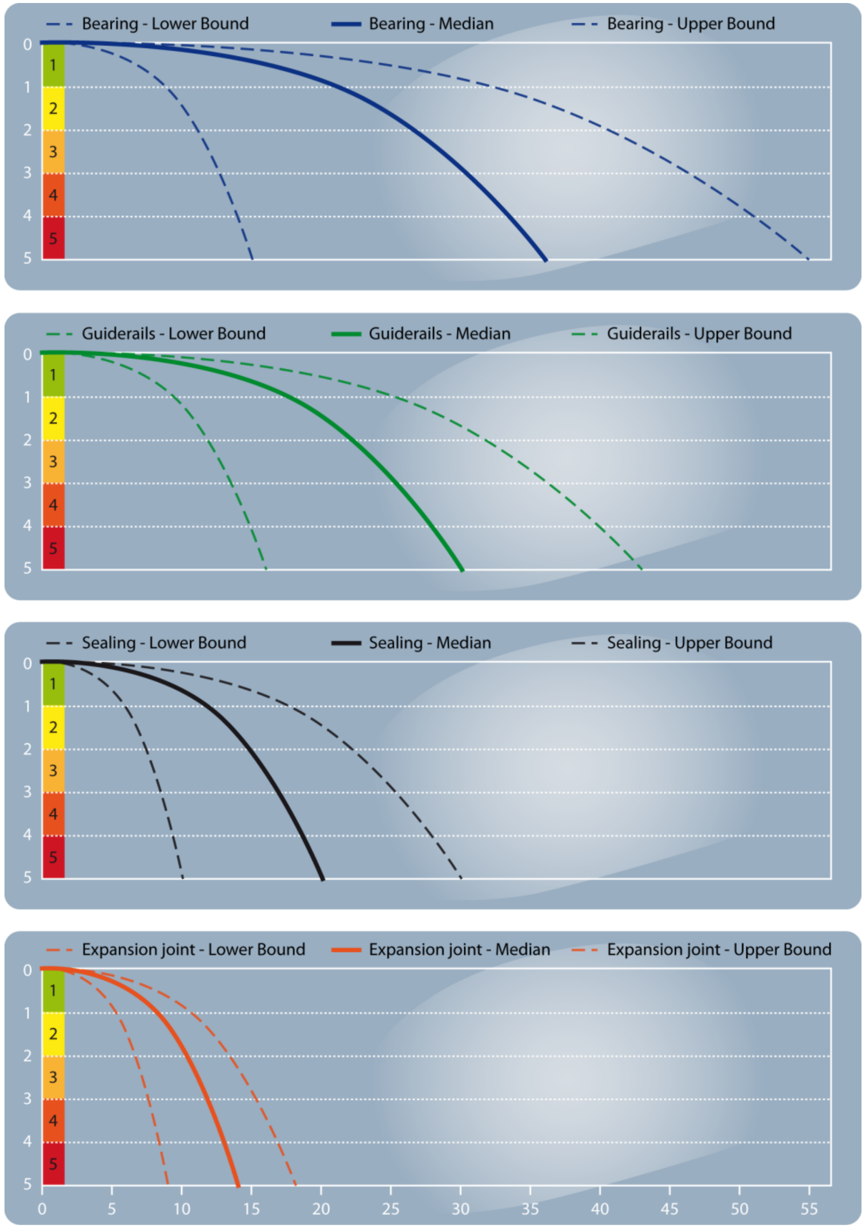

Figure 5-2: Comparison of a representative set of individual lifelines for the following succession of structural members: BEARINGS / GUIDERAILS / SEALING & EXPANSION JOINTS

Typical lifelines for different structural members as a single event are in Figure 5-2; a repeated event causing several points of intervention during service life of the whole bridge structure in Figure 5-3.

The determination/estimation of the residual life of existing structures

Basically for primary load bearing members as well as for secondary load bearing members the same methodology and the same sources of impact are utilized. What makes the difference for the analysis itself is the fact, that design assumptions are replaced as good as possible by everything, supporting a deeper understanding about the previous lifeline of the investigated structure.
The lifecycle curve of a structure is determined from the superposition of the individual curves of its components and elements. Considered are the following categories:

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

a) ORIGINAL STATIC CALCULATION (STRUCTURAL DESIGN)
   Possible reduction of safety level reflecting a paradigm change from previous binding codes to the current ones
b) JUDGEMENT / RATING FROM BRIDGE INSPECTIONS (REPORTS)

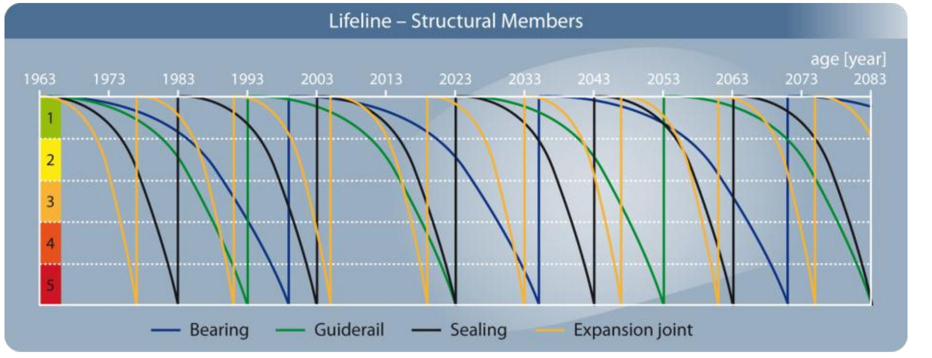

Figure 5-3: Telescoping of the individual structural members lifelines in the course of the whole timeframe of service life of the bridge itself - causing numerous theoretical points of intervention (shown again for BEARINGS / GUIDERAILS / SEALING & EXPANSION JOINTS)

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, carbonatisation, etc.)
g) data on the environmental conditions

These datasets are merged via maintenance condition matrix as provided below in order to determine the respective lifecycle 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 judgment.
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 new structure – but of course 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.

➔ spread of remaining lifetime 16 / 30 / 40 years

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

Assessment criteria whether the real degradation process (determined by bridge diagnosis) corresponds with the assumed and applied life cycle model

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 structures. Thus the methodological approach based on the determination of the design life of new structures has necessarily to be used and adapted due to the determination of residual life time of 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 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)

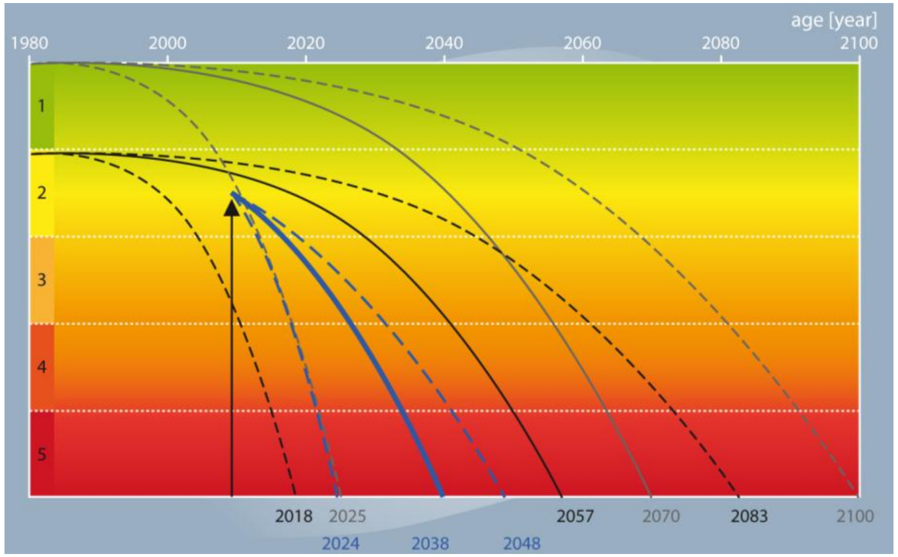

Figure 5-4: Enhanced Lifetime Prognosis of an existing bridge by means of visual inspection 2008 and static safety evaluation - reflecting a paradigm change from previous binding design code to Eurocode

Bridge assessment based on dynamic measurements by means of 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 5-5 provides an example for a structure which has been assessed by in case of the application of successive periodic or permanent monitoring.

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 of 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 (Figure 5-5).

BRIMOS 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 1000 investigated structures worldwide has been incorporated into the assessment procedure.

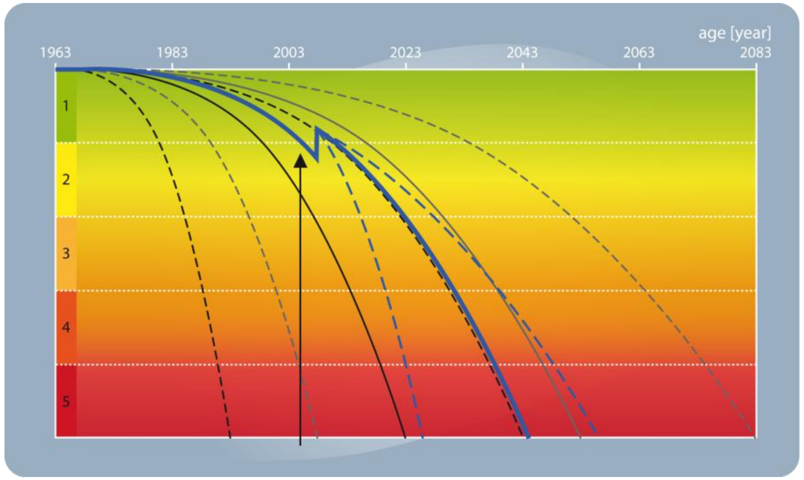

Figure 5-5: Life Cycle Curve with regard to global safety: The enhanced prognosis is based on the visual inspection in 2005, the dynamic safety evaluation in 2006/07 and the successive rehabilitation and strengthening in 20008. A narrow spread of remaining lifetime (16 / 30 / 40 years) is the result.

