Modern Artificial Intelligence Solutions for Bridge Management Systems

Bartosz Bien

Wrocław University of Technology
51-639 Wrocław, Slewinskiego 15, Poland
mail@BartoszBien.com, http://www.BartoszBien.com

Abstract

This article briefly presents recent AI-related solutions for bridge management systems supporting the operation of the transportation infrastructure. The generic structure of a management system is presented, and some current research and practical developments are introduced. Additional ideas concerning design and construction stages are also mentioned. The focus is put on bridge structures but the presented methods are easily applicable to highway and road management tasks.

Introduction

Among many domains of technology, the civil engineering is frequently considered as the "artistic" one – however, in scientific terms, the word "heuristic" would be more appropriate. Design challenges, location fixing, construction course, load and traffic control, maintenance and repair – all these aspects involve heuristic issues. The difficulties with modelling the reality in bridge and road management systems are mostly caused by large complexity of engineering structures and intricate relationships among the mentioned aspects. An additional problem appears due to a need to make decisions in an environment characterised by an incomplete or imprecise data on the managed object [Bien 97]. Thus, there is a little possibility of settling an exact mathematic model for these problems while the management practice requires a model that can be a subject to a professional expertise. These factors determine a necessity of equipping such systems with AI methods, namely the so-called *utilitarian AI*. This term encompasses a range of highly specialized components that suitably serve a specific need of the management system. Until recently nearly only symbolic processing has been used. At present the evolutionary algorithms, neural networks and fuzzy logic-based systems are all on the stage.

The most widely exploited domain of AI applications in civil engineering is the design of the transportation infrastructure. There has been plenty of research projects affiliated with this subject [Reich 95] expressing such ideas as a preliminary conceptual design of bridges, determining an optimal location of the structure, automatic design of the basic components (e.g. design of bridge foundations or safety evaluation for high seismic activity areas), scheduling construction works, and aesthetics issues. The techniques applied include rule-based expert systems, AI-related multiobjective optimization algorithms, neural mappings, and a case-based reasoning. It should be noted that many of these concepts have been implemented for the real-life purposes.

However, handling the design and construction stages seems easier than the subsequent management of the infrastructure. There are several causes for this [Bien 02]:

- the design process is individually adjusted to each structure, while a global management requires the comprehensive solutions,
- designing is performed according to the specific law standards and a management must be done with regard to the actual state of structures and user requirements,
- during the operation-time management a question of degradation arises along with a need for technical condition and serviceability evaluation methodology,

- the management purposes often require the system to use an incomplete or uncertain information.

Due to a significantly smaller bibliographic representation and a complexity of the problem, this article focuses on the evidence, maintenance and operation management of bridge structures. Specialized systems that aid these activities are commonly called the BMS *(Bridge Management Systems)*. Among the bridge structures one may distinguish bridges, viaducts, overpasses and footbridges. On the area of Poland, there are circa 30000 road structures and 10000 railway structures of these types. These constructions are usually relatively aged (almost half of the rail objects have been erected in 19^{th} century), which means that they require especially efficient monitoring and management [Bien 97]. The bridge administration units often supervise other engineering structures, such as tunnels, underpasses, retaining walls and culverts, the latter constituting almost 70% of the total structure quantity. The number of all civil engineering structures in Poland exceeds one hundred thousands and this stock of infrastructure definitely requires a "large-scale" management. However, in the bridge management systems which are currently used in Poland, no elements of AI are applied. The systems also need precise terminology for semantic unification of the collected data. This challenge is even more apparent than in more prosperous UE countries and the United States.

The BMS Architecture

The architecture of a typical bridge management system consists of the four following functional modules:

Inventory. The goal of the inventory part is to collect, store, process and present required information on bridge structures along with their locations in a transportation system. Information concerning each object is usually organized as follows:

- identification data (name and number, geographic and administrative location, obstacle information – commonly presented using GIS techniques),
- a numerical model of the object, containing geometry data, material and construction types of each component,
- additional information, such as technical documentation, description of non-construction components, personal details of people and companies affiliated with the object.

