Allocation of bridge maintenance costs based on prioritization indexes

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Abstract
Prioritization indexes (PI) are a need-based bridge maintenance approach, which allows making short-term maintenance decisions. They generally use just the bridge condition as an explanatory variable, therefore, prioritizing is easy to do. When these indexes are multidimensional, prioritization depends not just on the bridge conditions, but also on variables such as vulnerability and their strategic importance. This paper discusses a simple and direct procedure to allocate bridge maintenance costs by using a PI based on the bridge condition, their strategic importance and vulnerability. The procedure combines maintenance activities within the strategies of routine and preventive maintenance, repair, reinforcement, reconstruction or replacement. It includes the calculation of maintenance costs by maintenance activity and strategy, in order to integrate them in a cost matrix. The procedure is applied to a 24-m long bridge, whose infrastructure is made of concrete, steel beams and concrete deck. Unit costs of 60 maintenance activities were calculated, and a sensitivity analysis was carried out to establish the cost by linear meter in relation to PI explanatory variables. The cost was sensitive to bridge condition, their vulnerability, and relevance within the road network.

Keywords: Bridge maintenance, maintenance costs, prioritization index, condition index, strategic importance, hydraulic and seismic vulnerability

Introduction and description of the problem

Bridges are road assets aimed at giving continuity to roads and highways when faced to geographical accidents, such as watercourses or ravines. Among all road assets, bridges are the most vulnerable and expensive ones. Likewise, their absence or restricted operation by load, width or height limitations considerably reduces the level of service on the respective road segment. In this case, the level of service is not restored so quickly, thereby increasing the user operating costs, the travelling costs, and others costs such as accidents, connectivity loss, alteration of the productivity and competitiveness of the economic activities that use transport and infrastructure as a production factor.

Consequently, the mission of bridge management is to anticipate the negative impacts associated to the infrastructure's deficient operation and to implement preventive and/or corrective measures. Therefore, bridge management systems (BMS) are an essential tool. A BMS is a formal procedure for analyzing bridge data with the purpose of predicting its future conditions, thereby estimating maintenance needs, recommending projects, and considering budget and policy constraints (AASHTO, 1993).

This procedure involves the following processes: bridge inventory and inspection, behavior models, socioeconomic evaluation models, data systems and computer platforms, which are used to make maintenance decisions based on the actual needs of the network or plan the long-term maintenance investment (Echaveguren et al., 2000; AUSTROADS, 2004; de Solminihac et al., 2018).

From the road agency perspective, the BMS includes two relevant variables for allocating the maintenance budget for bridges: the overall qualification of the bridges and the costs associated to maintenance strategies aimed at improving this overall qualification. Valenzuela et al. (2010) proposed a prioritization index (PI) for bridges, which considers the structural condition, the hydraulic vulnerability and the seismic risk, in addition to the importance of the bridge within the road network and the productive system. The PI of Valenzuela et al. (2010) allows technically prioritizing maintenance activities and strategies at the network level under a need-based framework. However, on its own, it does not allow estimating and allocating costs to maintenance strategies.

This work proposes a systematic method that integrates the priority index of Valenzuela et al. (2010) to the maintenance decisions and their associated costs. First, it discusses the application of priority indexes to bridge maintenance, including their advantages and limitations, emphasizing the work of Valenzuela et al. (2010). Then, the following is proposed: the cost allocation methodology, which considers criteria to allocate maintenance costs at the network level; a maintenance strategy matrix based on the PI explanatory variables of Valenzuela et al. (2010); a characterization of the different maintenance strategies; and a procedure for calculating the maintenance costs based on the bridge condition Subsequently, the procedure is applied to a study case, which consists in evaluating a bridge with concrete deck, steel beams and concrete abutments (named CSC, concrete-steel-concrete).

State of the arts

The prioritization indexes

Prioritization is defined as the process of ranking of maintenance options based on predefined qualification criteria, with the purpose of selecting those options that comply with predetermined selection requirements. For instance, the cost of maintenance options or the structural bridge condition (de Solminihac et al., 2018). Prioritization indexes are used for determining short-term maintenance needs (Echaveguren et al., 2014). Kurt (1988) defines them as a combination of weighted qualitative criteria, as shown in Eq. 1, where K_i is the weight of the i-nth criterion, $f_i()$ is the mathematical function describing the qualitative criteria a, b and c, such as bridge condition, or their relevance within the road network, among others.

$$\text{Prioritization Index} = \sum_{i} K_i\, f_i(a, b, c, \ldots.) \tag{1}$$

The index of Eq.1 can be expressed as a bridge condition index or as bridge health index. Blackelock et al. (1999), Gattulli & Chiaramonte (2005), Jiang & Rens (2010), Wakchaure & Neeraj Jha (2012) and Inkoom et al. (2017) developed condition indexes based on Eq. 1. Chase et al. (2016) compared condition indexes from United Kingdom, South Africa, Australia, Austria, Finland, Germany and Japan. They concluded that the most indexes have a common structure based on weighed averaging and ratio-based approaches that calculate the element condition and the overall condition of bridges.

