Development of a software-tool for the life-cycle management of bridges

M. Kluth, A. Borrmann, E. Rank
Chair for Computation in Engineering, Technische Universität München, Munich, Germany

T. Mayer & P. Schiessl
Centre for Building Materials, Technische Universität München, Munich, Germany

ABSTRACT: This paper introduces a software tool for the predictive life-cycle management of reinforced concrete bridges. The novel aspect of this particular tool is the integration of non-destructive inspection techniques in combination with fully-probabilistic deterioration models. The use of these models requires that the building under examination be subdivided into multiple levels of detail. We employ a 3D model of the building for creating and visualizing the different system levels. At the same time the 3D model forms the basis of any data acquisition, analysis and evaluation. The system is implemented by coupling a Java 3D front-end with a relational database, in which the construction geometry and all related information is stored. Due to the long life span of bridge structures, the software is required to satisfy special requirements in terms of its flexibility. It is shown how new materials, inspection techniques, deterioration models, repair procedures etc. can easily be integrated into the software tool.

1 INTRODUCTION

1.1 *Motivation*

According to statistics published by the German Federal Ministry for Transport, Building and Urban Development (Bundesministerium für Verkehr, Bau und Stadtentwicklung 2006) there is a stock of about 120,000 bridges in Germany. The institutions that own these bridges are faced with the problem of maintaining these aging structures with just limited funds at their disposal (Schiessl & Mayer 2006). During the past 20 years or so, numerous so-called computer-aided bridge management systems (BMS) were developed to support engineers involved in the inspection or repair planning of bridge structures (see Section 1.2): information from inspections is stored in a BMS and can be consulted at any time. This data is also used to compute the condition of the structure, described as part of a marking system. One disadvantage of many existing BMS systems is that the lack of adequate deterioration models only allows for the detection of damage through visual inspection (e.g. cracking, staining, spalling). In most cases, the best time for (preventive) repair work on concrete component parts has already passed once erosion becomes visible on the concrete surface. Predictive life-cycle management systems (LMS) are a novel approach to overcome this major drawback of conventional BMS. To detect decay earlier on, additional non-destructive and visual inspection techniques are used in combination with fully-probabilistic deterioration models to predict the endurance and longevity of component parts. The prognosis will be constantly updated, thus being more precise concerning rate of deterioration. Such a LMS can thus be used to optimize the operation of bridges over their entire service life (Schiessl & Mayer 2006, see also Budelmann & Starck 2008). Furthermore, the system supports the institutions responsible for bridge maintenance in the long-term planning of inspections and repair measures at both bridge level and network level. Another advantage is that the required budget for funding the reconditioning measures can be planned more precisely.

In an ongoing research project we develop a software tool for the predictive life-cycle management of reinforced concrete bridges. A 3D building information model (BIM) is at the heart of this system. All relevant data like measurement results, photos or condition prognoses are stored in this BIM. In this way, the owner of a stock of bridges can easily obtain an overview of the condition of individual structures or the complete bridge stock. The hierarchic subdivision of structures into component parts, sub-elements and hotspots chosen for the BIM allows for a more precise allocation of information.

1.2 *Related work*

Several life-cycle management systems for bridges are already in operation. In Germany "SIB-Bauwerke" was developed by the Federal Highway

Research Institute (Bundesanstalt für Strassenwesen). This software is used on a national and federal state level (Haardt 2002). The city of Düsseldorf developed another system for the maintenance planning of all bridges and tunnels within the city (Landeshauptstadt Düsseldorf 2007). The following list shows some systems from other countries (the list does not claim to be complete):

- Bridgelife in Finland (Vesikari 2006),
- Danbro in Denmark (Henriksen 1999),
- Eirspan in Ireland (Duffy 2004),
- Kuba-MS in Switzerland (Haller & Basurco 2006),
- Pontis (Robert et al. 2003) and Bridgit (Hawk 1999) in the USA
- Ontario Bridge Management System in Canada (Thompson et al. 1999).
- "Mobile model-based bridge lifecycle management systems" are currently being developed in Canada (Hammad et al. 2006).