Summarizing emphasis on life cycle analysis

Based on VCE's experience in the field of structural bridge assessment (about 1000 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 (Fib, 2006)) that is used in many countries in the context with residual lifetime calculations.

This fact gets also very evident when comparing Figure 5-6 & Figure 5-7.

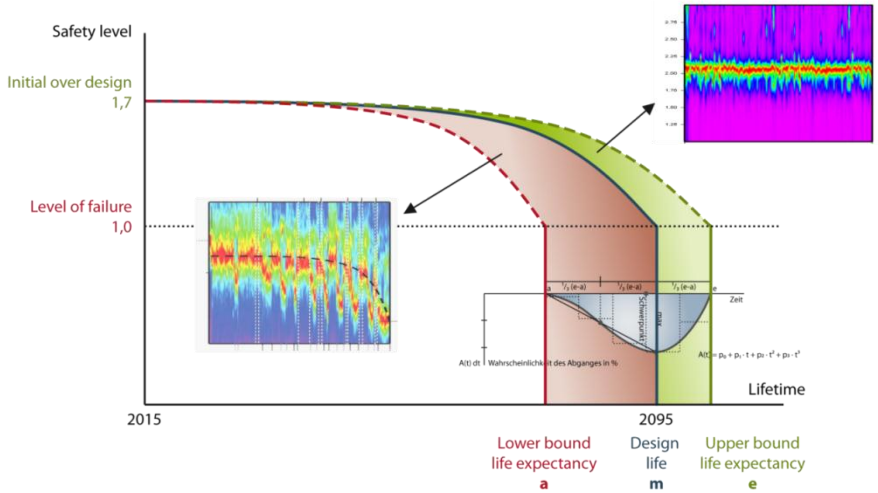

Figure 5-6: Expected (analytical) lifeline of structure, validated with dynamic measurements (BRIMOS®) & Bridge inspection

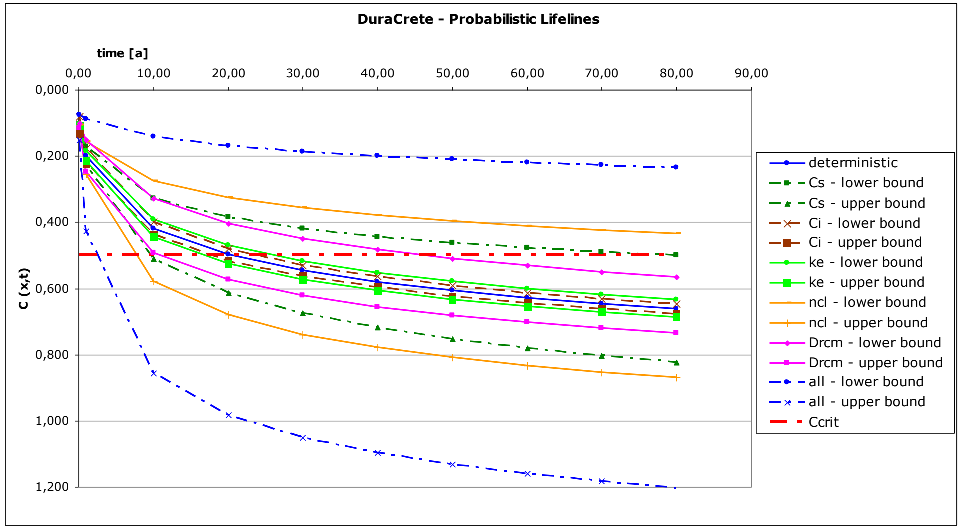

Figure 5-7: Lifelines taken from chloride penetration measurements - analysis over time

It gets clearly evident, that the real degradation process can only be sufficiently covered with in-situ investigations, especially full-scale dynamic monitoring, which turned out to reflect structural resistance and load bearing capacity in a most suitable manner.

It seems to be very conservative relying exclusively on the Model Code for Service Life Design (Fib, 2006) – based, chloride analysis driven approach – reflecting only parts of reality, especially when dealing with the primary load bearing structure.

Maintenance Instructions to guarantee the original Design Life and Preservation of Functions

Regarding Life Cycle and Maintenance projects – the contractor is usually obligated 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 the new structures.

Structural Members considered in the Maintenance Instructions

To guarantee the functional capability of a bridge object during the entire contract the individual service life of the bridge's structural members has to be considered.

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, what supports the operator's decision process in the course of maintenance planning as it enables the scheduling of appropriate maintenance instructions.

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.

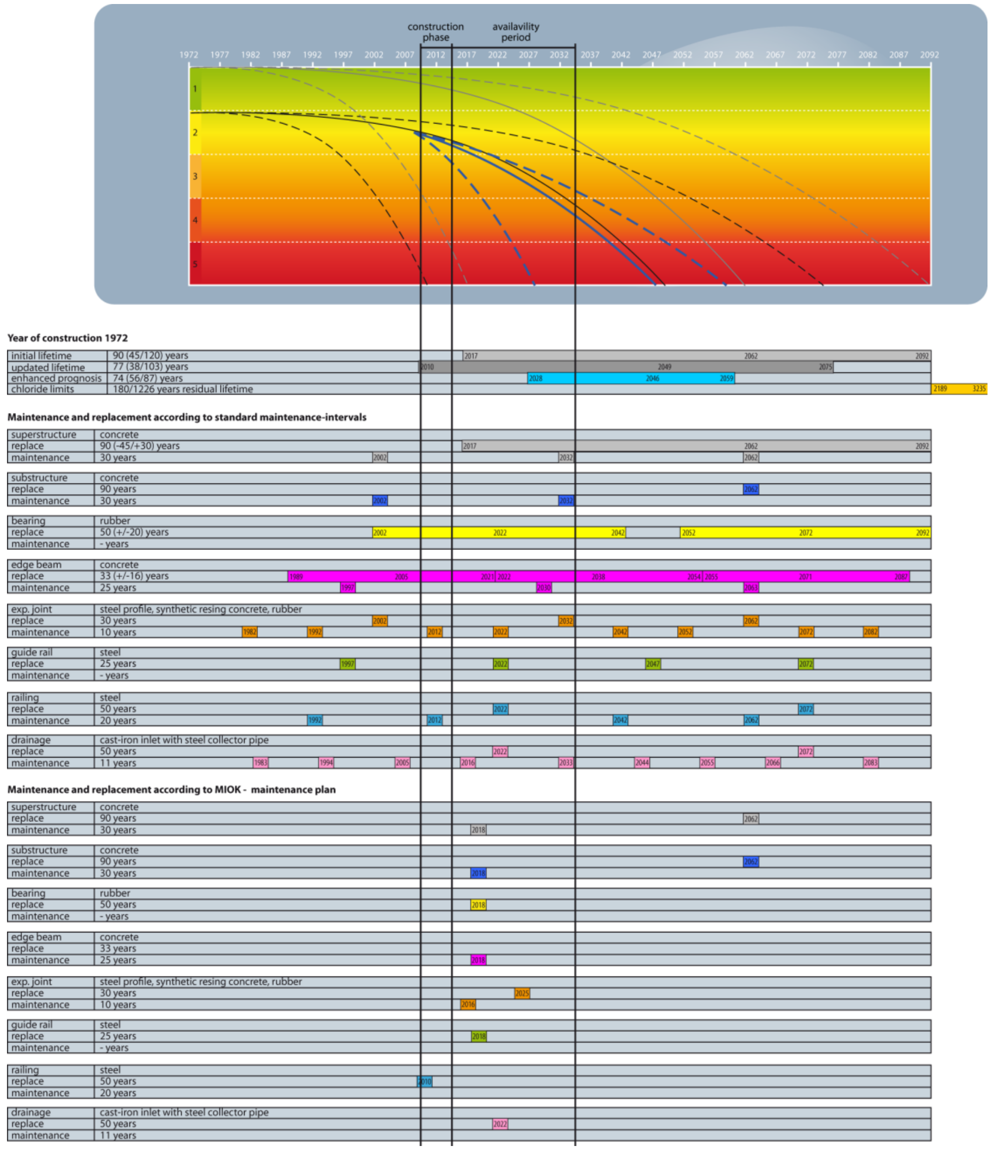

Figure 5-8: Maintenance plan – first and second stage

Harmonised Maintenance Intervals and Specification of Services

Once service life regarding replacement and heavy maintenance for the introduced categories of structural components are known, all the possibilities regarding periods of replacement and maintenance are to be harmonised to meet the demands of the certain investigation.

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 the probably already existing, officially scheduled maintenance measures of the latest inspection reports only (Figure 5-8 at the bottom). For structures, where no official maintenance plans 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.

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 over the whole contract period. This is done for every single object.

Afterwards maintenance plans for existing structures and for new structures for each traffic junction are merged and harmonized. The corresponding tables to this methodology can be found in WD-502.

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

All Bill of Quantities listed within the tables are to be understood in terms of the total mass for maintenance measures per component.

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. 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 by a Management Information System automatically. The system software automatically updates the lifecycle 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 minimization of the traffic impediment and a maximization of the availability.

This method has been developed within the IRIS project and already been used for an international Bridge, Wayne, NJ (USFD), the S101 Bridge in Austria (Frequencies and confidence intervals during progressive damage), some PPP projects in Europe and also a Life Cycle Cost Benefit Analysis for Offshore Wind Turbines Utilizing Monitoring (BAM) has been performed.

6 EQVIS simulation and crisis management platform (IT) (WP8)

This chapter compiles the research results related to the IT platform of the IRIS project. There were several topics to be treated in order to achieve a platform that is useful for and used by all industries, in particular: to improve the geo-hazard assessment (here achieved by means of GIS and remote sensing RS); to improve the field of data acquisition, monitoring, data visualization, data archiving and data treatment (GreenEye and GreenNode dedicated softwares have been improved).