Based on the Kurt's concept, Valenzuela et al. (2010) proposed the Integrated Bridge Index (IBI) of Eq. 2, 3 and 4, which explicitly defines Equation 1 for bridges in Chile. Valenzuela et al. (2010) calibrates that equations for Chilean bridges based on in-field visual inspection, expert judgments and 60 damage scenarios.

$$PI = -1.4 + 1.3(BCI) + 0.75(HV) + 0.46(SR) + 0.39(SI) \tag{2}$$

In Eq. 2, the IBI depends on the bridge condition (BCI), their hydraulic vulnerability (HV), seismic risk (SR) and strategic importance (SI). The index varies from 1 to 10, where 1 is a deficient operating condition and 10 is the best service condition. The hydraulic vulnerability (HV) is obtained based on a semantic qualification scale derived from on-site inspections. The seismic risk (SR) is obtained by estimating the magnitude of the damage, based on Fisher et al. (2002). The bridge condition (BCI), is defined as the weighted sum of each structural element condition (ECI_i), divided by the effect of the materials (m) of each element (i) of the bridge (Eq. 3). In Eq. 3 w represents the effect of the i-th ECI on the overall condition of the bridge. The condition of the structural elements is obtained through the on-site visual segmental inspection of the bridge (Ryall, 2010).

$$BCI = \sum_{i=1}^{n} w_i m_i ECI_i \Big/ \sum_{i=1}^{n} w_i m_i \tag{3}$$

The strategic importance (SI) is estimated as a linear model (Eq. 4), dependent on the presence of alternative routes (EA), the traffic level (T), the type of economic activities carried out in the area of influence of the bridge (SEE), the width (W) and length (L) of the bridge and the load restrictions (R).

$$SI = 0.26(EA) + 0.2(T) + 0.2(SEE) + 0.09(W) + 0.13(L) + 0.11(R) \tag{4}$$

Proposed method to allocate maintenance costs

The objective of the proposed method is to allocate maintenance costs based on the priority index of Valenzuela et al. (2010). The method has seven components: a) criteria for allocating maintenance strategies, b) maintenance strategy matrix; c) characterization of maintenance activities; d) estimation of the amount of maintenance work; e) calculation of the maintenance activity cost; f) calculation of the maintenance strategy cost; and g) cost allocation matrix.

Criteria for Allocating Maintenance Strategies

The index of Valenzuela et al. (2010) enabled the identification of a sequence of variables that allow recommending maintenance strategies, from which the four criteria of Table 1 were defined to allocate maintenance strategies.

Table 1. Criteria for allocating maintenance strategies. Source: Self-Elaboration.

Criterion	Variable Level	Variable Range	Priority Level
Priority Index (PI)	PI1	PI ≥ 8	Very Low
	PI2	6 ≤ PI < 8	Low
	PI3	4 ≤ PI < 6	Medium
	PI4	2 ≤ PI < 4	High
	PI5	PI < 2	Very High
Bridge Condition Index	BCI1	BCI < 2.3	High
(BCI)	BCI2	2.3 ≤ BCI < 3.6	Moderate
	BCI3	BCI ≥ 3.6	Low
Strategic Importance (SI)	SI1	SI > 2.5	High
	SI2	SI ≤ 2.5	Low
Seismic and/or Hydraulic	HVSR1	SR, HV > 2.5	High
Vulnerability (SR, HV)	HVSR2	SR, HV ≤ 2.5	Low

Maintenance strategies matrix

When combining the scenarios of Table 1 with the bridge components (substructure, superstructure and complementary elements), we obtain the Matrix of Figure 1, which allows selecting maintenance strategies. In order to build this matrix, seven maintenance strategies were defined: routine maintenance (RM), preventive maintenance (PM), repair (REP), reinforcement (REI), reconstruction or replacement (REC), additional studies (AS) and load limitation (LIM).

The routine maintenance (RM) refers to the maintenance activities carried out on a regular basis on the structure, even though there may be no visible deterioration signs. It depends on the type of bridge and comprises activities such as joint cleaning, recoating with anti-corrosive paint, barbican cleaning, bolt adjustments, etc. The objective is to maintain the original condition of the bridge, even if there are no deterioration signs yet. The preventive maintenance (PM) refers to the activities whose purpose is not to repair the deterioration but to delay its progression. These activities include, for example, crack sealing, treatment with preservers, replacement of angle beads, which aim at stopping the progress of deterioration. The repair (REP) deals with the activities needed to repair the damage and restore the service conditions. The reinforcement (REI) addresses the activities that seek to restore and increase the capacity of the structure to prevent deterioration and extend the durability of the bridge.

In case the reinforcement of the structure is not advisable, it is possible to reconstruct or replace (REC) under similar design conditions, or replace the bridge by a structure with a completely different strength, material, road capacity, structuring and location. The additional studies (AS) are carried out when there is not enough background information after a detailed visual inspection or following the application of non-destructive tests or continuous monitoring programs to establish the real condition of the structure. The AS can include load tests, follow-up or destructive tests or structural health monitoring The load limitation (LIM) refers to restrain the magnitude of the load circulating through the bridge when, for example, the decision has been made to perform additional studies with the aim of executing larger reinforcement, or reconstruction or replacement projects.

Figure 1. Matrix for allocating maintenance strategies. Source: Melgarejo (2009).

