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THE EFFECT OF MANAGEMENT DECISION PROCESSES ON THE MANAGEMENT OF BRIDGES

Amin JAMALI, Bryan T. ADEY

Institute of Construction and Infrastructure Management, Swiss Federal Institute of Technology,
Wolfgang-Pauli Strasse 15, 8093 Zurich, Switzerland

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Abstract. It is necessary to execute interventions on bridges to ensure that they continue to provide an adequate level of service. It is necessary to inspect them to ensure that these interventions are timed appropriately. As there are negative impacts associated with both inspections and interventions, e.g. the impact on the owner due to the hours of labor and amounts of materials required to perform an inspection and execute an intervention, it is desirable to determine inspection and intervention strategies that minimize these negative impacts (i.e. the optimal management strategy). An important, however often overlooked, factor in determining optimal management strategies, is how management processes affect the determination of the optimal management strategy. In this article it is shown that it is not always possible to determine an optimal management strategy without explicitly taking into consideration management processes, how variations in management processes can be evaluated and that the significance of these variations is dependent on the values of the incurred impacts.

Keywords: management decision process, optimal management strategy, inspection strategy, intervention strategy.

Introduction

In order to ensure that bridges continue to provide an adequate level of service over an extended time period it is often necessary to execute interventions. During the execution of interventions stakeholders incur negative impacts. Negative impacts that can be attributed to the owner, for example, are the hours of labor and the amounts of materials required to execute interventions. A negative impact incurred by the user is, for example, the increases in travel time that results from traffic flow disruptions. The time to execute interventions to minimize these negative impacts depends on the existing and future levels of bridge performance. The estimation of the levels of performance, however, normally includes performing inspections, during which negative impacts are also incurred.

Keeping in mind that it is desirable to minimize these negative impacts many researchers have focused on developing methodologies to determine optimal inspection strategies (OSSs), i.e. the optimal times to perform inspections and the optimal types of inspection methods to be used that result in minimal negative impacts, e.g. Baker and Descamps (1999), Faber and Sørensen (2002), Qin and Faber (2012), and optimal intervention strategies (OISs), i.e. the optimal times to execute interventions and the optimal types of interventions to be executed, e.g. Thoft-Christensen and Sørensen (1987) and Frangopol (1997). In both cases there has been no explicit consideration of the management processes used to determine the SSs or the ISs.

Management processes can, however, affect the SS and IS deemed optimal, and, therefore, need to be explicitly taken into consideration when determining the OSSs or OISs. For example, one process to determine the SS to follow may exclude advanced inspection technologies, perhaps due to their high up-front costs, where another may not. It is then feasible that the ISs coupled with the SSs in order to determine the management strategy (MS) that results in the lowest negative impacts on bridge stakeholders, i.e. the optimal management strategy (OMSs), are different. In both cases, however, OMSs would be determined, but the latter case would result in lower overall negative impacts then the former.

In order to determine OMSs, it is, therefore, necessary to take into consideration the management processes used. In this article it is shown, with a more extensive example as mentioned above, that it is not always possible to determine an OMS without explicitly taking into consideration management processes. This is done be developing a realistic process to determine the SSs to be followed for a reinforced concrete bridge deck and demonstrating that without modeling the management processes the OMS, and therefore the OSS is not always determined.

Corresponding author: Amin Jamali
E-mail: *jamali@ibi.baug.ethz.ch*

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It is also shown how variations in management processes can be evaluated and that the significance of these variations is dependent on the values of the incurred impacts. This is done by showing how changes in an example process can affect the OMS when different values of unit impacts are used.

The article is structured as follows: following the introduction, there is a literature review that shows the advancement of the state-of-the-art in process analysis and evaluation giving clear indication of how process analysis can be used to improve the management of infrastructure. The main processes used by managers to determine OMSs for bridges are then explained. Building on one of these processes as an example, it is then showed how variations in a process can affect the optimality of MSs. The paper is concluded with a conclusion section.

1. State-of-the-art in process analysis and evaluation

Analysis and evaluation of processes are elements of a business process management (Weske 2007) through which a process is visualized and its performance is tracked, communicated and (if necessary) improved. In the analysis phase, processes are first identified and then expressed in a standard notation to facilitate communication with different stakeholders for possible improvement. In the evaluation phase, a performance index is defined, and an evaluation of the process is conducted.

Rigorous and systematic analysis and evaluation of business processes is relatively recent and has emerged from the areas of computer science and information technology. Some of the research has been focused on structural analysis in order to identify semantic errors in business process constructs. This has principally been done by both identifying a set of base metrics (e.g. events, activities, etc.) deemed important in the evaluation of the elements of a process construct (Weske 2007), and then developing measures to be used to evaluate the construct (e.g. the total number of events). Some of the measures that have been proposed are:

- size, length and breadth of processes when represented in graphs, e.g. Nissen (2002);
- simplicity, flexibility, integration and efficiency, e.g. Tjaden (1999);
- total number of start, intermediate and end events, e.g. Rolón *et al.* (2006) and Reynoso *et al.* (2009);
- degree, density, distance and connectivity, e.g. Mendling (2008);
- role integration, role dependency and transition delay risk, e.g. Balasubramanian and Gupta (2005) who attempted to quantify the degree of automatic decision making.

Other research has been focused on process semantics through mapping into formal languages for which analysis tools are well-developed. For example, Dijkman *et al.* (2008) proposed a mapping of BPMN into Petri nets (a language for modeling and simulation of discrete events that is popular among computer and automation control scientists), and Wong and Gibbons (2008) mapped a business process model into CSP (a language for describing patterns of interaction in concurrent systems). Similar work, but using different mapping formalisms include that by Puhlmann and Weske (2006) who converted a number of BPMN subsets into π-calculus (a model of computation for concurrent systems) and showed how this could be used to check the correctness of the process.

Other research has been focused on the performance evaluation of processes. For example, Canevet *et al.* (2003) developed a technique for mapping from the Unified Modeling Language (UML) to stochastic process algebra that can be used to evaluate the performance of software systems, and Braghetto *et al.* (2010) proposed a conversion algorithm for mapping of BPMN models into the so-called Stochastic Automata Networks.

This brief, and certainly not exhaustive, overview of some of the recent work in process analysis and evaluation indicates that it is both an emerging and an advancing field of research. Although the work to date has led to multiple ways that can be used to analyze and evaluate processes, often in preparation for implementation in software development and computer systems, no-one has yet attempted to evaluate the management decision processes inside a bridge organization, or the effect that these processes may have on the OMS to be followed. The work presented in this article is the first step in this direction.

2. Management processes

2.1. General

One of the goals of a bridge management organization is to determine the SS and IS to ensure that bridges provide an adequate level of service over the investigated time period while causing the least total negative impact. In a typical bridge management organization, the principal management processes used to achieve this goal are:

- Process *Determine optimal SS*;
- Process *Determine optimal IS*;
- Process *Plan inspections*;
- Process *Build work program*;
- Process *Plan and supervise interventions*.