Geographic Information Systems

Geographic Information Systems (GIS) used with integrated remote sensing (RS) data, contribute to the analysis and representation of information required for the geo-hazard assessment, that could cause industrial accidents and cascading, interfering effects affecting the safety of industrial facilities.

Remote sensing and GIS data and the hereby derived results were combined with updateable scenarios for natural hazards in GIS integrated geo-databases, assisting the procedure of preparedness and increasing the organization and effectiveness of response activities.

GIS integrated evaluations of different satellite data contributed considerably to the detection of subsurface structures and of those areas that are assumed to be prone to relatively higher susceptibility to a natural hazard such as to earthquake ground motion due to the aggregation of preparatory / causal factors. These results, filling a gap in the engineering practices transfer to communities, stakeholders and decision makers, can support the safety of industrial and infrastructural facilities.

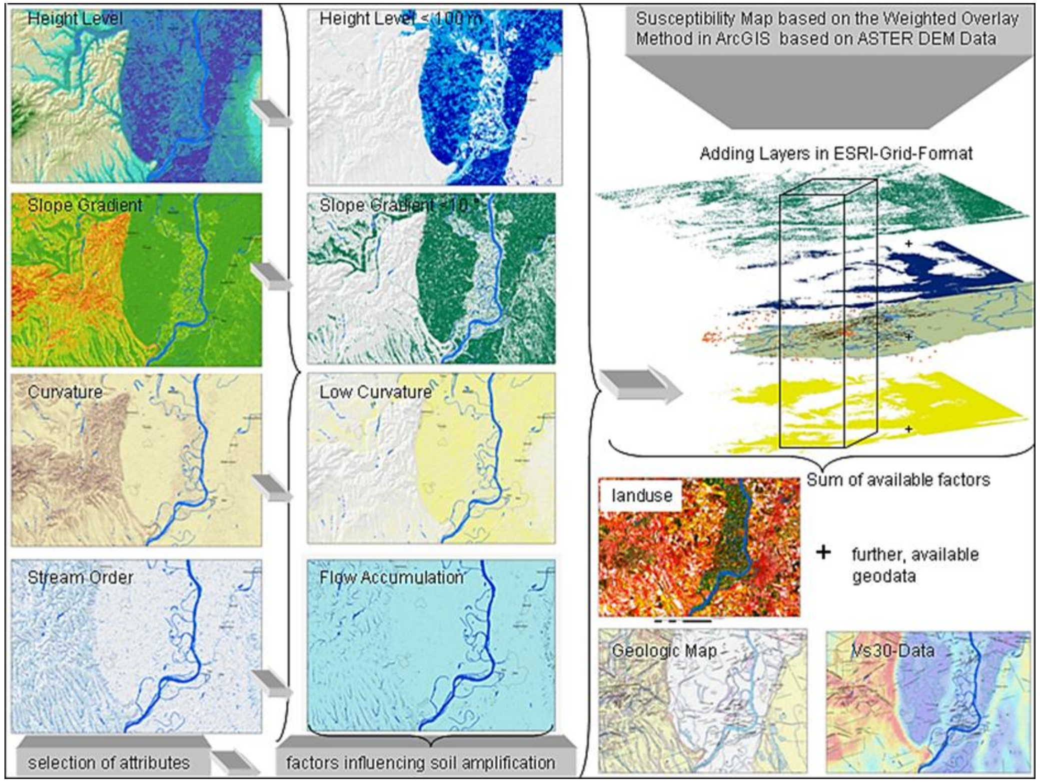

Figure 6-1: Extraction of causal or preparatory factors influencing earthquake shock as input for the weighted overlay-tool of ArcGIS.

GreenEye, GreenNode and WNode-Network

In the field of data acquisition, monitoring, data visualization and data archiving, IRIS objective was to push the frontiers in the monitoring business and make new technologies available for the people working in the industry and in civil engineering.

Three different but related subjects covered the work with respect to data handling: first of all to substantially improve the GreenEye visualization software especially for mid- and long term monitoring applications to deal with large collections of archived monitoring files and monitoring databases; furthermore to improves the GreenNode data management software to transmit monitoring data directly to server-side commercial databases and remote file servers; and last but not least the third part of the work concentrated on the research and development of a distributed, accurately synchronized wireless sensor network (WNode-Network).

The final result is the successful integration of the three work topics above. GreenEye and GreenNode work perfectly together as a pair of data producer and data miner. Both software packages now have database interfaces and the ability to handle huge amounts of data. Naturally, the WNode-Network has interfaces to GreenEye as well as to GreenNode so the acquired data can be either directly visualized or archived together with other measurement data.

Visualization techniques

The next step is to be able to treat a big amount of data; the important information has to be separated from the unessential one. Case-based reasoning, time series analysis, and passive decision support was therefore treated in numerous different frameworks and computation environments. Advantages and disadvantages of the procedures and tools subject to examination have been detected, the context to the research subjects has been outlined and the utilization of these tools in order to achieve the desired result has been found out.

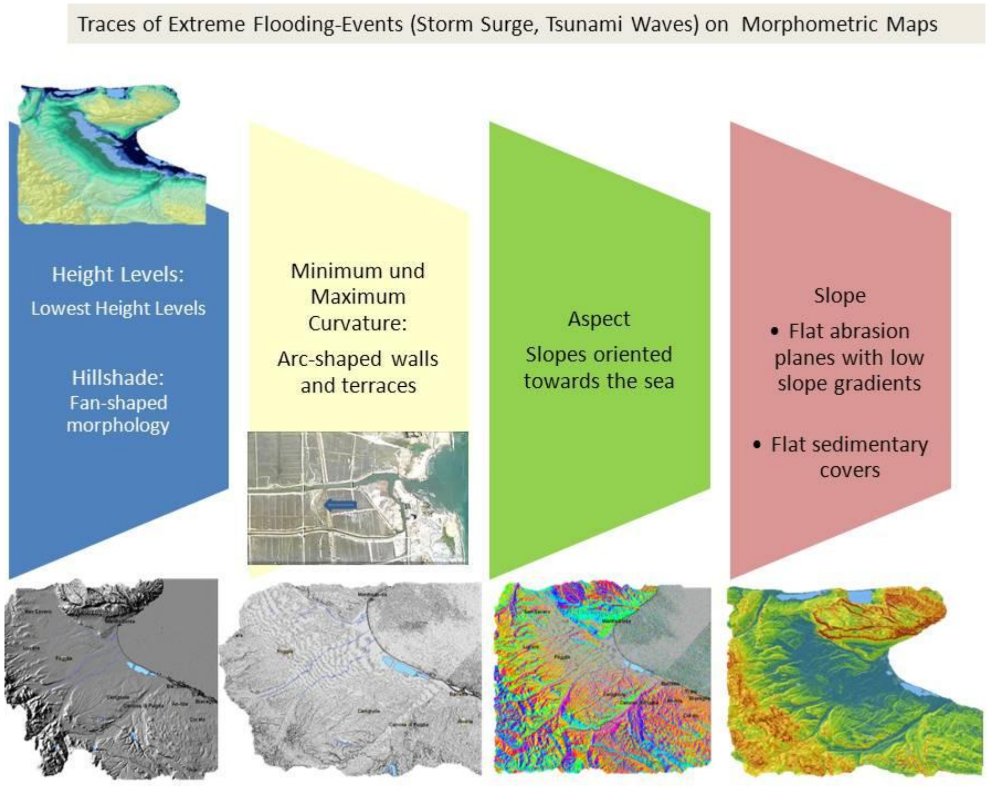

Figure 6-2: Morphologic traces of high-energetic flooding events enhanced on morphometric maps.

The integration of visualization concepts to the interdisciplinary research partners has been focused by using the advantages of real-time computer graphics techniques for data exploration. At the beginning of the project the visualization of S101 and the reconstruction of the 20th district of Vienna were realized. In the last phase of the IRIS project the main focus was on a general overview of several visualizations for areas covered in IRIS work packages. Physical sciences are handled primarily with the description of flow visualization. Statistical data analysis is covered by information visualization techniques. Finally the combination of the IRIS risk paradigm and visualization tools shows how cooperation of several fields of research lead to improved risk analysis.

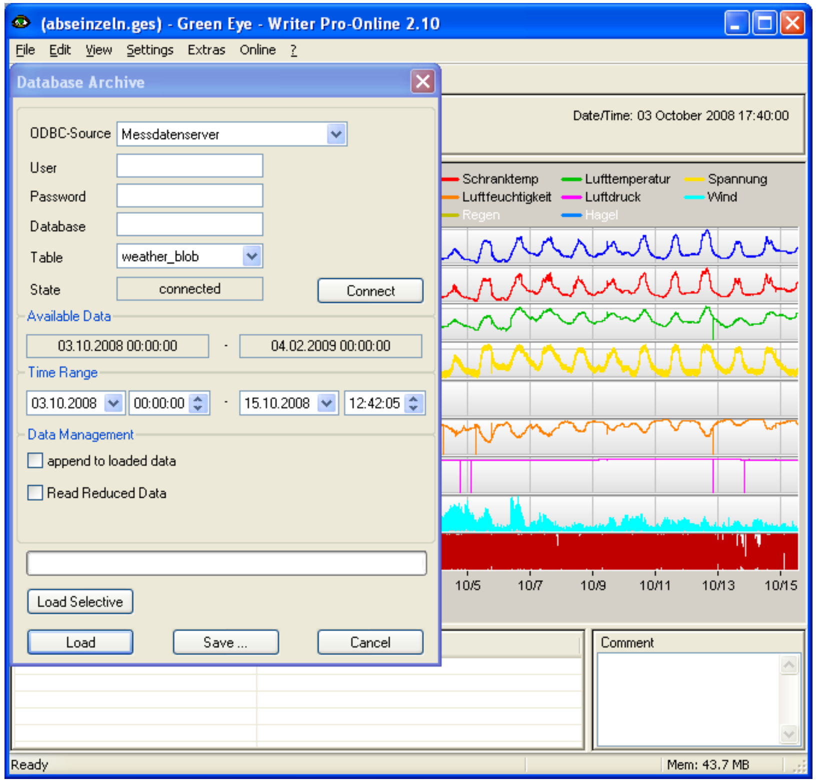

Figure 6-3: Database Access with Green Eye

Figure 6-4: real-time render for interactive inspection of cables inside a bridge (obtained by using visualization techniques).

