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# Intelligent Bridges - Adaptive Concepts for Holistic Condition Evaluation

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**Summary:** *In the German federal highway research institute (BASt), comprehensive R&D work is being carried out to develop and realize a system for real-time information processing and reliability-based evaluation of bridge structures - Intelligent Bridges. This paper describes this concept, summarizes the recent research and development work carried out so far and gives an overview about further intended R&D as well as first steps towards an implementation into existing bridges.*

## 1 INTRODUCTION

The Bridge structures within the German highway network are facing new challenges. These include increasing traffic loads, effects of climate change, modifications in design codes and new sustainability-related requirements. Aging of bridge structures and insufficient financial means for maintenance add significant logistic dimensions to these challenges.

Up-to-date condition information is essential for the evaluation of the bearing capacity and the durability of structures. Continuous observation and inspection of the assets is in this context an important effort that the local road administrations provide as part of the maintenance management of infrastructure. Standardized databases according to the guideline ASB-ING are implemented at state level. The road information database SIB-Bauwerke is an important tool the road administrations have been using since 1998 to register structure-related data and evaluate the results of regular inspections. The current condition rating approach is based on regular inspections according to DIN 1076 [1]. Detected damages are evaluated with respect to their influence on structural integrity (safety and stability in all failure modes), structural condition (durability and serviceability) and traffic safety. The distribution of the condition index indicates that measures have to be taken in a considerable percentage of the engineering structures (according to RI-EBW-PRÜF [2], short-term repair is required from condition index 2.5 onwards). Furthermore, a deterioration of condition index can be noticed over time (Figure 1). This can be explained by the fact that a large part of bridges has by now reached a service life of 40 to 50 years. On the other hand, approx. 350 million Euros were invested for maintaining the engineering structure assets in 2008. This amounts to only about 50% of the amount that would have been required according to the prediction of the federal traffic route plan. The situation was similar during the two previous years [3].

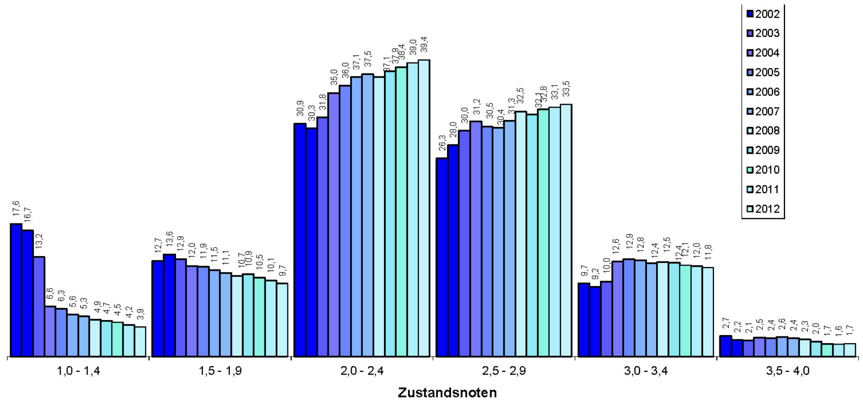



Figure 1: Condition index [% of bridges] of federal road bridges in Germany [BASt]

In the future, it will be crucial to support the current – rather reactive and damage based – maintenance management of bridge structures through adopting innovative approaches in order to further guarantee the reliability and availability of the highway network. Currently, maintenance measures are mainly based on the existing damages, which are detected in the course of visual inspections in a six-year interval (main inspections). It is assumed that measures on damaged structural components are performed before the failure probability reaches an unacceptable value. However, this approach is only useful when the structure indicates its failure, when the load situation does not change over time and when sufficient maintenance funds are available [3]. Since this is hardly the case, new tools are needed in order to obtain in-depth information about the condition of bridges and its development early enough before significant, precarious damage cases occur.

In 2011, the Bundesanstalt für Straßenwesen (BASt) together with the Federal Ministry of Transport and Digital Infrastructure (BMVI) launched the research program "*Intelligente Brücken (Intelligent Bridges)*", which aims at evolving systems for information and holistic evaluation in real time for bridge structures as a supplement to inspections. Several external and internal projects dealt with the topic in the last few years and gave first answers and approaches that represent guidelines and a solid basis to move towards the next step – a first implementation considering the input of all research projects carried out so far. This next period starts shortly with a first partial implementation within a real existing bridge near the BASt and will be accompanied by further R&D work over the next few years in order to answer new questions generated through practical experience and solve structure-specific problems.

In the following, the concept of Intelligent Bridges is described and results achieved so far within internal and external research are briefly summarized.

## 2 THE INTELLIGENT BRIDGE

For several years, bridge monitoring systems have been installed mainly because considerable risks were discovered, e.g. either as a result of recalculating a bridge with upgraded load assumptions or during inspections. Measures taken in such a case are reactive in their nature, i.e. they represent a reaction against presumed insufficient structural performance, propagating deterioration or damage already visible. In a lot of cases, initiated measures come too late and are time-consuming and costly. This can be overcome by equipping structures with a sensor-based computational system that goes further than monitoring does and sets the starting point for taking measures before a potential threat to safety is expected to appear. Properly planned measures in this case are actions which would be taken to prevent condition deterioration – a preventive bridge management [3].

Such an extended monitoring system – the intelligent bridge (Figure 2) - would not only provide as much in-depth information as possible about the equipped bridge structure, but also a holistic condition evaluation in (quasi) real time. The instrumentation of a bridge in order to gather relevant information regarding actions, reactions and resistances is the basis for a reliable condition evaluation. By including life cycle i.e. deterioration models, life cycle predictions can be generated, e.g. concerning condition development and damage. At the end, recommendations regarding preventive maintenance measures can be suggested and evaluated. A corresponding software system generates warning messages and forwards them to executive personnel (bridge owners or users), who would then take appropriate action [3].