In Figure 1 these processes are shown in BPMN. Although each one of these processes affects the OMS, only the process used by management to determine the SS to follow is discussed in detail. For other processes and their effects on MS to follow, see Jamali and Adey (2012).

2.2. Process 1: Determine optimal SS

2.2.1. Process

The process *Determine optimal SS* is used to determine the times, types and methods of inspections to be performed (Fig. 2). Although the exact process will most likely be different from organization to organization, the process shown is representative of one possible process and it is believed that the principal activities shown will be included in the processes of most bridge management organizations. The process is started by identifying the types of inspections that are appropriate according to the inspection needs and a number of relevant inspection methods for each inspection type. A list of appropriate inspection methods per inspection type is then determined based on various, often incomplete, criteria, e.g. upfront costs of each method, and the type and accuracy of information each provide. This results in a range of possible SSs, as shown in a collapsed format in Figure 2. The optimal SS is then identified through the sub-process *Determine optimal SS*.

2.2.2. Effect on the optimal management strategy

The process used to determine the optimal SS can affect OMS. Four ways that this may happen can be attributed to the following activities (shaded grey in Fig. 2):

- *Identify inspection methods per inspection type:* If not all appropriate inspection methods are taken into consideration, then some SSs will not be considered in the search for the optimal SS. This may happen, for example, if the task of identifying the appropriate inspection methods is assigned to a less experienced and less knowledgeable engineer rather than to a more experienced and more knowledgeable one.
- *Evaluate inspection methods:* The evaluation conducted in the sub-process used to evaluate the inspection methods should concurrently consider costs, type and certainty of the information to be obtained through the inspection methods. If any of these factors are ignored or are not considered concurrently, some SSs will not be considered in the search for the optimal SS.

It is also possible that variations in the sub-process *Investigate type and certainty of information* can result in different MSs being deemed optimal:

- Set acceptance criteria: The use of inadequate criteria for evaluating type and certainty of inspection methods may result in the exclusion of some inspection methods and, therefore, some SSs will not be considered in the search for the optimal SS. For example, one may evaluate a concrete resistivity testing method based on its ability to indicate corrosion of reinforcing bars in a reinforced concrete when the corrosion does exist. If the required level of certainty is set too high, then concrete resistivity is no longer considered. It is, therefore, not passed into the sub-process *Identify SSs to be considered* and thus will not be included in the search for the optimal SS.
- Determine optimal SS: The optimal SS among the SSs to be considered may be determined incorrectly, if the sub-process *Determine optimal SS* (shaded grey in Fig. 2) is conducted based on inadequate or incorrect information, or is in itself conducted incorrectly. Two examples are as follows: (1) If all appropriate inspection time-intervals are not taken into consideration in the determination of the SSs to be investigated, then some SSs will not be considered in the search for the optimal SS. This may be the case when, for example, the organization sets a minimum interval for inspections (Fig. 3); (2) If the expected future behavior is ignored or estimated incorrectly. If the estimated deterioration rate is higher than what it actually is, then the estimated time-intervals of inspections will be shorter than what is actually required. If the future behavior is not known and thus not taken into account, then the inspection time-intervals are likely to be longer or shorter than the optimal ones (Fig. 4).
- Inaccurate estimation of, or overlooking, the ability of the SS to reduce the uncertainty with respect to the bridge behavior in the future (Fig. 5). For example, a manager may choose to use a crack detection technology to identify surface distresses as indicators of on-going corrosion in reinforced concrete when it is believed that the deterioration process is carbonation-induced corrosion. However, if the predominant deterioration process is actually chloride-induced corrosion, it is possible that no surface distress is developed, e.g. where highly soluble corrosion products, as opposed to solid rust, are generated (Angst *et al.* 2012).

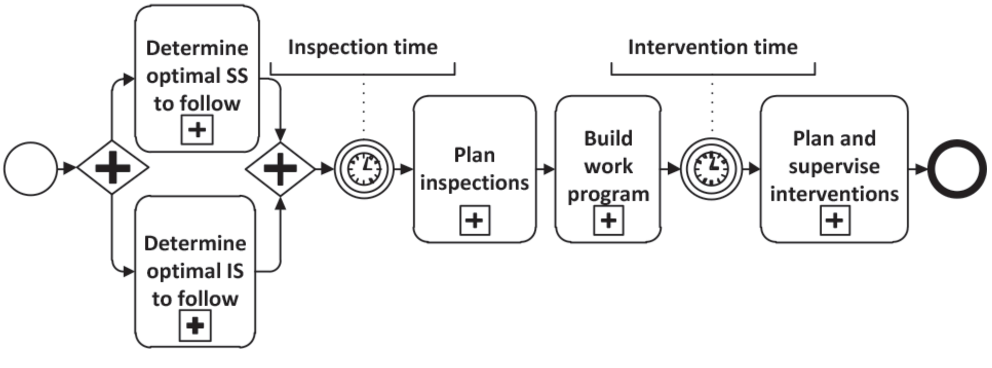

Fig. 1. Principal management processes in a typical bridge management organization