7 Integrated Decision Support System (WP3)

The subject of this innovation topic is the safety of workers in the construction industry. There are several aspects concerning the safety of workers in the construction industry with respect to risk assessment and decision support. The developed tools in IRIS should be able to handle all risk related problems starting from critical scenarios for workers on construction sites, including the monitoring of not only workers but also the surrounding, including critical parts like scaffolds, up to the monitoring of the structures opened to usage until the end of the life of the construction.

Set-Up of a Combined Indoor and Outdoor Positioning Solution and Experimental Results (TUB)

A real-time positioning and communication system was developed within the IRIS Project, suitable to get workers position on construction sites to increase workers safety. The prerequisites and requirements for such a positioning system had to be applicable for indoor and outdoor environments. Based on this, adequate sensors have been selected and the information fused to a multi-sensor positioning system. The developed methods were tested in different simulations and real environments.

An important aspect in the developed positioning solutions is bidirectional data communication, for which an adequate solution was found.

Architecture of the positioning system

The hybrid position system mainly consists of a Radio-Frequency Identification system (RFID) for indoor and a Differential Global Navigation Satellite System (DGNSS) for outdoor environments. The positioning system will be supported by additional hardware like barometric sensors, Inertial Measurement Units (IMU) and an Ultra-Wide Band system (UWB).

As depicted in Figure 7-2 Figure 7-1 and Figure 7-3, parts of the positioning system are carried at the worker. A normal building-site helmet was modified to carry several sensors; additional equipment is attached to the body-belt.

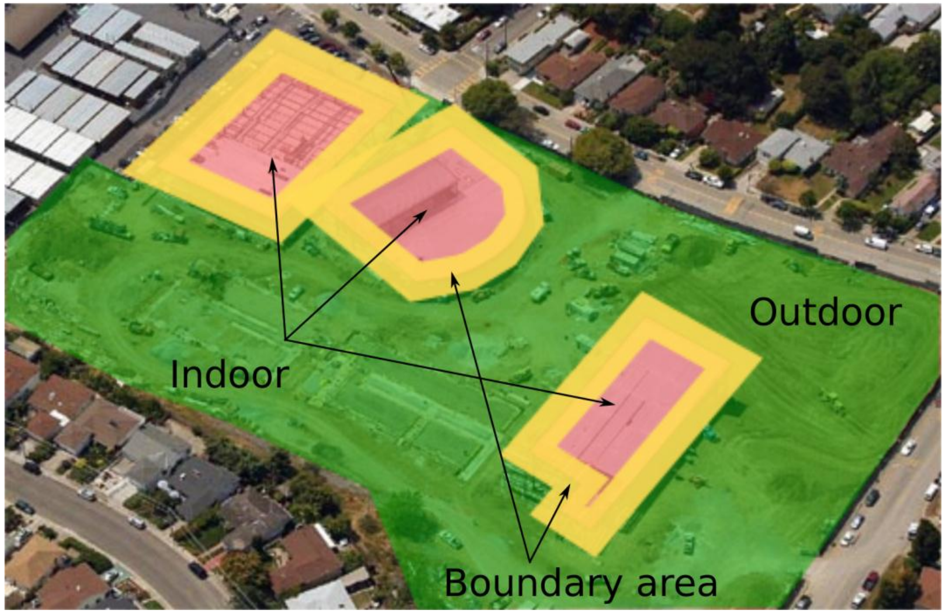

Figure 7-1: Indoor, outdoor and boundary areas on a construction site. Photo by Dave Piper (Common Creative License)

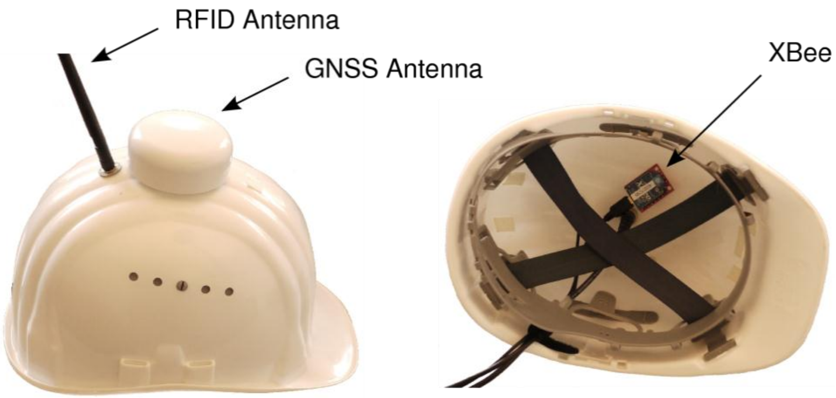

Figure 7-2: Building-site helmet with integrated positioning and communication technology

Software Framework for complete system

For processing the data a software framework is developed. All sensors which are directly connected with the worker operate with tact frequencies between 1 and 120 Hz and deliver the raw data over serial connections. The data are then available for coupled evaluation.

The main part of calculation will be done in an integrated processor directly at the worker; only the calculated position and additional attributes like health data of the worker are transmitted. The data exchange within the software is designed by an event system to have the most flexibility to couple all kind of collected data. Every retrieval or graphical module has access to these events. The framework is designed and transcribed for real-time applications and simple extensions or changes of sensors.

Sensorfusion - Extended Kalman Filter (EKF) – Indoor and Outdoor

The data from the IMU, DGNSS, barometers, RFID and the infrastructure was fused by a Particlefilter (Figure 7-4).

Worker safety behind construction vehicles

Additional to this multi-sensor system, a high accurate local positioning system was developed to take care about workers directly behind large construction vehicles.

The system is based on the Ubisense RTLS to calculate positions of people related to a vehicle. The mounted system on the vehicle is able to communicate with the detected workers using a communication network of the construction wide positioning system. The awareness of the vehicle to the workers is momentary evoked by a high pitched tone which can be replaced by warning messages only for the workers in the relevant area.

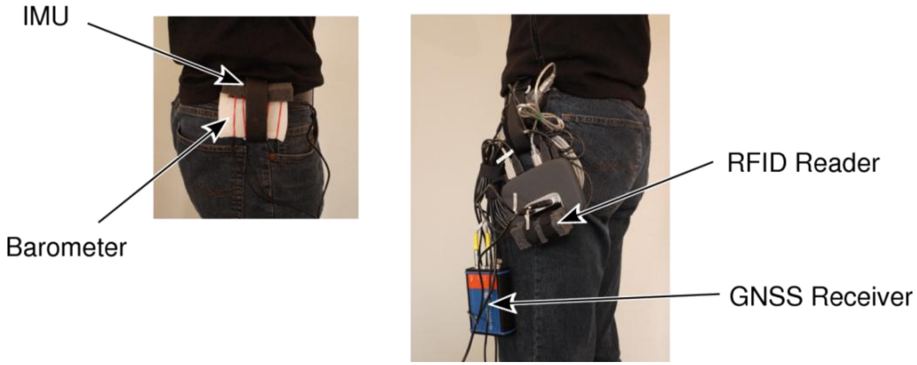

Figure 7-3: Body-belt with integrated positioning technology

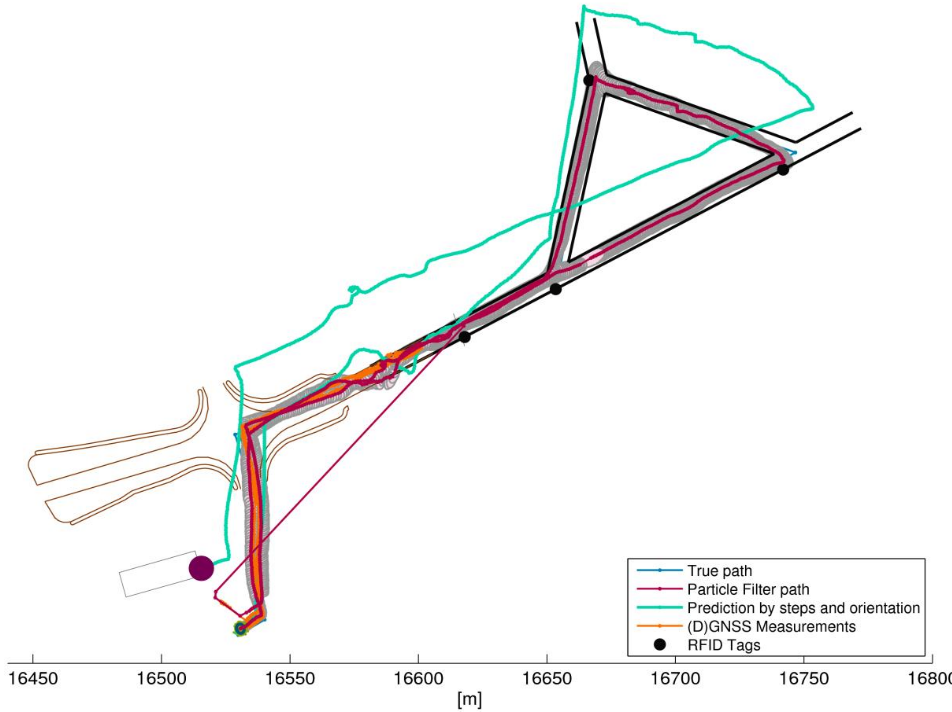

Figure 7-4: Filtered path (red line) with a Particlefilter. The relative Positions from the gathered by the IMU measurements are shown as a green line. The count of RFID tags is reduced to four.

Workers Safety in Tunnel Construction (BBT)

Working on underground worksites poses many dangers. In addition to the general hazards typical to all kinds of worksites there are some hazards particular to underground worksites which result in a higher accident and health risk to personnel working in such worksites.

