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Case-based Decision Support for the Assessment of Bridges

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Abstract—**The main idea of this contribution is computer aid for Structural Health Monitoring activities. The increasing age of infrastructure makes actions necessary to predict lifetime and to guaranty safety, especially for critical structures like bridges for example. Thereby, acceleration sensors are widely-used to measure (ambient) vibrations of structures, which are stored by a connected computer system for later processing. These records are a basis for following procedures and make an assessment of a building's condition possible. Due to several reasons, the process of analysing a signal is very complex in particular because of the individuality of each structure. This means that the measurement results (characteristics of a building) strongly depend on structure-design and a marginally different design (from layman's point of view) can cause completely different measurement results. Consequently, only an experienced expert can interpret a measurement correctly and still, this analysis process is difficult and time-consuming, what necessitates computer aid for the interpretation to speed it up and to improve the quality of results. This is the point where decision support in terms of Case-based Reasoning can be introduced. The idea is to transfer the expert's experience (description of the structures' designs and measurements incl. interpretation) into a so-called case base which is continuously growing and enhanced by future experience. The Decision Support System can, relying on these cases, compare new measurements of possibly unknown structures with measurements of known buildings (from the case base) and suggest an interpretation by means of adapting past interpretations, which were taken under similar conditions (similar structure design) using certain similarity measures.**

Keywords: Bridge Monitoring; Case-based Reasoning; Decision Support System; Structural Health Monitoring

I. INTRODUCTION

Bridges play a major role in the higher transportation infrastructure. They represent large and expensive civil engineering structures with great importance to our economy and society and are, moreover, often exposed to extreme environmental and meteorological conditions. In order to deal with problems caused by these possible influences, intelligent solutions are needed. Fortunately, engineering and monitoring can ensure the bearing capacity of bridges to resist these conditions and thus, negative impacts on our economy and society can be prevented.

When bridges reach the end of their service life, which can be the result of structural damage and/or material degradation, they should have reached a minimum acceptable performance level. For the determination of this level many significant factors have to be taken into account. A Bridge Management System (BMS) can evaluate the adequate time for improvements on a bridge and it can improve the overall condition of an agency's network of bridges right in time.

A BMS is a decision support tool that consists of the following three major parts:

- Inventory (data regarding the characteristics and condition of the bridge),
- Inspection (examinations of the bridge) and
- Recommendations (regarding the maintenance and improvement of the bridge).

As an additional and actually very important feature, a BMS is also capable of prioritizing the allocation of funds. Therefore, BMSs are important for every stage of a bridge's life.

The importance of the current topic comes even clearer, when considering that the global higher transportation network operates about 2.5 million bridges. Current BMSs categorise these bridges with various methodologies and approaches. This results in very inhomogeneous figures. In 2005 the U.S. Federal Highway Agency (FHWA) stated that 28% of their 595,000 bridges are rated deficiently. Only a portion of it (about 15%) has structural reasons. In Europe this figure varies around 10%, whereas for Asian networks no such figures are available. Nevertheless, if we consider an average of 10% deficiency, we look at 250,000 bridges that definitely require structural health diagnostic, improvement and monitoring. Structural Health Monitoring (SHM) shall also be used preventively before bridges become deficient. This considerably enlarges the number of applications of Bridge Monitoring [21].

SHM is the implementation of a damage identification strategy to the civil engineering infrastructure. Damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity. Damage affects the current or future performance of these systems.

The damage identification process generally is structured into four levels [19]:

- Damage detection, where the presence of damage is identified,
- Damage location, where the location of the damage is determined,
- Damage typification, where the type of damage is determined and
- Damage extent, where the severity of damage is assessed.

Extensive literature on SHM has been developed over the last 20 years [8]. This field has matured to a point where several broadly accepted principles have emerged. Nevertheless, these principles are still challenged and further developed by various groups of interests. The strategies in mechanical engineering or aerospace take different approaches. However, the civil engineering community can considerably benefit from these efforts.

At the Stanford SHM workshop in 2005 Farrar and Worden [10] specified axioms for Structural Health Monitoring, which are an attempt to formulate common rules and understanding to support the “fundamental truth” that has been argued by the community. These axioms do not represent operators for SHM. In order to generate methodologies, it will be necessary to add a group of algorithms, which carry the SHM practitioner from data to a decision. The discipline of statistical pattern recognition is proposed for this approach. The axioms formulated are:

- Axiom 1: The assessment of damage requires a comparison between certain system states.
- Axiom 2: The existence and location of damage can be identified in an unsupervised learning mode, but the type of damages and damage severity can only be identified in a supervised learning mode.
- Axiom 3: Intelligent feature extraction is necessary because the more sensitive a measurement is to damage, the more sensitive it is to operational and environmental changes which do not have to be classified as damages.
- Axiom 4: There is a trade-off between the sensitivity of an algorithm to damages and its sensitivity to noise.
- Axiom 5: The size of a damage that can be detected from changes in the system dynamics is inversely proportional to the frequency range of an excitation.

The information of greatest interest is the knowledge about the condition of a bridge or its single elements. SHM provides the opportunity to quantify the condition and to provide the basis for decisions. Fortunately, due to bridges’ importance for economy and society as well as their high vulnerability, procedures and tools of SHM may be best developed for them.

This contribution illustrates the possibilities of (semi-) automatic assessment in the field of Structural Health Monitoring, whereas at first the related research is discussed. The next chapter (Motivation for Bridge Monitoring) shows the requirements of the industry to support the conventional evaluation of measurement data by an intelligent system. For this purpose, an introduction to Decision Support Systems and Case-based Reasoning is provided. Finally, the current state of a research prototype for the Case-based Decision Support System for Bridge Monitoring and intended future work is shown.

II. RELATED RESEARCH

Due to the constant aging of our infrastructure, the field of Structural Health Monitoring has attracted a great deal of attention. In order to reduce the costs for maintenance and to increase the safety level of structures, the request of structural reliability, evaluation and remaining lifetime assessment is assuming a major importance. The use of non-destructive dynamic testing methods for the evaluation of the structural performances provided important steps forward. On the one hand, an improvement of the data reliability could have been gained; on the other hand, it succeeded in overcoming the limitations of traditional visual inspection methods.

In a next step, the measured response of a structure can be used in conjunction with several different numerical methods. These methods can mainly be divided into two categories: model-based and parameter-based. The first one is relying on a reference model, e.g., Finite Element (FE) model. By contrast, the main characteristic of the second one is a general mathematical description of specified parameters or system features, e.g., analysis of time series details by means of wavelet theory.

System identification with respect to determination of damages usually is done by extracting normal modes and frequencies. Based on them, engineers are able to calculate stiffness and damping coefficients. By updating initial mathematical models with finite element methods to predict the expected values of the actual measurements, damages can be localized and quantized as well. A comparison with reference data from earlier measurements allows experts to make statements on the structure’s safety and furthermore gives the possibility to make lifetime predictions for the investigated bridge. However, Structural Health Monitoring produces a flood of data and the fact that each bridge - actually any arbitrary structure - has different dynamic parameters makes a manual analysis and interpretation very time-consuming and expensive.