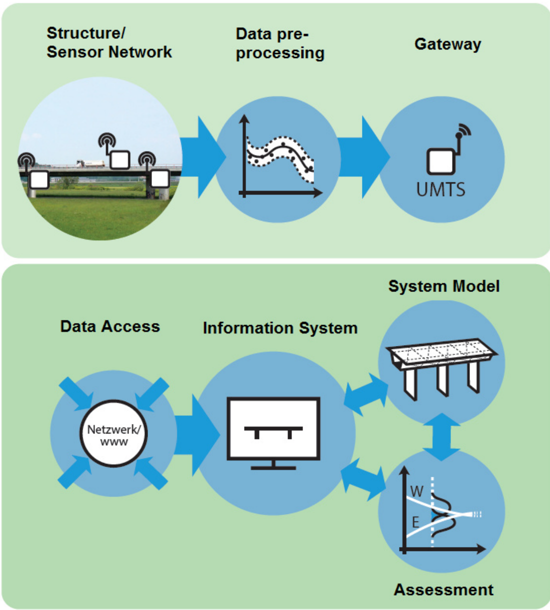



Figure 2: Introducing the “Intelligent Bridges”

Within the complex structure of an adaptive intelligent bridge system, the variety of components and aspects affect each other decisively. Most of these components and aspects can be classified into one of the three following component groups (Figure 3):

- Intelligent sensor technology
- Intelligent modeling and assessment methods
- Intelligent maintenance management

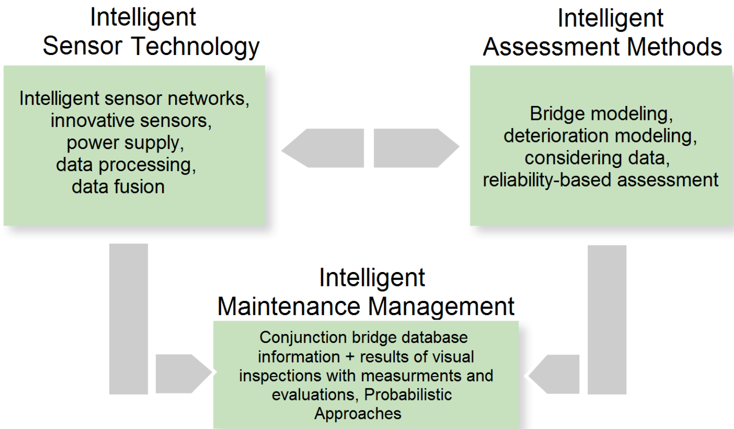



Figure 3: Component groups within the adaptive intelligent bridge system [3,4,5]

Each group is supposed to fulfill different tasks and functions. The hardware and software retrieve the required information: sensor and sensor networks with an intelligent data management and a sufficient energy supply are substantial. The measured data feeds the evaluation models, which on the other hand imply specific requirements regarding e.g. measurands or sampling rates. These two component groups have to be implemented into one adaptive system, which should in turn be integrated in the progressive management and inspection strategies. The structure of the intelligent bridge is intended to be integrated into the existing maintenance management. Results of regular inspections according to DIN 1076, a thorough damage analysis and the structure-related data belong to the overall system architecture [3,4].

Although primarily intended for newly constructed bridges, the concept can be partially adopted and/or adjusted for existing bridges. Sensors can be better installed on or embedded in newly constructed bridges than in existing structures, where drill cores in case of embedding are necessary and installation might be complicated if the interior of the bridge is not or hardly accessible. In addition, traffic, load and deterioration processes histories in existing bridges are not known, which makes a holistic evaluation of a more complicated manner [4].

The mentioned main groups of the research program generated various research projects, which were mostly carried out externally by specialized scientific institutions that have the necessary know how since the project themes are quite interdisciplinary. Some projects with a strong technical development character were carried out by research teams from several institutes or firms. The federal ministry and the national road administrations were also represented in steering committees to insure an early networking and coordination between bridge owners and scientific institutions and facilities. This is also to insure a sufficient support of the bridge owners by providing access to real bridges and, furthermore, to implement their interests and worries in the development process

In the following chapters, results of this research work are summarized accordingly.

# 3 SENSOR TECHNOLOGY AND SENSOR DATA PROCESSING

## 3.1 SENSORS AND SENSOR NETWORKS

The chain of information within an intelligent bridge begins with the sensing elements – sensors or rather the network of sensors – installed on/in it. The sensors are usually exposed to harsh conditions, starting from temperature and humidity variations, dynamic influences and not ending with vandalism. This in turn poses high technical requirements on the sensor components to provide reliable measurements as a basis for further analysis and interpretation. At the time, much development was achieved in the field of sensor technologies for civil structures and bridges. These include RFID-based sensors (Radio-Frequency-Identification) [13,4], Piezo-electric sensors [6,7], MEMS sensors (Micro-electric-mechanical systems) [6,7] and optical fiber sensors (OFS) [19]. In addition to externally installed sensors as common in SHM-systems, the intelligent bridge is supposed to include embedded sensors as well as sensors integrated in bridge equipment elements, such as expansion joints and bearings (See 5.1). These elements can then provide local information about their own condition and can give global indications as to the performance of the overall structure.

A big challenge bridge structures pose is predicting where exactly the next damage(s), e.g. cracks, are going to appear. The most important task in structural health monitoring of bridges is therefore to provide comprehensive information about as much deterioration areas of a bridge as possible. In discrete measuring, significant or representative points “hotspots” of such areas have to be localized, which represent the installation points of the discrete measuring sensors. Carrying out a hotspot analysis per each individual bridge prior to conceiving the sensor network is therefore extremely important for its quality and for the value and reliability of measurements [4].

Though the vast majority of sensors sense at discrete points in the structure, a few OFS technologies enable multiplexed sensing (Fiber-Bragg-Gratings), quasi-distributed (SOFO long gage sensors) and fully distributed sensing (Brillouin, Raman or Rayleigh scattering effects) along the optical fiber [19]. These technologies are very promising for an implementation in bridges, especially for crack detection or deformation monitoring problems. Current research is being planned at the BASt to compare these technologies with conventional strain and displacement sensors on field conditions.

**Wireless Sensor Networks**

In the framework of the research program “intelligent bridges”, advances in wireless sensors and wireless sensor networks are of a particular importance. Conventional wired structural monitoring systems have in this context a serious drawback. Wiring up the sensors to data acquisition (DAQ) Systems is labor-intensive, time-consuming and costly. This is especially the case in a star topology, where every single sensor has to connected individually to the DAQ-System i.e. data logger. Maintenance costs as well as vulnerability of cables are additional aspects to be considered in wired systems. On the contrary, WSN are much easier to deploy, more flexible and expected to be more cost-efficient on the long term [20].