The aforementioned systems are characterized by the following properties:

- Except for the "mobile model-based bridge lifecycle management systems" (Hammad et al. 2006) no explicit geometry is used. Photos or measurement results can only be allocated to component parts as text information.
- Adding a bridge to a system of this kind, the bridge is structured horizontally into "parts" and vertically into levels. The number of levels differs from system to system. The smallest "unit" in all these systems is a component part. No further subdivision is used in any of these systems.
- For predicting the progressive condition of component parts or the whole bridge, respectively, deterministic models (such as Haardt (2002), Landeshauptstadt Düsseldorf (2007), Henriksen (1999)) or Markovian Chain systems (Vesikari (2006) etc.) are used. Fully-probabilistic deterioration models are not used in any of these systems.
- The condition of a building is assessed manually, solely on the basis of visual inspections. Hardly any other non-destructive inspection methods are ever used.

2 PREDICTIVE LIFE-CYCLE MANAGEMENT

2.1 *Architecture*

The architecture of the life-cycle management system we are developing is shown in Figure 1. This system is primarily developed for bridges but it can also be used for other reinforced concrete structures subject to severe environmental loading (such as tunnels, multi-storey car parks and offshore structures). The features of the system are described for bridges without loss of generality. The system consists of five modules: acquisition module, condition acquisition module, prognosis module, assessment module and repair module.

The database represents the centre of this system, in which the following information of every construction is stored:

- general information,
- geometric data,
- characteristic material properties for every component part,

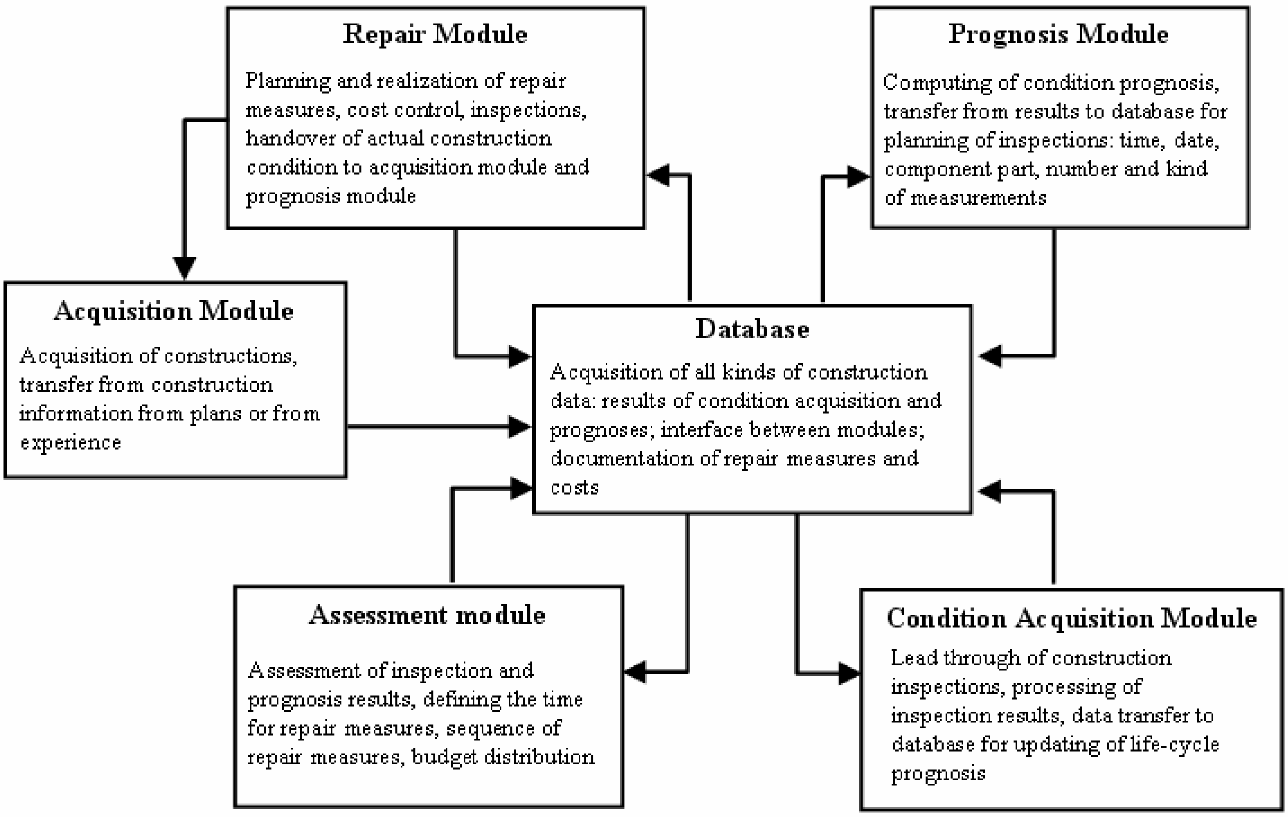

Figure 1. Assembly of the predictive life-cycle management system (according to Schiessl & Mayer 2006)

– environmental loads,
– inspection results,
– located deteriorations,
– inspection and repair planning,
– type of structure.