Another main disadvantage of manual analysis is the subjective interpretation of human experts. Each expert interprets a measurement differently, based on his level of experience. Therefore, there is a strong need for intelligent Decision Support Systems (DSS) in safety assessment and lifetime prediction for civil engineering structures in general, and for bridges in particular. Case-based Reasoning (CBR) seems to be an appropriate approach to work with huge measurement data packets. For supporting engineers in interpreting measurement results and in making decisions, reasonable case sensitive DSSs have to be developed and adapted. CBR systems have a powerful cyclic problem solving core process. Based on known similar cases (stored past problems and their solutions), CBR helps engineers in interpreting certain situations. Since the main objective of CBR is not to develop new solutions for new problems but to reuse known problems and solutions, the reasoning process is comparably fast. CBR can be used for example to interpret measuring data of periodic measurements or as an integrated alert system for permanently monitored civil engineering structures.

A very common model for Decision Support Systems is the phase model by Simon [20]. It consists of three phases [15][12], namely

- Intelligence,
- Design and
- Choice.

The phase “Intelligence” is responsible for recognising problems. The indicators are very often weak, so that they have to be identified in advance. Hence, the engineer realises divergences of the norm and recognises the existence of a problem.

The phase “Design” serves decision makers as a platform to find alternative solutions for recognised problems by using already known solutions of similar problems.

Finally, the phase “Choice” allows decision makers to define and set criteria for finding new alternative solutions, which actually might perform better. Solutions for the actual problem can either be found by using known alternatives or new ones can be created. The objective is to select one single solution for the problem. The support for the decision-making process in this phase is exactly the typical application area of Decision Support Systems.

A. *Ambient Vibration Monitoring*

Each structure has its typical dynamic behaviour, which may be interpreted as “Vibrational Signature”. Changes in a structure, such as all kinds of damages are leading to a decrease of the load-carrying capacity and have effects on the dynamic response. This fact implicates to use the measurement and monitoring of the dynamic response characteristics for evaluation of the structural integrity.

Different types of bridge vibration tests exist: the bridge can either be excited with a heavy shaker or drop weight (Forced Vibration Testing) or by ambient excitation such as wind, traffic and micro seismic activity (Ambient Vibration Testing). The latter (Ambient Vibration Monitoring) is the fundamental principle used in the BRIMOS® technology (Bridge Monitoring System) which has been used in the field of Structural Health Monitoring for many years. It has the big advantage that no expensive equipment is needed to excite the bridge and that the traffic does not have to be interrupted.

The term Structural Health Monitoring in the meaning of Ambient Vibration Monitoring comprises the recording of the dynamic behaviour by the use of measuring instruments as well as the evaluation and analysis of the measured signals. The fundamental tools of health monitoring are system identification, damage determination and localization as well as safety assessment and the maintenance management for infrastructure.

The analysis provides the determination of the modal parameters, namely the structure’s natural frequencies, its mode shapes and its damping coefficients. These parameters, which are gained from the measurements, represent the real condition of a structure and are used to update mathematical models of a structure or are simply compared to reference data from earlier measurements.

Up to now, the analysis of measurement data requires the knowledge of an expert. This forms a weak point in the whole procedure, since the work done by experts is time-consuming and results are subjective. Therefore, a system supporting the engineer who interprets measuring data would be desirable, in order to make analysis easier and faster.

B. *System Identification*

Unfortunately, calculation models for determining stresses and consequently for measuring structures only represent an approximation to reality and have to be calibrated. For the determination of the conformity between the calculation model and the actual load-bearing behaviour up to now frequent stress tests (for example at railway bridges) have been carried out and the measured deformations (flexures) were compared with calculated reference values. Based on this, conclusions can be drawn on the load-bearing safety and performance capability of the structure.

A simpler and by far better method for the determination of these parameters is based on the determination of the dynamic characteristic by ambient vibration measurements. With these measurements, the vibration behaviour of a structure is recorded, evaluated and interpreted under ambient influences, e.g., without artificial excitation, by means of highly sensitive acceleration sensors.

The methodology to make conclusions on the load-bearing capacity of a structure by measuring its dynamic behaviour and to check mathematical model assumptions already is very old. In [9] there is a report on stress tests between 1922 and 1945 in Switzerland where tests by free oscillations at the aerial Beromünster in 1941 are described. The results were used for checking the calculation assumptions, deviations between measured and calculated results were interpreted and statements for similar future towers were done.

The checking of structures by means of dynamic measuring methods has a long tradition in Switzerland. It was carried out until the beginning of the 1990s in the form of tests by free oscillations by means of initial strains or intermittent stresses and by excitation with unbalance exciters or hydraulic shakers. Similar tests were also carried out in Austria and Germany for scientific purposes but at a much smaller scope. However, they were not extensively applied for system identification or check and calibration of calculation models. In [5] it is suggested to further develop dynamic procedures for the assessment of the maintenance condition of structures.

The rapid development of measuring technology on the one hand and computer technology as well as software on the other enables us to carry out dynamic measurements of ambient structure vibrations and their evaluation very quickly and with relatively low expenditures today.

Vibrations influencing the structure, which are due to natural excitation sources like micro-seismic phenomena, wind, waves etc., are regarded as ambient causes. The measuring and evaluation system BRIMOS® takes advantage of these progresses and opens a wide field of application to technology.

The dynamic characteristic of a structure can not only be used for a single check of calculation models. Furthermore, statements on the chronological development of the load-bearing capacity and therefore estimations on the remaining service life duration are enabled by measurements at certain intervals. Measurements at any moment supply snapshots of structural integrity and can be used in combination with parallel mathematical analyses for the determination of possible damages to the structure.

The list of decisive dynamic parameters to be determined for system identification is quite long and consists of eigenfrequencies, mode shapes (an example is shown in Figure 1), damping coefficients, vibration intensities, etc. During monitoring all analyses of system identification are applied.

In addition to the procedures of structure mechanics and dynamics, statistical methods have to be used which determine trends from large data quantities. The use of so-called trend cards, which clearly represent an eventual change of individual parameters by means of a time-frequency diagram, has proved successfully.

The eigenfrequencies are an essential parameter for the description of the vibration behaviour of a structure in the linear elastic field. A mode shape like in Figure 1 is a vibration form in which the structure oscillates with the respective eigenfrequency. The actual oscillation of a real structure is composed of the respective shares of the individual mode shapes.

The mathematical modal analysis provides both, the eigenfrequencies and the mode shapes of a structure, whereas in experimental modal analysis the eigenfrequencies are obtained as well and the mode shapes can be determined point by point (at the measuring points). Both methods have to be carried out for system identification. The actual static system is obtained by comparing the measuring results with the calculated values and by adaptation of the calculation model to the measurements. In order to get a correct image of the actual load-bearing system, one must not restrict oneself to the first eigenfrequency and the respective modal form. In fact, the consideration of several, also higher frequencies and the respective forms is required.

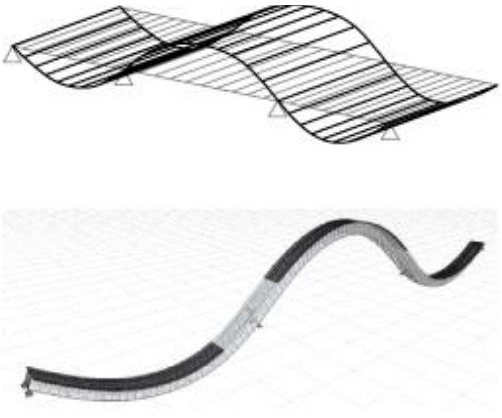


Figure 1. First Modeshape of an Austrian Danube Bridge consisting of three Spans

C. *BRIMOS®*

BRIMOS® (Bridge Monitoring System) is an application for system identification and the detection of damages in bridges as well as any other civil engineering structure. Its development is based on several research projects started almost 15 years ago. About 1000 structures have been assessed so far and the experience has been incorporated into the assessment procedure. It is based on the already mentioned “Vibrational Signature” of a structure, which is obtained by a measurement campaign. Depending on the extent of this campaign various properties can be computed, which are combined to the BRIMOS rating. This classification allows a fast identification on the structure’s integrity as well as the corresponding risk level. The results are based on

- Measured dynamic parameters (like eigenfrequencies, mode shapes, damping pattern in the lengthwise direction, vibration intensity and static as well as dynamic vertical displacements),
- Visual inspection,
- Finite Element model-update and
- Reference data (BRIMOS-Database and BRIMOS Knowledgebase).