PI		Bridge Components		SI	BCI: High (BC1)		BCI: Moderate (BCI2)		BCI: Low (BCI3)	
					HV or SR: High (HVSR1)	HV or SR: Low (HVSR2)	HV or SR: High (HVSR1)	HV or SR: Low (HVSR2)	HV or SR: High (HVSR1)	HV or SR: Low (HVSR2)
PI	Very Low (PI1)	Substructure	Abutments	SI1	PM		PM		MR	
				SI2			RM			
			Piers	SI1	PM		PM		MR	
				SI2			RM			
		Superstructure	Deck	SI1	PM		PM		MR	
				SI2			RM			
			Beams	SI1	PM		PM		MR	
				SI2			RM			
		Complementary Elements		SI1	PM		PM		MR	
				SI2			RM			
	Low (PI2)	Substructure	Abutments	SI1	REP / AS	REP	REP / AS	REP	REP / AS	REP
				SI2			PM / AS	PM	RM / AS	RM
			Piers	SI1	REP / AS	REP	REP / AS	REP	REP / AS	REP
				SI2			PM / AS	PM	RM / AS	RM
		Superstructure	Deck	SI1	REP /AS	REP	REP / AS	REP	REP / AS	REP
				SI2			PM / AS	PM	RM / AS	RM
			Beams	SI1	REP / AS	REP	REP /AS	REP	REP / AS	REP
				SI2			PM / AS	PM	RM / AS	RM
		Complementary Elements		SI1	REP / AS	REP	REP / AS	REP	REP / AS	REP
				SI2			PM / AS	PM	RM / AS	RM
	Medium (PI3)	Substructure	Abutments		REP / AS	REP	REP / AS	REP	PM / AS	PM
			Piers		REP / AS	REP	REP / AS	REP	PM /AS	PM
		Superstructure	Deck		REP / AS	REP	REP / AS	REP	PM / AS	PM
			Beams		REP / AS	REP	REP / AS	REP	PM / AS	PM
		Complementary Elements			REP /AS	REP	REP / AS	REP	PM / AS	PM
	High (PI4)	Substructure	Abutments		REC / AS / LIM	REI / LIM	REI / AS / LIM	REP	REP / AS	REP
			Piers			REI / LIM	REI /AS / LIM	REP	REP / AS	REP
		Superstructure	Deck			REI / LIM	REI / AS / LIM	REP	REP / AS	REP
			Beams			REI / LIM	REI / AS / LIM	REP	REP / AS	REP
		Complementary Elements				REI / LIM	REI / AS / LIM	REP	REP / AS	REP
	Very High (PI5)	Substructure	Abutments		REC / AS / LIM		REC		REC	
			Piers							
		Superstructure	Deck							
			Beams							
		Complementary Elements								

The matrix of Figure 1 is used as following: The SI, HV or SR, and BCI indicators are calculated with the models of Valenzuela et al. (2010). Then, the PI/IBI is calculated (Eq. 2). With the values of these indexes, and the data on Table 1, the level of each one is determined and, in turn, these levels are used to enter the Matrix of Figure 1 and select the components of the bridge to be analyzed (substructure, superstructure or complementary elements). The strategy or strategies are selected from the cell resulting from the intersection of the level combinations of each variable and the components of the bridge. For example, for levels BCI2, SI1, HVSR1, and PI2, the available maintenance strategies for the deck component are REP /AS.

Characterization of maintenance activities

Maintenance activities are the operations related to a maintenance strategy (de Solminihac et al., 2018). Since they are applied on the structure, they depend on the materials and structuring of each bridge. The characterization initially considers the maintenance operations described by the Chilean Ministry of Public Works (MOP, 2018b). Then they are codified and a factsheet is prepared, describing each maintenance operation, its measurement unit, the objective pursued, and the summarized application procedure, in accordance with MOP regulations (MOP, 2018a and b). Afterwards, each maintenance operation is associated to a maintenance strategy.

Estimation of the amount of maintenance work

Once the maintenance activities are identified, bridge deterioration percentages are established, represented by “High”, “Moderate” or Low” deterioration levels according to Table 2. Then, each deterioration level is associated to the percentage of the whole structure, thus being able to estimate the amount of work to be considered in the calculation of the total value of each maintenance operation. These percentages can be improved insomuch as there are behavior models for specific bridge components or for the whole bridge, either mechanistic or Markov models, like the models proposed by Agrawal et al. (2010).

Table 2. Percentage of deteriorated structure according to the BCI level. Source: Self-Elaboration.

BCI Level	Deterioration Range (%)	Representative Deterioration Percentage (%)
BCI1	66 – 100	80
BCI2	33 – 65	50
BCI3	0 - 32	15

Calculation of the maintenance activity cost

Each maintenance activity has an associated cost depending on the deterioration level. This calculation requires unit costs related to each maintenance activity, expressed in the currency of the same year and adjusted by the project’s distance to a reference geographical location, in order to include the localization effect in the unit costs. The values obtained from road agency databases of each country serve as a source of information for the unit prices.

Once the unit prices are defined, the maintenance activity cost is obtained for each deterioration level by multiplying the unit price by the representative deterioration percentage in Table 2, and by the dimensions of every element of the bridge related to each maintenance activity, thereby obtaining the total cost of the maintenance activity. This calculation procedure is a simplification of the method of Gannon et al. (1995).

Calculation of the maintenance strategies cost

In order to estimate the total cost of the maintenance strategies, the costs of the individual activities, corresponding to each structure and elements of the superstructure, infrastructure and complementary elements, are added. Two criteria are considered for this calculation. On the one hand, certain complementary maintenance activities are developed jointly to achieve the objective pursued by each maintenance strategy. For example, a concrete deck requiring preventive maintenance (PM) needs maintenance activities such as crack injection, additives in reinforcing bars, and eventually waterproofing. These activities are carried out simultaneously, because otherwise the preventive maintenance objective of that particular bridge element is not fulfilled. On the other hand, in order to include the variability, the calculation considers high, medium and low cost values of the maintenance activities, which are obtained by categorizing the technically feasible combinations for each strategy. The purpose of this is to consider the uncertainty in the unit price estimates.