The database is the interface between all modules in this system. With the help of the acquisition module it is possible to store new constructions in the database. Once all construction information has been stored, all the other modules can make use of it.

The prognosis module can be used to calculate and predict changes in the condition of every component part over the course of time. Non-destructive inspection methods are used for updating the original prognosis results for each component part. It is accordingly necessary to define and store deterioration models in the database.

At the moment, sufficiently quantified deterioration models only exist for the depassivation of reinforcement due to carbonation or chloride ingress (see Gehlen 2000, for instance). For most reinforced concrete elements, reinforcement corrosion forms the main cause of decay. However, to allow for a deterioration prognosis for phenomena that cannot be properly modelled today (such as freeze-thaw-attack, ASR), simpler models like Markovian Chain-systems are used. These models can be replaced by suitable fully-probabilistic deterioration models at any time. Predicting the progressive decline (in a structure's condition) will be probabilistically calculated using the software package STRUREL (RCP 2007). We intend to establish a corresponding interface between STRUREL and the LMS to enable the required data exchange. If the system is used for a new bridge still under construction, an initial prognosis can be carried out during the planning stage and updated with the results of the acceptance inspection (“birth certificate”, Mayer, Schiessl & Zintel 2008).

The condition acquisition module is used to plan and carry out inspections. This module will be used to assign measurement results, which were collected during inspections, to component parts. These results are mainly generated by means of non-destructive inspection techniques. In this way, it is possible to detect damage (like depassivation of reinforcement) at a very early stage. The correct interpretation of the inspection results still relies on engineering experience and cannot be left to the software. Using the measurement results and deterioration models, the condition prognosis for every part is updated by means of the prognosis module. In the next step, the acquisition module develops an inspection programme based on the computed condition changes. This programme not only contains all the inspection methods available but also the number of inspections (per component part, for example).

The assessment module determines the optimum time for any kind of repair measures on the basis of the predicted condition changes at any one time. One purpose of repair measures is to eliminate possible damage at an early stage, thus enabling the construction to last longer while saving money because such “preventive” repair work is usually cheaper than mending a damaged component part. Further information about planning of repair measures is given in Empelmann et al. (2008). The repair measures are approved using the repair module. The structural condition following these repair measures is stored on the database. The prognosis module uses this information to compute a so-called Bayesian update for all condition prognoses.

2.2 *3D Building model*

In conventional life-cycle management systems the allocation of information is done textually. In the system we propose, a 3D building information model forms the core of the data acquisition and data retention system. This is because we regard 3D building models as the most suitable form of data representation in the LMS context. This model stores the components’ geometry as well as all the information on material properties, environmental loads, deterioration, inspections, repair measures and condition changes related to the geometry. In addition, all the results of non-destructive inspection techniques or photos taken during inspections can be attached to the geometric representation of the corresponding component. This way, information is easily allocated and a very good overview is guaranteed.

To adapt a construction to the building information model, it is subdivided vertically into levels and horizontally into “parts” to achieve the best allocation of measurements, deteriorations, repair measures, etc. So up to five levels of detail (LoD) are used. These are shown in Figure 2 (Schiessl & Mayer 2007).

The first step is to subdivide the construction (level 1) under consideration into modules (level 2). This subdivision is done from an organizational or functional point of view (Schiessl & Mayer 2007). For instance, the modules of a construction of type *bridge* are: foundation, bridgehead, pylon and superstructure. Although the system is mainly developed for bridges, it is also possible to organize other constructions with this tool. For this reason, a fifth type of module is defined: a *general module*. Whereas the four aforementioned modules may appear only once in every construction, the general module can appear several times. Every general module is defined by a different name.