The result is a factor, which relates to a predefined risk level.

D. *Bridge Monitoring*

The extent of monitoring is mainly depending on required results. Currently five levels are used in order to determine the depth of investigation [21]:

- Level 1: Rating
  It represents the conventional assessment of the structure starting with a visual field inspection that provides a subjective impression of the condition of a structure. Some preliminary analytical investigation is performed in order to provide a rating as a basis for decisions. This would be a typical application of a bridge management system like PONTIS or DANBRO. Many bridge owners use certain databases to store the results.
- Level 2: Condition Assessment
  A rough visual field inspection has to be an element of any SHM campaign. Afterwards a decision has to be reached whether the conventional approach is satisfactory or an extended or even sophisticated

additional approach has to be considered. This determines the type and quantity of instrumentation. For condition assessment a simple instrumentation is sufficient and a simple Decision Support System would provide the necessary additional information. Storage and pre-processing of data should be done in the existing database where a link to existing conventional tools is available. The monitoring can be performed at single spots only.

- Level 3: Performance Assessment
  This intermediate level uses the same procedure as described in level 2. The level of assessment and performance elaboration in the decision support process is considerably higher since additional information like mode shapes is measured and determined. This provides additional indicators for the assessment and will illustrate the performance of a structure.
- Level 4: Detail Assessment and Rating
  The next step is to establish an analytical model representing the structure and the model is compared with the monitoring results. In case that phenomena are detected that cannot be explained based on the records, further steps have to be taken to clarify the situation. The most obvious method is to introduce a permanent record over a certain period of time to capture the necessary phenomena being responsible for the specific case. Load testing also has been proven successfully to establish performance parameters. With these results a simple model update can be performed to assess the results and provide a rating. Certainly, extensive monitoring is required. The records shall cover at least 24 hours, but shall rather be much longer to capture environmental aspects and traffic situations as completely as possible.
- Level 5: Lifetime Prediction
  For a serious lifetime prediction, the records taken have to be long enough to cover at least three cycles relevant for the structure. This normally is in an interval of three years. Simulation should be run on the analytical model in order to achieve a theoretical performance for comparison. To handle the major quantity of data, software for decision support is required. Load testing would be done targeted and extensive. In addition, micro structural testing might be useful in order to look into the performance of single elements of a structure. The update process would be extensive and considering several conditions of a structure. This in particular includes the loaded and unloaded case and all the nonlinearities involved. The monitoring system shall be operated online, probably web-based, providing a warning in case of critical/unknown situations. The final lifetime prediction could be performed.

The costs related to these procedures are mainly depending on the extent of the monitoring campaign and the number of man-hours to be invested in modelling, simulation and update procedures. The effort can also be influenced by the type of a structure (e.g., number of spans). For the future of Structural Health Monitoring it is expected that the monitoring-costs will be rather reduced than increased. This can happen through the introduction of time saving modelling procedures and sophisticated monitoring software [21].

III. MOTIVATION FOR BRIDGE MONITORING

Bridge Monitoring (BM) has undergone a long development period and many useful results have been produced. Nevertheless, the transformation into a business case has been scarcely managed by 2008. The three main reasons for that are:

- BM is a very complex issue. The key players concentrate on issues which the ordinary bridge owner is not interested in. A joint language has not been found and appealing method statements are lacking.
- The discrepancy between the expectations of the owners and the services that can be provided by the available budget is huge. The community has not been able to explain that the new methods do not eliminate the problem of aging or damaged bridges but can only serve it in a better way. For this reason, monitoring campaigns, which are so expensive that they can only be of scientific interest, mostly are performed in the frame of research projects.
- The involved hardware is still very expensive and not robust. The discrepancy of life expectation of a typical bridge with 100 years and three years for a monitoring system is unacceptable.

Apart from these facts there are other aspects which are related to the national practice of bridge management and cultural differences.

Three main driving forces have been identified that enable the performance of a reasonable BM campaign:

- Responsibility: Meaning the existence of a standard or recommendation that obliges the owners to monitor their structures.
- Economy: If BM can prove that it saves money.
- Curiosity: Owners of bridges are very often willing to spend money on creating better knowledge of their bridge stock, especially when there has been reasonable doubt of an actual condition.

The monitoring community has managed to issue some guidelines and recommendations. The latter form the basis for eventual orders. Nevertheless, they cannot be seen as an obligation to apply Bridge Monitoring.

A good conception has been promoted and implemented in Austria. The regulations for bridge management allow both, the visual inspection and the monitoring campaign. In case that monitoring enables to achieve better quantified results, the inspection period can be increased up to 100%.

This saves money on inspections which can be invested in monitoring. A better service is performed at the same costs.

A. *State of the Art*

The selection of a suitable observation concept has to be mainly based on external factors. These are the number of structures to be observed in combination with the budget available. For this purpose it is necessary to offer services on increasing quality levels. The levels can be subdivided into spot, periodic, permanent and online assessment campaigns at structures [13]. The respective features are:

- A spot observation shall comprise a very quick measurement campaign with only few sensors which can be simply handled. It shall provide information on the general condition of a structure in order to create a ranking.
- Periodic assessment means a measurement campaign on a structure which is repeated after a specified period of time, to generate information on the performance over time. The single spot information might comprise rather long periods.
- Permanent observation and assessment of structures becomes necessary when certain limits are passed. This observation allows a very detailed assessment based on permanent recordings and can help to implement quick decision making.
- Online observation and assessment allows warning through electronic media, either by SMS (Short Message Service) in the simple case or by online status through the internet. Decisions might be taken by the computer based on the measurement data. These alert systems would only be applied at extremely critical structures.

In general, it has to be stated that clients need and desire support of their work and not to create issues that make it more complicated. In respect to that the procedures have to be carefully watched and permanently improved. The information policy also plays a major role in the client-consultant relationship. The new methodologies are rather complex and require a deep understanding of structural dynamics, physics and measurement techniques. Due to the fact that this expertise is rarely available at the owners engineering department, the fear to be exposed to unknown black box applications has to be taken from them with bringing transparency to the systems.

Nevertheless, they spend considerable amounts of money on monitoring actions and would like to be informed frequently about progress and results. Therefore, it has to be ensured that the technology-part is in good and competent hands and that they will receive the information they desire. From a historical point of view the best success has been achieved with very simple reporting techniques. A periodic report received by e-mail comprising single page information generally turned out to be preferred.

The main information is provided in a single window, where upper and lower normalized thresholds are given and measurement results of this period are placed within these thresholds. With a single look at this graph, the personnel can see whether any of the thresholds has been exceeded at once. When all indicators are green, the client can be pacified and knows that the ordered observation is permanently working.

The periodic report mentioned above provides the following information:

- A photo and a system plot of the structure of interest for an easy and quick identification.
- A window where the periodic results are placed within the relevant thresholds over the observation period.
- Eventually a second window, containing special information required by the client, such as wind speed information or any other desired quantity.
- Finally, a rating should be provided, based on the measurements taken in the reporting period. This should enable the client to immediately see whether any changes have happened.
- Eventually, the specification of a remaining life capacity can be provided if the necessary data are recorded.