Apart from the classic forms of data representation, the modern systems offer a possibility of storing multimedia, such as images, sound and video clips, or hypertext. The basic inventory data processing functionalities include data verification, searching, filtering and sorting. Documents, reports and statistical sheets can also be generated, either when required by regulations or user-defined.

Maintenance. This part of the system targets systematization of data collected during technical inspections which contains descriptions of detected damages and measured values of their significant parameters. The key aspect of describing damages is the uniformity of its classification, identification and modelling scheme. This data, handled with an objective methodology of evaluating the individual damages contribution to the technical condition of the whole structure, can be used later to forecast how the technical condition would change and to plan the maintenance works. In advanced systems the maintenance function is often enriched with extra functionality, such as the possibility of storing survey results (material analyses, nivelations, deformations and movements, structure test loads) or monitoring the technical condition.

Operation. In this module the system stores and processes time-changing data concerning the following structure elements:

- traffic arrangement – road traffic lanes, railroad tracks, sidewalks, safety and emergency lanes;
- operation parameters – clearance over and under the structure, speed and load limits);
- operating conditions – environment aggressiveness, traffic intensity and composition load.

Using above data, the system evaluates the current serviceability. This parameter is needed later by the forecasting and planning functions. Additionally, the operation function allows for analyzing the possibilities of special (e.g. extra-heavy) transports. It also aids managing information about specific events, such as failures, building or natural disasters, collisions and traffic accidents.

Planning. The planning module aids the decision processes, especially the optimization of resource distribution for maintenance works, taking technical condition and serviceability evaluation into account. The applied forecasts are based on the appropriate degradation and rehabilitation models [Bien 02]. Apart from economic advising, the planning module can be designed in a way so it could assist in developing maintenance strategies, e.g. by the selection of materials and technologies or by monitoring work execution.

Possible applications of AI to BMS

The potential applications of AI to the individual aspects of transportation infrastructure management may be multiplied, according to the considered detail level. Some of the possible expert tools (also called the "expert functions") within the main parts of the BMS are presented in the fig. 1., followed by a short description of their target applications, inbound and outbound data, knowledge acquisition sources, proposed AI techniques and validation methods. This diagram also shows a proposed flow of information in an integrated system.

Currently an essential source of knowledge for most of the mentioned tools is the human expertise. With the growing quantity of standardized data collected in the BMS, a significant part of knowledge could possibly be acquired through data mining facilities. Needless to say, that the standardization is crucial here – parameter classes and scopes should be formally defined and commonly used text descriptions should never be used for meaningful factors to avoid obvious discrepancies and ambiguities with the modelling of a knowledge base. The high modelling precision allows utilizing the data mining technology, which may be helpful with the successive correcting and supplementing the knowledge of the system, especially the degradation and rehabilitation models and the economic planning criteria.

The most apparent advantages of the expert functions applications to the civil engineering management systems are: an increase of efficiency in finding the solution for complex problems, high reliability and quality of the expertise (thanks to a consequent inference and an effective tuning), a possibility of simultaneous use of various domain experts' knowledge, and – last but not least – the lower cost of obtaining the results than with human experts.

