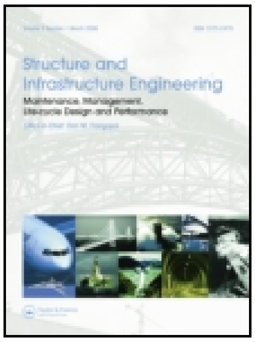

Taylor & Francis
Taylor & Francis Group

Structure and Infrastructure Engineering
Maintenance, Management, Life-Cycle Design and Performance

ISSN: 1573-2479 (Print) 1744-8980 (Online) Journal homepage: http://www.tandfonline.com/loi/nsie20

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To cite this article: Zanyar Mirzaei & Bryan T. Adey (2015) Investigation of the use of three existing methodologies to determine optimal life-cycle activity profiles for bridges, Structure and Infrastructure Engineering, 11:11, 1484-1509, DOI: 10.1080/15732479.2014.976577

To link to this article: http://dx.doi.org/10.1080/15732479.2014.976577

Published online: 17 Nov 2014.

Structure and Infrastructure Engineering, 2015
Vol. 11, No. 11, 1484–1509, http://dx.doi.org/10.1080/15732479.2014.976577

Investigation of the use of three existing methodologies to determine optimal life-cycle activity profiles for bridges

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(*Received 21 January 2014; final version received 12 August 2014; accepted 13 August 2014; published online 18 November 2014*)

Bridges are vital objects in public road networks. They should be managed to ensure that they result in minimum costs for all stakeholders, e.g. intervention costs for the owner and travel time costs for the user. An important part of bridge management is, therefore, the determination of the optimal interventions to be executed on a bridge over its life cycle, i.e. the optimal life-cycle activity profile, which adequately takes these costs into consideration. This is challenging as some of the costs to be considered are related to the condition of the elements of which a bridge is composed, whereas others are related to the performance of the structure as a whole and only indirectly to the performance of the individual elements. Among the methodologies developed recently, a few have the potential to overcome this challenge. In this paper, the possibility of using two state-of-the-art methodologies and a state-of-practice methodology to determine optimal life-cycle activity profiles are investigated. This is done by using them to determine the optimal life-cycle activity profile for a multi-span weathering steel girder bridge. The strengths and weaknesses of each are discussed.

Keywords: optimal life-cycle activity profiles; bridge maintenance; element-level; structure-level; interventions

1. Introduction

Over the past two decades, an increasing number of computer-aided bridge management systems have been developed (Mirzaei, Adey, Klatter, & Kong, 2012). One of their functions is to help the bridge manager in determining when to intervene on bridges and what intervention to execute once it is decided to intervene. This is done through the determination of optimal intervention strategies for elements and bridges and the resulting work programmes.

(1) Element intervention strategies are defined herein as all-encompassing plans as to the interventions that should be executed, and the conditions under which the intervention should be executed, for an element without consideration of the other elements in a bridge.
(2) Bridge intervention strategies are defined herein as all-encompassing plans as to the interventions that should be executed, and the conditions under which the interventions should be executed, for all elements in a bridge taking into consideration all other elements in the bridge.
(3) Work programmes are defined herein as the specific plans as to the interventions to be executed for a considered set of bridges taking into consideration the actual conditions of all elements in the bridges. When a work programme is made for a specific bridge from construction to demolition, it is referred to as a life-cycle activity profile. Life-cycle activity profiles can be used as a precursor to the determination of work programmes for multiple bridges over time periods that do not necessarily coincide with the life cycle of a bridge.

Many of the methodologies used to determine the element intervention strategies, bridge intervention strategies and work programmes to be followed are focused on the minimisation of owner costs (Andersen & Lauridsen, 1994; Green & Richardson, 1994; Saito & Sinha, 1989; Thompson, Ellis, Hong, & Merlo, 2003; Thompson, Small, Johnson, & Marshall, 1998). Due to the increasing desire to ensure that our society is sustainable, however, it is of increasing interest to be able to take into consideration costs to other stakeholders in the determination of the optimal intervention strategies and work programmes, e.g. travel time costs and accident costs. Work that has been conducted in this area includes that done by Thompson et al. (2000), Thoft-Christensen (2008), Pakrashi et al. (2011), Gervasio and da Silva (2013) and Fernando, Mirzaei, Adey, and Ellis (2012).

The consideration of costs to other stakeholders is challenging as many of the costs are related to the performance of the structure as a whole and are only indirectly related to the performance of the individual

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elements. Something that requires more sophisticated modelling than that currently used in state-of-the-art management systems, which relate costs to the condition of elements. Among recently developed methodologies, however, there are a few that appear capable of doing this: one by Fernando, Adey, and Walbridge (2013), which can be used to build global condition states (CSs) for the bridge based on the CSs of the elements and associates bridge performance levels with each global CS, and another by Adey and Hajdin (2005), which can be used to bundle element-level interventions using inventory theory.

In the work presented in this paper, these two methodologies were compared with a state-of-practice methodology, which is considered representative of those used in recent generation bridge management systems, e.g. QBMS (Ellis et al., 2008). They are compared with respect to their ability to be used to determine the optimal life-cycle activity profiles for a weathering steel box girder bridge with a concrete deck over a 75-year period, taking into consideration numerous element-level and bridge-level costs. Only maintenance interventions were considered, i.e. no improvement to the structure. The strengths and weaknesses of using each methodology to take into consideration element and structure-level costs are discussed.

