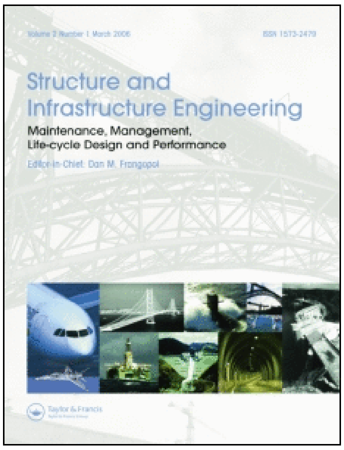

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A simplified management procedure for bridge network maintenance

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A simplified management procedure for bridge network maintenance

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Structural problems due to corrosion, ageing, durability, aggressive environments, materials defects, lack of ductility and unforeseen behaviour under seismic loads may significantly compromise the resistance and safety of bridges. Scheduled maintenance of bridges becomes important to ensure complete serviceability of the road network. Among existing bridge management systems (BMSs), this work is a contribution to the evaluation criteria of bridge condition by means of visual inspection, prediction of future structural condition and planning of maintenance intervention. After a brief review of some existing BMSs, a simple new procedure for evaluation of bridge condition by means of visual inspection, aimed at general planning of maintenance in a BMS framework, is presented in this paper. This procedure is applied to stock, including about 200 bridges and viaducts, of the Veneto region road network in the north-eastern part of Italy, and is then discussed.

Keywords: bridge management system; evaluation; maintenance; intervention; planning

1. Introduction

Due to the rapid growth of automobile and truck usage and the development of massive transportation infrastructures in past decades, there are increasing demands to improve the management methods of bridges, which constitute the most vulnerable elements of the road network. Many agencies responsible for infrastructural networks have recognised the difficulties of the available bridge management approaches, in which decisions are traditionally made only on a single project level. As a result, a significant effort has been undertaken in many countries to develop bridge management systems (BMSs) with the aim of evaluating the condition of a single bridge in the global network level during its life cycle, and to provide, at the same time, efficiency information when allocating resources and establishing management policies in a bridge network. A BMS is a rational and systematic approach to organising and carrying out all activities related to managing network level bridges (Hudson *et al*. 1993); in this way, decision makers should select optimum solutions from an array of possible alternatives, and must evaluate and compare alternatives for all bridges in the road network from the viewpoint of life-cycle management, in order to avoid similar problems in the near future. Several BMSs have been developed for specific purposes: e.g. Gralund and Puckett (1996) developed one for the rural environment, Markow (1995) developed one for highways, Thoft-Christensen (1995) developed one for reliability theory and Kitada *et al*. (2000) developed one for steel bridges. Some preliminary studies, developed at the University of Padova, about evaluation criteria for bridge maintenance, while also taking into account seismic risk and fatigue evaluation, are described in Franchetti *et al*. (2004), Pellegrino *et al*. (2004) and Pipinato (2008a,b).

Innovative techniques that include the implementation of new technologies and BMSs have to give bridge inspectors and engineers the necessary information to determine an appropriate action. Such a decision is often dependent on a combination of the quantitative information obtained from various measurements, qualitative information obtained from a bridge recognition and general engineering knowledge about the entire bridge system. To properly allocate funds, a bridge owner needs a BMS that uses historical deterioration trends and predictive relationships. Combining existing management system specifications with bridge specific deterioration models, which consider the system structural behaviour and ageing of the infrastructural network investigated, will improve an infrastructural owner's ability to make bridge specific-decisions and allocate funds for specific and accurate programmed interventions.

In this work, a simple new procedure for evaluation of reinforced concrete, steel, masonry and timber bridge condition by means of visual inspections aimed at the general planning of maintenance in a BMS framework is presented. This procedure is applied to

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stock, including about 200 bridges and viaducts, of the Veneto region road network in the north-eastern part of Italy, and is then discussed.

2. BMS review

Probably one of the most significant applications of contemporary BMSs could be found in the US. In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) required all states to develop, establish and implement a BMS by October 1998. The ISTEA requirements, first distributed in 1991, stated that the BMS must be implemented on all state and local bridges. New Federal legislation, however, required implementation of BMS only for bridges on the National Highway System (NHS); therefore, use of BMS inspection for non-NHS bridges was optional (Sunley 1995). The principle BMS used in the US is PONTIS, developed in the early 1990s for the Federal Highway Administration (FHWA) and became an American Association of State Highway and Transportation Officials (AASHTO) product in 1994. It performs functions such as recording bridge inventory and inspection data, simulating condition and suggesting actions, developing preservation policy and developing an overall bridge program. The system allows representation of a bridge as a set of structural elements, with each element reported based on its condition. In 2002, 46 agencies throughout the nation had PONTIS licensing, and each State Highway Administration (SHA) could customise the system according to its needs (Robert *et al.* 2003). BRIDGIT was developed in 1985 by the National Cooperative Highway Research Program (NCHRP) and the National Engineering Technology Cooperation in an attempt to improve bridge management networks. This system has capabilities similar to the PONTIS system. There have been many research projects throughout the nation on which local agencies have worked with universities to develop their own BMS. Other BMSs developed by individual state agencies do have good specific functions and qualities, but they lack features that can satisfy all the demands of effective bridge management and maintenance procedures on a national scale. Other notable research and development efforts on BMSs took place in Iowa, Washington, Connecticut, Texas and South Carolina (Czepiel 1995).