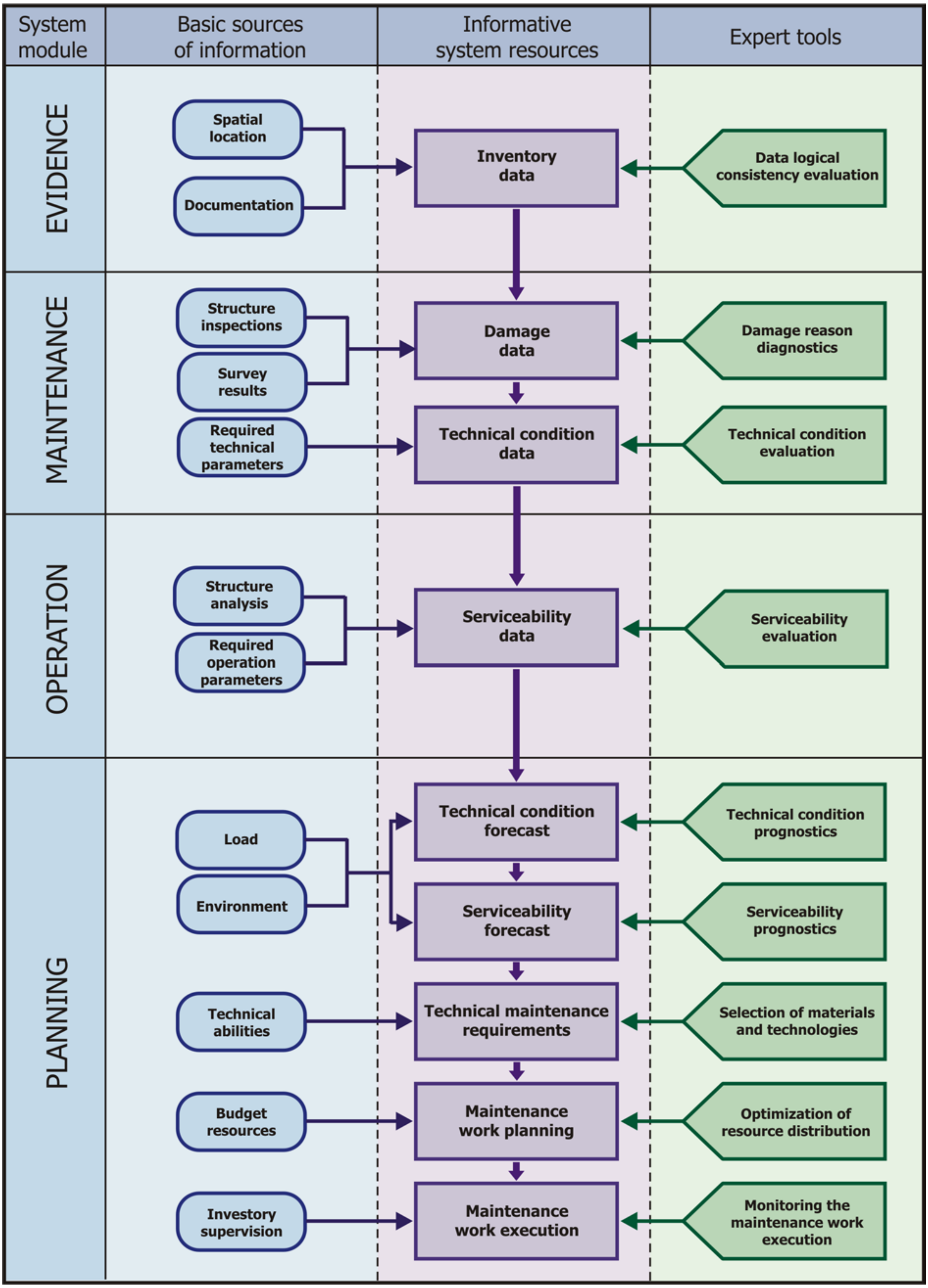

Fig. 1. The potential applications of expert tools to the bridge management systems.

Data logical consistency evaluation

- *target application:* controlling and verifying the logical consistency of the data collected in the system, detecting possible contradictions in technical data (e.g. a material that does not match a construction type),
- *inbound data:* inventory data inserted into the system by inspectors;
- *outbound data:* data logical consistency evaluation in a normalized scale, a report on found irregularities;
- *knowledge acquisition sources:* system database, expert knowledge;
- *AI techniques:* rule-based reasoning;
- *algorithm validation methods:* verification by experts.

Damage reason diagnostics

- *target application:* determining possible causes of the detected damages; this information is used to plan the types and range of maintenance (repair) works;
- *inbound data:* inventory data, numerical description of the construction damages (a damage class identification, location and quantitative parameters – usually numeric or linguistic variables describing the intensity and the extent of the damage);
- *outbound data:* a list of the possible damage reasons, along with the probability weights;
- *knowledge acquisition sources:* maintenance database of the system, expertise, opinions and bridge engineering handbooks, expert knowledge;
- *AI techniques:* analogical to those used by medical diagnostics (a similar character of the problems) – rule-based reasoning, neural networks, causal modelling, etc.
- *algorithm validation methods:* a comparison of system results to the existing reports (created by experts) containing the identification of damage causes.