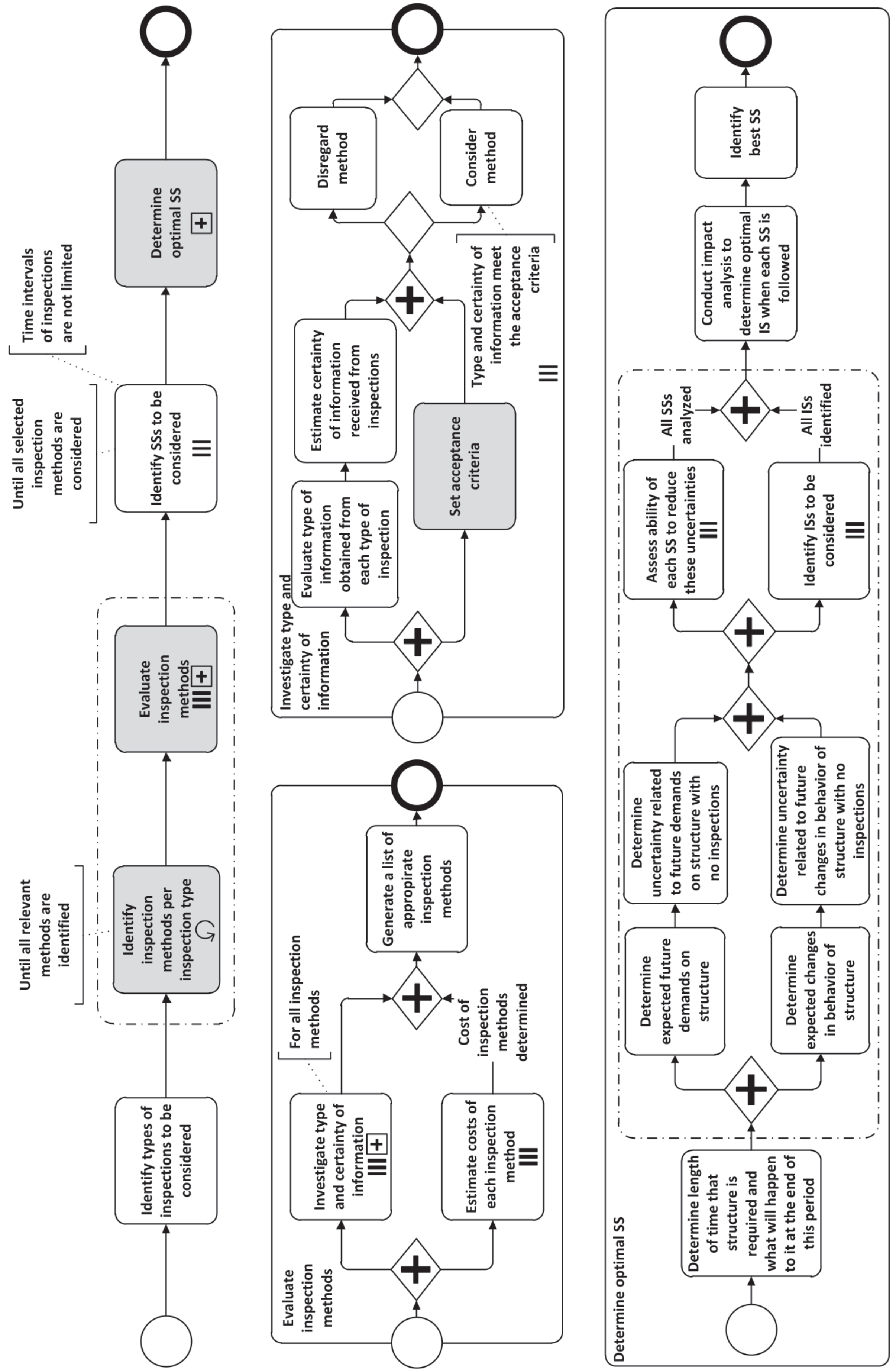

Fig. 2. Process *Determine optimal SS*

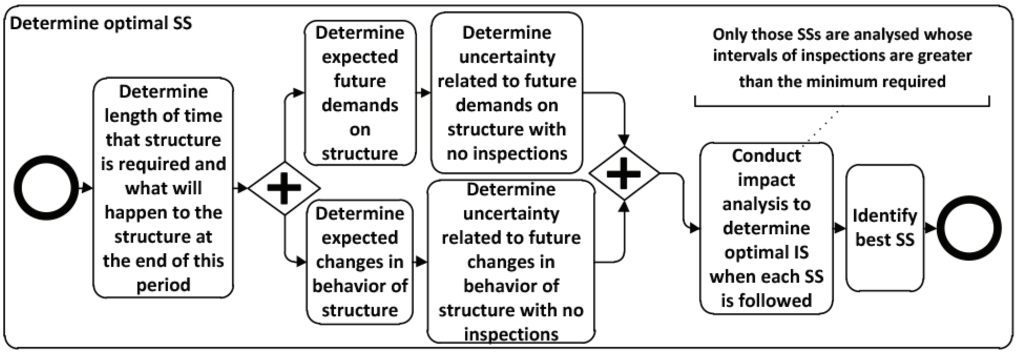

Fig. 3. Sub-process *Determine optimal SS* with limited number of SS to be analyzed

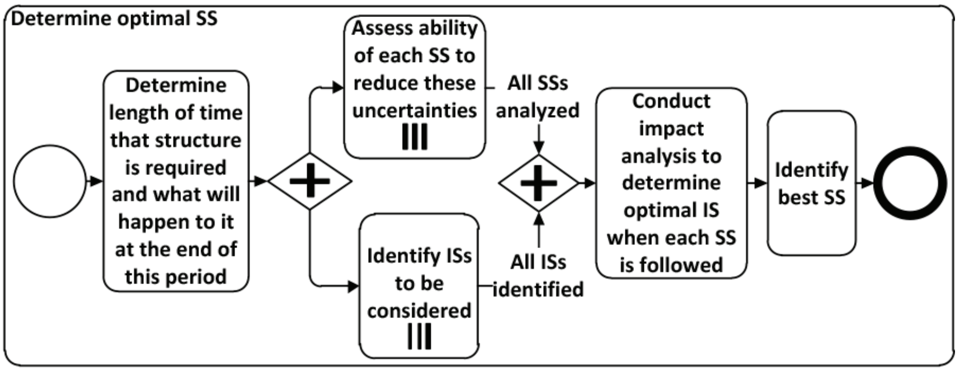

Fig. 4. Sub-process *Determine optimal SS* that does not consider the change of behavior/demand over time

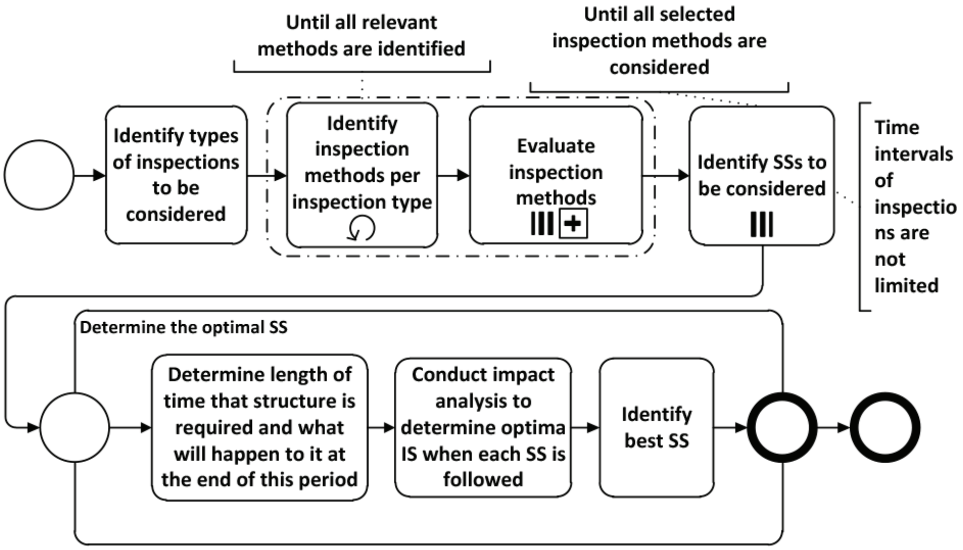

Fig. 5. Process *Determine optimal SS* which does not explicitly take into account the ability of SS to reduce uncertainties

3. Example

3.1. General

In order to show that it is not always possible to determine an OMS without explicitly taking into consideration management processes, how variations in management processes can be evaluated and that the significance of these variations is dependent on the values of the incurred impacts, an example is conducted. This is done by defining three similar but different processes to determine optimal SS (one is the original process shown in Figure 2, and the two others are variations to the original process). These three processes are used to determine three SSs to follow for a reinforced concrete bridge deck and then three MSs are built by combining the three SSs with an IS. The MSs are, then, compared with respect to the total negative impact that each one of the MSs has on the considered stakeholders (owner, user and public) over

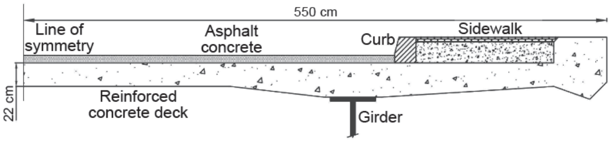

Fig. 6. Bridge deck under consideration

75 units of time. The actual OMS is then determined for sets of unit impact values, and used to demonstrate the ability of each process, in each situation, to be used to find the actual OMS. The following sections give details of how these are done.

