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Bridge management system techniques application to italian highways network

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ABSTRACT: This paper describes the main bridge management techniques applied by Sineco to manage the highway bridge network. Using two integrated approaches Sineco can verify the actual maintenance needs and grow maintenance program reliability. The paper describes two integrated Bridge Management System. Integrating the two systems allows Sineco to manage inspection data and process them focusing on maintenance actions programming and prioritizing and on budged allocation, on the basis of both deterioration probabilistic models definition and different maintenance program simulations. The two tools are used to calculate maintenance needs, and provide 5-10 years time frame maintenance programs and annual projects details. Programs identify the maintenance policy that minimizes the annual expenditure by the agency, while integrating the objectives of public safety and risk reduction, user convenience and preservation of program policies.

1 INTRODUCTION

This paper describes the main bridge management techniques and tools Sineco adopts to assess more than 1000 km of italian highways infrastructures network, on which the company yearly performs inspections, evaluates needs, programs maintenance activities and develops single-bridge rehabilitation projects. The Bridge Management Systems tools Sineco adopts are:

- SIOS (Sistema Ispezione Opere Sineco), an inspection system, directly developed by Sineco since 1994, actually applied to 1300 highway assets (including bridges and viaducts).
- PONTIS, a computer-based bridge management system licensed through the American Association of State Highway and Transportation Officials (AASHTO) to over 45 state transportation departments and other agencies nationally and internationally.

2 BRIDGE MANAGEMENT SYSTEM AIMS

A BMS allows bridge owners to manage a large number of data and to assess items such as:

- Economic analysis and programming: defining an adequate programming, on one hand, helps owners to reduce economical efforts and, on the other hand, planning maintenance and improvement activities ensures structure safety and functionality and increases structures life cycle;
- Maintenance costs optimization: a BMS recommends a preservation strategy that minimizes the long term maintenance funding requirements while keeping the structures out of risk of failure and evaluates the economic impact of delaying any recommended action or taking extra actions;
- Serviceability targeting: defining a performance measure limit for posting the bridge or closing it, allows maintenance planning on the basis of logistic opportunities directed to minimize and reduce work impact on traffic.

In the present paper BMS is intended both as a technique, both as a tool able to assist highway agencies to choose the optimal bridge network maintenance or improvement policies, consistent with agency's usual policies, long term targets and budget constraints. Using BMS techniques and tools allows Sineco in addressing the bridge life cycle, and in developing polices and programs that help ensure the safety and functionality of agencies' structures.

On these basis Sineco has been developing an integrated system based both on SIOS both on Pontis.

3 INSPECTING STRUCTURES

It is widely recognized that performing periodical inspections aimed at the condition state evaluation is one of the most effective way to assess structures.

Periodical inspections should be performed following well-defined procedures, with the purpose of acquiring information about deterioration evolution, on the basis of which it is possible to understand, explain and asses the actual state.

The experience acquired performing inspections simultaneously on a great number of structures and the need of attaining to synthetic evaluations have inducted Sineco to refine inspection procedures adopting the following operating methodologies:

- associate a number or an index representing the inspector observations to the corresponding qualitative condition state evaluation;
- computerize inspections;
- employing adequate staffing, provided with special training on the structures to inspect;
- employ and maintain the same staff inspecting structures belonging to the same highway network;
- grant the presence of supervisors whose objective is to control the different inspectors evaluation uniformity.

All structures in the network are classified on the basis of structural types and grouped in homogeneous groups, on the basis of deck design, materials and structural elements morphology. Each structure is successively divided into its own elementary structural elements.

The detailed inspection collects data on the element level basis that are stored in the database:

- inventory data;
- structural and morphology data;
- environment data;
- maintenance data;
- condition state of the structure, in terms of damage description and extension.

For every different kind of structures or of structural components a list of defects that may be found has been created. To each defect a class coefficient, depending on the structural element considered, has been assigned. This coefficient is one of the parameters in the index value calculation.

Performing the inspection each defect is divided into three gravity classes, (low, medium, high). To each gravity class and to each defect a numeric coefficient is assigned to be entered in the index value calculation.

Defects inspected and registered in the sketches are accurately computerized and recorded on the corresponding graphical file.