Technical condition evaluation

- *target application:* determining technical parameter values of the structure when compared to designed (ideal) values; this information is used for monitoring the degradation process and in maintenance planning tasks;
- *inbound data:* inventory data, numerical descriptions of the construction damages;
- *outbound data:* technical condition evaluation of the construction element, normalized to the established BMS scale;
- *knowledge acquisition sources:* maintenance database of the system, expert knowledge, results of the survey and construction analysis;
- *AI techniques:* rule-based reasoning, fuzzy inference, neural networks, hybrid techniques; several efforts are made to create an evaluation system that learns during operation;
- *algorithm validation methods:* comparing evaluation assessed by the expert to the results gained independently by the system.

Serviceability evaluation

- *target application:* determining the conformity of the actual operation parameters of the structure to the requirements stated by users; this information is used to estimate the appropriate operating conditions (e.g. traffic constraints, such as speed or load limits); serviceability data is also an important factor in the planning process;
- *inbound data:* the actual operation parameters of the structure (loads, clearance, speed limit, etc.), the required operation parameters, qualitative and quantitative data on the existing damages;

- *outbound data:* serviceability evaluation normalized to the system scale;
- *knowledge acquisition sources:* system database, statistical traffic data, expert knowledge;
- *AI techniques:* rule-based reasoning, fuzzy inference, neural networks, hybrid techniques;
- *algorithm validation methods:* verification by the experts.

Technical condition forecast

- *target application:* estimation of the expected technical condition in a given period with respect to the various operation conditions; this information is used by the planning functions;
- *inbound data:* age of the structure, forecast period, description of the existing structure damages and its possible origins, the history of the technical condition, environment aggressiveness (traffic intensity, load structure) and the maintenance level during the analysed period (a rehabilitation outlay expressed in % of the total reconstruction value);
- *outbound data:* the predicted damage parameters and a technical condition evaluation for the given period;
- *knowledge acquisition sources:* the maintenance database of the system, expert knowledge, statistical algorithms for traffic load prediction, the results of the structure analysis, statistical data characterizing an environment, information on the structure maintenance level;
- *AI techniques:* various, dependent on the existence of degradation and rehabilitation models for the structure; the ability of the machine learning from the results of the consecutive technical inspections is desirable;
- *algorithm validation methods:* simulation of the forecast using the data collected by the bridge management systems.

Serviceability forecast

- *target application:* establishing the expected changes of serviceability in a given period with respect to the various operation conditions; this information is used in planning;
- *inbound data:* age of the structure, forecast period, description of the existing structure damages, the history of serviceability and operation parameters, a forecast of the operation parameters, environment aggressiveness, maintenance level;
- *outbound data:* operation parameters and serviceability forecast for a given period;
- *knowledge acquisition sources:* system database, expert knowledge, transportation development forecasts;
- *AI techniques:* neural networks, hybrid networks.
- *algorithm validation methods:* verification by experts, simulations with historical data.

Selection of materials and technologies

- *target application:* aiding the process of selecting an optimal maintenance (repair) work technology along with material recommendation;
- *inbound data:* inventory data, description of existing structure damages, the history and forecasts of technical condition and serviceability;
- *outbound data:* the suggested technology of rehabilitation (maintenance) works;
- *knowledge acquisition sources:* data extracted from the system database regarding previously executed maintenance tasks and their results (for various rehabilitation technologies), expert knowledge, information on materials, technologies and costs of the maintenance works, technical documentation;
- *AI techniques:* rule-based reasoning, neural networks, hybrid networks;

- *algorithm validation methods:* verification by experts, simulations with historical data.

Optimization of the resource distribution

- *target application:* optimization of the budget resource distribution for a given level of maintenance and user-defined optimization criteria, using technical condition and serviceability forecasts;
- *inbound data:* inventory data, a history and forecasts of technical condition and serviceability;
- *outbound data:* a ranking list of maintenance tasks, ensuring the maximum possible improvement of the technical condition and serviceability for a given general level of maintenance;
- *knowledge acquisition sources:* system database, expert knowledge;
- *AI techniques:* various multiobjective optimization techniques;
- *algorithm validation methods:* verification by experts, simulations with historical data.