Special projects like the 64 km long Brenner Base Tunnel connecting Italy with Austria need special attention and care when dealing with health and safety related issues.

The work performed in this context deals with preparing health and safety concepts for underground construction where all characteristics of the construction project and its surroundings have to be taken into consideration.

BBT developed an innovative warning system; this locating system has the great advantage of functioning even under damp, dirty and dark conditions such as those found in tunnel construction. With the system people can even be individually detected, which also fulfils the objective of only warning workers if they are in immediate danger.

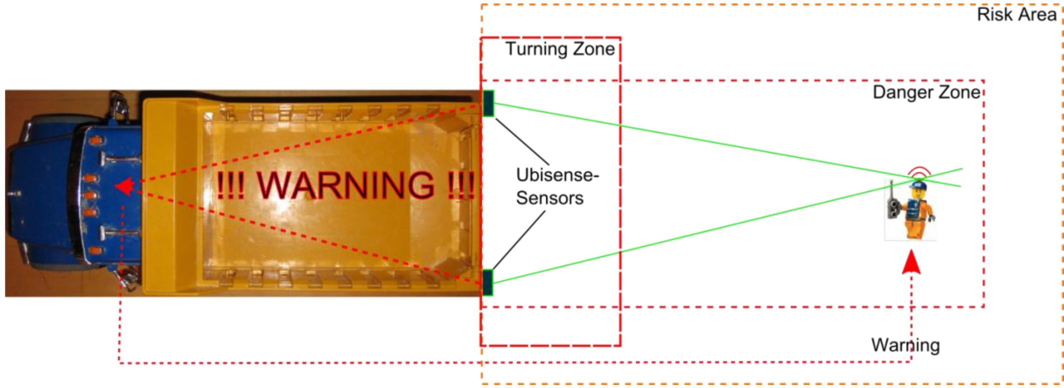

Figure 7-5: Intended installation for a warning system behind a vehicle using the Ubisense RTLS

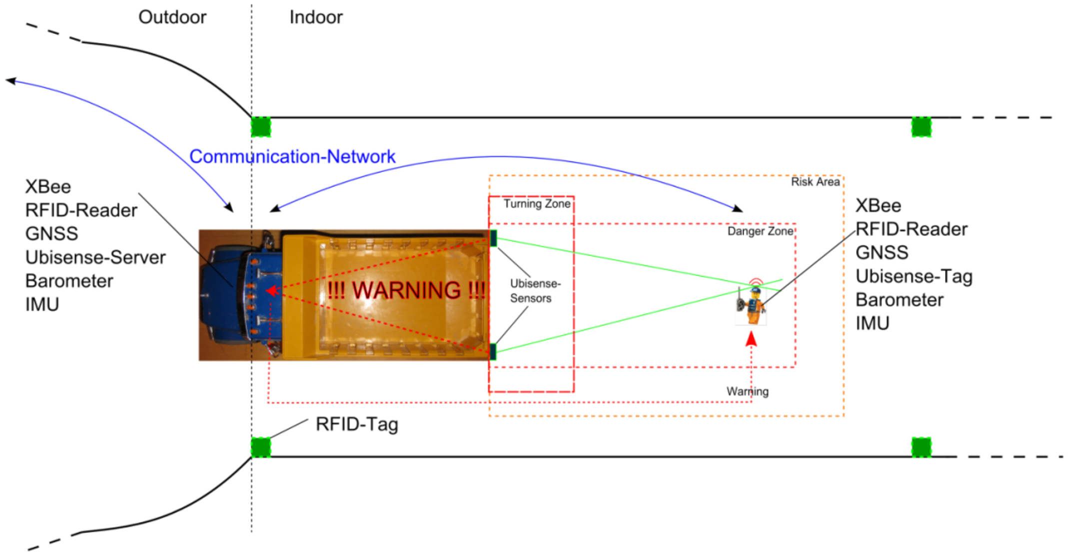

Figure 7-6: Embedded warning system at the vehicle in a construction wide positioning system

8 Vibration mitigation equipment (AVA, WP2)

Safe operation, availability and lifetime assessment of piping are of utmost concern for a chemical plant. One important IRIS goal is to identify risk reduction methods to avoid high cycle fatigue at a large vertical piping system.

The piping system is supported by a tall structure fixed at the base. As a result, the steel building stiffness decreases with height. Furthermore large piping-elbow forces act at the top of the building, which lead to large vibration amplitudes. Since both piping system and supporting structure exhibited these large vibration amplitudes, dampers or shock absorbers placed between them would prove ineffective. Therefore, special vibration absorbers were developed for such piping systems.

Because of the large vibrations in the upper region integrity assessments, investigations on the vibration behaviour and on possible corresponding failure mechanism are of utmost concern. The overall goal is to reduce the risk of failure by controlling the vibrations and to find constructive measures for reducing the vibration amplitudes to avoid

- Nozzle cracks,
- Leakages and
- Cracks in instrumentation nozzles.

To achieve this goal a large number of measures such as measurement campaigns, corresponding calculations for understanding the system behaviour and design calculations for vibration absorbers have been carried out.

A methodology is provided to quantify risk reduction in sense of determination of fatigue and lifetime assessment. The steps for achieving this goal are first to perform an evaluation model on the basis of vibration analysis (Modal Analysis) and Model-updating. Then a new excitation model with a new level of vibration – realized by vibration absorbers – was created. The final evaluation model showed the reduced risk. An assessment of lifetime extension could by derived.

Root cause analyses of the large vibrations at the piping reactor such as thorough measurement campaigns and detailed FE-models updated by operational modal analysis data brought about a system-identification and an

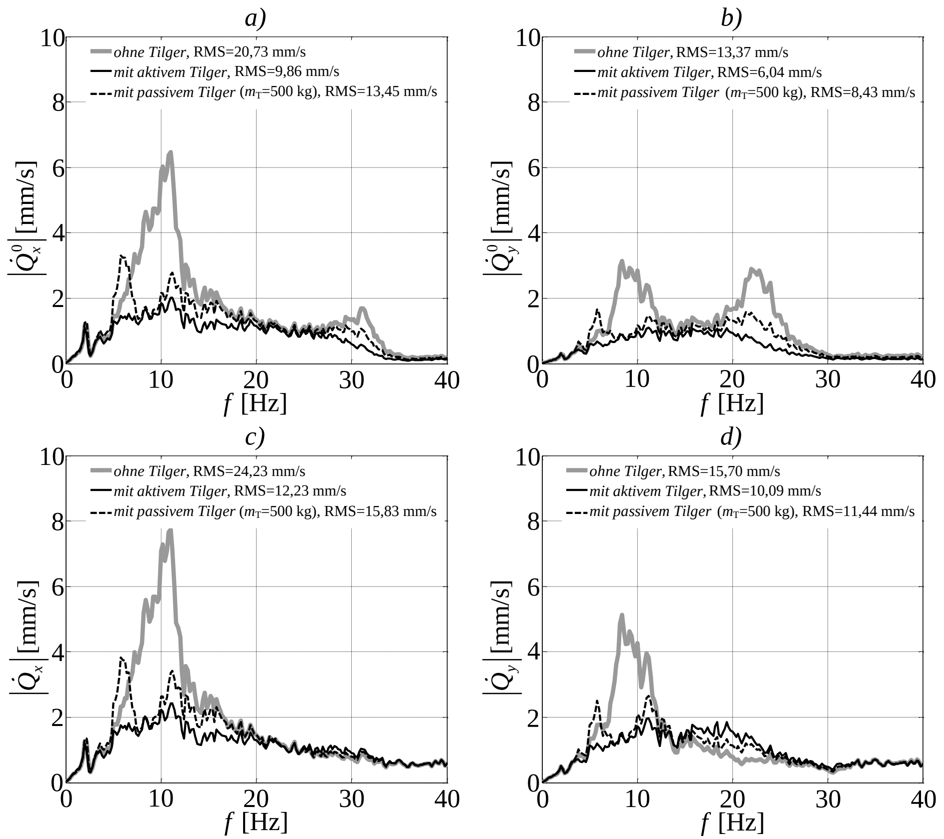

Figure 8-1: Comparison of the effect of active and passive absorber: a), b) at the location of the absorber; c), d) in the middle of the upper deflection

understanding of the resonance effect. On this basis several designs for vibration absorbers connected to the piping in the upper part of the structure were found.

Modal Analysis and system identification is still a challenge for piping in conventional high temperature power plants because of nonlinearities and stick-slip effects due to friction. Therefore it is of interest to provide an updated calculation model which reflects the current state of the system. Among other investigations, system changes due to blocked hangers could be reflected in the OOMA (Output Only Modal Analysis).

Investigations regarding the creep behaviour of high temperature piping systems and flaw detection by guided waves have also been analysed.

Finally, a solution for the design of passive vibration absorbers, an active vibration absorber was presented.

The design process started with an extensive system investigation up to the passive multi-axial vibration absorber design parameters. The aim was to establish a good basis for the risk reduction of vibration induced emergency conditions by use of vibration absorbers.

This included:

Laboratory tests with a mock-up pipe system, where the first design ideas for new passive vibration absorbers were investigated.

Vibration measurements were carried-out to investigate the current state of the vibration behaviour.

- The piping reactor was inspected; strain gauges were used to identify stress concentrations at welds and other notches due to ovalization.
- Finite element calculations were performed, first as a combined beam and shell model for the pipe without the support structure.
- A detailed model for the combined steel construction and pipe system was created.
- Modal-updating was done to fit the calculated model to the experimental modal analysis data.