A software tool is provided to:

- separate defects on the basis of classes (defect type) and gravity (inspectors judgement);
- calculate defects areas;
- calculate index values, based on an algorithm considering classes and gravity coefficients, and deterioration extension (in terms of effectively deteriorated area).

All the index values calculated are loaded into a database that allows for sorting, averaging, statistical incidence calculation, maximum and minimum values calculation, etc. To define the structure condition state, the index value is contextualized and related to the structure environment aggressivity.

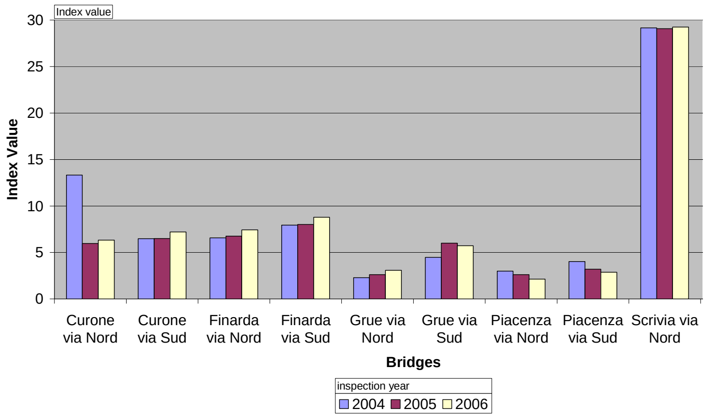


Figure 1: Summary index value graph of ten bridges during three inspection years.

This method predicts how the condition of the infrastructure would be adopting statistical criteria capable of evaluating the future damage evolution, on the basis of historical observations. Priorities are determined on the basis of the statistical analysis, both of the structure, both of each component performance levels changes.

The provisional method is efficient in the short – medium period thanks to the great amount of data collected during annual inspections, since 1998 and recorded in the Sineco database, in order to evaluate the short term needs and actions.

4 ADVANCED BMS METHODS

The SIOS methodology provides a detailed database intended to:

- collect historical deterioration data, in order to measure deterioration evolution;
- associate and collect as detailed as possible deterioration data, even graphically, for each element in each span;
- allow specific evaluations, damaged areas calculations, single defect evaluation;
- provide data for estimated bill of quantities.

The integrated SIOS-PONTIS system achievement is based on using detailed database information provided by the first to perform life cycle cost analysis and long term programming with Pontis BMS tool. This software supports a bridge management comprehending: data analysis, optimal preservation policy identification and recommendation, bridge needs and performance measure forecasts and development of projects to include in agencies’ opment of projects to include in agencies' economical planning.

In order to apply Pontis BMS methodology to SIOS inspection data, the databases were "normalized" to adapt the two different structural models and the two different damage evaluation.

4.1 *Commonly recognized elements*

In Pontis each structure is divided into one or more smaller units, called structure units. A structure unit is any logical grouping of structure components usually having the same structural design and material. Structure units can be used to represent groups of spans having the same structural design and material, or portions of the structure that might be rehabilitated separately. Each structure unit is made of elements, the "Commonly Recognized" (CoRe) structural elements developed by Federal Highway Administration. Sineco, on the basis of the AASHTO Guide for CoRe structural elements, has customized commonly recognized elements for Italian roads needs.

4.2 *Deterioration models conversion*

In Pontis the condition state categorizes the nature and extent of damage or deterioration on a bridge element. Each CoRe element can have up to five condition states. Condition states for each element have been precisely defined in terms of the specific types of distresses that the elements can develop.

As the deterioration of a structure is partially determined by its environment and operating practices (e.g. weather conditions or use of road salt), each element on a structure can belong to one or more of four environment classifications (benign, low, moderate, severe). Association between CoRe elements and environments defines condition units.

In order to normalize the SIOS database, a conversion criteria was used to "translate" the ratings described through the "Index value" into the Pontis condition-unit language. The conversion has been completed considering different items, relatively to environmental aggressiveness class and to different material tests and specialistic surveys performed on some structures. Each CoRe element area has been divided into the five or less condition states required by Pontis.

5 PRESERVATION POLICY

The preservation policy is the set of recommended preservation actions for each state of each condition unit, it is defined on the basis of deterioration and cost models. This policy consists of actions applied to bridge elements, that minimizes life cycle costs while keeping elements out of risk of failure. The preservation policy for a condition unit (CORe element in one of the four environments) is determined by formulating a Markov decision model with an infinite time horizon, discounted future costs, and the objective of minimizing long-term agency costs.