Monitoring the maintenance work execution

- *target application:* conformity controlling of a type, scope and time limits of maintenance works to the previously accepted schedule;
- *inbound data:* a scope and a schedule of the planned maintenance works, estimation of costs, technical parameters, current data on the realization progress;
- *outbound data:* an opinion on work progress conformity to a schedule, a forecast of changes in execution parameters;
- *knowledge acquisition sources:* technical documentation, system database, expert knowledge;
- *AI techniques:* various;
- *algorithm validation methods:* verification by experts, simulations with historical data.

The recent AI research projects for BMS

Recently there have been numerous approaches to apply AI techniques to the maintenance and operation phase of civil engineering structure life-cycle [Reich 95]. Among them a lot of interesting solutions for specific problems have been presented:

- **condition analysis** – static and dynamic load tests of bridges, using designated or random traffic load schemes;
- **structural monitoring** – bridge in-situ dynamic monitoring and analysis, providing support for early warnings against collapses, reducing mid-span deflection;
- **functional monitoring** – traffic safety evaluation, determining truck attributes, regulating the flow of hazardous materials over a bridge, prediction of frost conditions;
- **inspection and condition evaluation** – bridge fatigue investigation, damage assessment, estimating the cumulative impairment, identifying vulnerabilities, scour estimation and susceptibility, scheduling future inspections;
- **rehabilitation** – rating of infrastructure objects, cost estimation, prioritizing alternatives under budget constraints, scheduling the works, selecting strategies and recommending actions.

Some general rules on applying AI to various problems have been confirmed by these works – a fuzzy inference is suitable for summation of individual assessment values, neural networks are more appropriate when it comes to signal processing, and evolutionary algorithms work fine as multiobjective optimizers. Though rarely used, machine learning techniques allow the knowledge acquisition from diverse sources, especially from the growing bridge databases.

However – at least for the practical development of a real AI-based BMS application – a deeper integration is still needed. Therefore, a hybrid expert tool **Neuritis™** has been developed [Bien 01a, Bien 01b] and is currently used by our company as an intelligent environment for creation of the practical applications.

Neuritis™ – an intelligent development environment

At first, this utility allows to define a problem in an abstract manner, in the form of the "problem tree". Then a solution is built up as a layered component diagram that we call the "expert graph". This diagram presents the architecture of a hybrid network of interfacing blocks, each of them being a data processing component. These components communicate by exchanging matrices of real or fuzzy numbers and the interfaces are independent of the internal processing. It enables easy modification of the graph structure and flow of information, and also reusing the developed knowledge blocks.

The system's codename may suggest a domination of neural networks in the produced solutions but the range of intelligent components is much richer here – among others, the system provides fuzzy components with fuzzy logic inference implementation and an evolutionary tuning, mathematical components integrating some useful techniques from algebra, calculus and statistics, and neural components with learning abilities (fig. 2).