Cost allocation matrix

The costs of the maintenance strategies allow creating a cost matrix similar to that of Figure 1, but replacing the maintenance strategies by the cost of each strategy, based on the criteria described in Tables 1 and 2. This new matrix completes the cells with the maintenance strategy costs, since we already know the maintenance strategy to be used under each combination of the decision variables in Table 2. Thus, it is possible to know the maintenance costs of each component individually, the costs associated to the abutments, piers, deck, beams and complementary elements.

The cells describing the bridge vulnerability, their strategic importance, deterioration level, and priority index are selected from the matrix, in order to calculate the total maintenance cost. Costs are calculated by spreading these values according to the bridge dimensions, and then they are added, thereby determining the total maintenance cost. This value represents the total maintenance investment needed to improve the present condition of the bridge. Subsequently, this cost can be allocated to an investment budget at the network level and, once executed, it allows updating the PI condition index of Eq. 2.

Case Study: Maintenance cost calculation for a CSC bridge

The method described in the previous sections was applied to the study of a CSC bridge with an 8m width, 24m long roadway, with an intermediate pier at the mid-span. The substructure is made of reinforced concrete, and the superstructure has a mixed configuration of steel beams and reinforced-concrete slabs. Additionally, the analyzed bridge included the following structural elements:

a) Reinforced-concrete abutments with a 4 m-high and 10 m-wide front wall, which supports the beams that penetrate up to 1.5 m into each abutment. The abutment wing walls were assumed with a triangular shape of 5 m high and a penetration of 3 m towards the road.
b) Frame-type or arch-type reinforced-concrete piers, with two columns of 1 m x 1 m section and 4m high, which support the right and left steel beams, and a reinforced-concrete beam that joins both columns, of 1 m x 1 m section, on which the central steel beam is supported.
c) Reinforced-concrete deck of 23 cm thick and a pavement layer of 6 cm thick, with a total width of 10.8 m.
d) Three double-tee steel beams of 27 m long, with section of 1000 mm high, flange width of 300mm, average flange thickness of 30 mm, and web thickness of 17 mm. They are located under the reinforced-concrete slab, on the central axis, and 4m to the right and to the left of the central axis. They include connectors to support the deck.
e) Cross bracings every 4 m with L-section steel of 80x80x8 together with stiffeners.
f) The complementary elements envisaged steel guard railing of 1.2 m high, with pillar section of 120x120x5 every 1.5 m attached to the deck with bolts and a handrail, and three steel band sections of 100x70x5 and 100x80x5, respectively.

Table 3 shows a catalog of 60 maintenance activities divided by strategies. Unit costs were calculated for each one and then the costs were associated by group of components of the studied bridge, and by maintenance strategy. The unit cost data were obtained from maintenance contract costs provided by the Chilean Road Agency. Table 4 shows the combination of maintenance activities considered for the cost calculation, codified according to the descriptions in Table 3. Subsequently, the cost matrix was assigned to the strategy matrix of Figure 1, thereby replacing in each case the strategies by the previously calculated costs. Figure 2 shows this allocation.

Table 3. Catalog of maintenance activities associated to each maintenance strategy. Source: Self-Elaboration.

Code	Maintenance Activity	Unit	Code	Maintenance Activity	Unit
			Preventive Maintenance (PM)		
200	Injection of cracks with pressure epoxy resin	m²	207	Silicones	m
201	Injection of cracks with gravity-fed sealant	lt	208	Corrosion inhibiting additive nitrite	m
202	Polymer-modified cementitious coating	m²	209	Corrosion inhibiting additive chromates	m²
203	Polymer impregnation	m²	210	Corrosion inhibiting additive phosphates	m²
204	Surface hardeners and pore blockers	m	211	Epoxy/zinc coating of rebars	m²
205	Linseed oil	m²	212	Cathodic protection	m²
206	Mineral oil	m²	213	Galvanization of steel elements	m²
245	Reconditioning of damaged parapets	m	251	Surface treatment with polymer	m²
			Routine Maintenance (RM)		
242	Routine maintenance of signs	unit	249	Cleaning of expansion joint	m
243	Structural steel paint	m²	252	Cleaning of concrete elements	m²
244	Cleaning of drains, spill cone	m	253	Cleaning of steel elements	m
246	Cleaning of supports	unit	259	Painting of steel railing	m
			Reinforcement (REI)		
225	Reinforcement with overlapped metal plates	m²	231	Pile drilling and grouting, to increase bearing capacity	m³
226	Plate reinforcement with anchoring to reinforced concrete	m²	232	Additional piles for increased support and bearing capacity	m³
227	Steel plates bonded with epoxy resin	m²	236	Post-tensioning	m
228	Lower reinforcement and additional mortar under the slab	m³	237	Concrete jacketing	m³
229	Slab reinforcement with FRP, fiber-reinforced plastic	m²	255	Reinforcing horizontal resistance of abutments using ground anchors	m
230	Additional cross bracing	m			
			Repair (REP)		
214	Degraded concrete repair with concrete patch	m²	234	Replacement of damaged steel element	m²
215	Repair with expansive mortars	m²	235	Repair of metal joints	Unit

Preventive Maintenance (PM)					
Code	Maintenance Activity	Unit	Code	Maintenance Activity	Unit
216	Repair with epoxy mortars	m^2	238	Repair of crack and reinforcing steel exposure	m
217	Hydraulic Portland cement grouting	kg	239	Replacement of metal angle bead of expansion joint	m
218	Sprayed mortar coating	m^3	240	Repair of expansion joint	m
219	Prepacked concrete	m^3	241	Change of elastomeric bearings	Unit
220	Barbican replacement	unit	247	Protection with timber sheet piles	Inch
221	Barbican complementation	unit	248	Construction of pile perimeter screen	m
222	Placement of gabions for piers, abutments and/or riverbanks	m^3	250	Resurfacing and membranes	m^2
223	Riverbank protection with masonry	m^3	256	Concrete layer for bridges	m^3
224	Placement of dikes to divert the river flow	m^3	257	Provision and placement of galvanized steel railing	m
233	Steel plating	m^2	258	Provision and placement of galvanized road protections	m

Table 4. Cost calculation method for each maintenance strategy by bridge component. Source: Melgarejo (2009).