Among recent European experience that we should remember is the TISBO Infrastructure Maintenance Management System, currently being developed by The Netherlands Ministry of Transportation, Public Works and Water Management. It is a system that integrates inspection registration and maintenance management.

Concerning the Italian current situation regarding BMSs, owner agencies usually manage their network with self-developed codes/procedures. The policy of the main Italian agencies is briefly presented in the following.

- *Rete Ferroviaria Italiana (RFI)*, is the national agency for the whole Italian railway network, consisting of about 16,000 km. The BMS is based on periodical visual inspections supported by special testing trains. All data are elaborated with specific software developed by the agency with the aim of defining economical and technical convenience of possible maintenance/rehabilitation/strengthening interventions.
- *Autostrade per l'Italia* is the most relevant highway agency in Italy and manages a network of about 3400 km. The BMS is based on the SAMOA programme for surveillance, auscultation and maintenance of structures.
- *ANAS* (ANAS 1997) is the Italian agency for roads having national interest and manages a network of about 26,700 km. The BMS is based on the 'National Road Inventory' and in-situ survey and is a web-based management application that is developed by the agency and updated regularly.

During the last decade, a number of research projects have been financed by the European Commission and some guidelines have been published, as an output from these projects, that deal with the assessment of existing bridges in Europe, i.e. BRIME (2001), COST345 (2004), SAMARIS (2005) and Sustainable Bridges (2006). All of these guidelines are meant for highway bridges specifically, except for the last one, which is particularly dedicated to railway bridges. The purpose of BRIME (2001) was to develop the modules required for a BMS that enables bridges to be maintained at minimum overall cost, taking a number of factors into account, including effect on traffic, life of the repair and the residual life of the structure. COST345 (2004) investigated the procedures and documentation required to inspect and assess the condition of in-service highway structures, not only bridges. SAMARIS (2005) have focused on inventorying the condition of highway structures in European countries choosing the optimal assessment and strategy selection for rehabilitation by the use of ultra high performance fibre reinforced concrete (UHPFRC) and similar technologies. Sustainable Bridges (2006) deals particularly with railway bridges, and is also related to structural reliability assessment based on in-situ non-destructive testing (NDT).

3. New procedure for evaluation of bridge condition

The architecture of a generic BMS generally includes a bridge database, an inspection system, a condition evaluation, a structural capacity evaluation, a lifetime prediction of the future condition of the structure, a cost evaluation system and maintenance system planning.

Maintaining the characteristics of immediateness and application rapidity, without losing the scientific approach, some BMS experiences developed in Europe, as well as in the US (RI-EBW-PRÜF 1998, DANBRO 1998, FHWA 2005) have been harmonised, improved and also adapted to the Italian case. After gathering the necessary data, a procedure has been arranged to evaluate the condition of the single bridge structural and non-structural components and the whole structure. The procedure includes two levels of analysis:

- The 'project level' considers every single bridge structure isolated from the road context in which it is included, exclusively studying the state of maintenance of the bridge, with the aim of obtaining some elements about its residual capacity and assuring a sufficient grade of structural safety and efficiency.
- The 'network level' is related to political and economical issues, considering the bridge as inserted in a global road network; the principal aim is to establish a priority of intervention that takes into account both the condition of the bridges and their importance in the network.

3.1. *The database*

The database or bridge inventory is the starting point of any BMS. The database used for the present work gathers information of about 400 bridges, is called the Italian Bridge Interactive Database (IBrID) and was developed at the University of Padova, Italy (http://ibrid.dic.unipd.it). Information on the bridges concerns identification (geographical position, road, etc.), technical data (geometry, materials, structural system, etc.) and maintenance data (condition, inspections, monitoring, etc.).

3.2. *Evaluation of the state condition by visual inspections – condition value (CV)*

The system of inspections is the visual survey, as prescribed by the standards of most countries (BRIME 2001) and by the Italian code. These inspections can be undertaken by road maintenance staff on main parts of the bridge to ascertain their condition without any particular and expensive equipment; generally, traffic management is not needed.

Inspired by UK Local Authority experience, an accurate value of the proposed index, the condition value (CV), which varies from 1 to 5, and which corresponds to a condition related to a precise group of defects of the element. The condition of maintenance of a structure is connected to the state of deterioration of the single elements that physically constitute it. As the greatest part of the infrastructure that authorities have applied (Ryall 2001), the CV index has been chosen to express the functional condition of every element. For every element of the bridge, the CV index points out five possible levels of deterioration, as shown in Table 1. When it is not possible to express an evaluation, the CV is assumed to be CV = 0. These numerical values have been chosen according to the results of BRIME (2001), Ryall (2001) and UK Local Authority experience. The CV is then converted to a condition factor (CF), see Table 2.