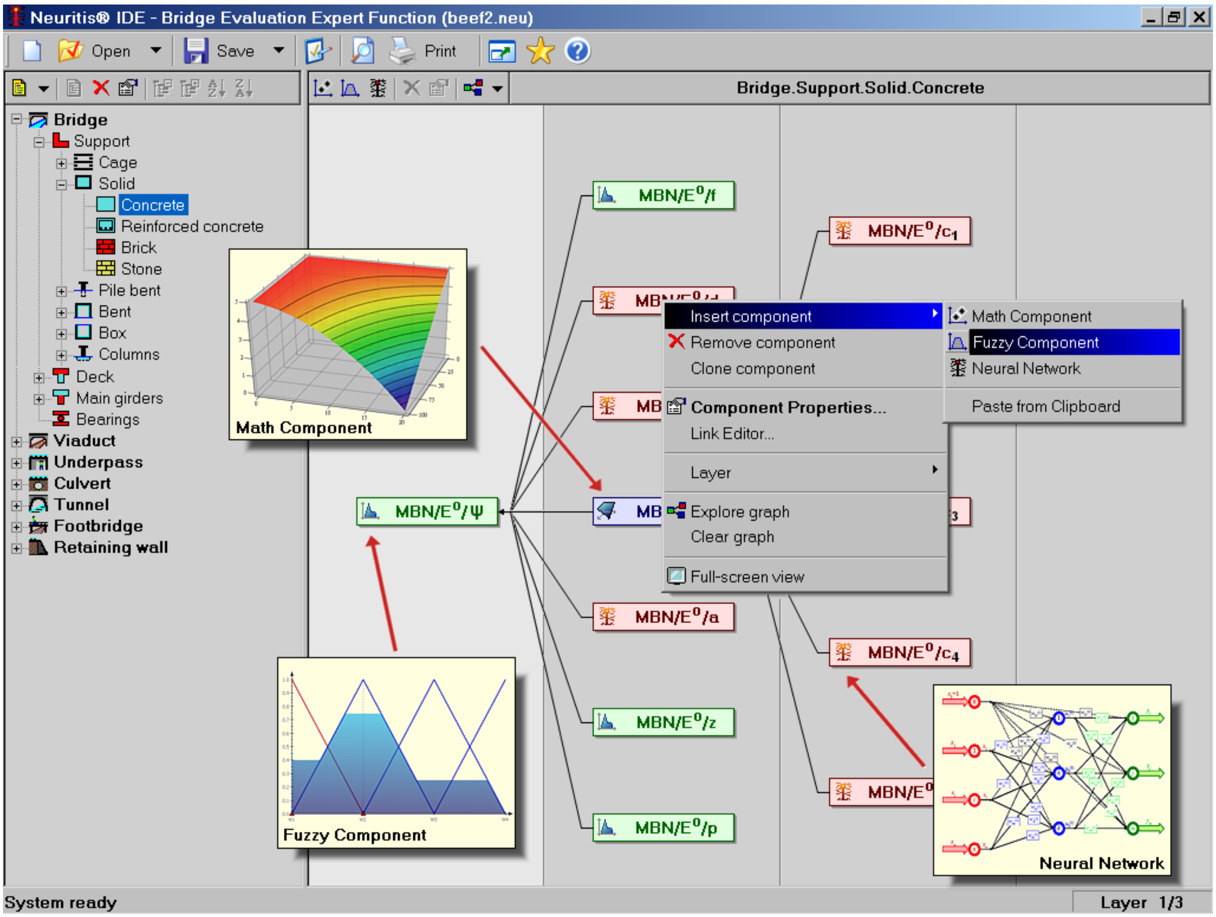

Fig. 2. The Neuritis™ IDE main window, showing the problem tree for technical condition evaluation and the expert graph for solid concrete supports; the yellow tip windows have been added to present the available component classes.

The system interface is highly intuitive and the predefined solution needs extensive tuning and testing processes. As these operations are completed, a ready-to-use expert system can be exported in an executable form and installed within a client application or simply transferred to the ordering client. As easy as it gets? Sure, though there's far more ahead!

The current applications of hybrid expert functions to the BMS

Currently the two existing bridge management systems use some of the hybrid expert functions discussed in this article. The first real-life application of Neuritis-generated system is the technical condition evaluation module named BEEF (Bridge Evaluation Expert Function). It has been used in practice since 2000 as a part of SMOK, the railway bridge management system designed and created for the Polish State Railways (PKP).

The similar solution is tested in the transportation structure management system SZOK, which covers roads and various kinds of engineering structures (fig. 3). SZOK is used by many provincial and district departments of transportation in Poland, as well as by the highway administrators.