2. Background

The development and use of computerised bridge management systems to support bridge managers in their decision-making began in the 1970s (Dunn & Bizette, 1972). This development was accompanied by the development of methodologies to determine the intervention strategies and work programmes to be followed. In the remainder of this chapter, the evolution of the methodologies is discussed. The discussion is grouped by time period and whether the methodologies were used in practice of research.

2.1. 1972–1982: practice

Methodologies developed between 1972 and 1982 were principally developed to provide an overview of current intervention needs and costs so that work programmes could be developed that did not exceed available resources. Only the owner costs of executing interventions were taken into consideration (National Research Council [NRC], 1973). This was done by estimating the costs of executing interventions of different types on elements in different CSs, by estimating the unit costs of these interventions and adjusting them to take into consideration the CSs of the elements to be included in the work programme and the extent of the intervention on the elements. No structure-level costs were taken into consideration in these methodologies (Richards, 1978). In most advanced of these methodologies, the intervention costs, together with the intervention effectiveness, were used to determine optimal element intervention strategies and in the element-level interventions to be included in the work programme (e.g. American Public Works Association [APWA], 1980; Kulkarni, Finn, Golabi, Johnson, & Alviti, 1980). These methodologies were, however, not capable of determining the optimal bridge intervention strategies or optimal work programmes.

2.2. 1983–1992: practice

Methodologies developed between 1983 and 1992 were principally developed to determine work programmes that were expected to result in the most benefit without exceeding constraints. Structure-level impacts were taken into consideration in the determination of work programmes by attributing additional benefits to interventions to be considered so that interventions could be prioritised using simple cost-benefit analysis when not all interventions could be executed due to budget constraints. The structure-level costs considered in these methodologies mainly comprised travel time and accident costs incurred by the users of the bridge. Their values were, either determined outside of the bridge management system, based on the values of bridge level performance indicators such as load capacity, clearance and alignment (Al-Subhi, Johnston, & Farid, 1989, 1990; Arner, Kruegler, McClure, & Patel, 1986; Jiang, 1990; Jiang & Sinha, 1989; Johnston & Zia, 1984; Kulkarni & Til, 1984), and entered into the systems manually, or determined within the systems using simplified estimation methods. The methodologies that gained in use during this period were those that could determine optimal element intervention strategies and gave suggestions as to the work programmes to be followed. They were not yet capable of determining optimal bridge intervention strategies or optimal work programmes.

2.3. 1993–2013: practice

Methodologies developed after 1992 and used in many existing BMSs, such as Pontis (Thompson et al., 1998) and KUBA (Hajdin, 2001; Ludescher & Hajdin, 1998), were developed to determine optimal element intervention strategies, and then, based on these suggest the work programmes to be followed. For example, Golabi, Thompson, and Hyman (1992) and Golabi and Shepard (1997) developed a methodology to determine optimal element intervention strategies for the Pontis BMS based on the Markov decision process. These optimal element intervention strategies were then used to determine the work programmes to be implemented using agency rules, e.g. if an intervention is to be executed on an abutment and the bridge deck is in CS 2, execute an intervention on the bridge deck even if it is not in a CS in which it is considered optimal to execute an intervention, or if any element in the bridge is to be painted, paint all elements. It is through the definition of these agency rules that the bridge intervention strategies were determined.

There was variation in the degree of conversion of element intervention strategies into bridge intervention strategies. Some methodologies implemented in bridge management systems determine the interventions to be included in work programmes directly from the element intervention strategies e.g. in KUBA an intervention included in the work programme was exactly the same as the intervention that resulted from following the optimal element intervention strategies. Others, such as those used in the Indiana DOT BMS (Sinha, Zhang, & Woods, 2000; Sinha, Labi, McCullouch, Bhargava, & Bai, 2009) and the OBMS (Ellis, Thompson, Gagnon, & Richard, 2008; Thompson et al., 2003), determined the interventions to be included in work programmes based on predetermined bridge intervention strategies, that have been developed taking into consideration the optimal element intervention strategy and were represented as knowledge-based models (Omer, 2005). In the determination of the work programmes to be followed when it is not possible to execute all interventions, most methodologies used some form of incremental cost-benefit analyses and include the interventions with highest overall benefit-cost ratios in the work programme.

Element-level costs were taken into consideration in the determination of the optimal element intervention strategy for each element type and structure-level costs were taken into consideration in the development of bridge intervention strategies, at least indirectly, and in the building of work programmes, through the prioritisation of interventions using incremental cost-benefit analysis in the cases where it was not possible to execute all interventions. The element-level costs were those incurred by the owner and calculated based on the extent of the intervention multiplied by the unit costs. The structure-level costs often included the reductions in accident costs, vehicle operating costs, and travel time costs (Bai, Labi, Sinha, & Thompson, 2011; Son & Sinha, 1997) and were entered manually for each bridge on which interventions were to be executed. The reason for consideration of the structure-level costs was principally to take into consideration improvements to the level of service to be provided by the bridge, such as the increasing of load carrying capacity, the widening of traffic lanes or the increasing of vertical clearance (Johnston, Chen, & Abed-Al-Rahim, 1994; Thompson et al., 2000).