Components		Strategy	Configuration of maintenance activity costs by strategy
Substructure	Abutments	RM	252
	Piers	RM	252
Superstructure	Deck	RM	252 + 249
	Beams	RM	243 + 246 + 253
Complementary elements		RM	242 + 244 + 253 + 259
Substructure	Abutments	PM	MAX [MAX(200;201) + MAX(208;209;210;211) + [MAX(202;203;204) or MAX(205;206;207)]
	Piers	PM	MAX [MAX(200;201) + MAX(208;209;210;211) + [MAX(202;203;204) or MAX(205;206;207)]
Superstructure	Deck	PM	MAX [MAX(200;201) + MAX(208;209;210;211) + MAX(203;204) + 251 MAX(200;201) + MAX(208;209;210;211) + MAX(205;206) + 251]
	Beams	PM	212 + 213
Complementary elements		PM	212 + 213 + 245
Substructure	Abutments	REP	MAX [MAX(218;219) + 247 ; MAX(214;215;216;217) + 238 + 247]
	Piers	REP	MAX [MAX(218;219) + 248 ; MAX(214;215;216;217) + 238 + 248]
Superstructure	Deck	REP	MAX [MAX(214;215;216;217;256) + MAX(220;221) + 238 + [239 or 240] + 250
	Beams	REP	233 + 234 + 235 + 241
Complementary elements		REP	MAX(222;223;224) + 233 + 234 + 235 + 257 + 258
Substructure	Abutments	REI	MAX [MAX(225;226;227) + 255 ; MAX(225;226;227) + 231]
	Piers	REI	MAX(225;226;227) + MAX(231;232) + 237
Superstructure	Deck	REI	MAX(228;229) + 225 + 236
	Beams	REI	230
Complementary elements		REI	0
Bridge		REC	254

The cost values summarized in Figure 2 were used for calculating the total costs per linear meter of bridge for high, medium and low cost levels. These data allowed identifying cost behavior patterns, based on the criteria of strategy cost allocation indicated in Table 1. These patterns are outlined in Figures 3, 4, 5 and 6.

Figure 2. Matrix for allocating maintenance strategy costs for CSC bridges, in US$. Source: Melgarejo (2009).