Besides this one-page record for the client, also a scientific report for the expert is generated by the DSS. This makes a quick assessment of all the single measurements possible in order to create expertises or to learn from operation. On average, the system is calibrated with the information gained over a certain period of time. This might also comprise a change in the rating and would update the remaining life capacity based on existing knowledge.

B. *System Requirements*

During the last decades, the capability of both, computers and sensors, have undergone an explosive growth presenting many new challenges of how to manage the resulting amount of data. Scientists have often found themselves confronted by gigabytes of complex data that contained comparatively little information of actual interest making successful management almost impossible.

The problem of searching for the right information is very difficult even if one precisely knows where it can be found. However, it gets almost insoluble if the location additionally is not known exactly. Due to the complexity of data itself and the “human error rate”, two phenomena can be recognized:

- Useful information is often overlooked, which leads to a poor utilization of data.
- Possible benefits of increasing data-gathering capabilities are only partially used.

Since humans have not undergone similar developments in measurement data management as has the technology behind the measurements themselves, one has to look for intelligent ways that help to solve this dilemma. Since manual data analysis is quite tedious and impractical, other concepts like computational tools and techniques for an automated analysis of large complex data sets have to be developed.

Furthermore, the evaluation of data and the assessment of structures must be carried out by experts with many years of experience at the moment. By developing a Decision Support System, the expert should not be replaced but essentially supported in his activities. Such a system should support the whole data process, from the receipt of data, preliminary sorting, filing, evaluation, assessment up to visualization of explored results. For the preparation of such a system it is required to establish something like a knowledge database. In the latter the criteria normally used by the expert for assessment could be mathematically formulated (= formulation of rules, knowledge acquisition). The advantage is that the knowledge basis can be continuously expanded and that no "forgetting" exists. By the use of several methods of statistics up to now unknown connections could be filtered out of the existing measurement data pool. It should be possible to integrate measurement data from third persons from different measurement systems. The whole system should be based on methodologies like being implemented by the BRIMOS software and include very recent approaches (fuzzy logic, neural networks in damage identification). For visualization of results a GIS (Geographic Information System) interface can be provided.

The backbone of such a system would be a huge database containing measurement data and corresponding results of the analysis from the past. This knowledge base is filled with material from past measurements up to present ones and consequently will grow continuously. Using such methodology, the system for the user may become a "living system" and may increase his/her trust. With every improvement the results are likely to become better and the thresholds might vary too. Thresholds should not be treated totally inflexibly and have to be adapted to new knowledge.

Finally, engineers would be interested in a system, where they can search for similar objects or similar measurement data for arbitrary objects and measurement data respectively. Then, by having the corresponding results of comparable measurements from the database, it might become possible to draw new conclusions for certain objects. This would represent a very interesting feature for periodic measurements but also for spot observations. Treating the database of the past measurements as a case base, by means of CBR and similar techniques, benefit might be expected for interpreting the measurement data of periodic measurements, spot observations and in particular of permanently monitored structures.

The annual expenses for bridge maintenance in Austria amount to approximately 130 million Euro. According to current predictions this value will triple in the next 15 years. New methods for structural assessment are required in order to identify urgently necessary measures and to reduce the expenditures for purely precautionary maintenance. The Decision Support System proposed in this contribution is to lower the costs and the time consumption for the evaluation of measurement data and condition assessment, and at the same time accuracy and objectivity shall be increased.

IV. DECISION SUPPORT SYSTEMS

Since 1950 [15] there were efforts to develop systems to support experts of various fields in taking decisions. Decision Support Systems represent an approach that tries to integrate many different disciplines into the field of computer science. A reason for the arise of DSSs was a wish to have a system helping humans to manage very complex situations. Soon these systems became more and more attractive for users and researchers.

Problem solving and decision making are very important tasks in all intelligent activities. One who makes decisions usually evaluates and chooses among different alternative decisions. Problem solving on the other hand is a task to find a "way" between a desired goal and what is given at the beginning, to find intelligent steps to reach this goal. Expert systems and artificial intelligence in general deal with this problem in the following way.

The stages of problem solving are:

- To recognise situations which call for actions,
- To formulate problems,
- To find actions and to set up goals,
- To evaluate and
- To choose.

There are two scientific approaches in this case:

1. The normative approach: Prescribe optimal behaviour, how decisions should be taken.
2. The descriptive approach: Understand how humans behave when they are solving problems and take decisions.

The normative approach was first developed in economics; "the rational economic man" is an important term in this connection. Later it was implemented in the fields of Operations Research and management science. The theory is based on a rationality paradigm; rational behaviour is prescribed by formal axioms. Normative models for decision making are called "formal models". The decision maker in the process of finding a decision calculates the consequences for each alternative decision, rates the results and tries to compute the optimal way to his/her goal. To do so, future consequences of current actions have to be predicted and suggestions have to be made. A DSS should make decision making more effective and implies a normative perspective of the problem. These normative theories help to analyse the structure of a decision.

The normative theories enable us to optimise decisions under certain conditions, as long as the problems do not get too complex. The complexity of real-world decision making mostly overtaxes this approach, see [15].

DSSs are useful especially when there is a fixed goal but no algorithmic solution. The paths of solution mostly are very numerous and user-dependant. This leads to the main goal of DSSs, namely to improve decisions by better understanding and preparation of tasks which lead towards evaluation and choosing. Ill-structured problems in this regard are processes where there is no known or clear method to reach a solution, because the nature of the problem is complex and unclear or there arise situations which are new and consequently unknown. Well structured problems can be seen as decision making processes which are routine and repetitive. Usually it is not possible to fully automatise information processing to reach a conclusion. Only if an information processing task can be mapped to an algorithm then the decision process is structured and it can be implemented in a computer program to reach an automated solution.

Decision support for "unstructuredness" is accommodated in:

- The nature of requests made on a DSS.
- The manner in which a DSS responses are utilised.
- The recognition of alternative methods for satisfying a request.

Structured problems are routine because they are unambiguous, as there is a single solution method. If problems become less structured, then there exists an increasing number of alternative solution methods whereby solutions may not be equivalent. A completely unstructured problem in contrast has unknown solution methods or solutions are too numerous to evaluate.

Mainly in the field of management there are many situations where decisions have to be taken for non-programmable problems. The development of Artificial Intelligence technology especially in such connection has enlarged the spectrum of application of DSSs.

A. Decision Support Systems for Real-World Problems

Computer Systems nowadays are frequently used to solve numerous "real-world problems". In 1958 for example a computer system was used to find the optimal allocation of water between Egypt and the Sudan. The water system contained five major dams, several other barrages and control points and the monthly volumes of inflow between 1905 and 1942 were used as input data. The system was developed by IBM; it became the first considerable example for a computer assisted real-world plan [15]. In the 1960s the use of such devices was spreading rapidly.

Due to improved computer hardware and because of a changed attitude of users towards computers in general, computer applications to real-world problems became more and more attractive. Today, computers are used to collect, store and retrieve data, display and present it in different ways and help humans in understanding complex situations and problems. The computer became a "complete" information processor as part of complex information systems. Real-world computer systems process information such as digital values, analogue signals, images, etc. A computer with sufficient software may represent the physics or chemistry laboratory for scientists for instance. With using computer simulations for experiments costs, risks and time can be saved in many scientific fields. Consequently, there is no need to prove that an idea for an experiment will be useful. Using computers for experiments allows the planner or manager to make mistakes without consequences.