The bridge structure has been divided into its fundamental components: structural elements that are fundamental for the structural capacity and the safety of the bridge against collapse and non-structural elements that do not contribute to the structural capacity of the bridge, but are relevant for functionality and durability of the structure.

A different weight is assigned to every element of the bridge that must be evaluated. This weight (W) varies from 10 (maximum importance) to 5 (minimum importance) and contributes to the calculation of the global efficiency. A location factor (LF) corresponds to each weight, as shown in Table 3. Structural elements are those contributing to the structural capacity of the bridge, whereas non-structural elements do not have a structural function (i.e. do not contribute to the strength of the bridge), but they provide containment of traffic (safety), durability, movement and smooth

Table 1. Condition value (CV).

Defects	CV
No judgement	0
No meaningful defect	1
Minor defects that do not cause damage	2
Moderate defects that could cause damage	3
Severe defects that cause damage	4
Non-functional or non-existent element	5

Table 2. Conversion from the condition value (CV) to the condition factor (CF).

CV	0	1	2	3	4	5
CF	0	10	7	4	2	1

Table 3. Location factor (LF) and weight (*W*).

Structural elements	LF	*W*
Principal elements (beams, arches, piers)	5	10
Transversal elements, bearings, non-seismic devices, slabs	6	9
Abutments, approach embankment, wingwalls	7	8
Abutment and pier foundations	8	7
Non-structural elements	LF	*W*
Waterproofing, road pavement, guard-rails, expansion joints	9	6
Pavements, parapets, drainage systems, accessories	10	5

Figure 1. Corroded bars with spalling of the concrete cover in a critical section of an arch bridge.

ride, and can influence the efficiency of the structural elements. The LF and corresponding weights are defined according to Blakelock *et al*. (1998) and Ryall (2001).

To classify, with hierarchical order, the defects that can be found in the structural elements, it is necessary to know the origin of the deterioration/damage and the possible causes. Structural materials of the bridge elements show different behaviour in relation to the environment and loads to which they are subjected. In this work, different considerations have been developed for the analysis of the deterioration/damage on the basis of the different bridge constituent materials, such as masonry, steel, concrete and timber. The deterioration/damage can be related to various factors. The damage process can be revealed, for example, by cracks in critical sections when corrosion of steel reinforcement occurs. Once corrosion of the steel starts, the cracks may appear very soon, its spread develops faster (Alonso *et al*. 1998) and could reach an advanced state that could compromise structural safety, as depicted in Figures 1 and 2. In this work, the main factors of deterioration/damage of a bridge have been considered to be constituent materials, applied loads, design mistakes, construction defects and lack of maintenance.

In this work, a number of datasheets have been implemented to allow a rapid evaluation of the CV of the single elements of the bridge and reduce the possible subjective factors. The study and the elaboration of the information related to the visible defects of the elements of a bridge and to their causes have allowed the preparation of the datasheets. These datasheets have been used for the evaluation of every structural element, accurately defining the CV for a number of situations. Four main categories of bridges have been considered in relation to the material of the superstructure: masonry bridges, steel or steel–concrete composite bridges, reinforced concrete and prestressed reinforced concrete bridges and timber bridges. For each category, a number of datasheets are collected in relation to the single elements of the bridge (arch, pier, abutment, beam, slab, devices, etc.). Every datasheet has the same structure and is divided into two blocks: one relative to the description of the element and the other relative to the definition of the CV of the element. In Table 4, an example of a datasheet for CV definition for concrete piers is presented.

Figure 2. Deterioration of the abutment and bearing zones.

3.3. *Element sufficiency rating (ESR) and total sufficiency rating (TSR)*

The evaluation of the condition of the elements through the CV is not enough to establish the priorities

Table 4. Example of a datasheet for condition value (CV) definition for concrete piers.

Material	Description	Visual aspects	Possible causes	CV
Concrete	No judgement			0
Concrete	No significant defects	No defects		1
Concrete	Minor defects not related to damage	Superficial defects of concrete	Construction errors	2
		Superficial removing of previous repair	Freeze–thaw phenomena, run-off, infiltration of water, overload, river current actions (for piers in river), shrinkage, temperature variations, localized tension on abutments, absence or lack of functionality of supports	
		Regular grid of thin cracks ($w < 0.3$ mm)		
		No deep cracks on the top ($w < 0.3$ mm)		
		Some exposed bars	Insufficient rebars	
		Moisture traces on the top	Lack of waterproofing, no drainage	
		Any protective elements corroded	Physical or chemical agents	
		Accidental superficial damages (only concrete cover involved)	Impact of vehicles, impact of vessels, solid transport (piers in river)	
Concrete	Defects that could cause moderate damage	Extensive and deep cracks ($w > 0.3$ mm)	Freeze–thaw phenomena, shrinkage, temperature variation, carbonation, chloride attacks, alkali–aggregate (AAR) or alkali–silicate (ASR) reaction, overloads, high localized tensions	3
		Network of horizontal and vertical cracks with branches around the aggregate's particles	Initial sulphur attack	
		Concrete discoloration, rust stains		
		Infiltrations of water, efflorescence, scaling, traces of salts	Carbonation, chlorides, problems in the drainage system and waterproofing, poor quality of concrete, deposits of salts	
		Non negligible accidental damages (concrete cover involved until rebars)	Impact of vehicles, impact of vessels, solid transport (piers in river)	
Concrete	Severe defects that cause damage	Craters, detachments, delamination	Freeze–thaw phenomena, insufficient rebars, carbonation, problems in the drainage system and waterproofing, chlorides, alkali-aggregate reaction	4
		Exposed corroded bars (loss of section < 20%)	Poor quality or porous concrete	
		Percolation of water, salt deposits, stalactites	Lack of waterproofing, no drainage, use of chlorides	
		Accidental significant damages (damaged rebars)	Impact of vehicles, impact of vessels, solid transport (piers in river)	
Concrete	Non-functional or non-existent element	Great detachment of concrete	Freeze–thaw phenomena, insufficient rebar, problems in the drainage system and waterproofing, attack of chlorides, alkali–aggregate reaction	5
		Exposed corroded bars (loss of section > 20%)		
		Great percolation of water, large deposits of salts and stalactites	Lack of waterproofing, no drainage, use of chlorides	
		Absolutely significant damages (cut rebars)	Impact of vehicles, impact of vessels, solid transport (piers in river)	