A module consists of component parts (level 3) of comparable material resistance, which are subdivided into sub-elements (level 4) of comparable environmental stresses. Furthermore every sub-element can be subdivided into hotspots (level 5). Hotspots

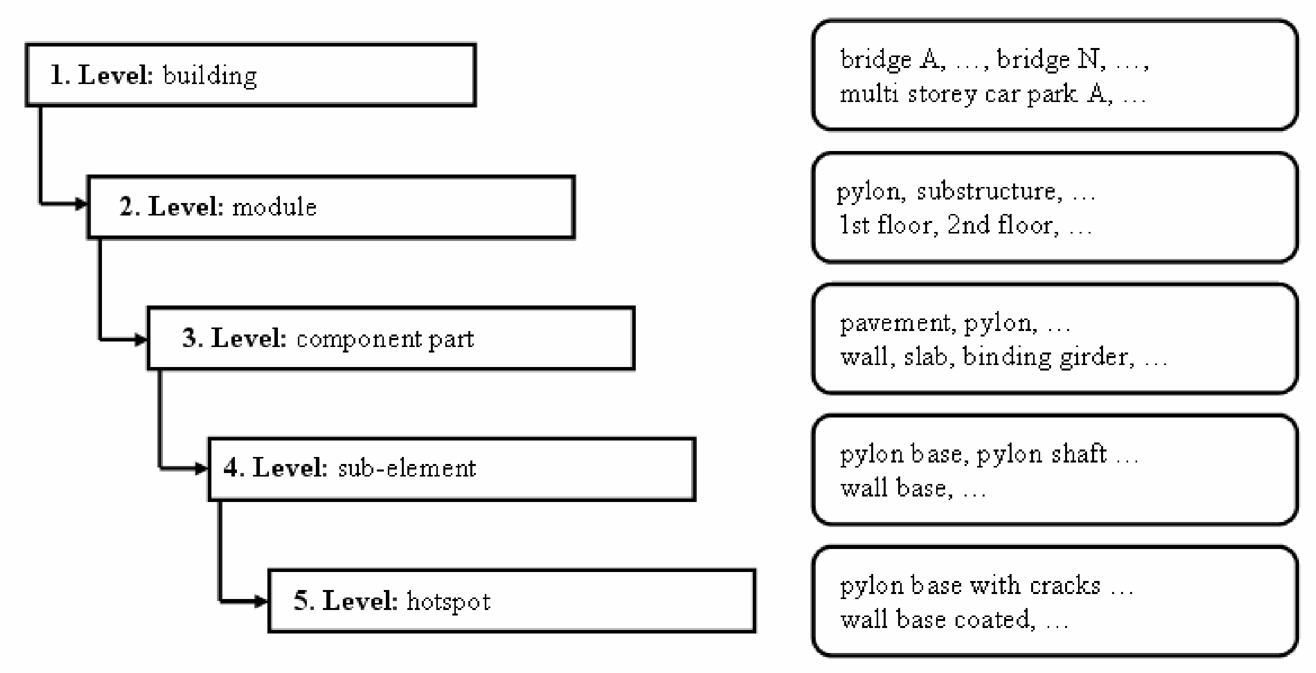

Figure 2. Structure for a bridge (according to Schiessl & Mayer, 2007)

are used for sections which have a low material resistance and/or extraordinarily high environmental loads which are critical for the condition of the construction. These hotspots can be set by the engineer or bridge-owner during planning. New hotspots can be defined at the implementation stage if local changes in environmental stress are observed during the course of inspections (Schiessl & Mayer 2007). Material resistance, environmental loads and geometric details are allocated only to elements at levels 3 to 5.

This subdivision of component parts into sub-elements and hotspots is tedious, but it is absolutely necessary in order to make optimum use of the fully-probabilistic deterioration models mentioned above. This makes it possible to achieve a much better allocation of deterioration to different areas, and the prognosis for the whole structure will be more precise.

All constructions that are stored in the database collectively form the network level. Inspections and repair measures can be planned at network level or building level.

Determining the condition of a structure is done by aggregation of the condition of all building levels. With the described levels of detail approach, the owner of a bridge can easily acquire detailed information or assess a construction's condition from the hotspot level to the whole construction at network level.