V. CASE-BASED REASONING

According to Aamodt and Plaza [2], "Case-based reasoning is a recent approach to problem solving and learning (…)". Case-based Reasoning is a cyclic problem solving process, whereby already known knowledge is used to solve new problems. This knowledge is represented in form of cases which consist of a problem and a corresponding solution. The cases are stored in the so-called case base mainly providing the functionality to search for similar problems. Main objectives of CBR are the reuse of solutions of similar problems, no new problem solving processes whenever it is not necessary, no new solutions have to be developed for new problems if the case base contains a comparable problem and finally, the creation of solutions is rapid and cost-effective. Figure 2 shows one of the most important fundamentals of Case-based Reasoning, namely the CBR-cycle according to Aamodt and Plaza [2].

The cycle is subdivided into four phases: Retrieve, Reuse, Revise and Retain.

- Retrieve: Due to a new problem a new case is defined. Accordingly similar cases are retrieved from the case base where all known cases and general knowledge are stored. The retrieval of similar cases is operated by so-called similarity measures such as the similarity measure by Hamming, the Tversky-contrast model or even the Euclidean distance in an n-dimensional space.
- Reuse: If one has found one or more similar cases, the most similar retrieved case(s) is(are) combined with the new case, whereon the CBR-system can suggest solutions for the initial problem.

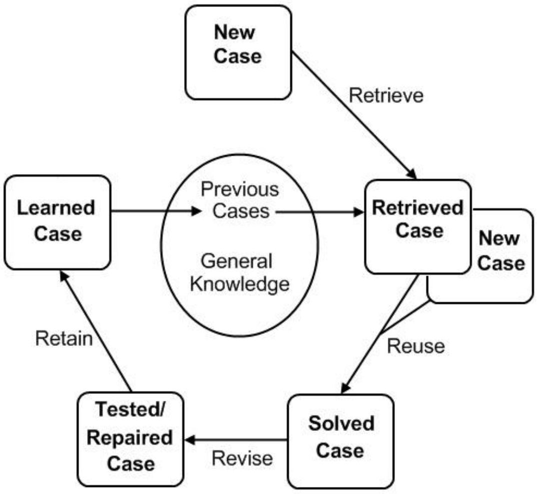


Figure 2. CBR-Cycle (According to [2])

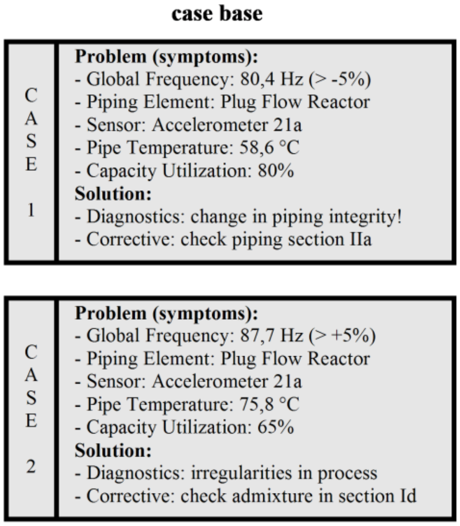
- Revise: The suggested solution is tested to demonstrate the ability of the CBR-system to solve the initial problem. If the retrieved solution is faulty, it can be adapted and a confirmed solution is created.
- Retain: Useful experience (significant cases) is stored for future reuse. The operator can add the new case or a learned case to the case base or the CBR-system creates and stores the new case automatically or semi-automatically. Finally, the case base grows and becomes more intelligent for future problems.

A. *Simple Example*

In this chapter we present a simple example to show how Case-based Reasoning could be used in the field of Structural Health Monitoring.

An example for a case base can be seen in Figure 3 where (in this very simple example) two cases are stored. A case consists of a problem (symptoms) with certain attributes and an appropriate solution (including diagnostics and corrective). When a new problem arises (shown in Figure 4) at first a solution is not available. To provide it, instead of starting a problem solving process, knowledge is reused from already known cases.

It has to be defined, which attributes or parameter values can be compared with each other. In this example, the attributes “Global frequency”, “Piping Element”, “Sensor”, “Pipe Temperature” and “Capacity Utilization” are used.



case base

C A S E 1

Problem (symptoms):
- Global Frequency: 80,4 Hz (> -5%)
- Piping Element: Plug Flow Reactor
- Sensor: Accelerometer 21a
- Pipe Temperature: 58,6 °C
- Capacity Utilization: 80%

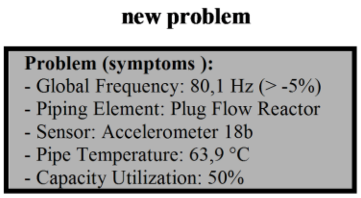
Solution:
- Diagnostics: change in piping integrity!
- Corrective: check piping section IIa

C A S E 2

Problem (symptoms):
- Global Frequency: 87,7 Hz (> +5%)
- Piping Element: Plug Flow Reactor
- Sensor: Accelerometer 21a
- Pipe Temperature: 75,8 °C
- Capacity Utilization: 65%

Solution:
- Diagnostics: irregularities in process
- Corrective: check admixture in section Id

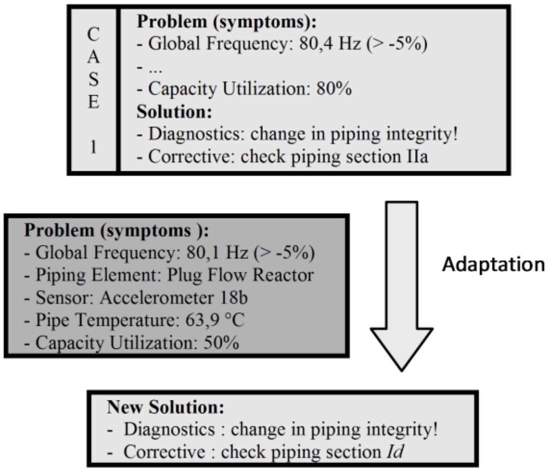
Figure 3. Simple Example – Case Base



new problem

Problem (symptoms):
- Global Frequency: 80,1 Hz (> -5%)
- Piping Element: Plug Flow Reactor
- Sensor: Accelerometer 18b
- Pipe Temperature: 63,9 °C
- Capacity Utilization: 50%

Figure 4. Simple Example – New Problem



C A S E 1

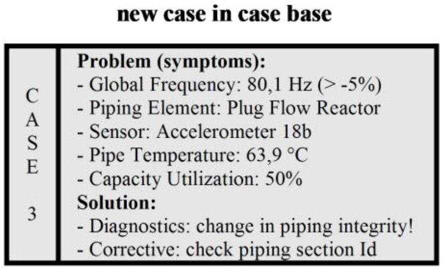
Problem (symptoms):
- Global Frequency: 80,4 Hz (> -5%)
- ...
- Capacity Utilization: 80%

Solution:
- Diagnostics: change in piping integrity!
- Corrective: check piping section IIa

Problem (symptoms):
- Global Frequency: 80,1 Hz (> -5%)
- Piping Element: Plug Flow Reactor
- Sensor: Accelerometer 18b
- Pipe Temperature: 63,9 °C
- Capacity Utilization: 50%

New Solution:
- Diagnostics : change in piping integrity!
- Corrective : check piping section *Id*

Figure 5. Simple Example – Adaptation



new case in case base

C A S E 3

Problem (symptoms):
- Global Frequency: 80,1 Hz (> -5%)
- Piping Element: Plug Flow Reactor
- Sensor: Accelerometer 18b
- Pipe Temperature: 63,9 °C
- Capacity Utilization: 50%

Solution:
- Diagnostics: change in piping integrity!
- Corrective: check piping section Id

Figure 6. Simple Example – Result

One can compare the values of the attributes of new problems with the values of the attributes of cases in the case base. In this simple example no kinds of weights are used, for a real world system weighted attributes in general would be useful. If one compares the new problem to the cases in the case base, one can see that case 1 is more similar to the new problem than the case 2.