of maintenance/rehabilitation/strengthening interventions on the structure, and does not allow maintenance planning of the bridge stock investigated.

The definition of the element sufficiency rating (ESR), as a 'grade' of the single bridge element, considers both project and network levels. Such an index has been calculated starting from the CV index (see Table 1) and taking into account that the elements of the bridge do not have the same importance; for example, it is necessary to give a higher weight (W) to the maintenance of a principal structural component, i.e. a pier, than that of a secondary non-structural one, i.e. the parapets (see Table 3).

From a 'network' point of view, it is also necessary to express the importance of the whole structure (to which the elements belong) in relation to the others that compose the bridge stock. The same element (i.e. a pier) will have a different priority of intervention if included, for example, in a bridge along a highway with high traffic or in a bridge along a secondary road with low traffic. Furthermore, the bridge has a different strategic importance, depending on the possible alternative road that must be taken if the bridge is not available; in this procedure, it is proposed to consider (1) the street type on which the circulation will be deviated and (2) the length of the deviation, to take into account the importance of the bridge into the network.

Finally, the age of the bridge is also taken into account for the quantification of the ESR.

Therefore, the calculation of the ESR has to be influenced by:

- the condition of the element, through the CF, linked to the CV according to Table 2;
- the importance of the element in the bridge, the LF linked to the weight of the element according to Table 3;
- the road type to which the bridge belongs, the road type (RT), see Table 5;
- the traffic on the bridge, the traffic index (TI), measured in average daily traffic volume (ADTV), see Table 6;
- the importance of the bridge into the network, the network bridge importance (NBI), see Table 7; and
- the age of the bridge, the age factor (AF), see Table 8.

According to the above considerations, the formula for the calculation of the ESR can be expressed as:

$$\mathrm{ESR} = \mathrm{CF} \times \mathrm{LF} \times (\mathrm{RF} \times \mathrm{NBI} \times \mathrm{AF}), \qquad (1)$$

where RF = RT × TI.

Table 5. Road type (RT) factors.

Road	RT
Highway	0.80
National road	0.90
Provincial road	0.95
Secondary road	1.00

Table 6. Traffic index (TI). (Vpd is vehicles per day.)

Traffic	ADTV	TI
High	> 20000 vpd	0.90
Middle	6000–20000 vpd	0.95
Low	< 6000 vpd	1.00

This index allows us to define the degree of efficiency of the components of the bridge, establish a priority plan of intervention for the single structure (project level) and establish a priority plan of intervention for the whole network (network level).

The following considerations could clarify the contribution of some factors to the ESR estimation:

- The AF takes into account that, from a probabilistic point of view, a limited amount of deterioration can be present, but not visible (hence not included in the CF), in old bridges rather than in new bridges (Ryall 2001).
- The RT factor is related to the importance of the bridge according to the strategic level of the road to which it belongs independently from the average traffic volume, whereas the TI takes into account the amount of traffic (ADTV) on the bridge independently from the importance of the road (bridges with a low amount of traffic but belonging to a strategic road can be included in the stock).
- The TI has been established relating to the ADTV, which is the ratio between the number of every vehicle type passing, at a given section, in both directions, in a year, the values in Table 6 have been evaluated according to the Regional

Table 7. Network bridge importance (NBI).

Situation		NBI
Situation 1:	long deviation on unsuitable alternative road	0.96
Situation 2:	short deviation on unsuitable alternative road or long deviation on suitable alternative road	0.98
Situation 3:	short deviation on suitable alternative road	1.00

Table 8. Age factor (AF).

Year of construction	AF
Before 1900	0.97
1900–1945	0.98
1946–1970	0.99
1971–present	1.00

Table 9. Efficiency and urgency levels of intervention for bridge elements.