During this time period, an increasing number of bridge management system developers began to represent the condition of the whole bridge with an indicator. This was done principally for communication purposes with non-technical persons, but in some cases for the prioritisation of interventions within work programmes. These indicators were generally based on multiple factors, such as serviceability, functional obsolescence and structural reliability. Examples include the Bridge Condition Index (Blakelock, Day, & Chadwick, 1999), *Sufficiency Rating* (Federal Highway Administration [FHWA], 1995), *Repair Index* (Soderqvist & Veijola, 2000) and *Weighting factor method* (Shepard & Johnson, 2001). These measures of the overall bridge performance were not yet being used to determine optimal bridge intervention strategies or optimal work programmes, and they had no direct link to how the condition of elements affect the performance of the bridge or the costs related to overall bridge performance.

2.4. 2003–2013: research

In research, numerous methodologies have been proposed that could be used to determine optimal bridge intervention strategies and optimal work programmes, namely Adey and Hajdin (2005), Elbehairy, Hegazy, and Soudki (2009), Fernando et al. (2013) and Huang and Huang (2012).

Adey and Hajdin (2005) investigated a methodology based on inventory theory (Zipkin, 2000) to determine optimal bridge life-cycle activity profile, explicitly taking into consideration the reduction in costs due to executing interventions on multiple elements simultaneously. In this methodology, both element and structure-level costs were taken into consideration. The element-level costs associated with the execution of interventions were taken into consideration using a fixed part, related to whether or not an intervention is executed, and a variable part, related to the extent of the intervention executed. The structure-level costs associated with the execution of interventions were taken into consideration using only a fixed part. Although not done in Adey and Hajdin (2005), the methodology could also be used to develop optimal element and bridge intervention strategies, as well as optimal work programmes.

Elbehairy et al. (2009) proposed a methodology based on the maximisation of benefit/cost ratios to determine the intervention to be executed on the bridge in the next 5 years, where benefits are considered as positive difference in overall bridge condition per year. The interventions to be included executed were the ones that maximise the benefit/cost ratio for the bridge. Only element-level costs were taken into consideration. This was done by estimating the intervention cost of each element for each year of the investigated time period. Although in this methodology an overall bridge condition rating was used in determination of the benefit/cost ratios, and not the structure-level costs, related to the overall bridge condition, it can be imagined that only small modifications would be necessary to do so.

Fernando et al. (2013) proposed a methodology based on the concept of structure-level performance states to determine the optimal bridge intervention strategies. In this methodology, as costs are directly attributed to each structure performance state, which can occur due to each combination of element CSs, both element and structure-level costs can be taken into consideration. Although it can be imagined that life-cycle activity profiles could be built using such a methodology, in a way similar to that done in existing bridge management systems, no such effort was made in Fernando et al. (2013).

Huang and Huang (2012) proposed a methodology to determine life-cycle activity profiles that result in the minimum owner and user costs during the interventions. In this methodology, the element intervention strategies are defined using element CSs and the combinations of interventions that would be executed in each year if an intervention were executed are determined. Using predefined CS ranges in which the interventions could be executed, an investigation is then undertaken to minimise owner and user costs during the execution of interventions by combining element interventions.

In this methodology, both element and structure-level costs are taken into consideration when determining optimal life-cycle activity profile. The element-level costs are taken into consideration as the direct costs of interventions incurred by the owner. Structure-level costs are taken into consideration as additional impacts incurred to the users due to the traffic disruption during the execution of interventions, i.e. travel delay, vehicle operation and accident.

2.5. Summary

Although there has been continual progress in the past 40 years in the use of bridge management systems, from the initial manipulations of data to support bridge managers to the automatised determination of optimal element intervention strategies and then the transformation of these strategies into work programmes, there are still improvements to be made. These improvements include the determination of optimal bridge intervention strategies, optimal life-cycle activity profiles and optimal work programmes.

The work presented in this paper furthers the development of a methodology to determine optimal life-cycle activity profiles, which can be used to determine optimal work programmes. It does this by investigating how three existing methodologies could be used to determine the optimal life-cycle activity profiles for single bridges, taking into consideration both element and structure-level costs.

3. Investigated methodologies

The three methodologies investigated are (1) the state of practice methodology, i.e. the methodology that is considered to be representative of the state art of practice (SOP), (2) the structure performance model, developed by Fernando et al. (2013) (SPM) and (3) the joint replenishment model as proposed by Adey and Hajdin (2005) (JRM). The SOP is considered to be a methodology representative of one of the most advanced methodologies applied in practice. The SPM is a methodology that can be used to determine optimal bridge intervention strategies taking into consideration costs associated with the performance of the bridge as a whole, in addition to costs associated with the condition of elements. This is done by developing so-called structure performance state-based sets of element CS combinations. Costs are estimated per structure performance state based on the values of the associated performance indicators. The JRM is a methodology developed based on the inventory management theory adopted by Adey and Hajdin (2005). It can be used to determine optimal life-cycle activity profiles, taking into consideration the reduction in costs due to executing interventions on multiple elements simultaneously. The main aspects of the three methodologies are summarised in Table 1.