3 SOFTWARE TOOL

3.1 *General information*

The software tool presented in this paper is implemented by coupling a Java application (Sun Microsystems 2006a) with a relational database. All construction information, including geometric data, is stored in this database. A relational MySQL database (MySQL 2007) was chosen as the database management system (DBMS). The advantages of this DBMS are fast access to data, the possibility of storing large amounts of data, and no licence fees. The three-dimensional representation of the construction's geometry is achieved with the Java 3D library (Sun Microsystems 2006b). A screenshot of the acquisition module is shown in Figure 3.

All geometric data is stored in the database in the form of a boundary representation model (B-Rep). For this purpose, a data structure similar to the geometric kernel ACIS is used (Spatial 2006).

The advantage of the programming language Java is that applications written in this language can easily be used on different operating systems like MS Windows or Linux. This aspect is very important because potential users of this application (such as administrations, construction firms with PPP-projects) may use different operating systems.

Although the first steps are done to develop a product data model for bridges (IFC-Bridge, Yabuki et al. 2006), no such product data model is available for practical services yet. As soon as it becomes available, we intend to use it as the basis of our life-cycle management system.

All construction information stored in the database can be visualized and edited by the graphical user interface (GUI). One special aspect of this GUI is that an intuitive and user-friendly interaction is possible everywhere – at an office desk or during a bridge inspection on the construction site. This is achieved in two ways:

– All dialogue boxes are clearly structured. The system provides assistance with every input. This is done using tooltip texts and a support system. In addition, the user is informed if incorrect in-

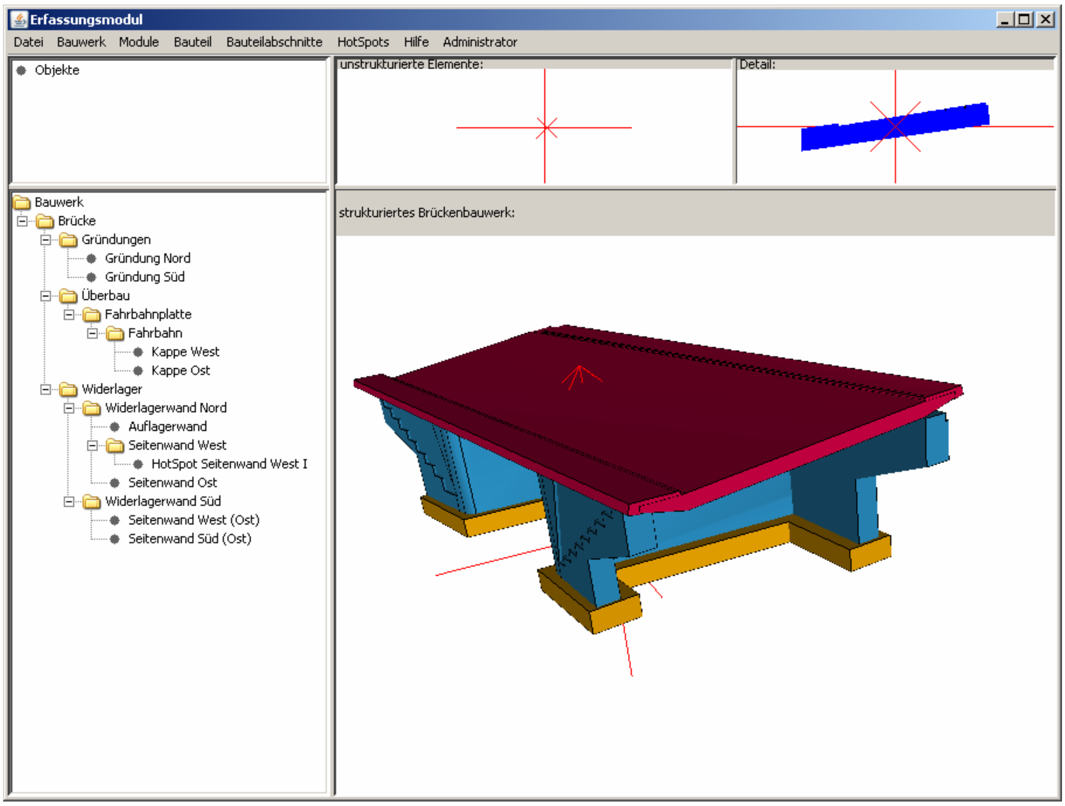

Figure 3. Graphical User Interface of the software tool (under development)

formation has been entered or information is missing when closing a dialogue box.