Efficiency level	Urgency level of intervention	ESR
1	Maximum urgency in intervention	1–10
2	Short-term intervention	11–20
3	Medium-term intervention	21–30
4	Long-term intervention	31–100

Bridge	44	Ponte sul fiume Mincio

Code	Elements	CV	CF	LF	Wel.evaluated	Wel.presents	RT	TI	RF	NBI	AF	ESR
C1	Longitudinal elements	2	7	5	10	10	0.90	0.90	0.81	0.96	1.00	27
C2	Pier	1	10	5	10	10	0.90	0.90	0.81	0.96	1.00	39
C3	Transversal elements	0	0	6		9	0.90	0.90	0.81	0.96	1.00	0
C4	Deck	2	7	6	9	9	0.90	0.90	0.81	0.96	1.00	33
C5	Support equipment	3	4	6	9	9	0.90	0.90	0.81	0.96	1.00	19
C6	Sismic devices			6			0.90	0.90	0.81	0.96	1.00	
C7	Abutment	1	10	7	8	8	0.90	0.90	0.81	0.96	1.00	54
C8	Embankment	1	10	7	8	8	0.90	0.90	0.81	0.96	1.00	54
C9	Walls			7			0.90	0.90	0.81	0.96	1.00	
C10	Aboutment foundations	0	0	8		7	0.90	0.90	0.81	0.96	1.00	0
C11	Pier foundation	0	0	8		7	0.90	0.90	0.81	0.96	1.00	0
C12	Watrproofing	2	7	9	6	6	0.90	0.90	0.81	0.96	1.00	49
C13	Pavement	2	7	9	6	6	0.90	0.90	0.81	0.96	1.00	49
C14	Guard-rail	3	4	9	6	6	0.90	0.90	0.81	0.96	1.00	28
C15	Joint	4	2	9	6	6	0.90	0.90	0.81	0.96	1.00	14
C16	Sidewalk	5	1	10	5	5	0.90	0.90	0.81	0.96	1.00	8
C17	Parapets	1	10	10	5	5	0.90	0.90	0.81	0.96	1.00	78
C18	Water selling	3	4	10	5	5	0.90	0.90	0.81	0.96	1.00	31
C19	Accessories	1	10	10	5	5	0.90	0.90	0.81	0.96	1.00	78

∑el.evalutated	14		
∑el.presents	17		
∑W evalutated	98		
∑Wel.presents	121		
CoF	81	>	70
TSR real	53		
TSR minimum	47		
TSR	51		

Figure 3. ESR and TSR calculation for the bridge over the River Mincio.

Authority managing most of the roads in the Veneto region (northeast of Italy) on the basis of the typical traffic volume data in their roads.

- The NBI index takes into account the length and the adequacy of the alternative way that must be covered due to the bridge closure. The terms 'long', 'short', 'suitable' and 'unsuitable' in Table 7 are defined as follows: 'long' deviation conventionally means that the ratio between the length of the alternative road and the length of the original one is >2, whereas 'short' deviation conventionally means that the ratio is ≤ 2; 'suitable' road is an alternative road with the same hierarchical importance as the original one, whereas 'unsuitable' road is an alternative road with a lower hierarchical importance than the original one (the Italian classification of roads and highways shown in the D.L. n. 285 (1992), has been used in this work).

Four levels of efficiency have been established for the bridge elements (see Table 9).

Once the ESR is defined, the calculation of the efficiency of the whole structure starting from the efficiency of its components is developed. Considering the network level, the problem is to give a 'grade' for every structure that allows the authority to have an overview on the general state of efficiency of the bridges of the stock. Such a 'grade', named the total

Table 10. Efficiency and urgency levels of intervention for the whole bridge.

Efficiency level	Urgency level of intervention	TSR
1	Maximum urgency in intervention	1–30
2	Short intervention term	31–40
3	Medium intervention term	41–60
4	Long intervention term	61–100

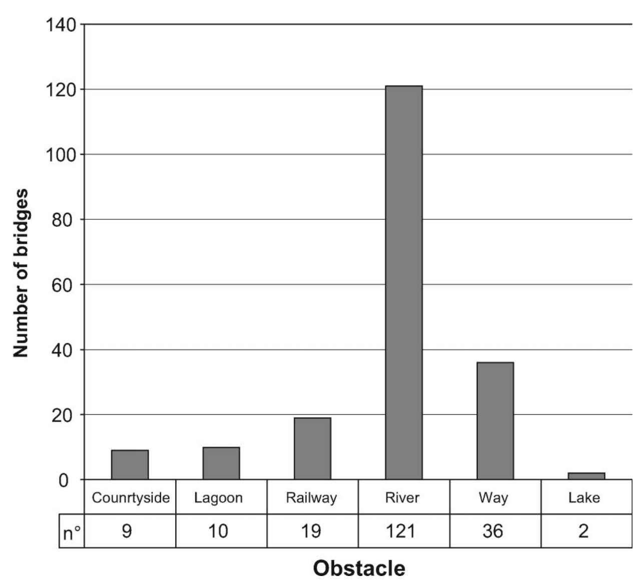

Figure 4. Bridge classification based on overcome obstacle.

sufficiency rating (TSR), is calculated with a weighted arithmetic average:

$$TSR_{real} = 10PF\left(\frac{\sum_{i=1}^{t} CF_i \times W_i}{\sum_{i=1}^{t} W_i}\right), \quad (2)$$

where CF_i is the condition factor of the ith element evaluated, W_i is the weight of the ith element evaluated and PF = (RF × NBI × AF) is the penalty factor, t is the number of elements evaluated and TSR_{real} is the index of total efficiency, referring to the elements evaluated.