A wireless sensor network is essentially a computer network consisting of many small, intercommunicating computers (sensor nodes or motes). A mote is equipped basically with one or more sensors needed for individually required measurements, a signal acquisition and conditioning unit, a processing unit with RAM (board), a power supply as well as a transceiver for radio-frequency transmission and communication with the network (Figure 4).

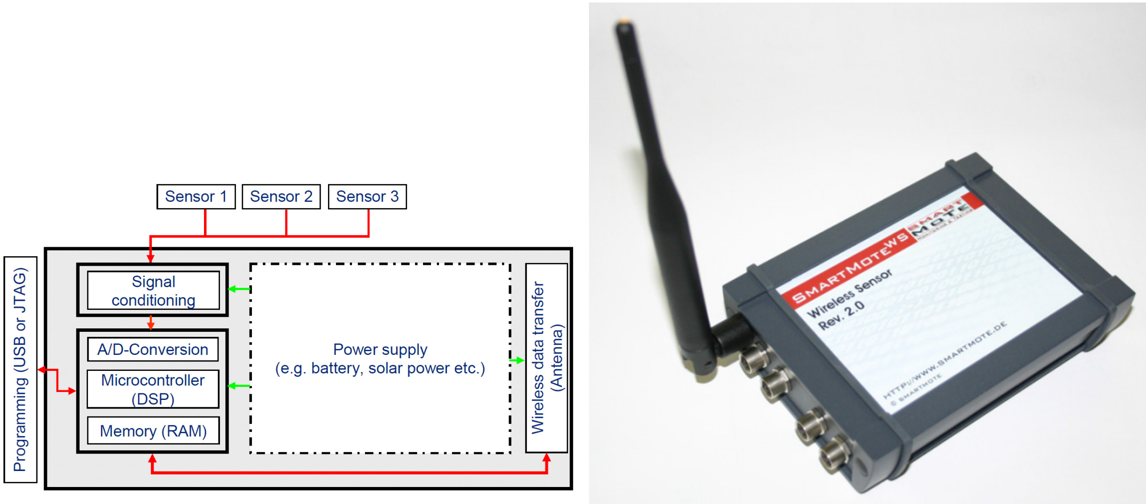



Figure 4: Mote hardware architecture (left) and a developed prototype [6]

## Wireless sensor communication

In order for the sensors to communicate with each other i.e. with a central unit, star or multi-hop network topologies are required (Figure 5). Star networking means each single sensor connects directly to the data logger or gateway and is less suitable for WSN due to the very high energy consumption. Multi-hop networking enables nodes to communicate with neighboring ones that forward its data towards a root node, the sensor nodes act as data sources and as relaying stations receiving and forwarding data from neighboring nodes.
In cases where e.g. surface damage due to corrosion has to be clearly detected and localized, a comparison of data coming from numerous sensors has to be carried out. This can be done by means of a multi-hop network with a cluster data analysis, where sensors are divided into groups or clusters. After data are processed individually in each mote, a central mote gathers the pre-processed cluster data and carries out a cluster data analysis. The cluster data are then forwarded to a central computer for further analysis and interpretation [6].

By taking the shortest communication ways between sensor nodes till the root node, the power consumption can be reduced substantially in comparison to star topology, since the required transmission power is proportional to the square of the transmission distance. Another factor is the communication route flexibility. In cases where the signal path or signal propagation is blocked due to physical objects, like when e.g. transmitting from inside a bridge girder to a master mote positioned outside, data can be transmitted via alternative routes and one or more relaying nodes to forward the signals.

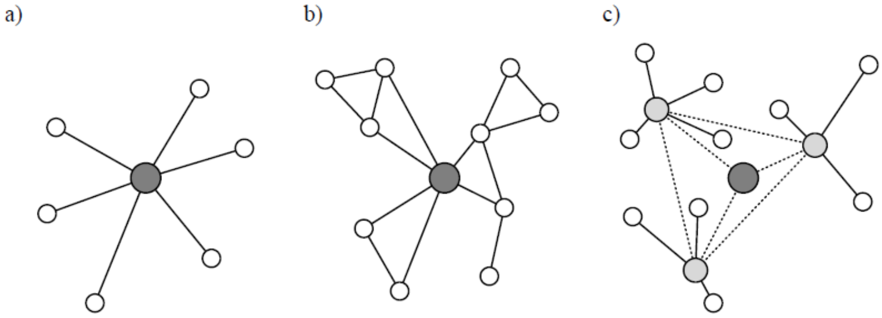



Figure 5: WSN topologies a) Star b) Multi-hop c) Multi-hop with clustering [11]

The master (root) mote is connected to the gateway where data is collected, pre-processed and transmitted wirelessly. For this purpose, various wireless communication standards exist, which differ in local availability, coverage range and performance. The most known standard is Wi-Fi. Another example is ZigBee, which is based on the IEEE 802.15.4 international standard. It is characterized by its low power consumption, a defined rate of 250 kbit/s and transmission distances between 10–100 meters. ZigBee devices can also transmit data over long distances by passing data through a mesh network of relaying devices to reach more distant nodes. These characteristics make ZigBee a very suitable choice for low data rate applications like WSN where long battery life is required. Compared to Bluetooth or Wi-Fi, ZigBee-based devices are intended to be simpler and less expensive [6,7].

## Energy supply

A big challenge in the field of wireless sensor technology is to guarantee an effective energy supply of the individual wireless sensor nodes on a long term. In a recent project commissioned by the BASt, current technologies of energy harvesting for the energy supply of sensor nodes as well as access points (Figure 6) were summarized and assessed [11]. Performance parameters of corresponding energy supply systems were identified and evaluated regarding availability, reliability, sustainability, space requirements and cost effectiveness. As a planning aid for the design process of autarkic sensor concepts in bridges, calculation tools were developed in order to determine energy demands for different sensors/components as well as to size energy supply/storage systems.