So, one can use the solution of case 1 and adapt it to the new problem. Figure 5 shows the adaptation of the reused solution to the new problem. The result shown in Figure 6 is a new case with the initial problem and the reused and adapted solution which can be stored in the case base. Thus, the case base grows continuously and probably becomes more intelligent for future problems.

B. *Similarity Measures*

Similarity measures play a great role for Case-based Reasoning. These measures are essential to be able to compare new problems with the cases in the case base. One can imagine that it is fundamental to choose the right methods of similarity measuring for given data. In the following, an example is shown to illustrate how one can calculate the similarity between cases. Therefore, the Generalized Similarity Measure by Hamming defined by the following formula (1) is used:

$$sim(x,y) = \frac{\sum_{i=1}^{n} w_i sim_i(x_i, y_i)}{\sum_{i=1}^{n} w_i} \qquad (1)$$

Table I shows a case base with five cases. The attributes again are “Global Frequency”, “Piping Element”, “Sensor”, “Pipe Temperature” and “Capacity Utilization” and each case x_1 ... x_5 has its individual parameter values.

When there is a new case y, one wants to know, which case in the case base is the most similar one to the new case y, see Table II.

To be able to use the Generalized Similarity Measure by Hamming, for each attribute functions have to be defined, e.g., how similar is a Plug Flow Reactor “PFR” to a Branch Connection “BC” or how similar is an Accelerometer “A15a” to an “A18b”? The functions e.g., can be defined like this:

- Global Frequency = $sim_{GF}(x_{GF},y_{GF})$ = For each hertz (Hz), which differs from case x_i to case y, the similarity value is reduced by 0,01.
- Piping Element = $sim_{PE}(x_{PE},y_{PE})$ =
  - Plug Flow Reactor: Similarity value of 1
  - Branch Connection: Similarity value of 0
- Sensor = $sim_S(x_S,y_S)$ =
  - Accelerometer 18b: Similarity value of 1
  - Accelerometer 15a: Similarity value of 0,75
  - Accelerometer 21a: Similarity value of 0,85
  - Accelerometer 24c: Similarity value of 0,5
- Pipe Temperature = $sim_{PT}(x_{PT},y_{PT})$ = For each degree Celsius (°C), which differs from case x_i to case y, the similarity value is reduced by 0,01.
- Capacity Utilization = $sim_{CU}(x_{CU},y_{CU})$ = For each percentage point (%), which differs from case x_i to case y, the similarity value is reduced by 0,01.

TABLE I. CASE BASE

Case	Attributes				
	Global Frequency (in Hz)	Piping Element	Sensor	Pipe Temp. (in °C)	Capacity Utilization (in %)
x_1	80,4	PFR	A 15a	58,6	80
x_2	87,7	PFR	A 24c	75,5	65
x_3	72,3	PFR	A 18b	78,4	53
x_4	92,7	BC	A 21a	71,9	90
x_5	78,4	BC	A 24c	85,1	50

TABLE II. NEW CASE Y

Case	Attributes				
	Global Frequency (in Hz)	Piping Element	Sensor	Pipe Temp. (in °C)	Capacity Utilization (in %)
y	80,1	PFR	A 18b	63,9	50

TABLE III. WEIGHTING COEFFICIENTS AND SIMILARITIES

Case	Attributes				
	Global Frequency (in Hz)	Piping Element	Sensor	Pipe Temp. (in °C)	Capacity Utilization (in %)
x_1	1	1	0,75	0,95	0,7
x_2	0,92	1	0,5	0,88	0,85
x_3	0.92	1	1	0,86	0,97
x_4	0,87	0	0,85	0,92	0,6
x_5	0,98	0	0,5	0,79	1
w_i	1	0,8	0,2	0,75	0,5

If one uses these functions for the similarity search, a new table with the similarities between the cases of the case base and the new case y can be generated, see Table III. The last row in Table III shows weighting coefficients (w_i), which represents the importance of an attribute for calculating the similarity.

To calculate the similarities between the cases in the case base and the new case y, the Generalized Similarity Measure by Hamming is used. The similarity between the case x_1 and the case y is shown in the following calculation (2):

$$sim(x_1, y) = \frac{(1*1+0{,}8*1+0{,}2*0{,}75+0{,}75*0{,}95+0{,}5*0{,}7)}{3{,}25} \approx 0{,}93 \qquad (2)$$

Using this formula for the other cases x_2 ... x_5, the following similarities can be calculated:

x1: 0,93
x2: 0,89
x3: 0,94
x4: 0,62
x5: 0,67

As one can see in this listing, the case x_3 is the most similar case to the new case y and would be used to find an already known solution for the new case y.

VI. CASE-BASED DECISION SUPPORT FOR BRIDGE MONITORING

The main idea of Case-based Decision Support for Bridge Monitoring is to support a human expert in the interpretation of measurement data taken from certain structures, especially from bridges. In general, the idea is to support the interpretation process by providing comparable measurements which may have lead to comparable interpretations. Thereby, in case of periodic measurements or spot observations, measurement results of similar structures should provide a basis for the interpretation of new measurements and in case of permanent monitoring, similar historical measurements can be taken into account to draw a conclusion to the state of the building. The ambient vibrations in the form of raw measurement data have to be interpreted by an engineer with profound technological knowledge and experience in the interpretation of such data. Another disadvantage of human interpretation, besides the time it consumes, is its subjectivity. Each expert interprets a structure differently. On the basis of these facts, a Decision Support System is needed to support engineers in interpreting measurement data and decision making in order to be able to take decisions faster and not to spend their time with doing rather easy routine work. Consequently, a main incentive of a Case-based Decision Support System for Bridge Monitoring is cost-effectiveness and promptness by finding solutions.

The development of the Decision Support System for the interpretation of periodic measurements is divided into the following steps, whereby for permanent monitoring step 1 in general is not necessary:

1. Search for Similar Bridges

First of all one has to search for similar structures to have a basis for further conclusions and comparisons. If the bridge, which should be observed, is already stored in the case base, then the engineer has to load its geometric data or has to feed the system with this information. The system now can compare this geometric information with the cases in the case base and search for similar bridges. Each kind of bridge (e.g., simply supported, continuous, cable stayed, suspended, etc.) has different attributes which have to be compared with each other. According to its nature, a bridge consists of different kinds of structural elements (e.g., bridge decks, cables, pylons, etc.) and for each structural element, different attributes are stored. For instance, a bridge deck among other things has attributes like length and breadth, main span, number of fields or material. The similarity between the cases in the case base in case of this system is the Euclidean Distance in an n-dimensional space. In case of two dimensions for instance the Euclidean Distance would be the “measurable” distance between two points. Using the following formula (3) the Euclidean (n-dimensional) space becomes a metric space. This fact makes the system become attractive for metric index structures to improve performance.

$$d(X,Y) = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2} \tag{3}$$

The system provides the most similar bridges with the distances to the analysed bridge. It is evident which bridge will be the most similar one in case that the observed bridge already is contained in the case base, namely the same one.