3.1. State of practice methodology

3.1.1. Element intervention strategies

In the SOP, possible element intervention strategies are first determined taking into consideration standards and engineering judgment, which can be represented by means of so-called knowledge-based models. These models consist of decision trees and tables that contain a myriad of agency rules, such as

(1) A high-performance concrete overlay is considered only if average daily traffic is more than 10,000 per lane, the deck is not post-tensioned, and it has no wide cracks.
(2) Painting of a steel element is not considered feasible if less than 5% of the coating is below the best CS.

Knowledge-based models are developed for rehabilitation, renovation and replacement interventions, as done in (Thompson & Ellis, 2000; Thompson et al., 2003). Although the feasibility of these element intervention strategies are evaluated and preferred options are selected, there is no verification of their optimality.

3.1.2. Bridge intervention strategies

The bridge intervention strategies are determined taking into consideration standards and engineering judgment and are illustrated as knowledge-based models. Although the feasibility of these bridge intervention strategies is evaluated and preferred options are selected, there is no verification of their optimality.

Table 1. Significant aspects of the investigated methodologies.

	Aspect								
	Deterioration modelling			Level on which cost types are considered in the determination of the LCAP		How element intervention strategies (EISs), bridge intervention strategies (BISs) and life-cycle activity profiles(LCAPs) are determined			Cost estimates
Methodology	Model type	Number of condition states	Connection between condition states (CSs) and cost of cost types	Element	Bridge	EIS are determined ...	BIS are determined ...	LCAP are determined ...	During intervention time period based on
SOP	Exponential probabilistic model	Small number of discrete CSs	Implicit	Yes	No	Based on expert opinion	Based on expert opinion	Using optimisation	Probabilistic bridge interventions
SPM	Exponential probabilistic model	Small number of discrete CSs	Explicit	Yes	Yes	Based on expert opinion	Using optimisation	Automatically once the CS known[a]	Probabilistic bridge interventions
JRM	Linear deterioration model	Infinite	Implicit	Yes	Yes	Based on expert opinion	Based on expert opinion	Using optimisation	Deterministic bridge interventions

[a] Since the expected time of executing intervention for each element is repetitive for all eternity, life-cycle activity profiles can be found by the inverse of respective steady-state probabilities from optimal bridge intervention strategies.

3.1.3. *Life-cycle activity profile*

Once the bridge intervention strategies are determined, all possible life-cycle activity profiles are generated. Each life-cycle activity profile includes an intervention to be executed in one of the first two consecutive 5-year intervals, when each possible bridge intervention strategy is followed. Each life-cycle activity profile is generated as follows:

(1) select a possible element intervention strategy for each element, e.g. for abutment 1 the element intervention strategy could be do nothing in CSs 1–3 and do a rehabilitation intervention if in CS 4 or 5,
(2) determine the intervention that should be included in the life-cycle activity profile for each element, e.g. abutment 1 is in CS 3 at $t = 0$ and therefore no intervention is to be executed,
(3) select a possible bridge intervention strategy,
(4) modify the element interventions taking into consideration the condition and interventions on the other elements, e.g. if the selected bridge intervention strategy suggests that if an intervention is to be executed on the deck and the abutment is in CS 3 then execute a rehabilitation intervention on the abutment, then a rehabilitation intervention is included on the abutment even though it is not in the original element intervention strategy.

The optimal life-cycle activity profile includes the interventions that produce the maximum benefit over the entire investigated time period, i.e. during the first two 5-year periods and for the subsequent 50 years (Equation (1)). The benefit of a life-cycle activity profile is defined as the difference between,

- the costs incurred when specific interventions are included in the first two 5-year periods of the life-cycle activity profile taking into consideration budget constraints, and associated element intervention strategies are followed for the subsequent 50 years (in this case only costs due to the execution of interventions are considered) and
- the costs incurred when no specific interventions are included in the first two 5-year periods of the life-cycle activity profile and reference element intervention strategies are followed for the entire time period.

The associated element intervention strategies are the ones used to generate the initial interventions during the first two 5-year time periods, which are then modified taking into consideration the condition and interventions on the other elements.

$$\underset{\varphi}{\mathrm{ArgMin}}\left(C_{\mathrm{wp}}^{\varphi} + C_{\mathrm{awp}}^{\varphi} - C^{r}\right) \quad \text{for } \varphi = 1 \text{ to } n, \tag{1}$$

where $C_{\mathrm{wp}}^{\varphi}$ is the total costs incurred during the first two 5-year periods when intervention φ is executed in the first two 5-year periods (Equation (2)), $C_{\mathrm{awp}}^{\varphi}$ is the total costs incurred after the first two 5-year periods when intervention φ is executed in the first two 5-year periods (Equation (3)), C^{r} is the total costs incurred both during and after the first two 5-year periods if no intervention is executed the first two 5-year periods, and

$$C_{\mathrm{wp}}^{\varphi} = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{s=1}^{S}\left(P_{j,t}^{\varphi}(s)\cdot\left(Q_j\cdot UIV_{j,t}^{\varphi,i}(s)+\sum_{i=1}^{I} IV_{j,t}^{\varphi,i}(s)\right)\cdot\frac{1}{(1+\lambda)^{t}}\right), \tag{2}$$