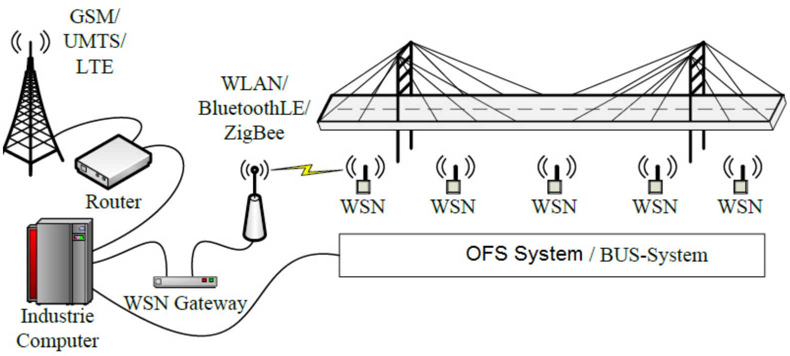



Figure 6: Power consumers at the access point [11]

In general, the sources for power generation a bridge environment offers are limited. In addition, these sources are strongly dependent – in time and space – on different climatic and structural parameters (e.g. regular availability of sun shine, wind or regular specific vibrations combined with a suitable stiffness of the structure). This means it is essential to reach utmost optimization in energy consumption but also to further develop solutions for effectively bridging power generation gaps by means of e.g. carefully sized energy storage systems.

For the assessment of autarkic energy supply technologies, the sensor system components were divided into two main performance classes (I and II) depending on required the energy consumption. Class I involves the power consumers at the access point of WSN (router, industry computer, gateway, optical fiber interrogators), class II involves the components of wireless sensor nodes. For **class I** components, hybrid systems (combination of photovoltaic systems and small wind power systems) were recommended for an autarkic continuous power supply in almost all regions of Germany. These systems represent an economical and technical optimum since any other solution leads to a (costly) oversizing of either the generation system (e.g. solar module) or of the energy storage system (battery) to guarantee a continuous supply. Furthermore, H-systems provide a higher reliability in case one of its components is out of service. For **class II** components, small photovoltaic modules or other energy harvesting methods can be utilized, such as piezo-electric, electro-dynamic or thermo-electric generators. However, the currently possible energy outcome through using these methods is very limited (few μW). Again, the necessity of best possible consumption optimization on a hardware and software level becomes evident. It is also necessary to develop efficient energy management systems in order to monitor and optimize the charging process of energy storage systems.

The energy demand of the sensors decisively depends on the sampling rate, even if typically energy-saving sensor technologies such as MEMS (Micro-electro-mechanical Systems) are used. If high sampling rates are set, the energy demand could become high enough to make PV supply modules with considerable sizes (few $dm^2$) inevitable. On the other side, the sensor power consumption becomes secondary for the total consumption in cases of low sampling rates. Here, the other components of the sensor node are put on standby most of the time, which means their energy demand during the low-power-modi is decisive for sizing the energy harvesting systems [11].

WSN technology is very promising, however not yet fully mature for a long-term deployment in the field. Practical aspects play a key role in this context. A main issue is the durability and reliability; there is still a wide gap between WSN prototypes in labs and the ones exposed to the inconsistencies and threats of a real environment. On the other hand, if WSN are to be broadly used on bridge structures, they will be deployed by maintenance crews, not by research teams, which is why they also should be straightforward to install. Furthermore, it is crucial to achieve systems that enable short deployment time and an end-to-end connectivity of the multi-hop network within a reasonable time. Other practical issues to be considered in applications on bridges are e.g. guaranteeing continuous radio connectivity and radio propagation within the structure, security of data, packaging and attachment of motes to the structures (gluing, mechanical fastening?) etc. These and other issues were particularly relevant in the course of recent and actual joint projects dealing with WSN applications on bridges (see 5.1).

## 3.2 DATA PROCESSING

The data processing includes several operations which are intented to produce data of highest quality possible for further analysis and bridge condition assessment. One problem with many bridge monitoring systems to date has been the sheer amount of raw data they collect, which requires intensive analysis and post-processing in order to extract relevant and useful information about the structure. On the other side, there are often cases where sensors deliver data which were manipulated through different unforeseen influences or failures. The integrity of sensor data is then violated and false alarms might result.

Data processing involves at a primary stage specially a reduction of the data volume intended for transmission and further analysis in a manageable and energy-efficient way. This can be done by computing e.g. minima, maxima or average values of sensors data within a given sensing period. In this way, only characteristic measurement values of a sensing period can be transmitted instead of all measurements, which effectively reduces the energy needed for (wireless) data transmission [4]. Furthermore, data compression algorithms can be implemented in order to reduce the data volume without compromising the value of information of the data. Usually, the most effective way of doing so is the implemetation of these complex algorithms into the processor core of motes [5]. A well known example of such algorithms are the Fast-Fourier-Transforms (FFT), which are used to compute the discrete Fourier transform (DFT) in order to convert time to frequency and vice versa.

Data volume depends mainly on the data acquisition (DAQ), which can be continuous, time-discrete or event-based (triggered). Obviously, a continuous “online” data acquisition leads to high energy consumption on the long term especially if combined with high sampling rates, which produce a huge data volume in need for processing. However, online monitoring is required and justified in certain scenarios where e.g. a significant bridge is in critical state and other measures such as an immediate long-term full closure are out of the question.
Time-discrete DAQ methods are typical when measuring temperature, humidity, corrosion and chemical parameters, where rapid changes are not expected. In triggered sensing, the sensor nodes (and the monitoring system) are basically put on an energy-efficient standby modus. The sensor are “woken up” i.e. measurements are started when a certain threshold is exceeded, which marks a corresponding event (e.g. passing heavy vehicle and traffic in general) relevant to start measuring for a defined time span. A series of further operations can be triggered along with measuring, from data pre-processing on motes and cluster analysis to sending alarm messages if limit values are critically exceeded [7].