<table>
<tr><td colspan="4"></td><td colspan="6">BCI</td></tr>
<tr><td colspan="2"></td><td colspan="2">Bridge Components</td><td colspan="2">High (BC1)</td><td colspan="2">Medium (BCI2)</td><td colspan="2">Low (BCI3)</td></tr>
<tr><td rowspan="35">PI</td><td rowspan="10">Very Low (PI1)</td><td rowspan="4">Substructure</td><td rowspan="2">Abutments</td><td colspan="2" rowspan="2">9.480</td><td colspan="2">6.320</td><td colspan="2" rowspan="2">2.880</td></tr>
<tr><td colspan="2">2.880</td></tr>
<tr><td rowspan="2">Piers</td><td colspan="2" rowspan="2">4.320</td><td colspan="2">2.880</td><td colspan="2" rowspan="2">1.320</td></tr>
<tr><td colspan="2">1.320</td></tr>
<tr><td rowspan="4">Superstructure</td><td rowspan="2">Deck</td><td colspan="2" rowspan="2">50.760</td><td colspan="2">43.920</td><td colspan="2" rowspan="2">6.640</td></tr>
<tr><td colspan="2">6.640</td></tr>
<tr><td rowspan="2">Beams</td><td colspan="2" rowspan="2">12.120</td><td colspan="2">12.120</td><td colspan="2" rowspan="2">16.560</td></tr>
<tr><td colspan="2">16.560</td></tr>
<tr><td colspan="2" rowspan="2">Complementary Elements</td><td colspan="2" rowspan="2">9.800</td><td colspan="2">8.800</td><td colspan="2" rowspan="2">2.920</td></tr>
<tr><td colspan="2">3.160</td></tr>
<tr><td rowspan="10">Low (PI2)</td><td rowspan="4">Substructure</td><td rowspan="2">Abutments</td><td rowspan="2">15.160</td><td rowspan="2">13.240</td><td>14.440</td><td>12.520</td><td>13.720</td><td>11.800</td></tr>
<tr><td>8.280</td><td>6.320</td><td>4.800</td><td>2.880</td></tr>
<tr><td rowspan="2">Piers</td><td rowspan="2">6.280</td><td rowspan="2">4.360</td><td>4.640</td><td>2.680</td><td>3.000</td><td>1.040</td></tr>
<tr><td>4.800</td><td>2.880</td><td>3.240</td><td>1.320</td></tr>
<tr><td rowspan="4">Superstructure</td><td rowspan="2">Deck</td><td rowspan="2">50.440</td><td rowspan="2">48.520</td><td>47.160</td><td>45.240</td><td>43.960</td><td>42.040</td></tr>
<tr><td>45.840</td><td>43.920</td><td>8.560</td><td>6.640</td></tr>
<tr><td rowspan="2">Beams</td><td rowspan="2">14.280</td><td rowspan="2">12.360</td><td>9.760</td><td>7.800</td><td>4.600</td><td>2.680</td></tr>
<tr><td>14.080</td><td>12.120</td><td>18.520</td><td>16.560</td></tr>
<tr><td colspan="2" rowspan="2">Complementary Elements</td><td rowspan="2">33.640</td><td rowspan="2">31.720</td><td>21.200</td><td>19.280</td><td>8.200</td><td>6.280</td></tr>
<tr><td>10.720</td><td>8.800</td><td>4.880</td><td>2.920</td></tr>
<tr><td rowspan="5">Medium (PI3)</td><td rowspan="2">Substructure</td><td>Abutments</td><td>29.920</td><td>13.240</td><td>14.440</td><td>12.520</td><td>5.000</td><td>3.080</td></tr>
<tr><td>Piers</td><td>16.640</td><td>4.360</td><td>4.640</td><td>2.680</td><td>3.280</td><td>1.360</td></tr>
<tr><td rowspan="2">Superstructure</td><td>Deck</td><td>24.880</td><td>48.520</td><td>47.160</td><td>45.240</td><td>38.520</td><td>36.600</td></tr>
<tr><td>Beams</td><td>7.960</td><td>12.360</td><td>9.760</td><td>7.800</td><td>14.080</td><td>12.120</td></tr>
<tr><td colspan="2">Complementary Elements</td><td></td><td>31.720</td><td>21.200</td><td>19.280</td><td>9.640</td><td>112.760</td></tr>
<tr><td rowspan="5">High (PI4)</td><td rowspan="2">Substructure</td><td>Abutments</td><td rowspan="5">112.760</td><td>30.320</td><td>21.520</td><td>12.520</td><td>13.720</td><td>11.800</td></tr>
<tr><td>Piers</td><td>17.000</td><td>13.320</td><td>2.680</td><td>3.000</td><td>1.040</td></tr>
<tr><td rowspan="2">Superstructure</td><td>Deck</td><td>25.240</td><td>16.480</td><td>45.240</td><td>43.960</td><td>42.040</td></tr>
<tr><td>Beams</td><td>8.320</td><td>10.240</td><td>7.800</td><td>4.600</td><td>2.680</td></tr>
<tr><td colspan="2">Complementary Elements</td><td></td><td></td><td>19.280</td><td>8.200</td><td>6.280</td></tr>
<tr><td rowspan="5">Very High (PI5)</td><td rowspan="2">Substructure</td><td>Abutments</td><td colspan="2" rowspan="5">112.760</td><td colspan="2" rowspan="5">91.640</td><td colspan="2" rowspan="5">91.640</td></tr>
<tr><td>Piers</td></tr>
<tr><td rowspan="2">Superstructure</td><td>Deck</td></tr>
<tr><td>Beams</td></tr>
<tr><td colspan="2">Complementary Elements</td></tr>
<tr><td colspan="4"></td><td>High (HVSR1)</td><td>Low (HVSR2)</td><td>High (HVSR1)</td><td>Low (HVSR2)</td><td>High (HVSR1)</td><td>Low (HVSR2)</td></tr>
<tr><td colspan="4"></td><td colspan="6">HV or SR</td></tr>
</table>

Figure 3. Maintenance costs per linear meter for Low BCI. Source: Self-Elaboration.

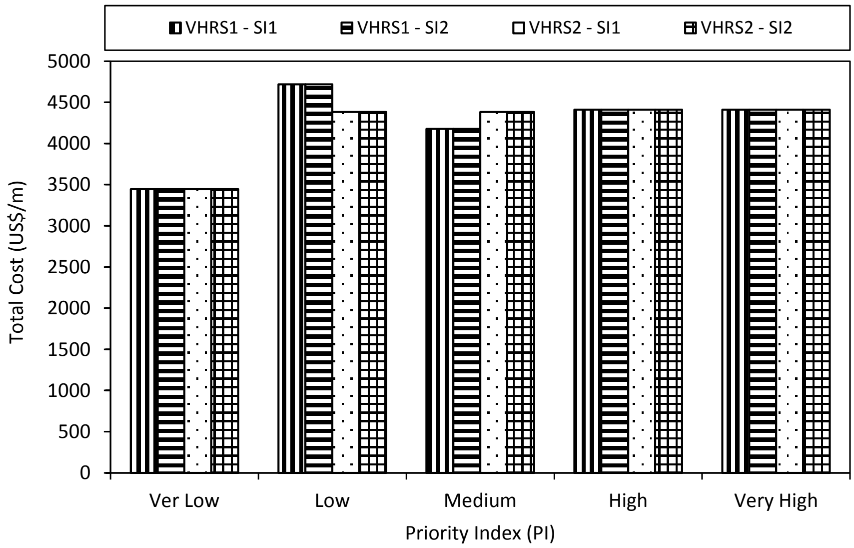


Figure 4. Maintenance costs per linear meter for Medium BCI. Source: Self-Elaboration.