3.2. Bridge deck description

The object used in the example is a cast-in-place reinforced concrete bridge deck (Fig. 6). The nominal cover depth of the deck section reinforcement is 25 mm at all locations.

Corrosion of the deck reinforcement, where the corrosion results in an expansive rust product, is the main deterioration process affecting the bridge deck. With time the corrosion of the reinforcement, accelerated by the application of de-icing salts to the road surface, will most likely result in the development of longitudinal cracks in cover concrete followed by spalling and delamination. Eventually, the level of service provided by the bridge deck will no longer be adequate. This behavior is modeled using the Duracrete (1998) corrosion initiation and crack propagation models and the corrosion rate model proposed by Vu *et al.* (2005), as follows:

$$t_i = \left\{ \frac{(1-n)\,\mathrm{c}^2}{4k_e.k_t.k_c.D_0.\mathrm{t}_0{}^n} \left[erf^{-1}\left(1-\frac{C_{cr}}{C_s}\right)\right]^{-2} \right\}^{\frac{1}{1-n}}; \quad (1)$$

$$w(t) = 0.05 + \beta.\left[\int_0^{t_p} i_{corr}.W_t.d\tau - (s_1 + s_2.\frac{c}{d} + s_3.f_t)\right]; \quad (2)$$

$$i_{corr} = \left[\frac{32.13(1-P)^{-1.64}}{d}\right](t-t_i)^{-0.29}. \quad (3)$$

The parameters are described in Table 1. These were obtained by reviewing the design documents, as-built drawings, and measuring the concrete chloride content in a number of core samples taken from the deck. The change over time of the deck condition, if the mean values given in Table 1 are used, is illustrated in Figure 7.

Table 1. Parameters of deck deterioration modeling

	Description	Unit	Distribution	Par. 1	Par. 2
β	position factor	–	normal	0.0104	0.001
X	uncertainty factor	–	normal	1	0.02
P	water/cement ratio	–	normal	0.45	0.02
C	cover depth	mm	normal	25	2
W_t	wetness factor	–	const.	0.4	–
T	time	time units	const.	–	–
N	age factor	–	normal	0.37	0.07
k_e	exposure factor	–	gamma	0.265	0.045
k_t	testing factor	–	const.	1	–
k_c	construction factor	–	const.	1	–
D_0	Diffusion Coeff.	$\mathrm{mm}^2/\mathrm{s}.10^{-12}$	normal	473	95
t_0	constant	–	const.	0.078	–
C_{cr}	critical chloride	% wt. of concrete	log-normal	0.48	0.15
C_s	surface chloride	% wt. of concrete	log-normal	0.146	0.04
S_1	constant	mm	normal	74.4	5.70
S_2	constant	mm	normal	7.3	0.06
S_3	constant	mm/MPa	normal	–17.4	3.20
D	size of rebars	mm	normal	12	0.2
f_t	tensile strength	MPa	normal	5.0	0.5

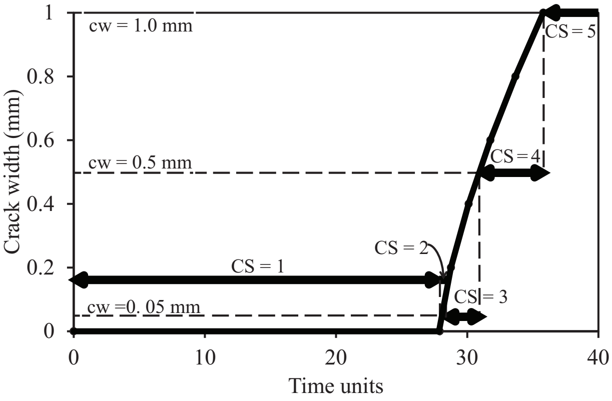

Fig. 7. Illustration of one possible future scenario of the change of deck condition

3.3. Management process to determine inspection strategies

In the original process used to evaluate the inspection methods (hereafter referred to as Process 1) once it is determined which inspection type is to be considered (in-depth inspection in this example), the manager chooses a range of relevant inspection methods, i.e. inspection methods that allow the detection of the speed or severity of the deterioration process (corrosion of the reinforcement in this example), e.g. visual inspection, chloride testing and concrete

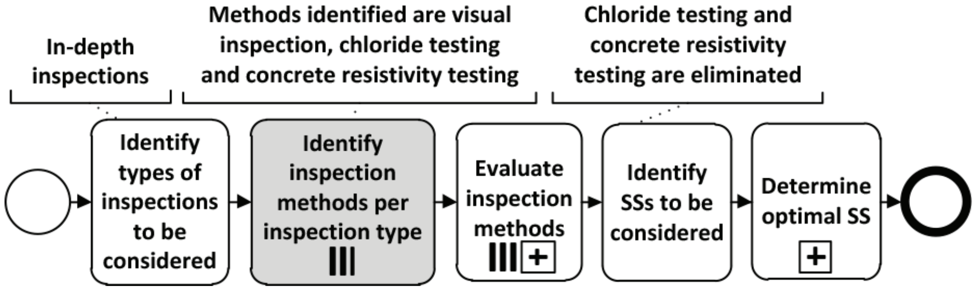

Fig. 8. Process 1: *Determine optimal SS* producing visual inspection as the SS to follow

resistivity testing. If the type and certainty of information obtained from any of these methods do not meet the acceptance criteria set by the manager then those methods are no longer considered. The process is shown in Figure 8.

It is not difficult to imagine that there could be many variations in Process 1. Two possible variations are shown in Figure 9 and Figure 10, which hereafter are referred to as Process 2 and Process 3, respectively. The difference between Process 1 and Process 2 is in the sub-process *Evaluate inspection methods*. The difference between Process 1 and Process 3 is in the activity *Identify SSs to be considered*.

In the original sub-process used to evaluate the inspection methods in Process 1, the upfront costs are considered in conjunction with the type and certainty of the information provided by the inspection method. This is indicated by using the parallel splitting and merging gates. In the sub-process used to evaluate the inspection methods Process 2, however, the evaluation criteria are set in series, i.e. upfront cost criterion comes first and other criteria come later. As a result, some of the inspection methods are initially eliminated due to their higher upfront costs, and thus are not considered in the search for the optimal SS. It is assumed, in this example, that the concrete resistivity test has higher upfront costs and is eliminated in this activity. The remaining inspection methods, i.e. visual inspection and chloride content measurement (CCM), are, therefore, included in the SSs to be investigated.