Important assumptions in solving the preservation policy include the following:

- Preservation actions are based on a policy that specifies the action that must be taken, given the current state of a particular element/environment combination (condition unit);
- The optimal policy may be determined independently for each condition unit;
- Cost and deterioration transition probabilities may be specified for each condition state for a given condition unit. The costs and probabilities depend only upon the condition unit most recent state.

5.1 *Forecasting models*

Pontis forecasting models are developed for each type of element of a bridge (e.g., timber deck, painted steel column). These models are probabilistic, rather than deterministic, and are structured to predict the behaviour of a population of elements within the network of bridges. Models consist of a set of transition probabilities, which predict the chances that the element, with a particular action applied during the following year, improve to a higher condition state (taking an action), or, not applying any action (Do Nothing), stay in the same condition state or pass to a worse condition state.

Deterioration models can be developed from different source of information. Sineco first step in defining forecasting models has been compiling expert elicitation data. Elicitation data is assembled into transition probability matrices, defined from most of the Usa Department of Transportations. This elicitation process is used to create deterioration models based solely on expert judgment. This allows reasonable models to be developed in advance of having actual data, which takes several years to assemble.

Expert transition probabilities are updated using historical inspection data collected by Sineco for several years accumulating all possible pairs of successive condition observations of element conditions, subject to certain constraints (e.g., there should not have been a spontaneous improvement in element condition between inspections).

The updating procedure, based on linear multiple regression, provides a transition probability matrix for each structural element as showed in figure 2.

		Transition Probabilities			
		1	2	3	4
State:	1 No deterioration				
>> 0	Do Nothing	96.20	3.80	0.00	0.00
State:	2 Minor cracks/spalls				
>> 0	Do Nothing	0.00	97.90	2.10	0.00
1	Seal cracks	86.00	14.00	0.00	0.00
State:	3 Delams/spalls				
>> 0	Do Nothing	0.00	0.00	96.17	3.83
1	Clean steel and patch	53.00	47.00	0.00	0.00
State:	4 Analysis warranted				
0	Do Nothing	0.00	0.00	0.00	87.06
1	Rehab unit	16.00	8.00	16.00	60.00
>> 2	Replace unit	100.00	0.00	0.00	0.00

Figure 2: Prestressed concrete girders - transition probability matrix for the structural element.

For the do nothing action, probabilities matrices have been transformed into graphs showing deterioration flow during the time, applying three different models: the only expert-based, the historical updated model or their combined averaged values.
Figure 3 shows deterioration graph for prestressed concrete girders.
For what concerns Italian highways network Sineco inspects and assesses, the most reliable models have been proven to be the averaged ones as these models follow historical data for condition states providing many observations (state 1 and 2) and follow expert evaluation for those other states characterizing a low number of structures (state 4 and 5). Transition probabilities are stored in the database for every combination of element, environment, condition state, and action.

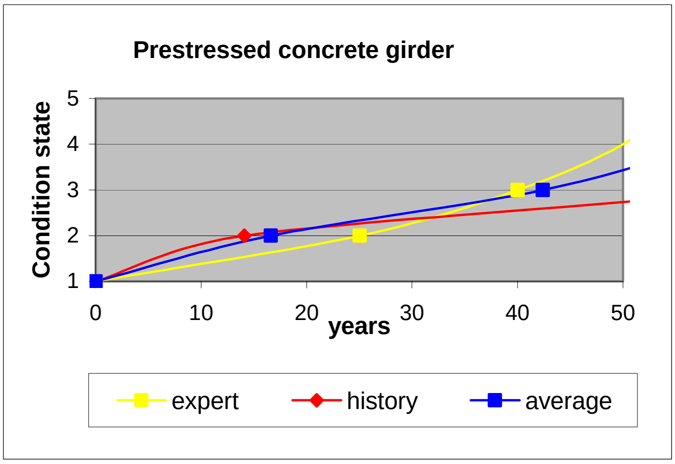


Figure 3: Prestressed concrete girders - forecasting models on historical inspection data and expert elicitation.

5.2 *Cost models*

The optimal policy and the benefit/cost ratio evaluation are defined on the basis of unit costs associated to each of the defined maintenance feasible actions associated to each element (cost matrix).