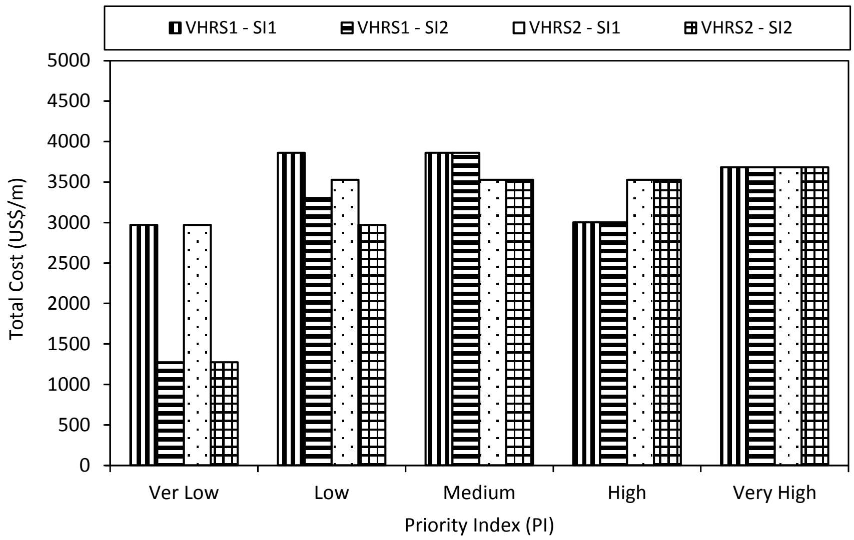


Figure 5. Maintenance costs per linear meter for High BCI. Source: Self-Elaboration.

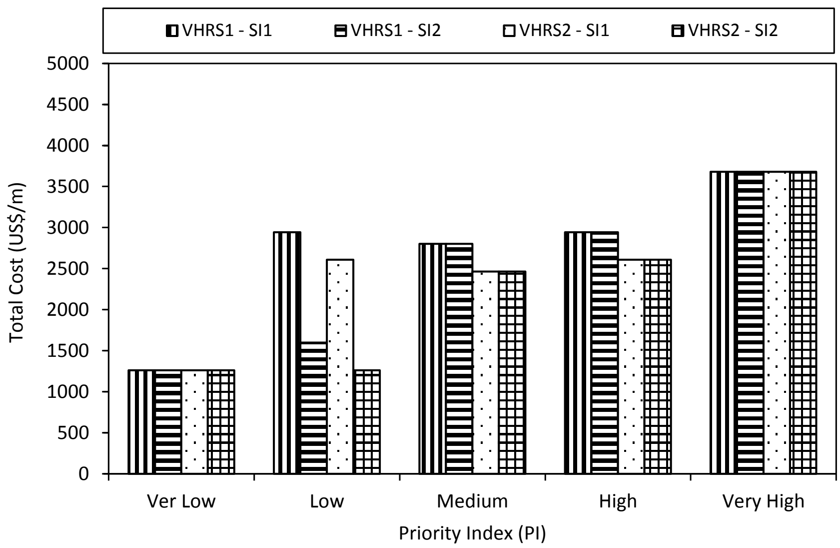
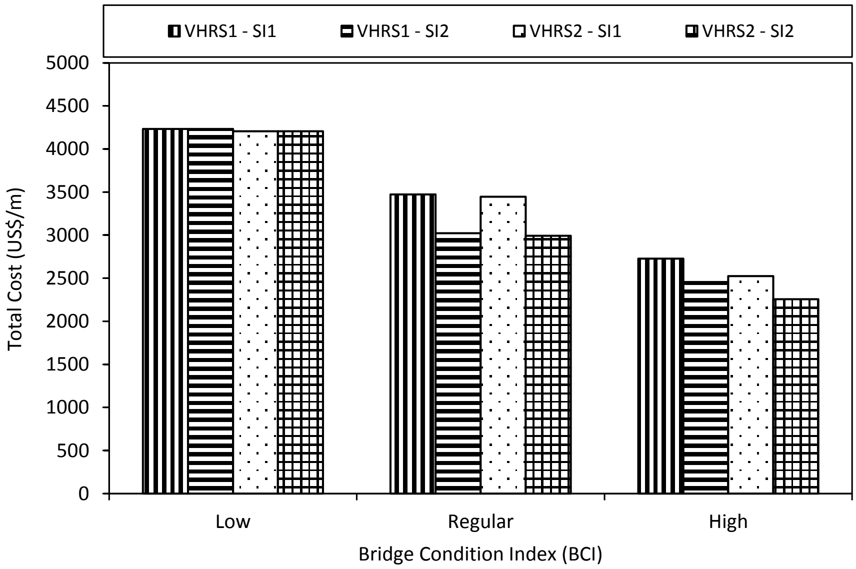


Figure 6. Average maintenance cost per linear meter by BCI. Source: Self-Elaboration.



Based on Figures 3, 4 and 5, the following cost behavior patterns were identified:

As the maintenance priority (PI) decreases, the maintenance costs tend to increase. However, when the condition of the bridge is on the "Low" level (Figure 3), the maintenance cost is not sensitive to the priority index. The opposite occurs when the bridge is in good condition ("High" BCI, Figure 5), where the maintenance cost is sensitive to the maintenance priority level.

Overall, the strategic importance (SI) has a greater impact on the costs when the priority index tends towards the "Good" level and, at the same time, the BCI level is "Moderate" to "High" (Figures 4 and 5).

The effect of the bridge vulnerability is similar to that of the strategic importance. The vulnerability has a greater impact on the maintenance costs, as long as the condition of the bridge is "Moderate" (Figure 4) to "High" (Figure 5).

The average maintenance cost calculated according to the BCI increases as the bridge condition is worse ("Low" BCI in Figure 6). Likewise, regardless of the maintenance priority level, the average cost becomes more sensitive to the vulnerability and the strategic importance as the bridge condition improves ("High" BCI in Figure 6).

Conclusions

The purpose of this work was to propose a method for calculating bridge maintenance costs by using a priority index that includes the vulnerability and strategic importance of the bridges, in addition to their condition. Thus, the selection of maintenance strategies and their associated cost depends on these variables rather than just on the bridge condition.