In the sub-process used to evaluate the inspection methods in Process 3, the activity *Identify SSs to be considered* in Process 1 is replaced with the sub-process *Identify SSs to be considered*. Whereas, in Process 1, the activity *Identify SSs to be considered* does not contain any explicit constraints in terms of inspection time intervals, the sub-process *Identify SSs to be considered* in Process 3 imposes minimum time intervals of inspections. It is assumed, in this example, due to the number of skilled inspection teams compared to the number of bridges to be inspected, that the average amount of time between inspections is to be a minimum of 10 units of time. As a result, any SSs with time intervals smaller than 10 units of time are eliminated from further consideration.

3.4. Management strategies

The MSs investigated were built from combinations of the SSs that emanated from the processes described above for the example concrete bridge deck, and an IS. The SSs are those given in Table 2. The interventions used in the IS are dependent on the condition state (CS) of the deck. The definitions of these CSs are given in Table 3 and the IS investigated and the descriptions of the intervention types of which it is composed are given in Table 4. The investigated MSs are presented in Table 5.

Note that the definitions of the CSs have been selected to take into consideration the criteria that could be used to trigger an intervention. Although it is possible to set many different values for these criteria as thresholds to trigger interventions, and it is possible to use many different criteria to trigger interventions, the ones selected to be used in this example can be detected using the SSs given in Table 2. The best criteria and threshold values to use is a large area of research. Some initial contributions have been made though, for example, Angst *et al.* (2009).

3.5. Estimation of the impacts

In order to evaluate MSs, it is necessary to determine their impacts on the bridge stakeholders. This requires an estimation of the possible impacts and the probability of their occurrence per stakeholder.

3.5.1. Probability of intervention under each management strategy

The probability that a specific condition, described by a limit state, $g_w(x,t)$ is reached at time t is obtained as:

$$P_f(t) = P[g_w(\boldsymbol{x},t) \le 0], \tag{4}$$

where: x is the vector of random variables used to determine if the threshold for entering the CS has been reached; and w is the threshold (e.g. development of

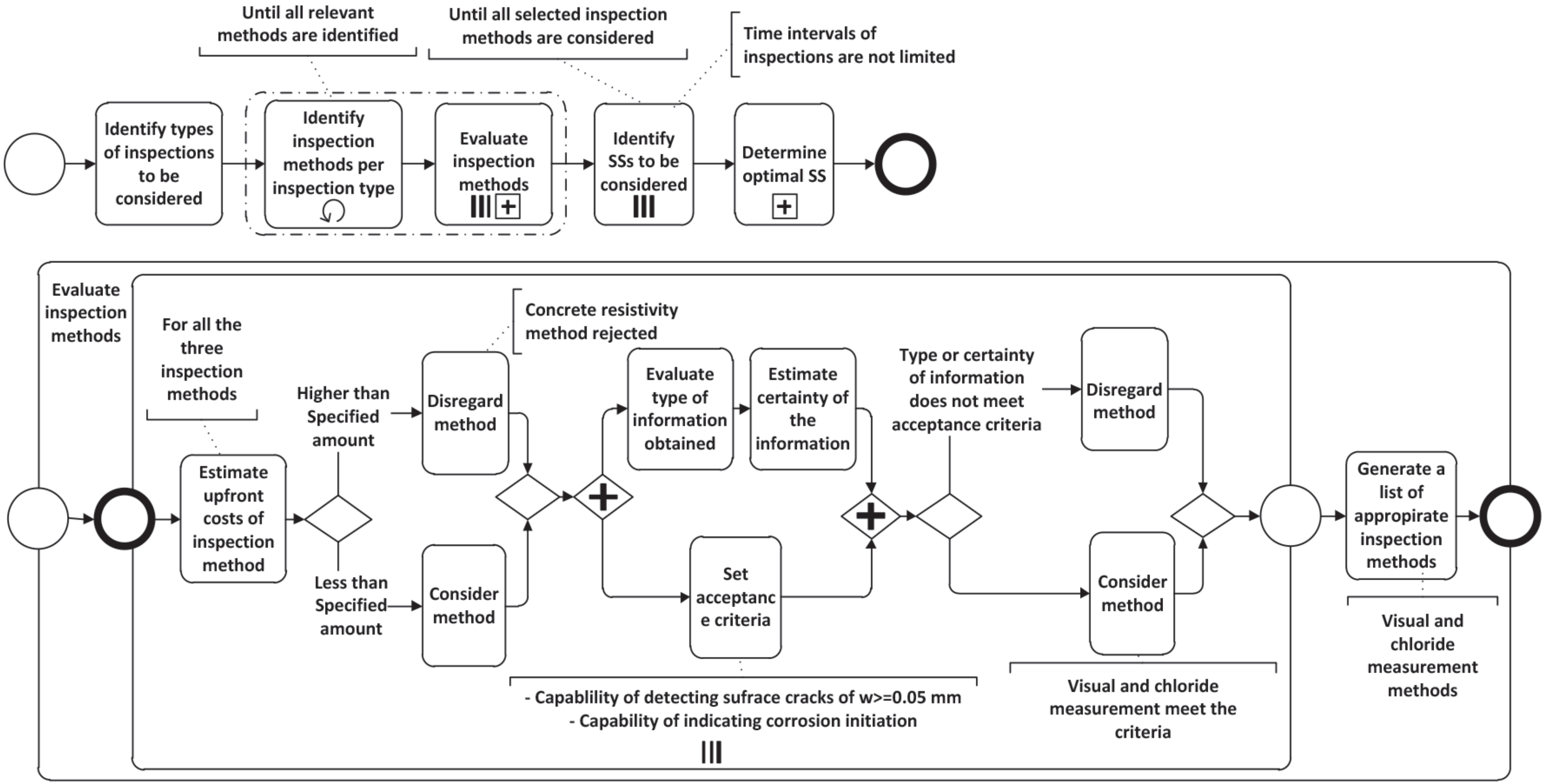

Fig. 9. Process 2 resulting in elimination of the concrete resistivity method in the search for the optimal SS