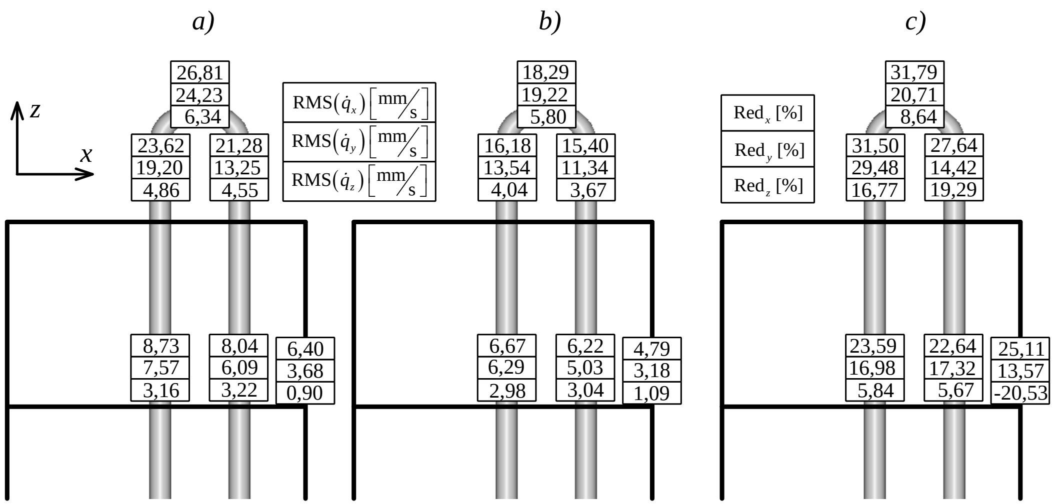

Figure 8-2: Rms-values of the vibration velocities: a) without AVA; b) with AVA; c) reduction of the rms-values by the AVA

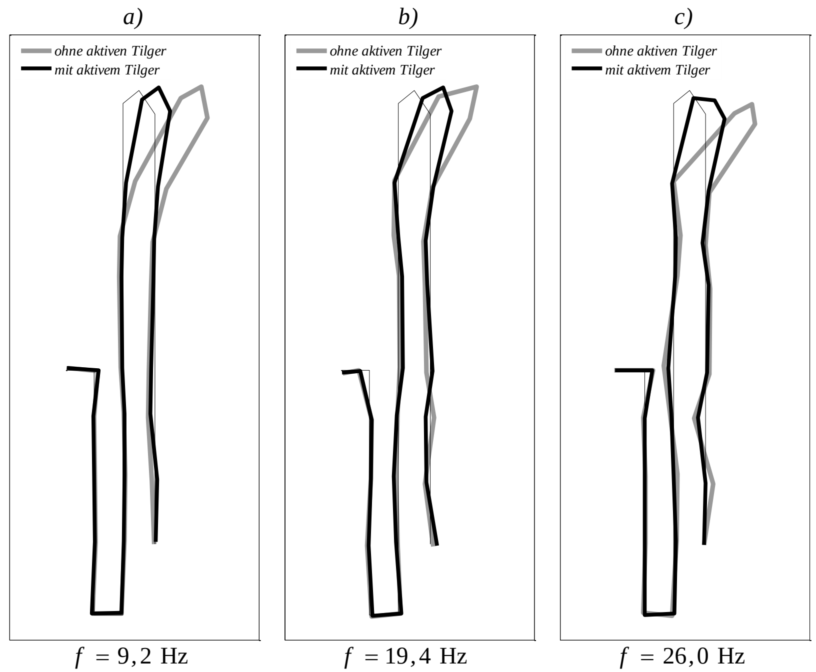

Figure 8-3: Operation deflection shapes with and without AVA (non-proportional representation)

- Load simulations were created to describe the mass flow.
- Excitation.
- Harmonic frequency analysis was performed.

On the basis of these calculations design parameters for the passive vibration absorber were determined.

A prototype of a semi-active vibration absorber was tested in the MPA laboratory but not yet tested in-situ.

9 New approach to tailing pond safety (WP4)

Larger and larger volume of industrial waste dumped into tailings ponds or storage yards as well as relatively low level of acceptance of local societies towards their enlargement or further exploitation, indicate the necessity for launching an interdisciplinary research project bonding multifaceted aspects of identification of hazards and their superimposing as well as determining effective and socially allowable and expected technical and organizational means of these hazards mitigation and prevention. Communities in industrial and post-industrial regions are often exposed to several hazardous processes developing within dam's and filling's structure of tailings pounds, resulting in possible earth dams instabilities following soil liquefaction due to e.g. strong mining-related seismic event associated with heavy rains. Hence, the adoption of a combined multi-risk-oriented analysis, in which investigations focus on the inter-correlation between events and their possible conjunction, seemed to be absolutely necessary. Therefore the main aim of this research was to elaborate such comprehensive risk management procedures, addressed particularly to tailings storage structures, which will be able to find a compromise between expectations of local communities, environment protection requirements and industry operational output.

The problem of risk created by tailings ponds, landfills and waste stockpiles is known widely for many years, particularly as an issue of earth dam's stability and a number of bulletins prepared by International Committee of Large Dams (ICOLD) were devoted to this subject. Pond embankments failure in Aurul S.A. Mine in Baia Mare (Romania) caused launching a large European research project TAILSAFE completed in 2004 by an international consortium. However, this valuable work does not indicate nor recommend computational procedures which may help in real risk values estimation, especially for a case of statistically non-homogeneous natural and man-made environment subjected to various randomly defined external natural inter-correlated influences such as floods, rainfalls, earthquakes, tectonic movement of surface geological deposits (rocks and soil). These effects in conjunction with possible mining-related static and dynamic influences are extremely complex and therefore their analytical (numerical) solutions are unavailable in literature. The second from shortcomings is lack of reference to risk management problems, which should be quantitatively and qualitatively confronted with allowable/tolerable/ultimate level of risk.

Unlike the previous works, the IRIS project offers integrating two basic paths of ponds safety estimation, each of them of extreme internal complexity:

- the path embracing analytical methods and measurement techniques addressed to a general problem of risk estimation in a case of possible structural instability due to natural and man-made hazards, and
- the path grouping analytical methods and measurement techniques useful for environmental risk assessment, for a case of soil/water possible pollution, in accordance with the European regulations, i.e. 96/61/EC (Integrated Pollution, Prevention and Control) and 99/31/EC (Landfill of Waste).

Each of the mentioned groups will utilize its own characteristic analytical and measurement methods as well as the specific methods of concluding. The final integration of the paths has taken place as the appropriate procedures permitting the total risk assessing.

This work package has been carried by major mining industries from Poland, Romania, Sweden and Spain. Opportunities for current practice as well as IRIS technology demonstration are many.

In this subproject three dam sites have been chosen for demonstration. These were dams in Poland, Romania and Spain. All of them have a different characteristic. The best suitable site for early demonstration will be chosen. An early warning system for eventual mass movements shall be demonstrated by triggering such a movement artificially. It is expected that this will provide information on the development route.

The project fills a presently existing gap in the engineering good practices transfer to communities, stakeholders and decision makers and furthermore, it should serve as a model for dissemination of the elaborated solutions. This will permit exploring new research domains concerning development of new methods and analytical tools for quantitative risk assessment as well as this knowledge promoting amongst practitioners. This may also create a space for long-term cohabitation with hazards related to industrial tailings storage structures, providing support for practitioners to produce a comprehensive risk management and prevention policy. The new approach also summarizes and utilizes the data taken from at least three large sites from different industry sectors.

Presently one may observe the increasing demand for risk level information, on measures applied for its mitigation and on the legal responsibilities. In the same time the industry and the government agencies encounter financial and labor limitations in initiatives which may satisfy involved communities. This is why all risk management procedures should presently seek a compromise between the purely engineering/scientific activity and public relation elements involving the society's subjective risk perception. Since risk perception level depends, among others, on quality of the knowledge about it, the principles and methods of knowledge dissemination within communities will be particularly important chapter of the project embracing technological/engineering issues and socio-psychological aspects of tailings ponds construction and exploitation.

There is also an increasing awareness amongst geotechnical engineers of the need for adequately representing on-site material conditions in numerical simulations: indeed, adequate characterization of material properties is now a leading issue in geotechnical engineering, and Eurocode 7 states that "selection of characteristic values of soil and rock properties shall take account of the variabilities of the property values".

The project focuses on the fact that natural materials are spatially variable and that representation of this variability appears crucial to getting a realistic understanding of certain geotechnical problems. Representing geologic variability involves the repeated analysis of specific boundary value problems as part of a Monte Carlo propagation of the effects of this geological uncertainty.

The distinctive feature of the tailings storage structures is their susceptibility to different external effects and loads of different nature as well as on their own internal physical imperfections. A wide variety of the hazard resources results in a large number of different modes of possible structural failure and in different events which may be considered as the catastrophic ones. Since failure events may be related to structural stability problems or may be treated as an environment protection issues, different analytical tools and approaches should be employed for the project's goal achievement. This was obtained through statistical integrating the calculated partial risks governed by different failure modes and related parameters of random nature, into spatially distributed total risk values. Thus an effective risk management procedure has been developed as a methodologically-ordered measures' system which permits continuous identifying and measuring of hazard elements which tailings ponds and landfills may be subjected to, developing, selecting and implementing the appropriate and effective means for risk assessment, mitigation and prevention.

The project looks specifically at the stability of tailings dams. These are particularly vulnerable to weak zones initiating catastrophic failures, as happened in the UK forty years ago at Aberfan. It is important to know what triggers these slides, and how risks might be quantified probabilistically and thereby minimized. Related problems include underwater slopes: e.g. the oil industry is concerned about hazards caused to seabed installations from large submarine flow slides. The differential settlements of offshore foundations and structures founded on reclaimed (hydraulically-filled) land are also relevant.

In the project a stochastic framework for the assessment of risks posed by tailings dams has been developed. It starts with the stochastic characterization of fill materials. It ends with the 3D finite element evaluation of slope reliability and volumes of potential slides, based on random field predictions of spatial variability of material properties. The developed algorithm is used to investigate the influence of various external loadings and variations in the spatial statistics.

