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Proposal of a Methodology for Bridge Condition Assessment

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Abstract

Due to the substantial role of bridges in transportation networks and in accordance with the limited funding for bridge management, remediation strategies have to be prioritised. A conservative bridge assessment will result in unnecessary actions, such as costly bridge strengthening or repairs. On the other hand, any bridge maintenance negligence and delayed actions may lead to heavy future costs or degraded assets. The accuracy of decisions developed by any manager or bridge engineer relies on the accuracy of the bridge condition assessment which emanates from visual inspection. Many bridge rating systems are based on a very subjective procedure and are associated with uncertainty and personal bias. The developing condition rating method described herein is an important step in adding more holism and objectivity to the current approaches. Structural importance and material vulnerability are the two main factors that should be considered in the evaluation of element structural index and the causal factor as the representative of age, environment, road class and inspection is implemented as a coefficient to the overall structural index. The Analytical Hierarchy Process (AHP) has been applied to evaluate the priority vector of the causal parameters.
Key words: Bridge, Inspection, condition assessment, structural importance, material vulnerability, causal factors, Analytical Hierarchy Process (AHP), Overall Structural Condition Index (OSCI).

1. Introduction

In the past two decades, deficiencies related to aging bridges have become a major concern for asset managers and society globally and, particularly, in Australia. Considerable effort went into the design and implementation of Bridge Management System (BMS) for the remediation of ageing road infrastructure. In the United States, more than 70% of the bridges were built before 1935 (Golabi, Thompson & Hyman, 1993), and a large proportion of the United Kingdom's current bridge stock was built between the late 1950s and early 1970s (Flaig & Lark; 2000). In the state of New South Wales, Australia, around 70% of bridges were built before 1985, with a significant percentage in the mid 1930's, and the peak in the 70's. The near completion of most of the road infrastructures and the ageing of the current bridge networks altered the emphasis of the bridge authorities from building new networks of infrastructures to the maintenance, repair and rehabilitation needs of the existing bridges (Ariyaratne et al., 2009).

The reliability of decisions to find a remediation strategy or fund allocation is highly dependent upon the exactness of the condition assessment and diagnosis process. Therefore many bridge authorities established their own strategies for inspection and specially for condition rating.

2. Bridge inspection

Bridge inspection is an essential element of any BMS particularly for aged and deteriorated bridges and a path way to condition rating. The accuracy of condition assessment is relied heavily on the quality of the inspection. Historically, bridge inspection of existing bridges has been assumed as a secondary

priority of a semi-random nature. The inspections were usually done as a consequence of warnings received from sources very often outside the bridge network system, or as a result of an obvious inadequacy of the bridge that did not allow it to fulfill the expected function (Branco & de Brito, 2004).

The inspection methods in Australia have primarily been extracted from the American Association of State Highway and Transportation Officials (AASHTO) and modified by the road authorities. However, many bridge agencies use their own strategies for inspection and condition rating but the element based inspection is regarded as the most reliable technique for condition assessment.

To reduce fixed costs and to enhance efficiency, an inspection system must be planned at the bridge network level and not at the single bridge level. The routine inspection schedule should not be changed frequently and must be performed at fixed period of time. The quality of the inspection is strongly related to the knowledge and experience of the inspectors and compliance with prescribed procedures (Little, 1990).

The functionality of the management system is based on a standardised inspection plan. It includes a periodic set of inspections based on a fixed timetable in which some flexibility is allowed to take into account a reasonable global allocation of inspection resources complemented by special inspections when something serious is detected or suspected (Branco & de Brito, 2004). A variety of inspections may be required on a bridge during its service life. The main types of inspection are addressed in the following sections.

2.1 Initial (inventory) Inspection

Initial inspections are performed on new bridges or when existing bridges are first entered into the database. This inspection provides a basis for all future inspections or modifications to a bridge.

Inventory inspections provide structural inventory and appraisal data along with bridge element information and baseline structural conditions. Inventory inspections usually start in the office with the construction plans and route information then proceed to the field for verification of the as-built conditions.

Initial defects are noted which might not have been present at the time of construction. Changes in the condition of the site, such as erosion, scour and re-grading of slopes should also be noted (Andrey, 1987).