For each maintenance action associated to each element a unit cost has been defined, on the basis of reference prices used by Sineco for the rehabilitation projects.
A typical 30 years old structure maintenance project includes:

- curbs and joints rehabilitation;
- concrete columns and caps seal cracks and minor patching and concrete repair;
- concrete girders and deck rehabilitation.

Assembling different group of these kind of works, maintenance action are defined, and associated to a unit cost, that varies depending on the importance of the action (minimum repair, rehabilitation or replace element).

6 BENEFIT-COST ANALYSIS

6.1 *Scenarios parameters*

On the basis of actual inspection data and of the previously described models, maintenance actions to maintain the actual network condition state are provided (work candidates). To obtain this, simulations are performed defining different scenarios governed by a set of parameters such as annual budget, simulation period, bridges considered, elements considered, simulation rules and benefits calculation method.

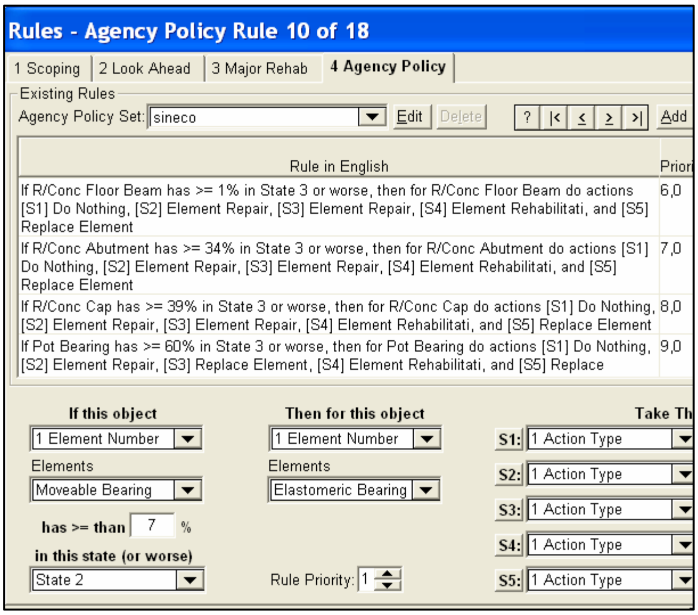


Figure 4: Maintenance practices applied by the Agency and translated into simulation rules.

Simulation outputs are:

- bridge needs (amount of money needed annually to maintain the actual network condition state);
- set of the generated work candidates (maintenance actions needed to maintain the actual network condition state).

Work candidates are prioritized on the basis of incremental benefit/cost ratios in order to maximize the benefits obtained from a fixed maximum budget.

6.2 *Benefits calculation*

The benefits calculation method is strategic for work candidates selection and prioritization.
Benefits can be calculated according to two different main methods: “shadow cost analysis” and “condition state analysis”.

In the first one benefits are obtained by multiplying the unit benefit of the recommended action by the quantity of the element. Unit benefit is defined as the difference between the shadow cost of doing nothing and the shadow cost of the recommended action.

In the second one benefits are function of:

- the difference between health index assuming that an action is taken and health index assuming that nothing is done;
- the asset value of the bridge: Sineco assumes it equal to the sum of failure costs of all the bridge elements.

According to Pontis standards, the health index adopted is a percentage indicator (from 0%, which corresponds to the worst possible condition, to 100% in the best condition) calculated as a function of the fractional distribution of the bridge elements’ quantities across the range of their applicable condition states.

7 MAINTENANCE PROGRAM

7.1 *Priority list and projects*

The result obtained running the simulation with the selected scenario is the single elements maintenance works (work candidates) priority list. Work candidates are grouped for each structure according to the year during which the simulation program performs single work candidates.

This way a structure priority list is obtained, ordered by the ratio between benefits deriving from the action application and costs of the single work candidates selected. A preliminary maintenance project is developed on each structure, modifying and optimizing selected work candidates, in order to satisfy logistical needs and match previous maintenance plans.