2. Search for Comparable Measurements (of Similar Bridges)

As a result of the first step (in case of periodic measurements), similar bridges due to their geometric data are retrieved. This is a preliminary selection in order to avoid the situation that different kinds of bridges, which accidently have similar measurement results, are compared which most likely would lead to a complete misinterpretation of the measurement. If the system only considers the measurement results of bridges and not the geometric data in a first step, disparate bridges (due to their geometric data) could have similar measurement results although they are totally different. In the second step, the already known measurement results of the retrieved similar bridges are provided. These results generally consist of modal parameters, namely the structure’s natural frequencies, its mode shapes and its damping coefficients which together represent the “real” condition of a bridge. In the following, the modal parameters of the similar bridges can be used as a suggestion for the interpretation of new measurement data of bridges which should be observed.

3. Support of Analysis Process

The steps for the interpretation and preprocessing of measurement data by a human expert can be stored in an adequate way in the case base. Thereby, similar bridges also have similar preprocessing steps for the interpretation of measurement results.

A. *Case-based Reasoning for Periodic and Permanent Monitoring*

As already mentioned in the previous chapters, there generally are two different applications of Structural Health Monitoring, namely periodic and permanent measuring. Depending on this kind of strategy the provision of decision support has to be adapted. While in case of permanent monitoring always one and the same structure is observed and decision support generally can rely on data from this certain structure, decision support for periodic or single monitoring on the other hand has to be handled differently. Decision support for structures which are measured periodically or ever for just a single time can only take into account measures of other structures to provide some kind of support. It is obvious that in this case only measures from similar structures can usefully contribute to the interpretation of such measuring data.

Below two activity diagrams are shown to illustrate the difference between periodic and permanent monitoring.

The first diagram represents activities for periodic monitoring and the second one for permanent monitoring.

Periodic Monitoring (shown in Figure 7):

- Measurement of a bridge
- Analysis of measured data
- Determination of similar bridges/cases by means of Case-based Reasoning
- Providing a suggestion about the condition of the bridge, based on the Case-based Reasoning system
- Accept or reject the suggestion

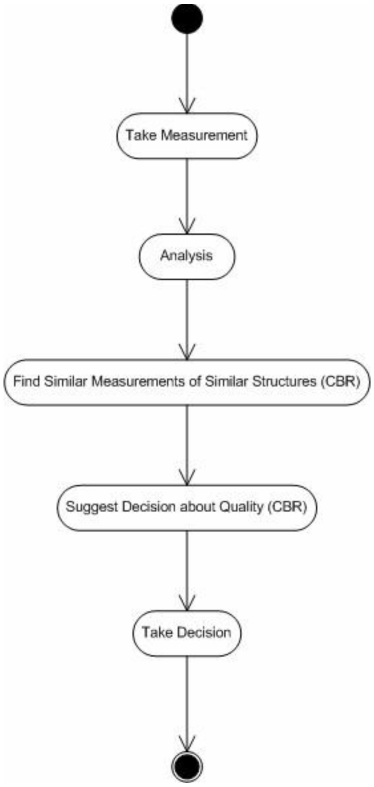


Figure 7. Activity Diagram – Periodic Monitoring

Permanent Monitoring (shown in Figure 8):

- Measurement of a bridge (automatically)
- Generation of attributes for a representation as cases (preprocessing)
- Finding similar situations with the Case-based Reasoning system
- If the Case-based Reasoning system classifies the current situation as critical, then the system suggests possible solutions for solving this problem

The following chapters introduce more details like the integration of monitoring data, performance enhancement and the database model of the CBR system for example.

B. Data Preparation

After measurements of certain structures are taken, engineers start to analyse and classify them. For the analysis, measurement results (eigenfrequencies), and in most cases additional data, e.g., from visual inspections, are taken into account. Consequently, each case consists of a set of weighted attributes with different meanings and different data types. Due to the aim of representing the cases as points in a normalised n-dimensional metric space (each dimension has a finite range between 0 and 1), the definition of similarities/distances has to be well-thought-out.

The (Euclidean) distance between two cases X and Y is defined as following:

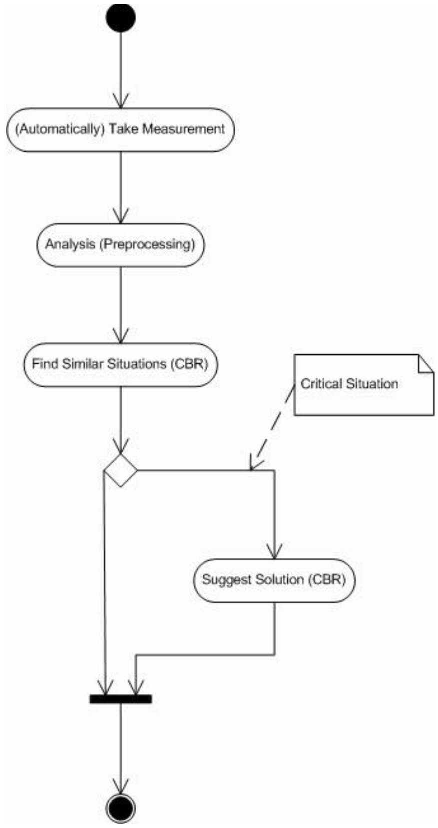


Figure 8. Activity Diagram – Permanent Monitoring

$$d(X,Y) = \sqrt{\sum_{i=1}^{n} f_i(x_i,y_i)^2} \tag{4}$$

The function f_i of the formula which is shown above returns a value between 0 and 1 representing the distance between two parameter values of a certain dimension. For the current application of the Case-based Reasoning system for Structural Health Monitoring it has turned out to be sufficient to rely on similarity representation in the metric space with numerical attributes (e.g., eigenfrequencies) on the one hand and predefined distances between parameter values on the other hand. Such distances for a certain attribute are defined in a matrix (which generally is symmetric: $d_{mn} = d_{nm}$) organised as following:

$$\begin{array}{cccccc} & \mathbf{v_1} & \mathbf{v_2} & \mathbf{v_3} & \mathbf{...} & \mathbf{v_n} \\ \mathbf{v_1} & 0 & d_{12} & d_{13} & ... & d_{1n} \\ \mathbf{v_2} & d_{21} & 0 & d_{23} & ... & d_{2n} \\ \mathbf{v_3} & d_{31} & d_{32} & 0 & ... & d_{3n} \\ \mathbf{...} & ... & ... & ... & ... & ... \\ \mathbf{v_n} & d_{n1} & d_{n2} & d_{n3} & ... & 0 \end{array}$$

Defining distances this way only is useful as long as all possible parameter values are known. As these distances in general have to be predefined by the user, the number of values has to be limited to a reasonable amount. In case of a symmetric distance matrix and a diagonal (d_{ii}) equal to zero, the number of predefined distances for a certain number of parameters n is $\frac{n^2-n}{2}$. Thus, for n = 20 the number of distances is 190. One has to realise that these dimensions soon will become unclear and unmanageable for a user.

f_i also can be a complex function, just having the constraint to return a value between 0 and 1 in our case. An attribute of the cases could be a graph for instance. There are algorithms to calculate the similarity between two graphs (Graph Edit Distance, see also [17][18]), so f_i would be this algorithm for distance calculation between attributes of the dimension concerned.