2.2 Routine Inspection

The routine inspection is a diagnostic method with the greatest potential and is generally based on direct visual observation of a bridge's most exposed areas. It relies on subjective evaluations made by the bridge inspectors. During an inspection, no significant structural defect is expected and the work recommended falls within the range of maintenance.

A period of fifteen months between routine inspections is recommended so that the influence of the weather on the general condition and degradation of the bridge can be assessed (Andrey, 1987). A routine inspection must be planned in advance to facilitate the best assured conditions (e.g. weather conditions, traffic) that may permit detection of defects (Branco & de Brito, 2004).

2.3 Detailed Inspection

Easy and fast nondestructive in situ tests are performed in detailed inspection in addition to direct visual observation as a way of exploring every detail that may potentially lead to future problems. There is a possibility that special means of access may be used if such is considered indispensable. The

period recommended for a detailed inspection is five years and replaces a routine inspection if the inspector's calendars agree (Andrey, 1987). A preliminary visit to the bridge site may be useful to evaluate existing conditions. If there is a need to follow up the evolution of certain defects with greater frequency, however, the period between visits may be reduced to one year, specially for local areas of the bridge.

According to Branco and de Brito (2004) planning a detailed inspection includes a careful study of a bridge dossier to get to know the reasons and evolution of the defects detected in the previous inspections and the specific points to be assessed closely. Based on previous inspection forms and a preliminary visit to the site, the eventual special means of access needed are planned. The following files must be brought to the site and/or prepared beforehand: a list of all single points to be checked, schematics with reference grids of the most relevant elements, and the last periodic inspection form and the inspection manual.

According to the outcomes obtained, the inspection may possibly have one of the following consequences (Andrey, 1987): the organisation of a structural assessment or of complementary surveillance measurements; the preparation of a list with particular aspects to follow especially carefully in the next inspection; the organisation of maintenance work needed; and the establishment of a medium-term maintenance plan (Branco & de Brito, 2004).

2.4 Structural assessment

A structural assessment is normally the consequence of the detection of a major structural or functional deficiency during a routine or detailed inspection. It may also be necessary if widening the deck or strengthening the structure is under consideration. The expected results from this inspection are: the characterisation of the structural shortcomings, the remaining service life estimation by using degradation mathematical models, and also evaluation of its present load-bearing capacity. It is not easy to predict the required means because a wide range of situations can initiate a structural assessment. The static and dynamic load tests and laboratory tests can be valuable complements to the information collected in situ. Nevertheless, they must be used with some parsimony since, as well as being expensive, they force the total interruption of traffic over the bridge for uncertain periods of time (Andrey, 1987). The final report of the structural assessment must include the index, structural identification form, schematic drawing of the bridge, structure general condition standard form, summary of the most significant results, equipment used and calibration sheets, photos and schematic representations of the cores, identification and description of the cores, identification and description of the asphalt surface samples, photos and drawings. All the data collected are dated and appended to the bridge dossier (OMT, 1988).

2.5 Special Inspection

This could be undertaken to cover special conditions such as occurrences of earthquakes, unusual floods, passage of high intensity loading, etc. These inspections should be supplemented by testing as well as structural analysis. For that reason the inspection team should include an experienced bridge design engineer (Raina, 2005).

2.6 Underwater Inspection

An underwater inspection is performed on bridges with structural elements partially located under water that are not easily accessible for inspection, and generally the inspection interval should not exceed sixty months (Washington State Bridge Inspection Manual, 2006). Underwater inspections are undertaken by experienced divers to assess the material condition specific material type and take under water photographs/videos as necessary.

3. Development of a unified bridge condition rating

Bridge condition assessment is the evaluation of differences between the as-designed, as-built, and as-is states of the structures. The subject can be a bridge component, a group of similar elements within a span, or in all spans, components, and eventually the entire bridge. The outcome determines the sufficiency of monitoring and maintenance and the effects of traffic and the environment and defining the present and future needs (Yanev, 2007).

Bridges are complex mixture of parallel and series systems, but almost all BMS use the evaluation of members or elements as input to calculate the overall structural reliability (Yanev, 2007). The review of the current practices in bridge condition evaluation reveals the need for a unified condition rating procedure in order to use the accessible data collected during the inspection and to account for uncertainty and complexity issues associated with the detailed visual inspection process (Abu Dabous and Alkass, 2010).