Another important aspect to guarantee high quality measurement data is the plausibility control, which can be done by means of model-based and statistic analysis methods a la smart data analysis methods. Through the implementation of one of these methods or in combination, a much higher standard can be reached regarding the quality of measurements than in SHM applications currently in practice. In a recent research project commissioned by the BASt [12], real measurement data sets from different projects were verified using plausibility control methods. The implemented methods and algorithms could reliably detect and filter various anomalies and signal manipulations such as outliers, noise and hum troubles.

Another important aspect in the course of the quality control of measurement data, yet often neglected in practice, is the consideration of measurement uncertainties. Uncertainties result from numerous influences depending on the used sensor technology/type as well as environmental conditions on the bridge location. Currently, a framework for the calculation of measurement uncertainties in concrete bridge monitoring scenarios based on the ISO/BIPM guideline GUM (***G**uide to the Expression of **U**ncertainty in **M**easurement*) is being worked out at the BASt.

## 4 INTELLIGENT MODELING AND ASSESSMENT METHODS

The approach of preventive maintenance requires in-depth knowledge of the actual condition of a bridge structure and more reliable prognosis of its development. The word prognosis implies the necessity of describing the probability of occurrence of events as well as their possible consequences to quantify risks (=probability * consequence) and improve the basis for decision making.

### 4.1 STRUCTURE MODELING AND ANALYSIS

In addition to the sensor system, a structure model is required that thoroughly simulates the structural behavior of the bridge i.e. especially the dependencies of its structural elements of each other and allows deriving the effect of a local damage on the global performance and integrity of the overall structure. Having such a model, risks can be identified and estimated taking the structural dependencies of its elements as well as available redundancies and damage interactions into consideration [3,4,5].

As a first step, the bridge is divided into its structural elements according to a defined level of detail. In order to simulate the dependencies between the structural elements i.e. to join them into a model of the bridge structure, logical connectives or operators are required.
Various available modeling methods as described in references were analyzed in the course of research within the intelligent bridge. Typically, *Event Tree Analysis (ETA)* and *Fault Tree Analysis (FTA)* are used for such system analysis applications. Both methods only allow – in respect with system modeling - operators AND and OR. Besides, interactions or redundancies can hardly be considered [4**].** To overcome this, a new approach was conceived in [9] – the *Influence Tree*. It can be seen as an extension to ETA according to DIN 25 424-1 and DIN 25 424-2. Instead of binary behavior and Boolean model, freely defined operators were utilized to enable describing structural dependencies between elements as well as interactions between faults and damages. The model enables to draw conclusions about damage causes and to gain information regarding the influence of damages or their indicators on single structural elements (local) and on the whole structure (global). In Figure 7, the model concept is drafted.

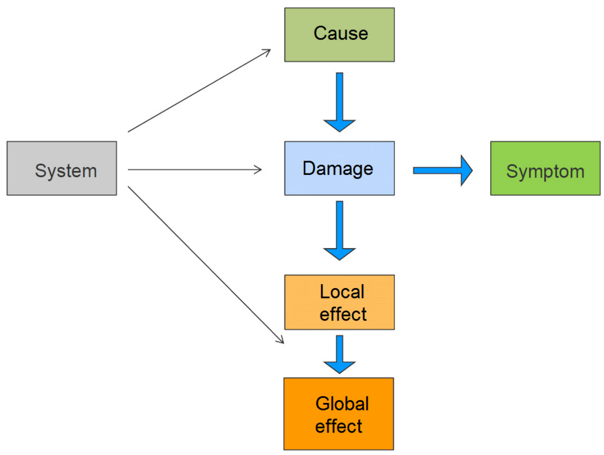


Figure 7: Concept of the System Model [9]

A damage can be diagnosed either by knowing its cause or monitoring one (or more) of its symptoms. Such a damage (or fault) usually affects a single structural element or a group of elements and potentially has an effect on the overall bridge structure.

The following example involving steel reinforcement corrosion in a concrete box girder section, typically caused by defective drainage systems, is intended to exemplify this concept. Through localizing damage *cause* and damage *symptoms*, it is possible to determine damage *extent*. Causes can be identified through e.g. the measurement of humidity or chloride content in concrete. Typical symptoms or outcomes of advanced reinforcement corrosion are spalling of concrete cover and/or rust stains on concrete surface. Depending on the case system, the *influence of damage* on the affected structural element and the overall structure can be described. This means, regarding the affected element, e.g. a reduction of the corresponding effective cross section. For the overall structure, it may lead to a reduction or potentially in a loss of serviceability or even structural integrity (This would obviously be a severe case. Deciding on the severity of damage and how it affects the overall system is dependent on the static system, construction method, materials etc.). [3,9]

With this in mind, the proposed *influence tree* consists of three modeling levels (Figure 8):
Level 1 – Structure
Level 2 – Damages
Level 3 – Parameters

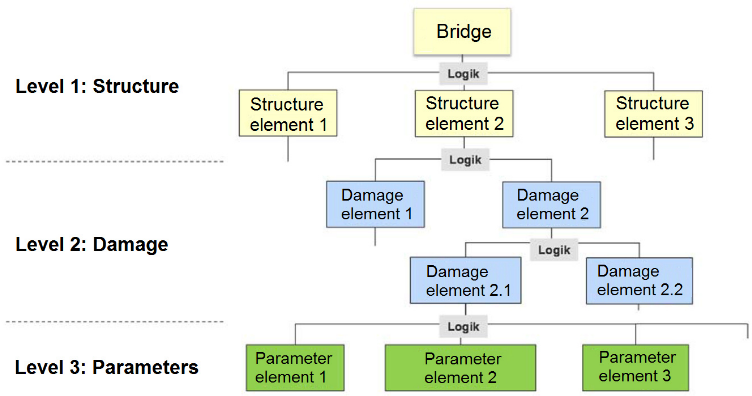


Figure 8: Scheme of the Influence Tree [9]

The structure level (Level 1), as the name implies, models the structure of a bridge by dividing it into elements and sub-elements (Figure 9). The damage level (Level 2) describes the correlation between an already occurred damage and the condition of the affected (sub)element and enables a corresponding connection through defining measurable parameters (Level 3) as an input value. It should be emphasized that these different parameters are processed and analyzed within the influence tree. In contrast to ETA and FTA, it is neither about pure error propagation nor is the effect of one occurrence solely analyzed [4].