C. Data Model

Figure 9 shows the Data Model which gives an overview of the Case-based Decision Support System. There is a class called “CaseBase” where the name and a description of the case base are stored. The class “Case” is a container for the cases of the system. “AttributeBase” consists of all available attribute types with certain weights, which represent their importance. “SolutionBase” describes all available solution types. The parameter values of attributes and solutions are stored in the classes “Attribute” and “Solution”. It is also possible to define standard values for attributes and solutions and for these values one can store standard distances (as shown in the matrix above). Standard values for an attribute type “material” could be “wood”, “concrete” and “steel” for instance. This property is represented by the class “StandardDistance”. Another class is called “IsPrototypeOf”. This class defines if a case has a prototype (a case which represents a group of cases) and vice versa if a case is a prototype of other cases.

D. Indexing

Experiments with data from “real-world” pointed out an important issue, namely run-time performance. As a case (measurement incl. background information) normally consists of numerous attributes and many distance calculations are necessary to retrieve a set of the most similar cases, it turned out to be necessary to improve runtime performance. Beside multidimensional indices (the current implementation uses an M-Tree), algorithms could be considered to reduce the dimensions of the data-vector and to speed up the system.

Effective and adequate indexing and prototyping can be efficient ways to reduce the runtime of searching similar cases. Groups of cases with very low distances can be represented by prototypes. Due to the fact that comparisons of attributes in this system are metric, the Metric Tree (M-Tree) is a possibility to improve runtime performance by approximately 67% [7]. The algorithm for inserting elements keeps the M-Tree balanced, it grows bottom-up. Figure 10 shows the structure of the Metric Tree and one can see the division of the metric space achieved by the M-tree in Figure 11.

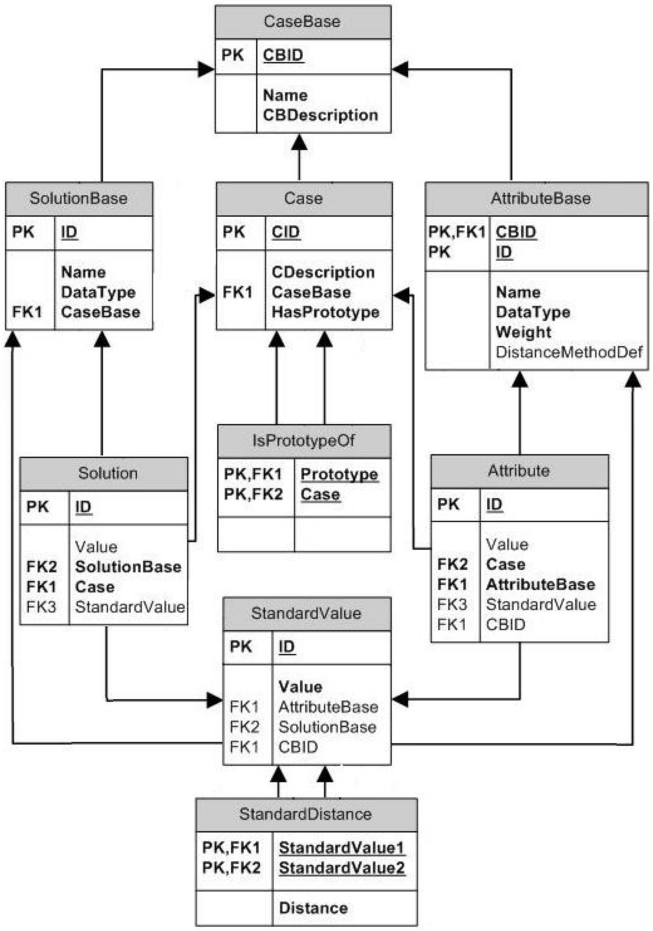


Figure 9. Data Model

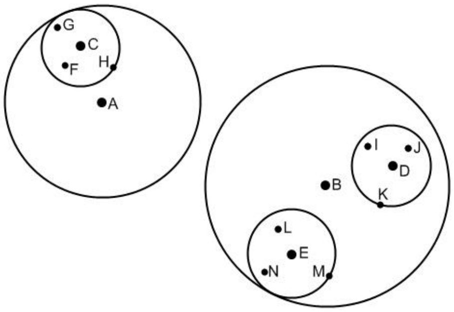


Figure 10. Example M-Tree

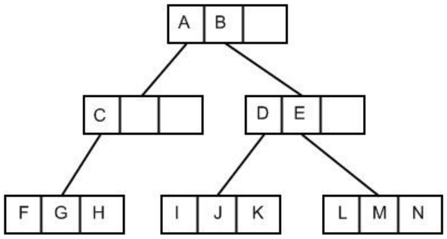


Figure 11. Example M-Tree

The M-Tree divides the space into hierarchically organised clusters. A cluster is represented by the centre and by the so-called partial tree covering radius. In the example above there are two clusters on the highest level (centres A, B) including lower-level clusters (C, D, E) and leaf-nodes (F...N). Relying on this scheme the model can speed up similarity search operations. In case of range queries or k-nearest neighbour queries, the search algorithm of the M-Tree only explores partial trees containing potential candidates and does not consider partial trees (incl. contained objects), where, according to the distance between query object and cluster-centre, also taking the partial tree covering radius into account, a valid search result is not possible.

For more information about the M-Tree model (e.g., insertion, nearest neighbour search) see [7].

VII. CONCLUSION AND FUTURE WORK

Bridge Monitoring is a very complex task. Any building has its individual dynamic parameters which make the automation of measurement analysis and interpretation become quite challenging problems. Aspects like the personal impression of the analyst have influence on the interpretation of measurement results, which by now rarely is represented in a formal way. As mentioned, the Case-based Decision Support System tries to provide decision support to the engineer by pointing out comparable historical measurements. The interpretation of measurement results can be supported well because similar bridges in similar condition have comparable measurement results. Due to using the M-tree model for indexing, the probably big number of entries in the case base, similar cases generally can be provided in a more adequate runtime, although the similarity search can still be a very time-consuming operation. The system described in this contribution currently is in the state of a “research prototype” and mainly provides the functionality to retrieve the most similar structures/objects of a query object.

The main reason for the system requirements explained in this contribution is not a possible redundancy of the expert in the analysing process of Bridge Monitoring but major assistance in his/her work in order to handle the overwhelming amount of measurement data. Besides, these routines might help to attract notice to new aspects which are, due to a lack of time and knowledge, ignored and unknown so far. All in all, the new procedures would support an expert in understanding and classifying the measurement of a bridge and, finally, lead to a better utilization of the measurement data. A design of such system was introduced in this contribution including suggestions for similarity measures and indexing methods.

The outcome of the current investigation is a prototypic implementation of the proposed Case-based Decision Support System for Structural Health Monitoring, drawing conclusions from measurement results (eigenfrequencies) and visual evaluation of buildings to their condition. First experiments with measurements from different types of structures indicated that this is a very promising field of research. Assessing simple structures perform well but the more complex the buildings become (e.g., bridges), the more obviously it turned out that many improvements on the part of computer scientists’ methods as well as on the part of civil engineers’ procedures are necessary. It may be not enough that the reasoning algorithm just relies on past cases, further rules and constraints might be essential. As an example the fact can be mentioned, that measurement results strongly depend on environmental influences (e.g., weather conditions like temperature, humidity, etc.) for instance, which has to be taken into account in order to be able to draw conclusions from the signal to the building’s state more precisely. On the other hand civil engineers would have to improve their inspection procedures in order to collect all data which influences a measured signal and which consequently is important for a computer system to assess a measurement correctly. Nevertheless, the current implementation already can provide support for interpreting signals and in case of evaluating more or less simply designed structures (first experiments with lamp posts were carried out), whereby the output of the Case-based Decision Support Prototype is very close to the engineer’s output.

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