The basic analytical tool applied in the project utilizes the probabilistic approach (Figure 9-1) employing advanced structural reliability methods. Since the theoretical/mechanical models of pond/dumps' structural failure modes are generally of mathematically complicated nature, there are not usually available the explicit dependencies between random variables describing phenomena, properties and loads and the failure criteria from the other side. Therefore where possible, the so called response surface methodology has been utilized for such cases. Environmental risk assessment however was based generally on the Bayesian statistical approach coupled with

A new statistical tool integrating three risk elements: the decision model of risk-cost-benefit type, the model of groundwater transport/flow and the model of hydro-geological structure uncertainty.

Statistical data base collected from three different sites play a vital role in the developed project. All parameters governing stability/instability of the considered storage yards/tailings ponds were carefully gathered in order to get the representative population of random variables distributed spatially and spatially correlated each other. The obtained statistical data were then refined using appropriate procedures and were implemented into a practice, scaled and validated in a course of the method field demonstration. The zones of the highest aggregated hazard were examined from point of view of substantial mitigating and preventing risks with maintaining the rational cohabitation with them within the frame of sustainable industrial development.

The conventional (deterministic) approach has been to adopt representative (or characteristic) property values for each soil layer (such as the mean or lower bound); for stability assessments, this leads to a single factor of safety for which there is no information regarding probability of failure. In contrast, the stochastic approach takes account of all property values within a layer; this leads to an alternative, more meaningful definition of stability—i.e. reliability, the probability that failure will not occur.

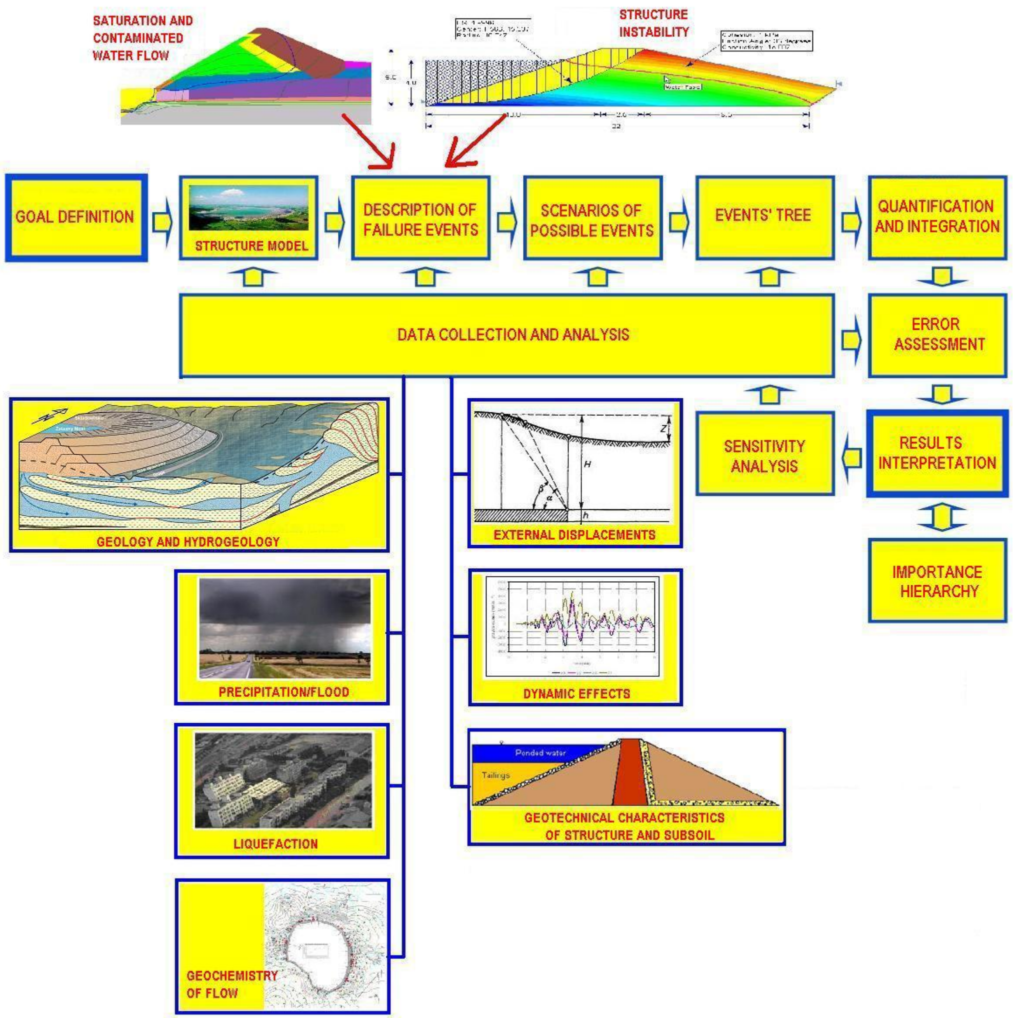

Figure 9-1: The general PRA (Probabilistic Risk Assessment) procedure for tailings ponds

Let's consider two examples of slope stability (Michalowski, 2002):
slope 1 characterized by:

$$\phi' = 23^0 \, , \; \frac{c'}{\gamma \cdot H} = 0.28 \;\rightarrow F_{s,1} = 1.5 \tag{9.1}$$

slope 2 characterized by:

$$\phi' = 32^0 \, , \; \frac{c'}{\gamma \cdot H} = 0.28 \;\rightarrow F_{s,2} = 2.0 \tag{9.2}$$

Assuming incautiously that if mean value of factor of safety is higher than slope is safer, one may conclude that slope 2 is "safer" since the deterministically calculated (limit equilibrium method) factor of safety Fs2 is greater than Fs1.

However considering these slopes using probabilistic approach (Figure 9-3) one may prove that in this example the "safer" slope has higher probability of failure. This is very clear evidence of the importance of departure from deterministic base (mean values) into more sophisticated methods based on probability/reliability analytical tools.
A classical approach has been applied first studying the existing decision trees, complete them to cover the whole topic and subsequently work on interrelations. The result is a multidimensional conditional event tree (Figure 9-4) made consistently with the complexity of the systems. This means a combination of decisions, multi fault tolerance (refer to other topic) and the consideration of unknown input and false positives. IRIS demonstrated this within the example of the tailing ponds under WP4. This example will then be extended to different industries.
Decision trees are a basic element for risk management. Prior a model can be implemented a complete decision tree has to be elaborated. A current practice is to erect decision trees for single input values in parallel.

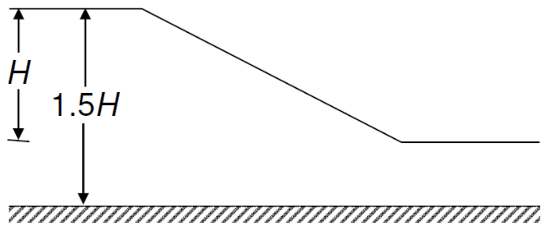

Figure 9-2: Scheme of the two considered slopes (Michalowski, 2002)