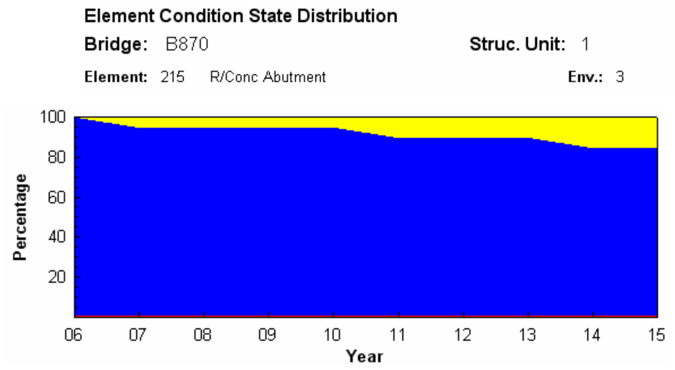
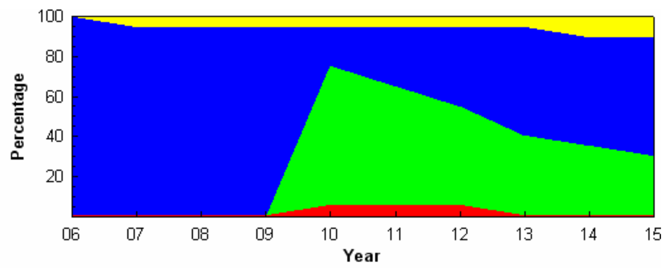


Figure 5: reinforced concrete abutment element, belonging to a single structure, condition distribution projected from 2006 to 2015, with no actions selected.

To update maintenance program on the basis of work quantities and programmed year changes, simulation will be repeated refining results. Maintenance program effects are reviewed and refined analyzing each bridge single structural elements graphs. These graphs show projected condition distribution for each element of the bridge, according to maintenance actions applied during the program period considered (Figure 5 and 6).

Figure 6: reinforced concrete abutment element, belonging to a single structure, condition distribution projected from 2006 to 2015 with maintenance actions performed in 2010.



7.2 *Maintenance minimum cost*

Once achieved maintenance objectives necessary to maintain the network at the current condition state, and, consequently, necessary to maintain the actual performance measures (Health Index) maximizing benefits and minimizing costs, it is possible to evaluate the additional annual costs necessary to target a particular performance measure value, eventually increasing the actual one. Similarly, the minimum annual cost necessary for preserving network elements at a specified minimum performance measure value can be evaluated. These two items, strictly connected, are shown on the graph in Figure 7 obtained for decks elements in a network section (115 Km, 220 bridges).

The Health Index minimizing annual long term cost is 55%. Minimum annual costs to maintain the actual network health index (70%) is about 4.000.000,00 €.

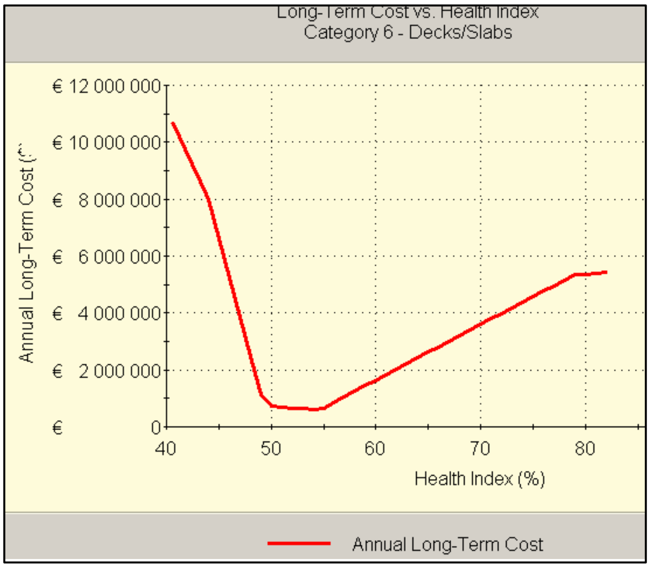


Figure 7: Annual long term Cost/Health Index.

8 CONCLUSIONS

The two BMS integration has provided medium to long term (five or ten years) scenarios forecasts detailing annually maintenance programs. Operative annual maintenance programs are drawn up focusing on minimizing users discomfort also considering other Assets maintenance needs. Development and continuous update of the following items have to be considered:

– deterioration and forecasting refining on the basis of annual inspections and maintenance programs updated on the network operations activities;
– managing bridges contextually to other assets applying asset management techniques to the entire network.

Sineco is actually implementing an Asset Management system able to support agencies in allocating economical resources among all the network linear Asset.

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