– The user can rotate, translate and scale the 3D model. This is done with the mouse device. Furthermore the user can select any single element (component part, sub-element, hotspot) in the graphic window or the tree view. The selected geometry is shown in a separate graphic window and can also be translated, rotated and scaled.

3.2 *Data input*

All data input is done at the graphical user interface (GUI). For easier and even faster input, extendable lists have been integrated for recurring inputs. There are lists for

– materials,
– defined material parameters,
– environmental loads,
– measurement methods,
– repair measures,
– deterioration models,
– types of component parts, and
– construction types.

Using these lists in conjunction with the software tool achieves highly effective standards of work. The lists are stored in the database and can be updated by the user or the administrator, respectively. For example, it is possible to define an arbitrary number of measurement methods, each of which is defined by a number of measurement parameters. This functionality for (re)defining measurement methods renders the systems extremely flexible, which is necessary to ensure its usability over the long life-span of a concrete building.

Measurement methods and parameters are stored in different tables on the database. A third table links measurement parameters and measurement methods. One parameter can be assigned to more than one measurement method. The generic database structure, which can hold any kind of measurement method, is shown in Figure 4. Materials and material-specific values are defined in the same way.

It is also possible to store new fully-probabilistic deterioration models on the database. To this end, the model's equation has to be defined by the user in a form readable by STRUREL.

All other lists are permanently stored in a single table.

Using dynamic programme structures inside the software-tool, not only the measurement methods

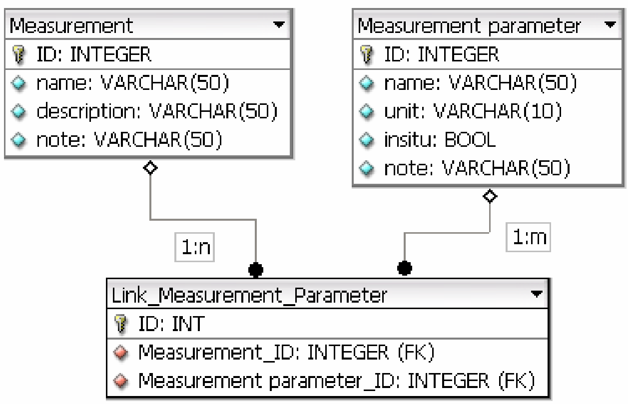

Figure 4. Generic database structure for measurement methods and measurement parameters

and measurement parameters but also the materials and material parameters are employed to compute degrees of deterioration and prognosis.

4 SUMMARY

In an ongoing research project, we develop a software tool for the predictive life-cycle management of reinforced concrete bridges. A key feature of our LMS is a 3D building information model which forms the basis of all data acquisition and evaluation functionality. This model serves to store all the information on component parts together with their relation to the geometry. What first distinguishes this software tool from other existing building management systems is the fact that a construction is subdivided into up to five levels (levels of detail). In an initial step, structures are first subdivided into modules and then into component parts. Component parts are subdivided into sub-elements and hotspots. The advantage of this approach is that results of inspections or photos can be directly allotted to the according geometries. This subdivision is necessary in order to use the fully probabilistic deterioration models in a goal-oriented manner.

For predicting future changes in the condition of a structure, these fully probabilistic deterioration models are used in conjunction with non-destructive inspection methods. The construction's condition is computed by aggregating the conditions on all five levels. It is accordingly possible to detect damage at a very early stage and plan repair measures to eliminate such damage. This consequently means a reduction in the financial outlay for the maintenance of the structure.

The predictive life-cycle management system is implemented by coupling a Java application with a relational MySQL database. The graphical user interface is a simple, innovative way to store new constructions in the database. All information can be entered and modified using this interface.

The software tool includes lists for recurrent inputs. These lists can be updated by the user or the administrator, respectively. Defined programme structures are used to compute the degree of deterioration or the prognosis for a component part with the information from these lists.

REFERENCES

Budelmann, H. & Starck, T. 2008. Integration of Degradation Prognosis of Concrete Structures into Life Cycle Management. Proceedings of the 1st International Symposium on Life-Cycle Civil Engineering (IALCCE'08), Varenna 2008.

Bundesministerium für Verkehr, Bau und Stadtentwicklung. 2006. *Bericht über die Qualität, Dauerhaftigkeit und Sicherheit von Spannbetonbrücken*. Berlin: Bundesministerium für Verkehr, Bau und Stadtentwicklung.