The final value of the TSR is calculated, starting from TSR_{real} and also considers the elements not evaluated. Therefore, the confidence factor (CoF) is introduced, and which must be superior to a threshold limit:

$$CoF = 100\left(\frac{\sum_{i=1}^{t} W_i}{\sum_{i=1}^{n} W_i}\right), \quad (3)$$

where n is the total number of elements.

The criterion that has seemed to be the most appropriate for the calculation of the final value of the TSR is to refer to a weighted arithmetic average between the real situation (TSR_{real}) and the worst situation that can happen (TSR_{min}). The TSR_{min} has been evaluated assuming CV = 5 for all the elements that are not evaluated, except for the foundations for

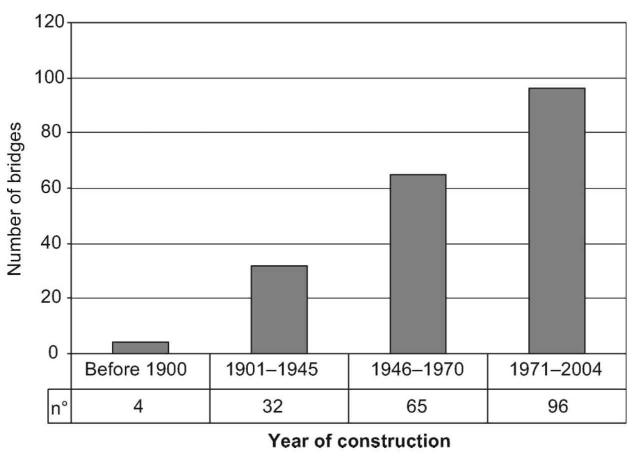

Figure 5. Bridge classification based on year of construction.

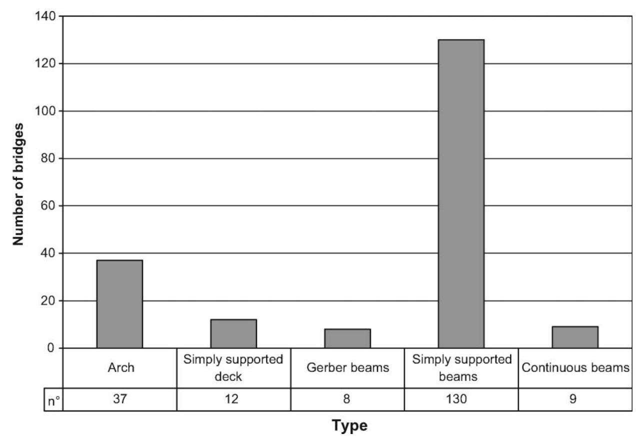

Figure 7. Bridge classification based on structural typology. (A Gerber beam is a straight beam that functions essentially as a cantilevered beam by the insertion of two hinges in alternate spans.)

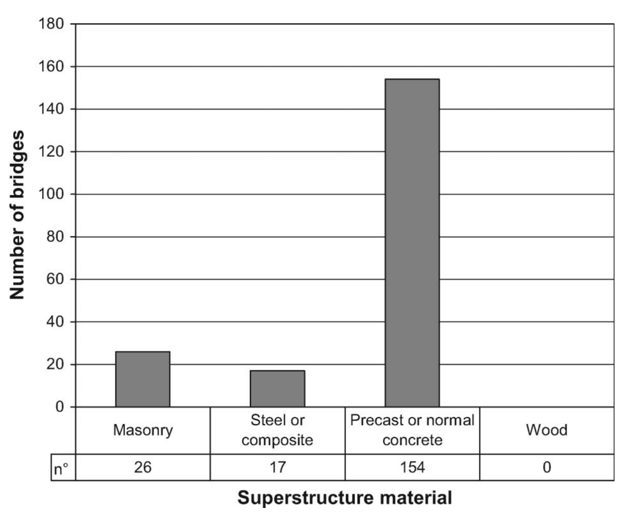

Figure 6. Bridge classification based on constitutive material.

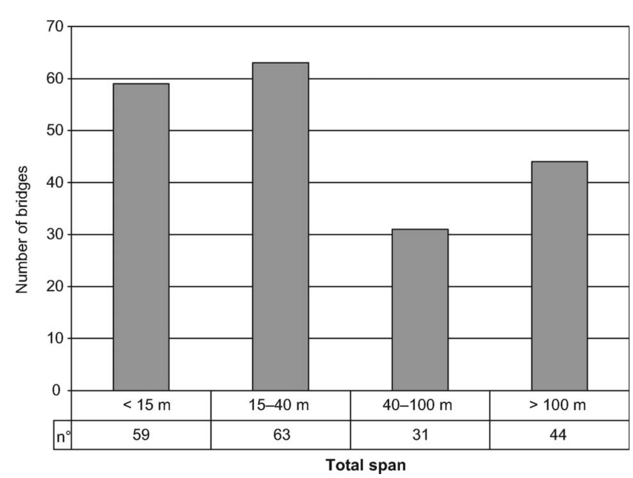

Figure 8. Bridge classification based on span measurements.