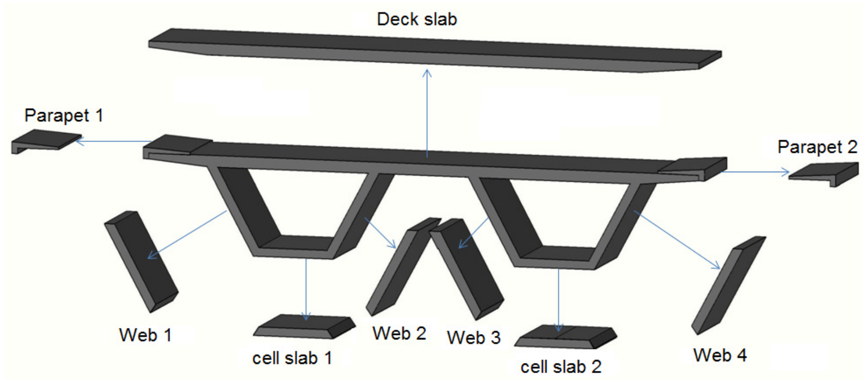



Figure 9: 3D Model Elements of a concrete box girder section [9]

Level 1 comprises so called "structure elements" of a "system". The term "system" in this context includes all structural aspects of a bridge such as construction method considering structural behaviors of longitudinal and transverse systems, relevant elements of the system as well as their material properties. Each should be understood as a system component and assigned an element within level 1, which can also comprise more than one sub-level.

In Level 2, faults (e.g. corrosion) corresponding to a specific structure element are accordingly assigned to that element within the influence tree in the lowest layer of level 1. In case various processes leading to a specific fault (as a level-2-element) exist, further sublevels can be added to that element. For example, the corrosion process (level-2-element No. 2) can be initiated through chloride contamination (level-2-subelement No. 2.1) or also through carbonation (level-2-subelelement No. 2.2).

In Level 3, "Damage" parameters that allow drawing conclusions regarding start and development of the degradation process should be assigned to the lowest sub-elements of level 2. Although it is better to acquire those parameters directly in-situ using appropriate sensors, it is also possible to integrate e.g. results of the latest bridge inspection [9].

The system model can be created by means of the Systems Modeling Language (SysML), which allows a graphic description of all relevant system elements. While constructing the influence tree of a system starts from level 1 and goes down through all sub-levels and elements to level 3, the analysis runs backwards to identify the influence of each parameter on a damage level and ends on a structure level (and overall system). Through the vertical connection between the tree branches, it is always possible to track and assign single parameters to corresponding faults, and single faults to corresponding structure elements. An example case of damage scenario "column settlement" is shown in Figure 10.

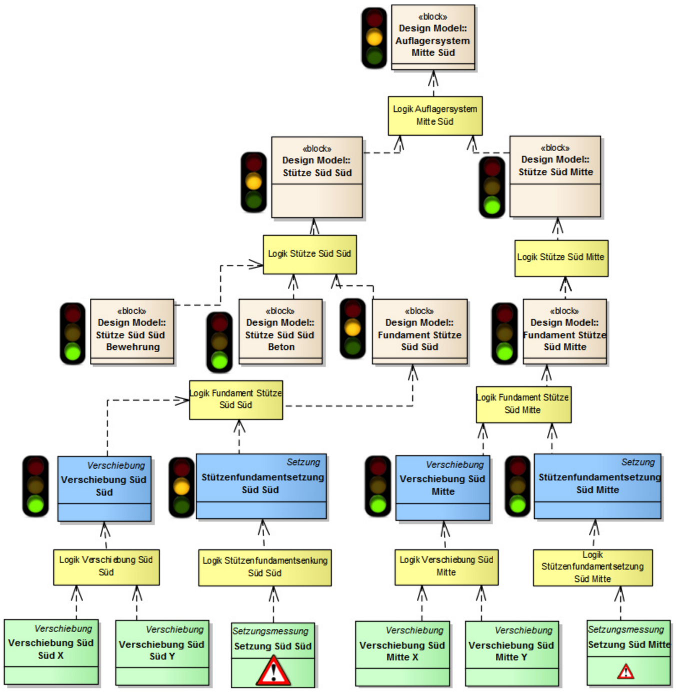


Figure 10: case scenario model « column settlement » [9]

It should be noted that for some degradation processes, merely empirical data but no comprehensive physical models currently exist. This means that the model cannot cover all aspects in such cases. However, the system model basically enables considering both probabilistic and deterministic approaches.

## 4.2 RELIABILITY-BASED CONDITION ASSESSMENT

As mentioned before, a more comprehensive management approach will be necessary in the future, which should consider detected but also expected damage and condition effects, actual loads (actions) and resistance. Demands resulting from future traffic should also be applicable. Because of the randomness of all parameters, a probabilistic (also: reliability-based) approach is helpful. The basic idea of which is that both actions and resistances of structures are time-dependent and random parameters. Typically, probabilistic analyses result in failure probabilities which should not exceed a pre-defined threshold value. If resistance and action parameters are measured sufficiently, optimized maintenance strategies including well balanced protective measures could be derived, which would lead to reducing maintenance costs and increasing service life of the object structure [4].

The most comprehensive probabilistic approach for reliability-based condition assessment was developed by the Joint Committee on Structural Safety in conjunction with the Probabilistic Model Code (2006). This approach enables consistently quantifying a structure’s reliability especially in consideration of inspection results. In this context, the reliability theory represents the basis for structural design (according to EN 1990) and consequently for condition assessment of structures [5].

The integration of inspection and monitoring data in the reliability-based condition assessment process has become vital in various engineering disciplines such as offshore wind turbine support structures [18]. One of the first research projects commissioned by the BASt within the Intelligent Bridges was dedicated to this topic [8]. The project aimed at identifying available concepts and methods for integrating inspection and monitoring data in reliability-based condition assessment and adopting/adapting them for the special case of deterioration in bridges. Here too, both deterioration and structural models are required for the system analysis and both as logical operators in the system (bridge) model. The input ("damage") parameters are afflicted with different significant uncertainties that ought to be considered by means of a probabilistic modeling. Having in mind that the condition assessment result is merely a snap-shot, the timely developments of condition and system analysis results can also be modelled (involving uncertainties), which enables helpful forecasts. This means that process of measures planning becomes not only a more precise one, but also more forward-looking.