With the purpose of being consistent with the majority of bridge inspection practices the recommended methodology is an element level index based on four condition states defined in the Road and Traffic Authority (RTA) in New South Wales in which the bridge element condition ranges from 1 to 4 in rising order. The general description of the four condition states for reinforced concrete bridge elements is presented in Table 1. In this system the bridge is divided into elements generally made of a similar material (Most bridges have about ten to twelve elements and bridge sized culverts usually have three to five elements). The inspector estimates and records the quantities of the bridge element in each condition state independently. The total quantity must be measured in the correct units for the elements. The units of measurement are square meters (deck, pier, and pile), meters (joints and railings) or each (bearing pad, waterway, etc).

Table 1: Condition states for concrete bridge elements (RTA, 2007)

Condition State	Description of defects
1	The element shows no deterioration. There may be discolouration, efflorescence and/or superficial cracking but without effect on strength and/ or serviceability.
2	Minor cracks and spalls may be present but there is no evidence of corrosion of non-prestressed reinforcement or deterioration of the prestress system.
3	Some delaminations and/or spalls may be present. No evidence of deterioration of the prestress system. Corrosion of non-prestressed reinforcement may be present bot loss of section is minor and does not significantly affect the strength and/or serviceability of either the element or the bridge.
4	Delaminations, spalls and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge.

The following example shows the bridge element condition concept. The data used in this example has been extracted from a bridge inspection report provided by Road and Traffic Authority for a concrete bridge in Illawarra region. The condition inspection results of pile element with a total area of 695 m^2 are presented in Table 2.

Table 2: Bridge Pile Condition Rating Results

Condition Rate	Area (m^2)
1	618
2	3
3	74
4	0

The overall condition of piles = [(618×1) + (3×2) + (74×3) + (0×4)] / [695×1] =3.01

As can be seen above the element condition index can be calculated as the current value divided by the initial value of the bridge element. To describe the overall condition status of structural elements, the Element Structural Condition Index (ESCI) is introduced as:

$$ESCI = \frac{\sum(qi \times ci)}{\sum qi}$$

-q_i is the quantity of elements reported in condition index c_i

-C_i is the condition of sub-element $c_i \in (1,2,3,4)$

As can be seen in the ESCI estimation process, deterministic values are used as an approximation for the element value at each of the four condition states. Quantities can also be used for the cost estimation of probable maintenance work. This approximation may not be quite reliable, since data collected through inspection process is usually associated with subjectivity and uncertainty (Aboudabus and Alkass, 2010). Many attempts have been conducted to reduce the uncertainty. For example Colorado Department of Transportation suggested a frame work for condition rating of deck cracking which is shown in Table 3.

Table 3: Conditions Rating of Deck Cracking (Colorado Department of Transportation, 1995; Abu Dabous et al., 2008)

Crack Width (mm)	Spacing of Cracks in Concrete Deck (m)			
	>3	2-3	1-2	<1
<1	1	1	2	3
1-2	1	2	3	4
2-3	2	3	4	4
>3	3	4	4	4

As a matter of fact, some elements require more attention than the others in terms of material vulnerability and/or structural significance. For example reinforced concrete has more potential damage than steel. A defective main beam will require more urgent attention than the bridge drainage outlets. One crack can be a flexural crack flagging an initial structural failure while the other may be due to creep and shrinkage of concrete, which has limited structural importance. However the determination of

structural/ material vulnerability of various bridge elements is a difficult task. Sometimes doing some structural analysis such as non-destructive testing program is unavoidable. Alternatively, bridge experts and inspectors can rely on their own experience and knowledge to determine these factors.

3.1 Material Vulnerability Factor

According to Valenzuela et., al (2010) and Austroads (2004) material factor is an important parameter that should be considered in structural assessment of bridge elements. Based on vulnerability of different material it ranges between 1 (steel) and 4 (precast concrete) (See Table 4). The greater M*i* reflects the higher material vulnerability.

Table 4: Material Vulnerability Factor Mi

Material of the element	Material Vulnerability Factor, mi
Steel	1
Reinforced Concrete	2
Precast concrete	3
Pre stressed concrete	4

3.2 Structural Significance Factor

Generally, the prevailing condition (rating) of the particular element may cause some inaccuracies in the overall structural assessment. For example, a minor component with worse condition may unreasonably raise the rating value of that element under which the component is grouped. This problem can be dealt with the introduction of element structural significance factor which is not dependent on the prevailing condition of components (Samsal and Ramanjaneyulu, 2008).