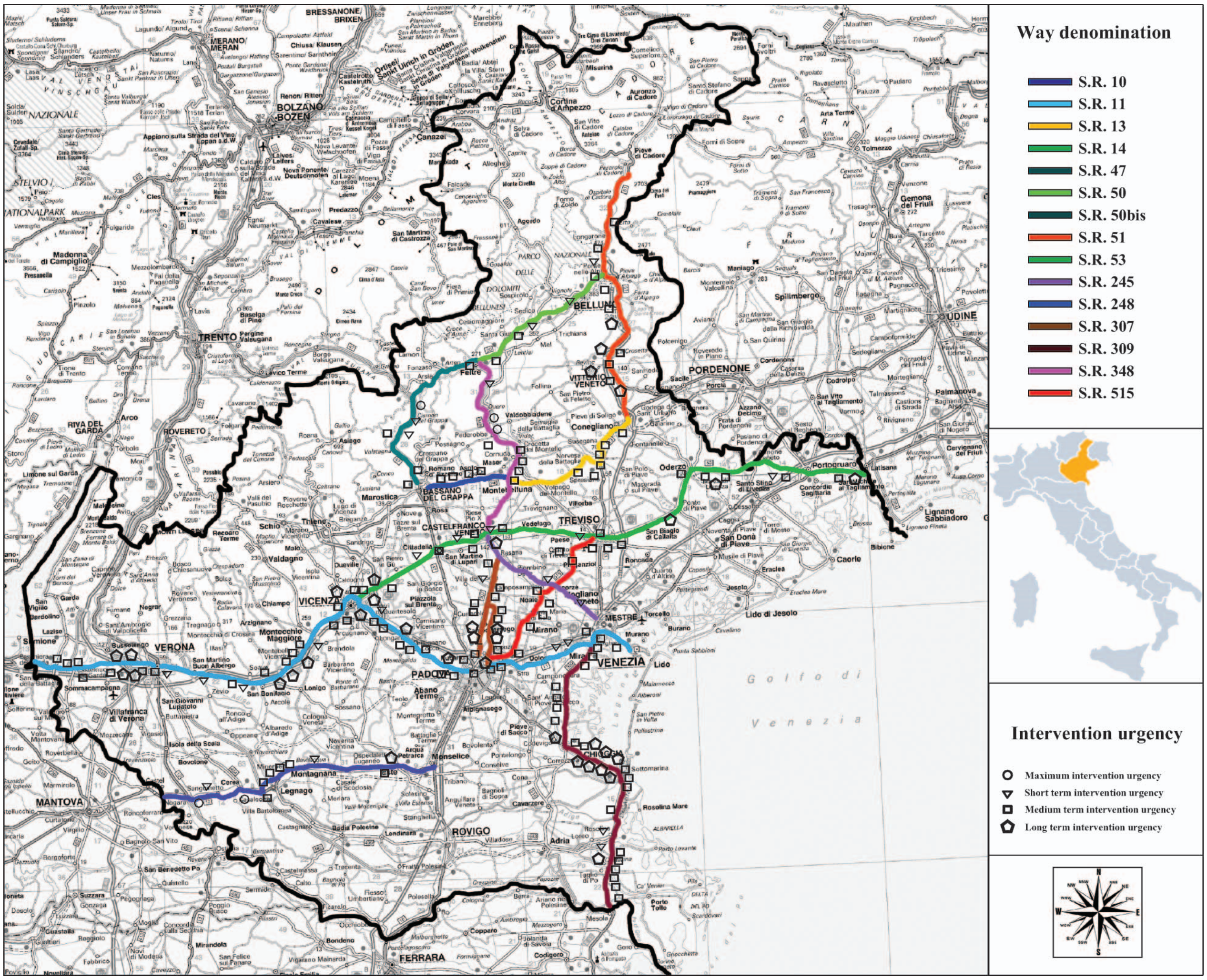

Figure 9. Bridge intervention urgency according to the TSR along some regional roads (S.R.) in the Veneto region (northeast of Italy).

which the worst-case scenario is assumed when CV = 3, since the foundations are usually not visible elements.

The final expression of the TSR is:

$$\mathrm{TSR} = \left(\frac{100\mathrm{TSR}_{\mathrm{real}} + \mathrm{TSR}_{\mathrm{min}} \times \mathrm{CoF}}{100 + \mathrm{CoF}} \right). \quad (4)$$

Shown in Figure 3 is the datasheet for ESR and TSR computation for one bridge taken as an example, the bridge over the River Mincio. It is possible to establish four levels of efficiency and urgency of intervention for the whole structure (see Table 10). Once the level of efficiency and urgency of intervention on the whole structure is determined, a priority plan of interventions can be prepared.