Another possibility is that a first analysis on the existing base would define the need of further information as a best measure. Each result of a inspection or monitoring allows an update of the model parameters, e.g. using Bayesian updating. This method permits an incorporation of all information in a consistent manner in a single model. Here, the accuracy and validity of measurements and observations are taken into account. By updating the model parameters, the accuracy of the system analysis and its prognosis can be increased, so that the dependent measures planning can be adjusted accordingly [8]. In this way, the instrumented bridge turns by means of tests, inspections and monitoring into an *Intelligent Bridge [4]*. One can go further and speak of an "adaptive" system which constantly adapts to changes occurring out of the structure and the environment by continually giving up-to-date condition and condition development statements. Figure 11 summarizes the mentioned aspects in a concept draft.

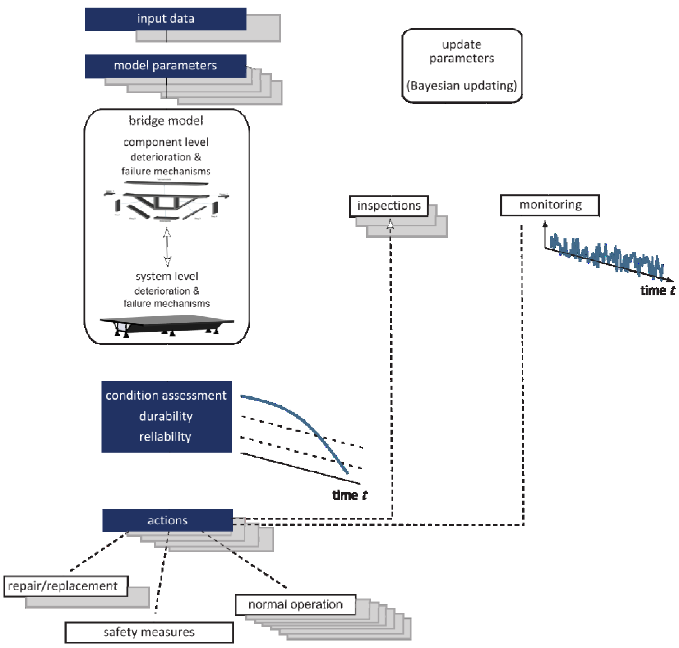
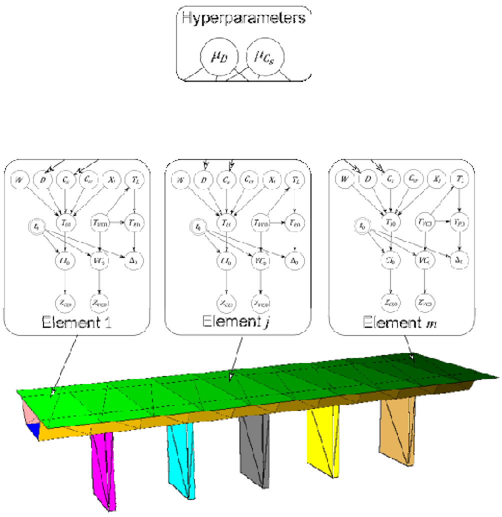



Figure 11: Overall concept « Intelligente Brücke » for an integral and adaptive estimation of a bridge system's deterioration and condition [9,10]

In another recent project [10], the proposed approaches of modeling and reliability-based condition assessment were implemented into a prototype for an estimate and forecast of the damage and condition states of a pre-stressed concrete box girder bridge superstructure. The prototype considers information and data from inspection and monitoring. Since only a probabilistic approach allows consistent integration of quasi-real-time data from monitoring and inspection, both the damage and condition modeling were probability-based. The probabilistic modeling of the bridge condition was carried out on the basis of Dynamic Bayesian Networks (DBN). DBN enables modeling and visualizing of dependencies within a system as well as including different deterioration processes and their stochastic dependencies. Furthermore, they allow considering information from inspection and monitoring and including them into the condition prediction. The practical applicability was demonstrated by the development of a user-friendly software prototype. The software is based on the system model, which is in turn based on DBN. It combines a user-friendly graphical user interface (front end) with a computational core (back end). The front end enables using the software by users without detailed knowledge in probability theory (Figure 12).



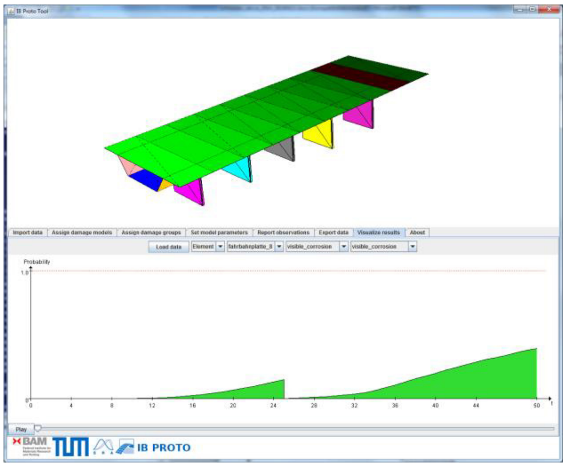


Figure 12: Example from the prototype software modeling – connective operators (left) and a screenshot of software front end [9,10]

The back end enables calculating the box girder’s damage-state probabilities in consideration of information from inspection and monitoring on the basis of a DBN model. It also enables calculating the system-failure probabilities of the damaged box girder using a structural model that was developed based on the finite-element method as well as on the plastic-hinge theory.

With the model and the software prototype for probabilistically assessing and forecasting the damage and condition state, a basis has been established for the identification of efficient inspection and monitoring strategies. The developed software prototype includes currently a model for chloride-induced reinforcement corrosion. As a next step, the software prototype should be extended to further deterioration processes. Moreover, it should be enhanced with reliability and risk-based planning of inspections, monitoring, and repair. Such a planning includes determining their influence on the structural reliability. This enables to consistently and quantitatively compare different strategies. By including action costs and quantifying risks, a fully risk-based optimization of actions is possible in the future. However, as a first step the full implementation of a reliability-based approach should be envisioned, where compliance with given target reliabilities is demonstrated [10].