The evaluation incorporates many parameters and human judgments that may cause the procedure to be slightly uncertain and imprecise. Tee et al., (1988), Melhem and Aturaliya (1996), Samsal and Ramanjaneyulu (2008) and Abu Dabous and Alkass (2010) tried to employ a systematic approach to quantify the structural importance of various bridge elements. Tee et al., (1988) defined the structural significance as the role of an element in comparison to the other components and quantified this factor for different elements at different condition rating based on survey results responded by 46 inspectors and bridge experts. Abu Dabous and Alkass (2010) described the structural importance of a bridge component as the level the component contributes to the overall structural safety and integrity of the bridge and proposed the Analytical Hierarchy Process (AHP) to estimate the value of that parameter. In this research the Element Structural Significance has been investigated through conducting semi-structured field interviews with bridge engineers/ inspectors. The outcome of the processed expert judgments considering the results of previous research is summarised in Table 5. The higher numbers represent the superior importance.

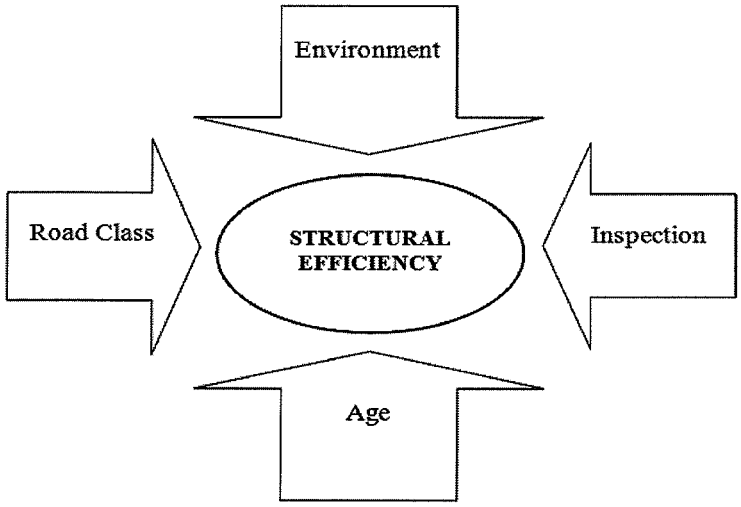
Table 5: Structural Significance Factor Si

Element	Structural Significance Factor, S_i
Barrier, Footway, Kerbs, Joints	1
Foundation, Abutment, Wingwall	2
Deck, Bearings	3
Beams, Headstocks, Piers	4

3.3 Causal Factor

Bridge elements deteriorate over an extended period of time and the rate of deterioration is a function of various parameters. The environment the structure is located in, the length of time the structure has been in service (Age), the function the structure is required to perform (Road Class) and the quality of inspection and monitoring (Figure 1).

Figure 1: The causal factors



3.3.1 Environmental Factor:

This parameter considers natural/ man caused environmental actions that cause chemical and physical deterioration of concrete. The major concerns are freeze and thaw cycles; chloride ingress, sulphate attack, acid attack and alkali-aggregate reaction (Rashidi and Lemass 2011).

3.3.2 Age Factor:

As bridges are designed to withstand fatigue loading (which increases with time), age is an important parameter involved in structural condition assessment. The life expectancy of current bridges is about 50 years and for major concrete bridges is around 100 years. In fact, for the structural safety of the bridge, the designers have the reference code actions, usually defined for a period of 50 years. They need to adopt durability measures for 100 years, but the code indications are usually referred to 50 years. They need to consider for that bridge bearings and other equipment capable of lasting at most 25 years. When service life is raised beyond the current 50 years, the study of major bridges requires that safety be reconsidered to integrate coherence into the design (Branco & de Brito, 2004). The service life of a bridge brings to end when one of the key components fails to function as designed. The rating of this factor is presented in Table 6. "Recently built" is allocated for the first quarter of bridge service life, "New", "Old" and "Very Old" are respectively assigned for the second, third and last quarter of that.