The priority index used herein is based on visual inspection results, which allow determining the bridge conditions, their relevance for the road network and their vulnerability in the face of seismic and hydraulic threats, in order to establish a prioritization scale. This index is efficient for bridge management based on needs, which allows planning the short-term maintenance.

In order to achieve this objective, the priority index has to be related to the direct cost of maintenance investment, which results from the technical selection of a maintenance strategy. Through this process, a road agency can measure the bridge maintenance cost in the short term at the network level in a more realistic way than when considering the bridge condition only.

The results obtained in the study case show that the average value of the maintenance cost decreases as the bridge condition improves. When the cost allocation was considered with a multidimensional approach, it was determined that both the strategic importance and the vulnerability gain relevance. In other words, the higher the strategic importance and the higher the vulnerability, the higher the maintenance cost, particularly when the priority index is in the medium range.

The proposed method needs to rely on a unit price database for maintenance activities, which takes into account the own characteristics of the local road networks, the local costs of materials and labor, a wider range of bridge structuring and, therefore, a more detailed catalog of maintenance activities. In this manner, it will be possible to rely on a catalog of costs associated to maintenance strategies that can be integrated as input data in the making of bridge maintenance decisions based on needs.

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References

American Association of State Highway and Transportation Officials. (1993) AASHTO Guidelines for Bridge management Systems. Washington D.C.: Author.

Agrawal, A., Kawaguchi, A., & Chen, Z. (2010). Deterioration rates of typical bridge elements in New York. *Journal of Bridge Engineering*, *15*(4), 419 – 429. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000123

Australian and New Zealand Road Transport and Traffic Authorities. (2004). *Guidelines for Bridge Management – Structure Information*. AUSTROADS Report AP-R252/04. Sydney: Author.

Blakelock, R., Day, W., & Chadwick, R. (1999). Bridge Condition Index. In Das, P. (Ed.) Management of Highway Structures (pp. 130 – 138). London: Thomas Telford.

Chase, S.B., Adu-Gyamfi, Y., Aktan, A.E., & Minaie, E. (2016). *Synthesis of National and International Methodologies Used for Bridge Health Indices*. FHWA Report FHWA-HRT-15-081, Georgetown, Pike, VA: Federal Highway Administration. Retrieved from https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/15081/15081.pdf

de Solminihac, H., Echaveguren, T., & Chamorro, A. (2018) *Gestión de Infraestructura Vial*. 3a Edición. Santiago: Ediciones Pontificia Universidad Católica de Chile.

Echaveguren, T., Cifuentes, O., & Echaveguren, E. (2000). Gestión de Mantenimiento de Puentes. Una Revisión Conceptual. In: *5o Congreso Internacional PROVIAL*: 6-10 November, La Serena, Chile.

Echaveguren, T., Dechent, P., Giuliano, M., & Sepúlveda, J. (2014). Proposal of a condition index for maintenance of runway beams. *Proceedings of the ICE – Structures and Buildings*, *167*(6), 369 – 379. https://doi.org/10.1680/stbu.11.00078.

Fischer, T., Álvarez, M., de la Llera, J.C., & Riddell, R. (2002). An integrated model for earthquake risk assessment of buildings. *Eng. Struct.*, *24*(7), 979 – 998. https://doi.org/10.1016/S0141-0296(02)00018-4

Gannon, E., Weyers, R., & Cady, P. (1995). Cost relationships for concrete bridge protection, repair and rehabilitation. *Transportation Research Record*, *1490*, 32 – 42. Retrieved from: http://onlinepubs.trb.org/Onlinepubs/trr/1995/1490/1490-005.pdf

Gattulli, V. & Chiaramonte, L. (2005). Condition Assessment by Visual Inspection for a Bridge Management System, *Computer-Aided Civil and Infrastructure Engineering, 20*, 95 – 107. https://doi.org/10.1111/j.1467-8667.2005.00379.x

Inkoom, S., Sobanjo, J., Thompson, P., Kerr, R., & Twumasi-Boakye, R. (2017). Bridge Health Index. Study of Element Condition States and Importance Weights. *Transportation Research Record, 2612*, 67 – 75. http://dx.doi.org/10.3141/2612-08

Jiang, X., & Rens, K. (2010). Bridge Health Index for the City and County of Denver, Colorado. I: Current Methodology. *Journal of Performance of Constructed Facilities*, *24*(6), 580 – 587. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000128

Kurt, C.E. (1988). Bridge management system software for local governments. *Transportation Research Record*, *1184*, 50–55. Retrieved from: http://onlinepubs.trb.org/Onlinepubs/trr/1988/1184/1184-007.pdf

Melgarejo, L. (2009). *Metodología para la asignación de costos de mantenimiento de puentes*. Tesis de Pregrado. Universidad de Concepción, Departamento de Ingeniería Civil, Concepción, Chile.

MOP (2018a). *Especificaciones técnicas generales de construcción*. Manual de Carreteras, Vol. 5. Santiago, Chile: Ministerio de Obras Públicas.

MOP (2018b). *Mantenimiento Vial*. Manual de Carreteras, Vol. 7. Santiago, Chile: Ministerio de Obras Públicas.

Ryall, M.J. (2010). *Bridge Management*. Oxford: Butterworth – Heinemannn.

Valenzuela, S., de Solminihac, H., & Echaveguren, T. (2010). Proposal of an Integrated Index for Prioritization of Bridge Maintenance. *Journal of Bridge Engineering*, *15*(3), 337 – 343. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000068

Wakchaure, S.S., & Neeraj Jha, K. (2012). Determination of bridge health index using analytical hierarchy process. *Construction Management and Economics*, *30*(2), 133 – 149. https://doi.org/10.1080/01446193.2012.658075