Duffy, L. 2004. Development of Eirspan: Ireland's bridge management system. *Proceedings of the Institution of Civil Engineering* 157: 139-146

Empelmann, M.; Henke, V.; Heumann, G.; Wichers, M. 2008. *Aspects of Sustainability of Repair-Systems for Concrete Structures*. Proceedings of the 1st International Symposium on Life-Cycle Civil Engineering (IALCCE'08), Varenna 2008.

Gehlen, C. 2000. *Probabilistische Lebensdauerbemessung von Stahlbetonbauwerken – Zuverlässigkeitsbetrachtungen zur wirksamen Vermeidung von Bewehrungskorrosion*. Berlin: Deutscher Ausschuss für Stahlbetonbau (DAfStb), Heft 510.

Haardt, P. 2002. *Entwicklung eines Bauwerks-Management-Systems für das deutsche Fernstraßennetz, Stufe 1 und 2, Schlussbericht zum AP-Projekt 99 245*. Bergisch-Gladbach: Bundesanstalt für das Straßenwesen.

Haller, H. & Basurco, G. 2006. *KUBA-DB Benutzerhandbuch.* Bern: Eidg. Drucksachen- und Materialzentrale.

Hammad, A. Zhang, C., Hu, Y. 2006. Mobile Model-Based Bridge Lifecycle Management System. *Computer-Aided Civil and Infrastucture Engineering* (21): 530-547.

Hawk, H. 1999. BRIDGIT: User-Friendly Approach to Bridge Management. *Proceedings of the 8th International Bridge Management Conference*: E-7/1-15.

Henriksen, A. 1999. Bridge Management – Routine Maintenance: Recent Experience with the Routine Management Module in the DANBRo Bridge Management System. *Proceedings of the 8th International Bridge Management Conference*: I-5/1-13.

Landeshauptstadt Düsseldorf 2007: *Lebensdauermanagement für Ingenieurbauwerke der Landeshauptstadt Düsseldorf.* Düsseldorf: Homepage (http://www.duesseldorf.de /verkehrsmanagement/bruecken_und_tunnel/index.shtml)

Mayer, T.; Schiessl, P.; Zintel, M. 2008. *Birth Certificate as an Important Tool for Public-Private-Partnership Projects*. Proceedings of the 1st International Symposium on Life-Cycle Civil Engineering (IALCCE'08), Varenna 2008.

MySQL, 2007. *Documentation of MySQL Ed. 1.5*. Uppsala: MySQL AB.

RCP, 2007. *Documentation of STRUREL Ed. 8. Munich: RCP*.

Robert, W., Marshall, A. , Shepard, R., Aldayuz, J. 2003. Pontis Bridge Management System – State of Practice in Implementation and Development. *Proceedings of the 9th International Bridge Management Conference*:49-60

Schiessl, P. & Mayer T. 2006. Lebensdauermanagement von Stahlbetonbauwerken. *Statusseminar zum Verbundforschungsvorhaben „Nachhaltig Bauen mit Beton“*: 65-74.

Schiessl, P. & Mayer, T. 2007. *Forschungsbericht 31006/05, DAfStB-Verbundforschungsvorhaben „Nachhaltig Bauen mit Beton“, Teilprojekt A3 „Wesentliche Bausteine eines Bauwerksmanagementsystems“*. Berlin: Deutscher Ausschuss für Stahlbetonbau (DAfStb), Heft 572..

Spatial 2006. *Documentation of 3D ACIS Modeler*. Westminster: Spatial.

Sun Microsystems 2006a. *Documentation of Java™ Platform Standard Ed. 6*. Santa Clara: Sun Microsystems.

Sun Microsystems 2006b. *Documentation of Java3D Ed. 1.5.0.* Santa Clara: Sun Microsystems.

Thompson, P., Merlo, T., Kerr, B., Cheetham, A., Ellis, R. 1999: The New Ontario Bridge Management System. *Proceedings of the 8th International Bridge Management Conference*: F-6/1-15.

Vesikari, E. 2006. *BRIDGELIFE, User Manual.* VTT, Finnland.

Yabuki, N., Lebegue, E., Gual, J., Shitani, T., Zhantao, L. 2006. International Collaboration for Developing the Bridge Product Model "IFC-Bridge". *Proceedings of the Joint International Conference on Computing and Decision Making In Civil and Building Engineering*. 1: 1927-1936.