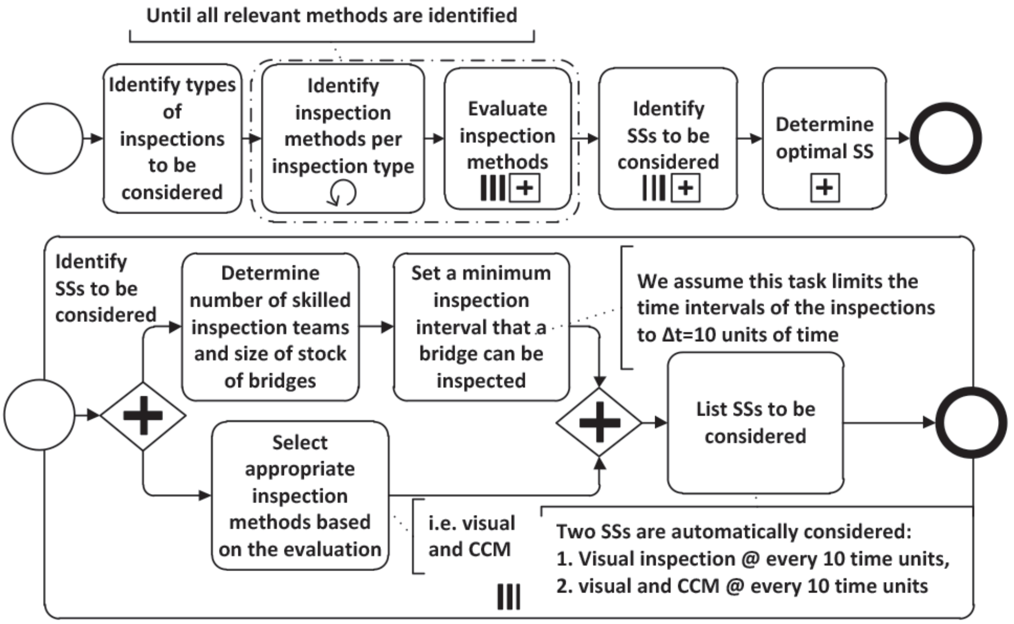

Fig. 10. Process 3 resulting to elimination of SSs with $\Delta t \leq 10$ units of time in the search for the optimal SS

Table 2. Investigated SSs

Mgmt. Process	SS No.	In-depth inspection	Condition indicator	Intervals (time units)	Description
1	1	Only visual	Corrosion-induced cracks width	10	A detailed visual inspection to identify crack of $cw > 0.05$ mm
2	2	Visual & CCM	Corrosion-induced cracks width, and, chloride content	10 (visual) 20 (CCM)	As above, plus, a chloride measurement to determine the chloride content in the cover
3	3	Visual & CCM	Same as above	10 (visual) 10 (CCM)	Same as above

Table 3. Description of condition states

CS	Description	
	Chloride content requirement, C, at the surface of the reinforcement	Crack width requirement, cw
CS 1	$C < C_{cr}$	$cw <= 0.05$ mm
CS 2	$C >= C_{cr}$	$cw <= 0.05$ mm
CS 3		$cw <= 0.5$ mm
CS 4		$cw <= 1.00$ mm
CS 5		$cw > 1.00$ mm

Table 4. Intervention types and expected effects

Intervention type	Description	CS expected immediately following intervention				
		1	2	3	4	5
Do Nothing	Only routine maintenance interventions are executed	1	2	3	4	5
Int. 1	Chloride removal	N/A	1	3	4	5
Int. 2	Chloride removal and sealing of all cracks	N/A	1	1	1	N/A
Int. 3	Removal of concrete and addition of a new layer	N/A	1	1	1	1

cracks x mm in width). It is assumed that an intervention is executed immediately once it is known that a CS is reached; thus the probability of executing an intervention is equivalent to the probability of identifying that the object has entered a CS. The probabilities are shown in Figure 11. The formulas used to estimate the probabilities of executing an intervention of each type is given in Table 6 where $g_A(x,t)$, $g_B(x,t)$, $g_C(x,t)$, and $g_D(x,t)$ are limit state functions that indicate the limits of CS 5, CS 4, CS 3 and CS 2, respectively, t_i is the intervention time (measured from the time of construction) and t_1 is the time elapsed after the last intervention. For example, an Int. 1 is conducted on the condition that the deck is in CS 2. Thus, the probability that an Int. 1 is needed equals the probability of the deck being in a CS greater than 2 minus the probability of the deck being in CS 1.

Table 5. Investigated MSs

MS	SS		IS						Indicator of CS
	No.	Description	No.	CS 1	CS 2	CS 3	CS 4	CS 5	
1	1	Visual (10)	1	DN	Int. 1	Int. 2	Int. 2	Int. 3	cw & C
2	2	Visual (10), CCM (20)	1	DN	Int. 1	Int. 2	Int. 2	Int. 3	cw & C
3	3	Visual (10), CCM (10)	1	DN	Int. 1	Int. 2	Int. 2	Int. 3	cw & C

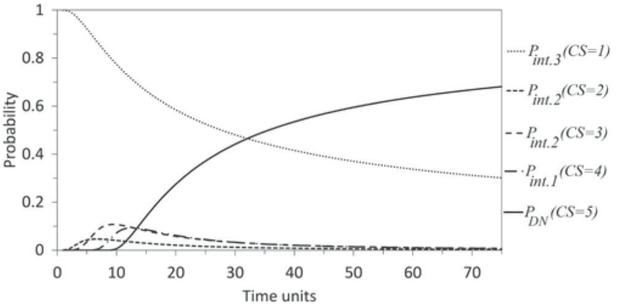

Fig. 11. Probability of the deck being in each CS

Since the ranges of values used to define being in CS 2, CS 3 and CS 4 are relatively narrow when compared to the ranges of values used to define being in CS 1 and CS 5 (Fig. 7), so are the probabilities that the bridge deck is in CS 2, CS 3 and CS 4 relatively small when compared to the probabilities of being in CS 1 or CS 5.

3.5.2. Probabilities of interventions

To determine the impacts, an event tree analysis is used. The probability that an intervention of type j is executed after inspection at time t_i when scenario k of MS l is being followed is obtained using Eqn (5), where $P_{Int.1}$, $P_{Int.1}$, etc. are the probabilities of the execution of interventions per IS (Table 6) and l is the MS investigated (l = 1, 2 or 3):

$$\left(\left[P_j(t)\right]_{t=t_i-t_l}\right)_k = \begin{cases} \left[\left(P_{DN}\right)t = t_i - t_l\right]_k \\ \left[\left(P_{Int.1}\right)t = t_i - t_l\right]_k \\ \vdots \end{cases}. \qquad (5)$$

The probability that scenario k of MS l is realized is:

$$P_{B_k} = \prod_{i=1}^{m}\left(\left[P_j(t)\right]t = t_i - t_1\right)_k, \qquad (6)$$

where: *m* is the number of inspections to be performed in the investigated time period (e.g. *m* = 7 for MS 3); and *k* is the number of branches of the event tree.

Table 6. Equations to estimate the probability of intervention under each MS

MS	Intervention type	CS	Probability
1, 2 or 3	Do Nothing	1	$P_{DN}\left(t\middle\vert CS=1\right)=$ $1-P\left[g_D(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$
	Int. 1	2	$P_{Int.1}\left(t\middle\vert CS=2\right)=P\left[g_D(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$ $-P\left[g_C(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$
	Int. 2	3	$P_{Int.2}\left(t\middle\vert CS=3\right)=P\left[g_C(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$ $-P\left[g_B(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$
	Int. 2	4	$P_{Int.2}\left(t\middle\vert CS=4\right)=P\left[g_B(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$ $-P\left[g_A(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$
	Int. 3	5	$P_{Int.3}\left(t\middle\vert CS=5\right)=P\left[g_A(\boldsymbol{x},t)_{t=t_i-t_l}\le 0\right]$

3.5.3. Stakeholders and impact types

Although it is possible to identify many different stakeholder and impact types, in this example, the ones in Table 7 are used. Details on the formula used to determine the impacts can be found elsewhere (Jamali, Adey 2012).