$$C_{\mathrm{awp}}^{\varphi} = \sum_{t=T+1}^{TT}\sum_{j=1}^{J}\sum_{s=1}^{S}\left(P_{j,t}^{\varphi}(s)\cdot\left(Q_j\cdot UIV_{j,t}^{\varphi,i}(s)+\sum_{i=1}^{I} IV_{j,t}^{\varphi,i}(s)\right)\cdot\frac{1}{(1+\lambda)^{t}}\right), \tag{3}$$

where t is the time interval counter, in units of 5, T is the number of time intervals in the first 10 years, $T = 2$, TT is the number of time intervals in the investigated time period, $TT \geq T$, J is the number of elements, $P_{j,t}^{\varphi}(s)$ is the probability of element j being in CS s, at t, when intervention φ is executed, Q_j is the extent of the element j. For example, the extent of the deck is its width multiplied by its length, whereas for the bearing, the extent is the total number of bearings in the bridge, $IV_{j,t}^{\varphi,i}(s)$ is the cost of cost type i that is related to element j, but not directly to the size of the element, in CS s of executing intervention φ at time t, $UIV_{j,t}^{\varphi,i}(s)$ is the unit cost of cost type i that is directly related to the size of element j, in CS s, of executing intervention φ at time t, and λ is the discount rate.

3.1.4. *Cost consideration*

In the SOP, element-level costs are attributed directly to the elements and used to determine the element intervention strategies to follow. These strategies are used to determine the possible interventions to be executed in the first two time intervals of the life-cycle activity profile, as well as the interventions that will be executed after these two intervals for the rest of the investigated time period. Structure-level costs are attributed directly to the structure after it is known which interventions are to be included in the candidate life-cycle activity profiles. The structure-level costs are added to the interventions in the first two intervals before the determination of the optimal life-cycle activity profile. The structure-level costs are not added to the element intervention strategies.

There is no systematic way within the methodology to link the structure-level costs to the performance of the structure or to the condition of the elements. There is also no systematic way within the methodology to take into consideration the changes in the structure-level costs or element-level costs when it is known that interventions are to be executed simultaneously on multiple elements.

Guidelines could be provided outside of the methodology to systematically link structure-level costs to the performance of the structure or the condition of the elements for the first two time intervals, and to take into consideration the changes in the structure-level and element-level costs when it is known that intervention are to be executed simultaneously on multiple elements in the first two time intervals.

This would, however, not necessarily result in the actual optimal life-cycle activity profile being determined because these structure-level costs are not taken into consideration in the determination of the element intervention strategies used to trigger an intervention in these two time intervals. The only way that the structure-level costs could be taken into consideration in the determination of the element-level intervention strategies to follow is to use a perceptual distribution of average structure-level costs to the elements of which the structure is composed. This, however, is not particularly credible, as there is no way of knowing the condition of the other elements in the structure when the element intervention strategies are determined, and without this information, a perceptual distribution of the structural-level costs would only result in an increase in the costs associated with the element intervention strategies and not in the intervention strategy being selected.

In addition to this, the introduction of structure-level costs in this way would result either in a double counting of the structure-level costs in the first two time intervals of the life-cycle activity profile or a discrepancy in how they are taken into consideration in the first two time intervals and the remainder of the life-cycle activity profile.

In all cases, it is impossible with the SOP to determine the actual optimal life-cycle activity profile if structure-level costs are to be considered, even though structure-level costs can be taken into consideration.

3.2. *Structural performance methodology*

3.2.1. *Element intervention strategies*

There are no element-level intervention strategies determined.

3.2.2. *Bridge intervention strategies*

Optimal bridge intervention strategies are determined (Equation (4)):

$$\text{Min}\, C^{is} = \sum_{sps=1}^{SPS} \left(P^{is}_{sps} \cdot \sum_{i=1}^{I} \left(\sum_{j=1}^{J} \left(C^{is}_{j,i,sps-cs} \right) + C^{is}_{i,sps} \right) \right), \tag{4}$$

P^{is}_{sps} is the probability of the bridge being in the structural performance states *sps* at an infinite point of time in the future if the intervention strategy *is* is followed, given by

$$P^{is}_{sps} = \prod_{j=1}^{J} \pi^{is}_{j,sps-cs}, \tag{5}$$

where $\pi^{is}_{j,sps-cs}$ is the probability of element *j* being in its required condition for the structural performance state–condition state, *sps*–*cs*, at an infinite point of time in the future if intervention strategy *is* is followed, $C^{is}_{j,i,sps-cs}$ is the cost of cost type *i* associated with element *j* being in its required condition for the structural performance state–condition state, *sps*–*cs*, if intervention strategy *is* is followed, e.g. the expenditures for labour and materials due to the execution of an intervention, $C^{is}_{i,sps}$ is the cost of cost type *i* associated with the bridge being in the structural performance state *sps*, due to the execution of the intervention itself and due to vehicles driving over the bridge, e.g. additional vehicle operating costs, and vehicles that would normally drive over the bridge being detoured, e.g. additional travel time due to deviated traffic. It is given by

$$C^{is}_{i,sps} = C^{is,ti}_{i,sps} + C^{is}_{i,sps-pi} + C^{is}_{i,sps-d}, \tag{6}$$