## 5 IMPLEMENTATION

### 5.1 JOINT PROJECTS - NATIONAL RESEARCH PROGRAMM

The presented projects are either carried out or directly commissioned by the BASt and are strongly application-oriented. In the following, projects with a rather innovative product development character are enlisted. These projects were carried out within the national research program and supervised by the BASt. The researchers developed their own systems with a strong reference to the "intelligent bridges" on a commercial basis. The developed systems were also tested and verified under near-real traffic and climatic circumstances.

- **FE 88.0106 "Road Traffic Management System (RTMS)**. In this project, a concept was developed (and implemented technically at a bridge) that allows real-time identification of actions and resistance as well as the condition evaluation of bridges and provides simultaneous data for traffic counting and for the determination of axle loads of vehicles. For data acquisition of traffic volume and of single vehicles, innovative traffic sensors were used. Furthermore, algorithms for axle load detection and for parameters describing the bridge condition were developed. [15]
- **FE 88.0110-0112/2011"Intelligente Schwenktraversen-Dehnfuge und intelligentes Kalottenlager. (*engl. Intelligent Swivel-Joist Expansion Joints and Intelligent Spherical Bearings*)".** In this project, swivel-joist expansion joints and spherical bearings for bridges were equipped with sensor systems. Based on standard bearing and joint components, these systems are capable of temperature-compensated self-monitoring and monitoring of traffic loads. Also developed was a web-based remote data transfer system as well as configurable data reduction algorithms. A first implementation and validation were carried out within large-scale tests at the University of the German Federal Armed Forces in Munich [16]. Another implementation is currently being planned for the BASt-initiated demonstration test field duraBASt (see 5.2).
- **FE 88.0113/2011 "Unterstützende Messtechnik für Fahrbahnübergänge von Straßenbrücken. (*engl. Supporting Sensor Instrumentation for Transition Joints in Road Bridges*)"**. In this project, robust (optical fiber) measurement instrumentation for embedding in transition joints was conceived. The instrumentation was intended for the acquisition of actions on bridges incl. the detection of extra ordinary stress situations, local/global reactions and changes in resistance and condition. Furthermore, self-monitoring functions were built-in to notify the user when attendance or replacement of components is due. First instrumented joints of this kind were installed in a test field in Sperenberg (Germany) and validated under real loading and climatic conditions.
- **FE 88.0122-0124/2012 "Instantaneous Bridge Assessment based on Sensor Network Technology – iBAST".** In this project, a WSN-based monitoring system was developed and made commercially available. The iBAST system is characterized by its flexibility and adaptability to various bridge monitoring scenarios. This is given

because of the modular composition of the system, consisting of pre-assembled hardware and software components. Also possible is the implementation of various energy supply technologies, from standard electricity or battery supply till energy harvesting using solar modules. In addition, deterioration models for further condition analysis can also be embedded. The developed system was installed and tested on a motorway bridge near Lübeck and is still in operation in order to test the system on a long-term basis [17].

- **FE 88.0125-0129/2012 "Intelligente Brücken – Informationssystem zum Strukturmonitoring und Erhaltungsmanagement von Brücken (IB-ISEB, *engl. Intelligent Bridges – Information System for Structural Monitoring and Maintenance Management of Bridges*)".** A development pattern for an intelligent structural monitoring system for motorway bridges based on wireless sensor technology is the objective of this project. The system allows embedding engineering models for data reduction/analysis and condition prediction. Main sensors under development within the project are MEMS acceleration/tilt sensors as well as accuracy-optimized GNSS displacement sensor systems (Global Navigation Satellite System). Making use of energy harvesting technologies for energy supply is also in the focus. A test sensor network was installed at the beginning of this year at the Neckar Viaduct near Weitingen (Germany). The project end is expected this year.

### 5.2 DEMONSTRATOR IN PLANNING

A first implementation of the research projects within the "intelligent bridges" will be carried out on a pre-stressed concrete bridge as part of a large demonstration, reference and test field of the BASt at the motorway interchange Cologne east – duraBASt. The test field allows for solutions and systems to be evaluated and demonstrated sustainably, traffic free (only test loading) and with real climate influences. The bridge is supposed to be partially renewed, so that embedded sensors can be installed and a partial demonstrator of an intelligent bridge realized. This will be the first implementation considering the input of all research projects carried out so far and will be accompanied by further R&D work over the next few years in order to highlight areas which still need further work and answer new questions generated through practical issues. The objective is to achieve a fully-functional implementation in the future that can be considered when making further bridges "intelligent".

## 6 CONCLUSIONS

The retention of availability and traffic safety as well as guaranteeing the initially planned service life of bridges structures is a high priority, especially at a time where infrastructure is facing new challenges. In the near future, maintenance and inspection of bridge structures will become even more vital. This implies the necessity to have in-depth knowledge of conditions and deterioration processes of the individual bridge structures. Implementing sensor technology in combination with reliability-based condition assessment methods represents a step forward into object-based assessment and a supplement to the existing bridge management systems, which are mostly deterministic and damage-based.

In the German federal highway research institute (BASt), comprehensive R&D work is being carried out to evolve a system for real-time information processing and reliability-based evaluation of bridge structures - Intelligent Bridges. This system follows a preventive strategy based on the early detection and evaluation of condition changes within a bridge structure as well as the prediction and evaluation of further condition development. Three main components characterize the architecture of an intelligent bridge system: intelligent sensor networks and data analysis methods, intelligent modeling and reliability-based assessment and intelligent maintenance management.

Several external and internal projects dealt with the problems and questions of the intelligent bridges in the last few years and gave first answers and approaches that represent guidelines and a solid basis to envisage a first implementation in the forthcoming period. In this paper, the concept of Intelligent Bridges is described and results achieved so far within internal and external research analyzed. Special attention hereby is paid to sensor technologies and networks, energy supply and methods of data processing as well as reliability-based evaluation. Future work regarding the implementation of the developed techniques and methods in a first prototype is also highlighted.

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