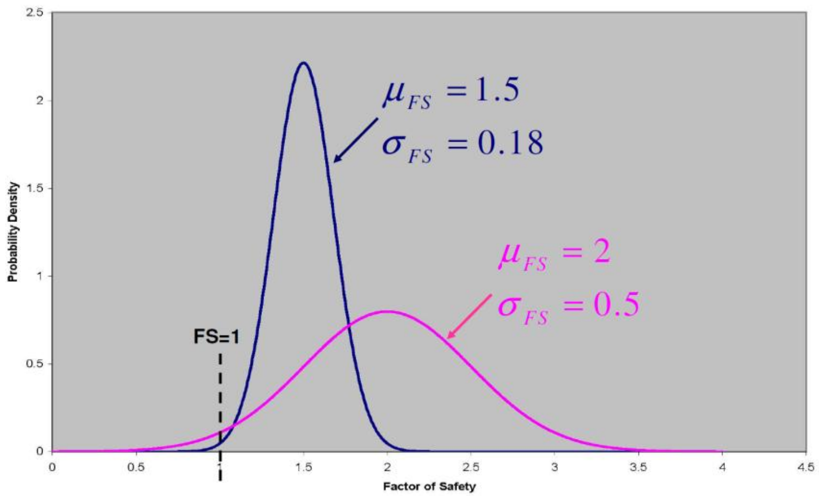

Figure 9-3: Probability density functions for the two exemplary slopes

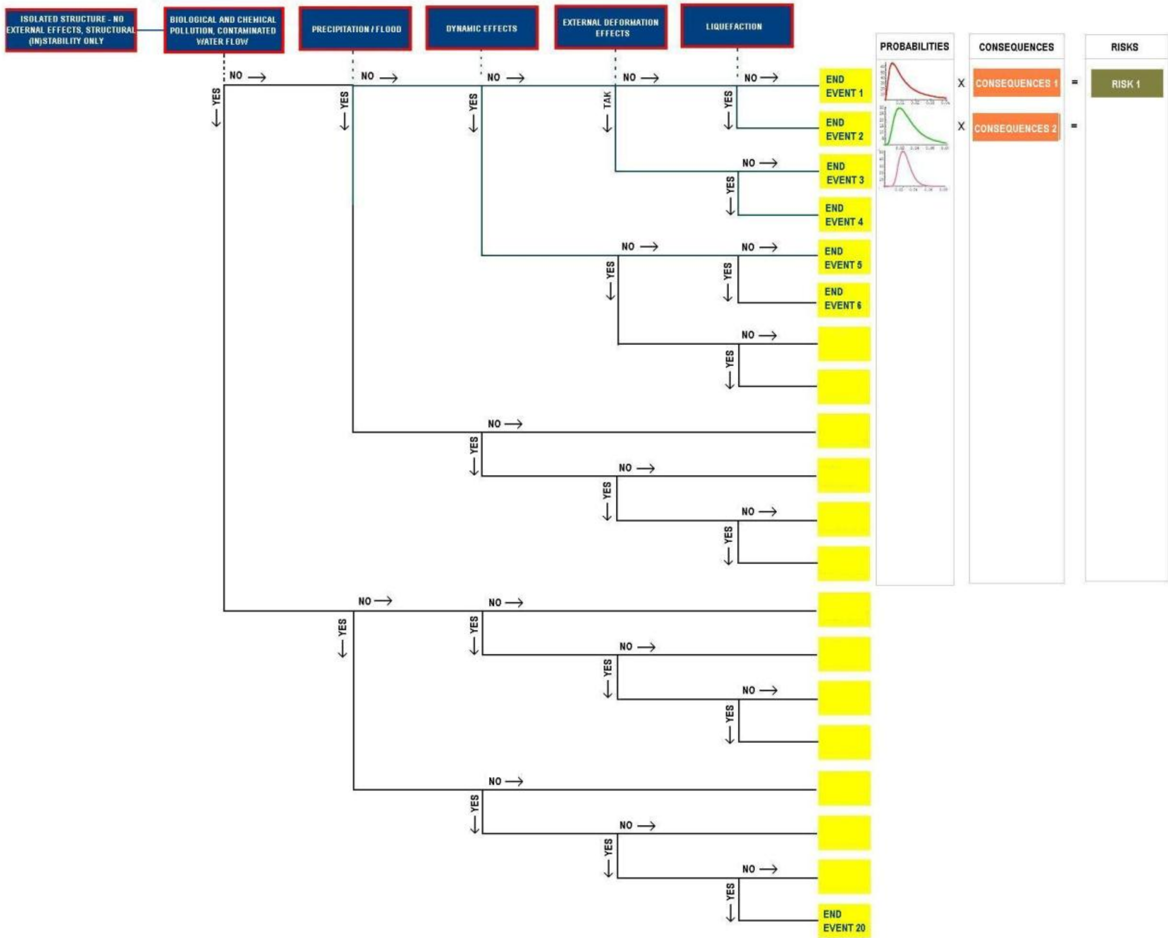

Figure 9-4: Event tree in tailings ponds risk assessment

10 Model based SHM system (WP5)

Why is condition or structural health monitoring necessary for piping systems in power plants?

For reasons of CO2-reduction, temperature is increased to over 700 °C especially in conventional coal-fired power plants. For such high operating temperatures of up to 720 °C at a maximum novel high-performance steels must be applied for the piping systems. The material life cycle and especially the creep rupture properties of these novel high-performance steels, however, are not yet sufficiently known so that periodical inspections of such plants are not sufficient, due to reasons of safety. Particularly piping systems made of these materials which are exposed to high internal pressure must be subject to integral monitoring.

A new safety philosophy, new rules and regulations as well as aspects of the economical operation of plants also require the integral monitoring of piping systems.

The safety risk due to the high energy content of such piping systems is of overriding importance. Material or structural failure leads to considerable property damage and possibly even personal injury must be expected. For that reason legal requirements exist as e. g. the German "Druckbehälterverordnung" or corresponding rules like British Standard, Stoomwezen or EC-directives. Moreover, there is considerable economic risk in case of structural failure with regard to the availability of the plant.

Higher temperatures lead to a higher risk of damaging and have direct impact on the structural stability and the damage behaviour. Adequately reliable results for the prediction of the residual service life of those high-strength steels are hard to achieve. This causes security problems that avoid the utilization of those steels or demand for early exchange of the pipe components. To overcome these problems the implementation of an online monitoring system in addition to periodic inspection is needed. The system should enable the characterization and evaluation of the actual state of the material. Only with an accurate prediction of the residual life time of the components, the safety and the availability and resulting therefrom the efficiency of power plants can be guaranteed.

The monitoring of modern combined heat and power plants is currently focused on the age consumption which is determined by the probabilistic calculation from real load data and in the advanced stadium by additional material investigation during shut-off times. The life-time reserves of the materials can be used more efficiently by applying monitoring systems. This leads to a more efficient and furthermore safer operation of the power plant.

State of the art for periodic inspections are high-resolution non-destructing testing (NDT)-methods based on ultrasound methods or X-ray in order to detect cracks and wall thickness reductions by perpendicularly introduced ultrasound. The clear disadvantage lies in the fact that only local condition information of the specimen (local wall thickness, local cracks) can be obtained. While using only NDT-methods - the testing of hundreds of meters of pipes would be very expensive. Additionally, the power plant has to be shut down during the measurement.

It has to be stated that the existing monitoring methods are applicable neither for the existing martensitic steels and nickel alloys nor for the materials under development. They do not allow for a detailed description of the damage processes. In contrast to the low alloyed steels applied in a lower temperature range, the structural stability which refers to the stability of the time- and load-dependent precipitation is of great importance.

For all these reasons there is need for integral monitoring of piping systems, but for this purpose novel monitoring methods are needed, applying modal and ultrasonic-based methods for the detection of bad spots. For the time being, however, there exist neither suitable sensors nor appropriate methods for high temperatures. Therefore, a respective method and sensor system shall be developed within the framework of the IRIS-project.

The newly developed sensors and SHM method will then be tested by means of laboratory tests in the power plant. For this purpose a test series was started at a bypass in the RWE Neurath power plant. The following questions were investigated:

- Application of low-frequent measurements aimed at the detection of changes in the boundary conditions, which often are due to the starting or shutting down of the plant. As a result of thermal expansions e. g. constant hangers can be blocked at the stop. Blocked spring hangers can lead to massive load redistributions in a piping system. This again can strongly affect the life cycle.
- Ultrasonic-based monitoring technology with guided waves for the detection of cracks and other bad spots, e. g. at high-temperature piping. The long-term objective consists in the detection of changes due to high-temperature creeping.

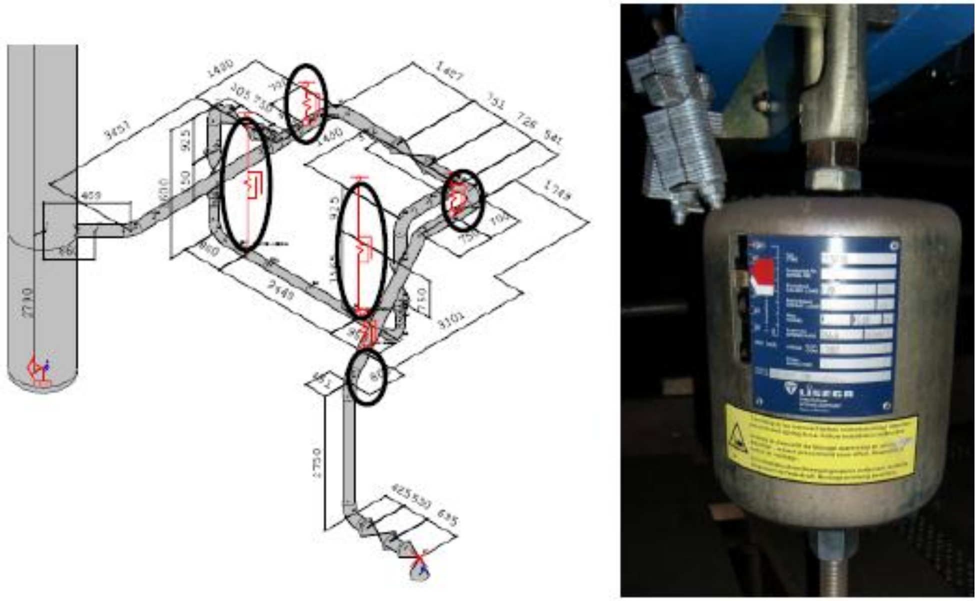

Figure 10-1: Positioning of the spring hangers in the system (left); mounted spring hanger (right).

(a)

(b)

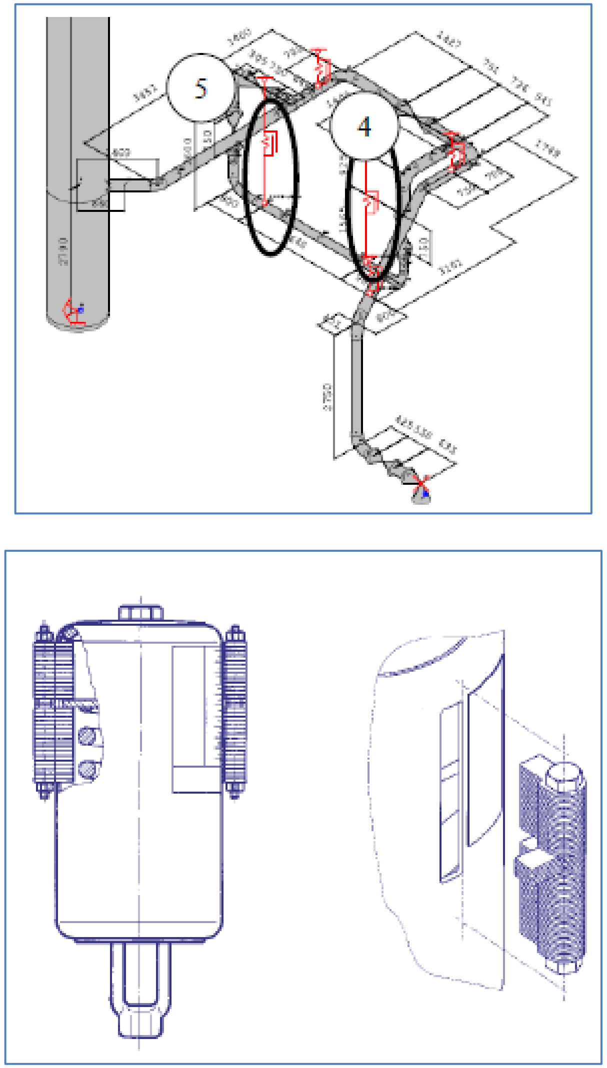

Figure 10-2: (a) Simulation of blocked hangers; (b) blocking procedure of spring hangers (source LISEGA)