3.6. Analysis of inspection strategies

In order to show how the values of impact types, defined in Table 7, can change the significance of the variation in management processes on the optimality of MSs, different sets of values for each impact type are considered (Table 8). The values for travel time and accidents are given in terms of cost per day, and must be multiplied by the number of days expected for each inspection or intervention (Table 9). Each set of impact values is different from the reference set with respect to at least one impact value. The impact types being different than those of the reference set are shaded grey in the table. In order to take into account time value of money, a discount rate of 2% is used. Using these values, the expected negative impacts if each MSs was followed over 75 units of time were then determined.

4. Results

The negative impacts associated with the investigated MSs are given in Table 10.

Table 7. Stakeholders, impact types and determination of the impacts

Stakeholder		Impact type level 1		Impact type level 2			Model (see Appendix for description of parameters)
L.	Description	Label	Description	Label	Description	Symbol	
Owner	the persons who are responsible for decisions with respect to physically modifying the infrastructure	Intervention	the impact of executing interventions	Detailed inspections	… used to perform detailed inspections	$I_{ins,o}$	$I_{ins,o} = \sum_k \left(I_{ins,o}\right)_k P_{B_k}$ $\left(I_{ins,o}\right)_k = \sum_{t_i=t_1}^{n_{VT}\times\Delta T_{VT}} \frac{I^o_{VT}}{(1+r)^{t_i}} d_{VT} + \sum_{t_i=t_1}^{n_{CCM}\times\Delta T_{CCM}} \frac{I^o_{CCM}}{(1+r)^{t_i}} d_{CCM}$
				Detailed intervention	…used to execute detailed interventions	$I_{int,o}$	$I_{int,o} = \sum_k \left(I^o_{ins}\right)_k P_{B_k}$ $\left(I^o_{ins}\right)_k = \sum_{i,j} \frac{\left(I^o_{ins}\right)_{i,j,k}}{(1+r)^{t_i}}$
Users	the persons who are using the roads	Travel time	the impact of travel in terms of time lost	Detailed inspection	the economic impact of wasting e time due to detailed inspections	$I_{VT,u}$ $I_{CCM,u}$	$I_{ins,u} = \sum_k \left(I_{ins,u}\right)_k P_{B_k}$ $\left(I_{ins,u}\right)_k = \sum_{t_i=t_1}^{n_{VT}\times\Delta T_{VT}} \frac{I^{u,t}}{(1+r)^{t_i}} d_{VT} + \sum_{t_i=t_1}^{n_{CCM}\times\Delta T_{CCM}} \frac{I^{u,t}}{(1+r)^{t_i}} d_{CCM}$
				Detailed intervention	… due to detailed interventions	$I_{int,u}$	$I_{int,u} = \sum_k \left[\left(\sum_{i,j} \frac{\left(d_{int}\right)_{i,j,k}}{(1+r)^{t_i}} I^{u,t}\right) P_{B_k}\right]$
		Accident	the impact of accidents on the users	Detailed intervention	the social impact due to injury or death	$I_{ac,u}$	$I_{ac} = \sum_k \left(I_{ac}\right)_k P_{B_k}$ $\left(I_{ac}\right)_k = \left(\sum_{i=1}^{m} \int_{t_i}^{t_{i+1}} f(t) \frac{I^a}{(1+r)^t} dt\right)_k$
Public	persons not in the vicinity of the road	Accident	the impact due to injury or death	Detailed intervention	the economic impact due to injury or death	$I_{ac,p}$	

Table 8. Values of impacts during inspections and interventions

Stakeholder	Impact type	Symbol.	Cost per	Set[a]	
				1 (ref.)	2
Owner	Int. 3	$I^o_{Int.3}$	int.	100	100
	Int. 2	$I^o_{Int.2}$	int.	12.5	12.5
	Int. 1	$I^o_{Int.1}$	int.	10	10
	visual insp.	I^u_{VT}	insp.	0.5	0.5
	CCM insp.	I^u_{CCM}	insp.	1.5	1.5
User	travel time	$I^{u,t}$	day	1	5
User/Pub.	Accident	I^a	day	200	200

[a] Values in percentages of the impact on the owner of executing Int. 3.

Table 9. Duration of inspection and intervention

Inspection/Intervention	No. of days
Visual insp.	1
CCM insp.	1
Int. 1	14
Int. 2	21
Int. 3	28

It can be seen that it is not possible to determine the OMS if the processes are not considered because if they were not the OMS determined would only be determined if process 2 was followed, if the set 1 of impact values were used. If process 1 or 3 were followed, MS1 and MS3, two sub-optimal MSs would be followed.

It can also be seen that variations in the process *Determine optimal SS* can have an effect on the ability to

Table 10. Expected impacts of the OMSs

Set of impact values	MS	Owner		User		User/ Public	Total[a]
		C_{INS}	C_{INT}	$(C_U)_{INS}$	$(C_U)_{INT}$	C_{AC}	
1	1	1.71	73.02	3.42	34.16	53.15	165.45
	2	3.08	69.52	4.34	28.03	48.01	152.97
	3	5.22	68.35	5.76	28.58	47.04	154.95
2	1	1.71	73.02	14.12	147.79	53.15	289.79
	2	3.08	69.52	21.68	140.15	48.01	282.44
	3	5.22	68.35	28.81	142.88	47.04	292.30

[a] All values given as a percentage of the owner cost of replacement.

determine the actual OMS. For example, the difference between process 2 and process 1, which result in neglecting CCM in inspections, means that the actual OMS is not found, if set 1 unit impact values are used. The value of an organization switching from process 1 to process 2 would, therefore, in this one particular case, be approximately 12 monetary units (mus). When set 2 is used the value is 7 mus.

The difference between process 3 and 2, which result in neglecting the possibility to do inspections every 20 units of time, means that the actual OMS is not found, if set 1 unit impact values are used. The value of an organization switching from process 3 to process 2 would, therefore, in this one particular case, be approximately 2 mus. When set 2 is used the value is approximately 10 mus. It is also interesting to note that, in this case, the MS in which more information is generated is less favorable than the one in which less information is generated (MS2 includes inspections with CCM ever 20 units of time where MS3 includes inspections with CCM every 10 units of time).

As can be seen, changes in the unit impact values results, unsurprisingly, in changes in the impacts incurred per MSs and, therefore, in different values of organization changing from one process to another.

Conclusions

The work presented in this paper shows that:

- it is not always possible to determine an optimal management strategy without explicitly taking into consideration management processes;
- how variations in management processes can be evaluated; and
- that the significance of these variations is dependent on the values of the incurred impacts.