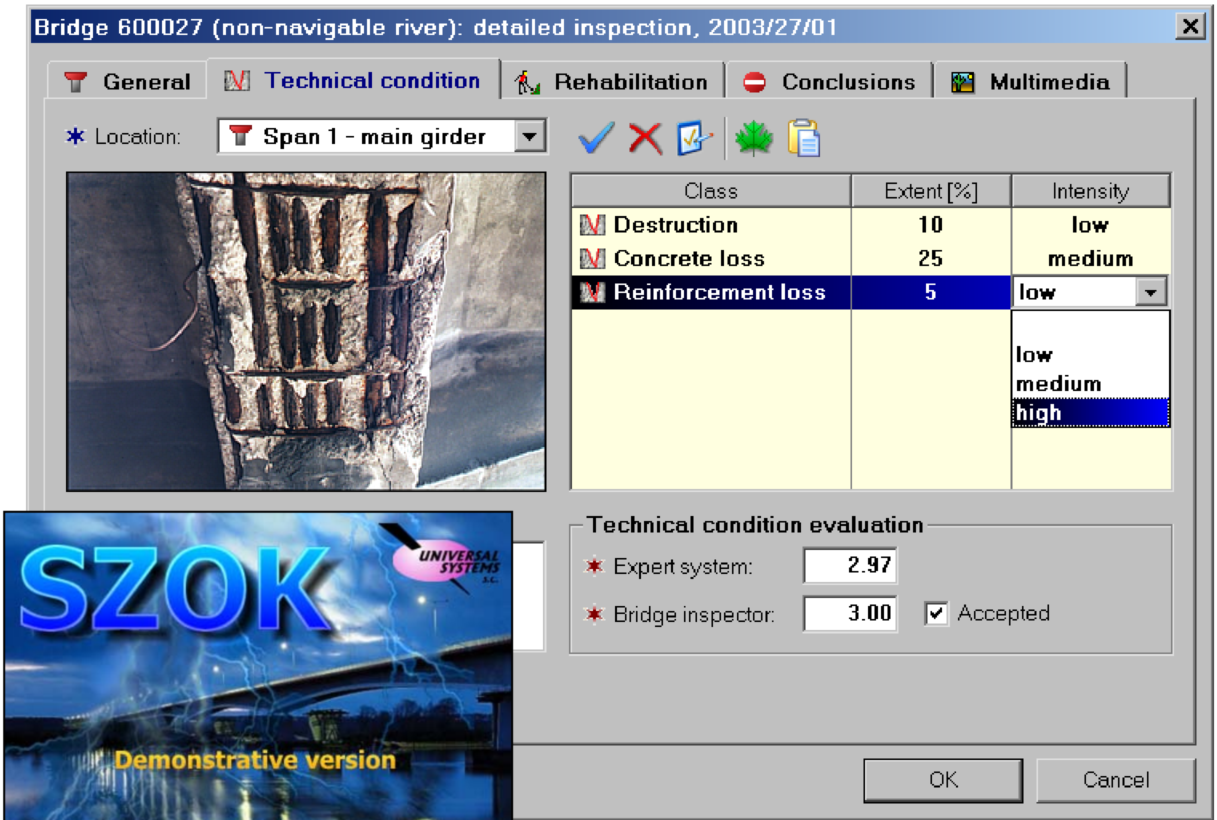

Fig. 3. The expert system interface integrated with the maintenance part of the transportation structure management system **SZOK**: the technical condition evaluation proposed by the expert system has to be accepted by a bridge inspector.

On the way to an ideal BMS

With the infrastructure management systems, the reins to the imagination may be freely given as the sight of the modern bridge or a highway often makes people think of the road to the future. Moreover, it is obvious that the scientific and practical progress in this subject has significantly accelerated in the last few years. Using the modern engineering and information technologies, just to mention the rapid application development tools, the intelligence may rise on our bridges and roads sooner that it is expected. In my opinion, the first and foremost general directions of further BMS development are:

- wider application of mechanisms that allow more effective knowledge processing and machine learning,
- independent decision making,
- physical infrastructure extensions that allow the system to affect it directly.

A futuristic bridge management system might for example perform the following tasks:

- noticing the existence and approximate location of a damage according to the detected change of technical and operation parameters (constantly monitored);
- acquiring an image or some other characteristics of a potential damage with a mobile camera or a robot,
- classifying the damage using detected features,
- evaluating the technical condition basing on the set of existing damages,
- updating a forecast of technical condition changes, concerning environmental conditions, traffic load and the expected outlay for rehabilitation and repair;
- inserting the updated evaluation and forecasted values into a central database (using intelligent agents);
- updating the rank list of objects requiring maintenance actions;
- limiting the operation parameters (dynamic-content road signs);
- if the object qualifies to be repaired automatically, performing the repair itself using specialized robots.

Conclusions

The thorough automation of the bridge and road management systems is probably not a direct task for the closest future, yet the consistent realization of the presented expert tools will allow the reduction of human resource involvement, and broadening the perspectives on the development of techniques for maintenance and operation of the transportation infrastructure.

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