where $C^{is,ti}_{i,sps}$ is the time-independent portion of the cost, indicated with the superscript *ti*, of cost type *i* associated with the bridge being in structural performance state *sps*, if intervention strategy *is* is followed, e.g. the expenditures for labour and materials due to setting up the work site, $C^{is}_{i,sps-pi}$ is the cost of cost type *i* associated with the value of the performance indicator that occurs when the bridge is in the structural performance state, denoted as *sps*–*pi*, if intervention strategy *is* is followed. These are incurred due to the vehicles driving over the bridge. It is given by

$$C^{is}_{i,sps-pi} = t^{is}_{sps} \cdot UC^{is,int}_{i,sps-pi} + (1 - t^{is}_{sps}) \cdot UC^{is,no-int}_{i,sps-pi}, \tag{7}$$

where t^{is}_{sps} is the time required to execute an intervention on the bridge if it is in the structural performance state *sps,* if intervention strategy *is* is followed. It is assumed that this time is related to the element with the maximum duration of intervention required, $UC^{is,int}_{i,sps-pi}$ is the unit cost of the time-dependent portion of cost type *i,* which is incurred during the execution of an intervention associated with the value of the performance indicator when the bridge is in structural performance state *sps*, denoted *sps–pi*, if intervention strategy *is* is followed, $UC_{i,sps-pi}^{is,no-int}$ is the unit cost of the time-dependent portion of cost type *i,* which is incurred before and after the execution of an intervention associated with the value of the performance indicator when the bridge is in structural performance state *sps*, denoted *sps–pi*, if intervention strategy *is* is followed, $C_{i,sps-d}^{is}$ the costs of cost type *i* associated with the detour that occurs when the bridge is in the structural performance state, denoted as *sps–d*, if intervention strategy *is* is followed. These are incurred due to the vehicles that would normally drive over the bridge that will now take the detour. It is given, in 1 year, by

$$C_{i,sps-d}^{is} = t_{sps}^{is} \cdot UC_{i,sps-d}^{is,int} + (1 - t_{sps}^{is}) \cdot UC_{i,sps-d}^{is,no-int}, \quad (8)$$

where $UC_{i,sps-d}^{is,int}$ is the unit cost of the time-dependent portion of cost type *i* which is incurred during the execution of an intervention associated with the detour when the bridge is in structural performance state (SPS), denoted *sps–d*, if intervention strategy *is* is followed, $UC_{i,sps-d}^{is,no-int}$ is the unit cost of the time-dependent portion of cost type *i* which is incurred before and after the execution of an intervention associated with the value of the performance indicator when the bridge is in structural performance state, denoted *sps–d*, if intervention strategy *is* is followed, *I* the number of cost types, *SPS* the number of structural performance states, *J* is the number of elements.

3.2.3. Life-cycle activity profiles

No optimal life-cycle activity profile is determined. However, if it is considered that the interventions on elements return the element to condition state 1, and interventions are always executed on structural units individually, the expected time of executing interventions on each element repetitively for all eternity can be found by the inverse of respective steady-state probabilities.

It is emphasised here for clarity that the determination of the life-cycle activity profile is determined by first determining the optimal intervention strategy using the above equations and then, taking into consideration the actual condition of the element of the bridge, determining the life-cycle activity profile.

The optimal intervention strategy includes the definition of all structural performance states of the bridge and the interventions to be executed if these structural performance states occur. It is determined by finding the steady-state probabilities (i.e. the probability of being in each of these structure performance states at an infinite point of time in the future) multiplied by the costs of the interventions associated with each of the CSs, which result in the lowest costs per unit time. The life-cycle activity profile that results from this strategy is determined by taking into consideration the actual structural performance state of the bridge at $t = 0$, estimating the probability of it being in each structural performance state at each *t* throughout the investigated time period and then determining when the interventions would be executed. This part of the SPS methodology is similar to that used in BMSs such as KUBA, or the systems formerly known as Pontis, but on an element level.

3.2.4. Cost consideration

In the SPM both the element-level and structure-level costs can be taken into consideration in the determination of the optimal life-cycle activity profile. As the SPM determines the optimal bridge intervention strategies based on the performance state of the bridge, which are based on the CSs of the elements of which the bridge comprises, it is possible to directly associate structure-level costs to each one of these performance states, and element-levels costs directly to the CS of the element and to take into consideration the change in element-level costs when multiple elements are to have an intervention simultaneously.

3.3. Joint replenishment methodology

3.3.1. Element intervention strategies

No element-level intervention strategies are determined. However, by applying the same methodology separately for individual elements, their optimal life-cycle activity profile can be determined and the optimal element intervention strategy can be approximated.

3.3.2. Bridge intervention strategies

No bridge intervention strategies are determined.