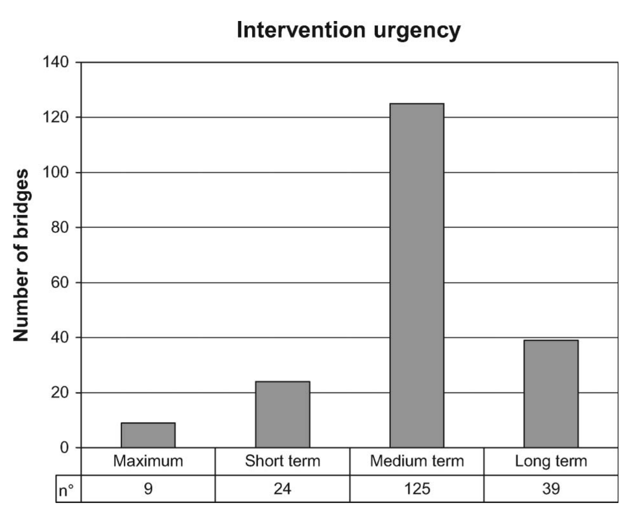

Figure 10. Bridge intervention urgency based on TSR values.

Among the bridges for which the intervention could be addressed, the agency will prefer to dedicate its resources to structures for which the TSR results in the interval of the maximum urgency of intervention. For each bridge, the interventions will be suggested on the basis of the indications given by the ESR of the single components.

4. The Veneto regional network: a case study

In this section, the main results concerning the application of the above procedure are presented. The results are related to 19 regional roads of the Veneto road network, located in the north-eastern part of Italy.

The network is composed of 197 bridge structures. In the following figures, some information related to these bridges is reported, such as the obstacle overcome (Figure 4), the year of construction (Figure 5), the constitutive material (Figure 6), the structural typology (Figure 7) and the span length (Figure 8). Most of them are made of concrete (normal or precast), and built with the common structural scheme of simply supported beams, as reported in Camomilla (1984) and CNR (1993).

The urgency of intervention, defined on the basis of the TSR according to Table 9 for the 197 bridges is geographically reported in Figure 9 and quantified in Figure 10. These results show that:

- Bridges requiring maintenance operations in the *short term* have a simply supported scheme (steel, ordinary or precast concrete). These are not recent bridges, are built between 1901 and 1945 or 1946 and 1970 and present a structural deficiency related to material degradation (more present in steel and, especially, concrete than in masonry constructions) and damage of bearing devices. Strong deficiencies in non-structural elements due to design or maintenance deficiencies and/or environmental factors are also detected. Absence or obsolescence of joints, inadequacy of guard-rail systems and water disposal are also found; these problems could lead to corrosion and accelerated material decay.
- Bridges requiring maintenance operations in the *medium term* are related to non-appropriate maintenance practice during their life, even with inadequate secondary elements; for example 46 among 125 expansion joints have an ESR between 1 and 10, corresponding to the maximum urgency stage. Other common causes of decay are the absence and/or non-functionality of the bearing devices and/or the rainwater system that, together with joints, are often the weak points of bridges.
- Bridges requiring maintenance operations in the *long term* are more recent structures built between 1971 and 2002 and older arch structures; their common characteristic is a well-performed and precise design.
- A significant fault of all these bridges, even if recently intervened with specific interventions, is the lack of foot passages in the lateral position of the deck for maintenance purposes.

5. Conclusions

This work presents a simplified approach that may be useful for local/regional authorities that are facing the problem of managing bridge stocks (as is the case in Italy). This procedure has the primary objective to give some indications on the basic intervention/maintenance priority to the regional agency, according to the evaluation of bridge condition based on visual inspections and quantitative rating.

The simplified management procedure for bridge network maintenance described in this work allows us to:

- manage the maintenance of a number of bridges located in the north-eastern part of Italy;
- give, for each bridge of the stock, the priorities of intervention according to the state of deterioration of the single components (project level) by means of the ESR; and
- obtain a maintenance plan for the bridges of the stock, considering the global state of efficiency (network level) by means of the TSR.

The procedure was applied to a stock of about 200 bridges, allowing some general information about the deterioration and damage mechanisms of the typical structures, and their critical structural and non-structural elements, which can be found in Italy, to be given.

Particular attention has been devoted to the development of a priority-ranking procedure that is able to roughly describe the health condition of the bridges belonging to the stock on a coherent and standardised basis. Bridge condition evaluation starts from visual inspections of bridge structural and non-structural elements and then assembles the element data. Hence, the procedure not only gives some insights into overall bridge condition, but also provides information concerning the condition of each bridge element.

As a result, this approach may be considered as a first step towards the definition of a more rigorous procedure for bridge network maintenance and could be improved by defining deterioration trends obtained from case studies with performance-based life-cycle models and integrated with quantitative information, such as damage indicators that are eventually obtained using proper instrumentation. Further research and development is required to improve the BMS through the development of additional modules regarding, for example, bridge safety, budgeting and economic optimisation of resources. The calibration of the coefficients was developed on the basis of the current standards of maintenance practice of most of the regional authorities in Italy, and could be improved by means of reliability-based methods.

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