3.3.3 Inspection Factor:

Quality and frequency of inspection play a key role in structural reliability of bridges. The inspection data provides an inclusive information source to track the condition development trends of bridge structures. However uncertainties and fuzziness associated to the inspection data cause many problems in its application (Wang and Foliente, 2008). Some of the probable errors in inspection process are as follows (Yanev, 2007):

-Inadequacy of equipments
-Exaggeration of some defects (loss of steel cross section to corrosion is usually overstated)
-The inability to recognise structurally significant features, such as support condition, bridge skew, fracture-critical members, and fatigue-sensitive details.
-Fear of traffic
-Lack of proper inspection training
-Inappropriate forms/ check lists
-Accessibility
-Visibility
-Time constraints
-Wind, rain and snow

3.3.4 Road Type Factor:

This factor is involved based on usage and importance of the bridge to the network addressing the road type of the bridge including street, road, freeway (FWY) or highway (HWY), bridge environment such as rural or urban, and the feature crossed such as road, waterway and railway (Wang and Foliente, 2008).

3.3.5 Rating and priority vector of the causal factors:

All the above mentioned factors have been classified based on definitions pointed out in section 3.3.1, 3.3.2, 3.3.3 and 3.3.4 and rated from 1 to 4 as such the higher numbers are associated with higher severity (Table 6).

Table 6: Rating of the causal factors

Rating	Causal Factors			
	Age	Road Class	Environment	Inspection Quality
1	Recently built	Minor	Low	Very High
2	New	Local access	Medium	High
3	Old	Collectors	High	Medium
4	Very old	Arterials	Very High	Low

For the purpose of finding the priority vector of the contributed factors, Analytical Hierarchy Process (AHP) developed by Saaty (1980) has been chosen. Fourteen experts (mainly bridge engineers and asset managers) have been asked to compare the involved parameters in pair and specify the quantity of the relative importance according to the Table 7.

Table 7: 1-9 scales for relative importance (Saaty 1980)

Importance Intensity	Explanation
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Absolute importance of one over another
2,4,6,8	Intermediate values between the two judgments
Reciprocals	Reciprocal for inverse comparison

The results of pairwise comparison are entered in a reciprocal comparison matrix as shown in Table 8. The importance level of the causal factors is developed as a vector of priorities which is a normalised eigenvector and estimated by dividing each element by the sum of that column and then computing the average of each row that shows the priority weight of the corresponding element.

Table 8: Pairwise comparison of the causal factors and their final weights

	Age	Environment	Road Class	Inspection	*Weights*
Age	1	3	5	1	*0.411*
Environment	1/3	1	1	1/3	*0.120*
Road Class	1/5	1	1	1/3	*0.107*
Inspection	1	3	3	1	*0.362*

The Causal Factor (CF) is calculated as follows. It ranges from 1-4:

$$CF = 0.411\boldsymbol{A} + 0.120\boldsymbol{E} + 0.107\boldsymbol{R} + 0.362\boldsymbol{I}$$

-A is the age factor

-E is the environmental factor

-R is the road type factor

-I is the inspection factor

3.3.6. Overall Structural Condition Index

The Structural Health Index (SHI) integrates all of the abovementioned parameters that influence structural efficiency and estimated as follows:

$$SHI = \frac{CF \sum Si \times Mi \times ESCIi}{n}$$

-CF is the causal factor

-Si is the structural importance factor

-Mi is the material vulnerability factor

-ESCIi is the Element Structural Condition Index

-n is the number of element types

The range of SHI is 1-256. This index will be applied for prioritisation of bridges in a network. The priority for remedial actions increases as the number rises.

Considering the identical upper limit (4) and lower limit (1) of all parameters and in order to keep the uniformity of quantity ranges, the condition of an entire structural element introduced as Overall Structural Condition Index (OSCI) has been re-rated based on HIS and defined as:

OSCI=1,	when SHI=1
OSCI=2,	when 1<SHI≤16
OSCI=3,	when 16<SHI≤81
OSCI=4,	when 81<SHI≤256

The re-rated rating number for OSCI is applicable for prioritisation and also selecting the major remedial strategies such as repair, strengthening and replacement.