As variations in the processes can be analyzed it is not hard to imagine that similar analyses could be used to identify areas of improvement within in bridge management organizations, which would result in the determination of management strategies that would result in lower overall negative impacts linked to bridges.

Further work should include investigation of decision making processes in real organizations and their effect on determination of management strategies, and the development of a simple methodology to be used by bridge managers to determine the effect of management processes on the optimality of management strategies.

References

Angst, U.; Elsener, B.; Jamali, A.; Adey, B. 2012. Concrete cover cracking owing to reinforcement corrosion – theoretical considerations and practical experience, *Materials and Corrosion* 63(1): 1–9.

Angst, U.; Elsener, B.; Larsen, C. K.; Vennesland, Ø. 2009. Critical chloride content in reinforced concrete – a review, *Cement and Concrete Research* 39(12): 1122–1138. http://dx.doi.org/10.1016/j.cemconres.2009.08.006

Baker, M. J.; Descamps, B. 1999. Reliability-based methods in the inspection planning of fixed offshore steel structures, *Journal of Constructional Steel Research* 52(1): 117–131. http://dx.doi.org/10.1016/S0143-974X(99)00031-0

Balasubramanian, S.; Gupta, M. 2005. Structural metrics for goal based business process design and evaluation, *Business Process Management Journal* 11(6): 680–694. http://dx.doi.org/10.1108/14637150510630855

Braghetto, K. R.; Ferreira, J. E.; Vincent, J.-M. 2010. Performance analysis modeling applied to business processes, in *Proceedings of the 2010 Spring Simulation Multiconference*, 11–15 April 2010, Orlando, Florida, 1–8. http://dx.doi.org/10.1145/1878537.1878665

Canevet, C.; Gilmore, S.; Hillston, J.; Prowse, M.; Stevens, P. 2003. Performance modelling with UML and stochastic process algebras, *IEE Proceedings, Computers and Digital Techniques* 150(2): 107–120. http://dx.doi.org/10.1049/ip-cdt:20030084

Dijkman, R. M.; Dumasb, M.; Ouyang, C. 2008. Semantics and analysis of business process models in BPMN, *Information and Software Technology* 50(12): 1281–1294. http://dx.doi.org/10.1016/j.infsof.2008.02.006

Duracrete. 1998. *Modeling of degradation*. The European Union – Brite EuRam III, Project BE95-1347.

Faber, M. H.; Sørensen, J. D. 2002. Indicators for inspection and maintenance planning of concrete structures, *Structural Safety* 24(2–4): 377–395. http://dx.doi.org/10.1016/S0167-4730(02)00033-4

Frangopol, D. M. 1997. Life-cycle cost design of deteriorating structures, *Journal of Structural Engineering* 123(10): 1390–1399. http://dx.doi.org/10.1061/(ASCE)0733-9445(1997)123:10(1390)

Jamali, A.; Adey, B. T. 2012. The evaluation of optimal inspection strategies considering management decision processes, in *Annual Conference of Canadian Society for Civil Engineers (CSCE 2013)*, 29 May – 1 June 2013, Montreal, QC, Canada.

Mendling, J. 2008. Metrics for business process models, in W. V. D. Aalst, J. Mylopoulos, M. Rosemann, M. J. Shaw, C. Szyperski (Eds.). *Metrics for process models: empirical foundations of verification, error prediction, and guidelines for correctness*. Berlin, Heidelberg: Springer, 103–133.

Nissen, M. E. 2002. *Toward enterprise process engineering: configuration measurement and analysis*. Monterey, California: Naval Postgraduate School. 28 p.

Puhlmann, F.; Weske, M. 2006. Investigations on soundness regarding lazy activities, in *Proceedings of the 4th International Conference on Business Process Management*, 5–7 September 2006, Vienna, Austria, 145–160.

Qin, J.; Faber, M. H. 2012. Risk management of large RC Structures within spatial information system, *Computer-Aided Civil and Infrastructure Engineering* 27(6): 385–405.
http://dx.doi.org/10.1111/j.1467-8667.2012.00757.x

Reynoso, L.; Rolón, E.; Genero, M.; García, F.; Ruiz, F.; Piattini, M. 2009. Formal definition of measures for BPMN models, in A. Abran, R. Braungarten, R. Dumke, J. Cuadrado-Gallego, J. Brunekreef (Eds.). *Software process and product measurement.* Berlin Heidelberg: Springer, 285–306.
http://dx.doi.org/10.1007/978-3-642-05415-0_21

Rolón, E.; Ruiz, F.; García, F.; Piattini, M. 2006. Applying software metrics to evaluate business process models, *CLEI Electronic Journal* 9(1): 1–15.

Thoft-Christensen, P.; Sørensen, J. D. 1987. Optimal strategy for inspection and repair of structural systems, *Civil Engineering and Environmental Systems* 4(2): 94–100.
http://dx.doi.org/10.1080/02630258708970464

Tjaden, G. S. 1999. *Business processes structural analysis*. Georgia Tech Center for Enterprise Systems. 26 p.

Vu, K. A. T.; Stewart, M. G.; Mullard, J. 2005. Corrosion induced cracking; experimnetal data and predictive models, *ACI Structural Journal* 102(5): 719–726.

Weske, M. 2007. *Business process management: concepts, languages, architecture.* Berlin: Springer. 368 p.

Wong, P. Y. H.; Gibbons, J. 2008. A process semantics for BPMN, *Lecture Notes in Computer Science* 5256: 355–374.
http://dx.doi.org/10.1007/978-3-540-88194-0_22

Appendix

The parameters used in the impact evaluation models (Table 7) are defined as follows: t_i – time of inspection number i (time units); d_{CCM} and n_{CCM} – time required to conduct a CCM (days) and number of scheduled CCMs, respectively; ΔT_{CCM} and ΔT_{VT} – time-intervals of the CCMs and visual inspections, respectively, (time units); $I^o_{Int.3}$ and I^o_{VT} – Impact on owner of conducting a CCM and a visual inspection, respectively (CHF/day); I^u_{CCM} and I^u_{VT} – Impact on user of increased travel time due to a CCM and a visual inspection, respectively (CHF/day); $I^{u,t}$ – Impact on user cost of travel time to be borne by users (CHF/day); $(I^o_{ins})_{i,j,k}$ and $(d_{int})_{i,j,k}$ – Impact on owner (in CHF) due to, and duration (in days) of, an intervention of type j executed after the inspection at time t_i, respectively; r – discount rate; I^a – Impact due to occurrence of spalling; $f(t)$ – probability density function.

Amin JAMALI. He is a Research Associate at the Institute of Construction and Infrastructure Management, Swiss Federal Institute of Technology. His research interests include optimal management strategies for infrastructure.

Bryan T. ADEY. He is the Chair of Infrastructure Management Group at Swiss Federal Institute of Technology. His research interests include optimal management strategies for infrastructure.