3.3.3. Life-cycle activity profiles

This methodology can be used to determine the optimal life-cycle activity profile when interventions are executed on specific groups of bridge elements simultaneously. This is done by establishing the different groups of bridge elements to have interventions simultaneously, determine the associated life-cycle activity profile and compare with the life-cycle activity profiles for all other groupings. If a bridge has *n* elements, the number of possible groupings is given by $2^n - 1$. The optimal life-cycle activity profile for each specific grouping ξ is determined as:

$$\text{Min}\, C_\xi(u) = \frac{\left(S_0 + \sum_{j=1}^{J} S_j \cdot \delta_j\right)}{u} + \sum_{j=1}^{J} \left(\gamma_j \cdot v_j + u \cdot \gamma_j \cdot h_j + \gamma_j \cdot p_j\right) \cdot \delta_j, \quad (9)$$

subject to

$$u \cdot \gamma_j > 1, \quad j = 1 \ldots J$$

where S_0 is the cost of executing an intervention on the bridge that is independent of the number or type of elements on which interventions are executed (e.g. the cost of installing signalling equipment to deviate traffic), S_j is the cost of executing an intervention on element j that is independent of the size of the element on which interventions are executed (e.g. the cost of bringing a specific machine on site), J is the number of bridge elements, u is the time interval between interventions, γ_j is the (linear) rate of deterioration of element j, v_j is the costs of executing an intervention on element j that varies as a function of the condition of the element, (e.g. the cost related to the amount of concrete to be placed), p_j is the costs of failure related to element j (i.e. the probability of failure multiplied by the consequences of failure) that varies as a function of the condition of the element, h_j is the costs of having element j in a CS worse than CS 1, δ_j is a binary variable, which $\delta_j = 1$ represents the presence of element j in combination ξ and $\delta_j = 0$ represents the absence of the respective element in the combination. The optimal life-cycle activity profile taking into consideration all possible element groupings is given by

$$\underset{\varpi}{\text{ArgMin}}\, C(\varpi) = \sum_{\xi=1}^{2^J-1} C_{\xi,\min}(u) \cdot \delta_j, \quad (10)$$

subject to

$$\sum_{\xi=1}^{2^J-1} \delta_j = 1 \quad \forall \; j \in \xi,$$

where $C(\varpi)$ is the total costs of life-cycle activity profile ϖ is followed and $C_{\xi,\min}(u)$ is the minimum costs for element group ξ.

3.3.4. Cost consideration

In the JRM, both element-level and structure-level costs can be taken into consideration in the determination of the optimal life-cycle activity profile. As the costs of a life-cycle activity profile are determined through the element groups, it is possible to link the condition of the elements in the group to values of a performance indicator, and therefore to costs that can be related to the value of the performance indicator. If the element group includes only one element, then only element-level costs can be considered and structure-level costs would have to be perceptually distributed among the elements. If, however, the element group includes all elements in the bridge than both the element-level costs and structure-level costs can be taken into consideration.

The JRM in the above presented form, however, presents difficulties in modelling the costs as the elements change condition over time. Because the JRM uses only linear models, one difficulty is that it is necessary to model the change in the structural performance and therefore the structure-level costs as linear changing with respect to the changing structural performance states which are based on the changing element conditions. This, of course, is something that does not reflect reality. Structural-level costs are not linearly related to the structure performance states.

4. Comparison

In this section, each of the three methodologies are used to determine the optimal life-cycle activity profile for an example bridge over a period of 75 years. The bridge is to be dismantled at the end of year 75, and all impacts due to dismantling it are the same for all intervention strategies and can therefore be ignored. The advantages and disadvantages with respect to their ability to be used to take into consideration element and structure-level costs.

4.1. Bridge

The bridge is a weathering steel girder box bridge (Figure 1), a part of a road network located in a mountainous area outside a city. It is composed of five types of elements: pavement surface, abutments/piers, bearings, deck and the weathering steel girder. The deck is a three-span cast-in-place reinforced concrete which is supported by an 86-m long (continuous) trapezoidal box girder. The girder consists of two web plates welded to a

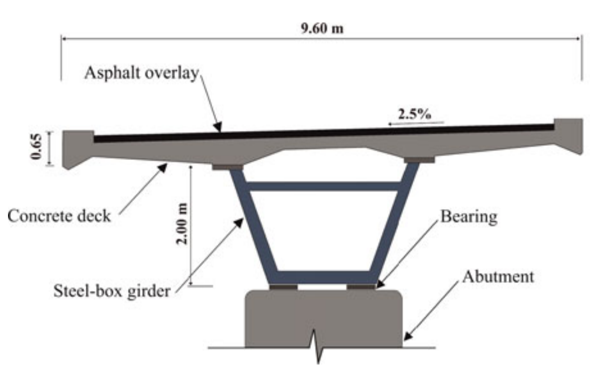

Figure 1. Cross section of the case study bridge.

Table 2. Cost types considered.

	Level 1		Level 2	
Stakeholder	Label	Description	Label	Description
Owner	Intervention	The cost of executing interventions	Labour	The cost of people performing tasks
			Material	The cost of people ensuring that materials are available for use
			Equipment	The cost of people ensuring that equipment is available for use
User	Travel time	The cost of travel condition in terms of time lost	Work	The cost of wasting work time travelling
			Leisure	The cost of wasting leisure time travelling
	Vehicle operation	The cost of travel condition on the vehicle cost	Operation	The cost of people ensuring that fuel and oil is vailable for use
			Maintenance	The cost of people repairing vehicles
	Accident	The cost on the users due to an accident	Property damage	The cost of any property damage
			Injury	The cost due to injury
			Death	The cost due to death
Public (direct and indirectly affected)	Accident	The cost on the public due to an accident	Property damage	The cost of any property damage
			Injury	The cost due to the injury
			Death	The societal cost due to death
	Noise	The cost due to coming in contact with sound emissions	Noise level	The cost due to coming in contract with high level of noise
	Air pollution	The cost due to the environment being costed by particle emissions	PM10	The cost of PM10 emissions emitted
	Climate	The cost due to changing the climate	CO_2	The cost of CO_2 emissions emitted