4. Case Study

In order to verify the application of the proposed model, a few concrete bridges located in N.S.W have been chosen. These bridges have a high asset value and limited financial resources are available to maintain these bridges at a high working standard. It is therefore important to put considerable effort into the risk assessment process to ensure that the structures are analysed carefully and any defects are rectified early, before they become a significant issue.
Required data was extracted from reports provided by the bridge management division of the Roads and Traffic Authority (RTA). The Condition Index of all those bridges has been calculated in order to prioritise them for any probable maintenance/repair strategies and possible budget allocation. The overall condition has been evaluated for all those bridges considering the parameters being addressed in section 3. Table 9 represents the condition assessment procedure of a 39 year old bridge situated approximately 10 kilometers south of Wollongong, adjacent to the coastline (introduced as Bridge X in this paper). According to the inspection reports all the piers are footed in saline water, and there is ongoing cracking of columns and headstocks. Testing revealed very high chloride contamination levels.

These levels implied that corrosion was past the acceptable threshold, and remediation was required that could slow the degradation process. The Structural Health Index (SHI) for bridge X was 33.64. In comparison to the condition index of the other bridges in the network (Y=7.872, Z=9.216, T=15.04 and U:20.736) it had the highest rate and therefore has been targeted as a top priority for remedial action.

Table 9: Evaluation of the Overall Structural Condition Index (OSCI) for bridge X

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state				ESCI (Eq1)	Si	Mi	ESCI*Si*Mi
					1	2	3	4				
1	BELA	Elastomeric Bearing Pad	83	ea	0	0	83	0	3.00	3	3	27.00
2	CABW	Concrete-Abutment and Wingwalls	65	m2	0	65	0	0	2.00	2	2	8.00
3	CDSL	Concrete-Deck Slab	7120	m2	15	6239	866	0	2.12	3	2	12.72
4	CPHS	Concrete-Pier Headstock	1893	m2	0	84	1008	801	3.38	4	2	27.03
5	CPIL	Concrete-Piles/Piers	744	m2	0	52	380	312	3.35	4	2	26.80
6	CPRG	Concrete-Pre-tensioned Girder	5934	m2	0	5739	162	33	2.04	4	4	32.61
7	JNOS	Joint - No Seal	38	m	0	0	12	26	3.68	1	3	11.05
8	JPOS	Pourable / Cork Joint Seal	555	m	0	0	125	430	3.77	1	3	11.32
9	MAPP	Approach Carriageway	4	ea	3	1	0	0	1.25	1	3	3.75
10	MBAT	Batter protection	158	m2	0	0	102	56	3.35	1	3	10.06
11	MGCL	General Cleaning	33	ea	0	0	33	0	3.00	1	3	9.00
12	MWES	Wearing surface	5025	m2	0	0	1214	3811	3.76	1	3	11.28
13	MWWY	Waterway	1	ea	0	1	0	0	2.00	1	3	6.00
14	RMET	Metal Railing	1222	m		70	63	1089	3.83	1	1	3.83
15	RMIS	Miscellaneous Railing	629	m	0	0	289	340	3.54	1	1	3.54
16	RPNT	Railing Paint Work	1216	m	0	0	13	1203	2.97	1	3	8.90
17	UCPL	Underwater CPIL - Concrete-Pile	722	m2	0	0	124	598	3.83	4	2	30.63
		∑(ESCI*Si*Mi)										***243.53***
		CF=0.411A+0.120E+0.107R+0.362I			**A=2**	**E=4**	**R=3**	**I=2**				***2.35***

SHI=CF * ∑(ESCI*Si*Mi)/n	***SHI=2.35*243.53/ (17)***	***33.664***

OSCI=1, when SHI=1 OSCI=2, when 1<SHI≤16 OSCI=3 when 16<SHI≤81 OSCI=4 when 81<SHI≤256	16<SHI<81	***OSCI=3***

Summary and Conclusion

A methodology for developing an element based structural index is presented. OSCI is expressed as a number 1 to 4 and enables the decision makers to simply understand and compare the condition of a variety of bridges in the network. OSCI of 4 corresponds to the worst condition of a bridge and OSCI of 1 represents a new bridge. Material vulnerability (Mi) and Structural importance (Si) are considered in the element based condition assessment and the critical parameters that influence structural efficiency are identified as age, environment, road type and inspection. The weight of each of those factors has been evaluated through AHP, and the overall influence factor, which is introduced as Causal Factor (CF) is implemented as a coefficient to the current structural condition. This methodology has been

examined in a network consisting of 5 bridges in order to prioritise them for maintenance actions and budget allocation.

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