single bottom flange plate. It is made up of two 200 cm × 1.6 cm and a 210 cm × 3 cm weathering steel plates. The thickness across the deck section changes from 20 to 50 cm. The deck and the girder act as a composite section. The pot bearings and rocker bearings transfer the loads from the superstructure to the abutments and piers, respectively. All elements of one type are modelled together as one structural unit, e.g. the abutments and piers are modelled as the abutment structural unit.

The bridge carries two lanes of traffic and has a total width of 9.6 m and total length of 89 m. The average daily traffic over the bridges is 2500 vehicles/day. It is assumed that all other objects in the network are fully operational when an intervention is executed on the bridge and road users have a possible 850 m detour.

4.2. Costs

The costs modelled are given in Table 2. The costs related to the movement of vehicles either on the bridge or on a detour, i.e. the structure-level costs, are estimated using the models given in Tables 3 and 4 (Adey et al., 2012). The costs not related to the movement of vehicles are related to the bridge itself and are given in section 4.5. The unit costs are given in Table 5. The variables used to take into consideration the costs of each cost type and whether these were considered to be element level or bridge level for each methodology are given in Tables 6–9.

It can be seen that in the SOP and JRM there are one-to-one relationships between the costs and the element CSs, whereas in the SPM, the costs are related to the values of performance indicators that are related to the structural performance states that are in turn related to the element CSs. When the SOP and the SPM were used, no cost reductions were given when elements were to have interventions simultaneously, but they were when the JRM was used. They were not when the SOP was used because the costs were assumed to arise directly from the element-level intervention strategies upon which it is not possible to assign costs due to multiple elements having interventions simultaneously. They were not when the SPM was used, in line with the example given in Fernando et al. (2012). They were when the JRM was used, in line with the example given in Adey and Hajdin (2005).

4.3. Deterioration

The main deterioration processes affecting the structural units are given in Table 10. The CS descriptions are given in Table 11. Deterioration is modelled in the SOP and SPM using transition probabilities between discrete CSs and in the JRM as linear deterioration. The models are considered

Table 3. Cost models (1/2).

Cost	Formula	Parameter	Parameter's description
Travel time	$I_{TT} = UC_{TT} \cdot t \cdot DTV$	UC_{TT}	Unit cost of travel time per vehicle
		DTV	Daily traffic volume
		t	Travel time per vehicle
	$v_{tech} = \min(v_{signal}, v_{Rough})$	v_{Tech}	Free flow traffic speed
	$t = \frac{s}{v_{tech}}\left(1+\alpha\left(\frac{u}{cap}\right)^{\beta}\right)$	v_{signal}	Posted speed limit
	$v_{Rough} = v_{Signal} - 2.3\frac{I_2-b}{0.6}$ when $I_2 \geq b$		
	$v_{Rough} = v_{Signal}$ when $I_2 < b$	v_{Rough}	Adjustment of the free flow speed
		S	Bridge span
		α	Parameter dependent on road characteristics (0.15 suggested)
		β	Parameter dependent on road characteristics (4.0 suggested)
		u	Traffic flow during analysed interval
		cap	Capacity of the road
		b	Speed reduction parameter
		I_2	Longitudinal unevenness
Vehicle operation	$I_V = DTV \cdot \left(t \cdot UC_{VH} + \left(\frac{13I_2}{800}+\frac{787}{800}\right) \cdot (s \cdot (UC_{Vkm} + T_v \cdot UC_F))\right)$	UC_{VH}	Unit vehicle operating costs per hour driven,
		UC_{Vkm}	Unit vehicle operating costs per kilometre driven
		T_v	Fuel use per kilometer at the driven speed
		UC_F	Unit cost of fuel
Accident	$I_A = \sum_{i=1}^{3} \theta_i(I_4) \cdot UC_i \cdot \mathrm{DTV} \cdot s \cdot \psi$	$\theta_i(I_4)$	Rate of occurrence of specific damage type
		i	Type of damage (property, $i = 1$, injury, $i = 2$ and death, $i = 3$)
	$\theta_{property}(I_4) = \frac{26.8}{99.8541+46.572 \cdot \ln(0.00981 \cdot I_4^2 - 0.1081 \cdot I_4 + 0.5966)}$	UC_i	Unit costs of damage
	$\theta_{injuries}(I_4) = \frac{10.72}{99.8541+46.572 \cdot \ln(0.00981 \cdot I_4^2 - 0.1081 \cdot I_4 + 0.5966)}$	I_4	Skid resistance of pavement
	$\theta_{deaths}(I_4) = \frac{0.201}{99.8541+46.572 \cdot \ln(0.00981 \cdot I_4^2 - 0.1081 \cdot I_4 + 0.5966)}$	ψ	Correction factor (to take into consideration the effect of the work site)

to be equivalent as average amount of time between construction or the execution of an intervention and entering CS 5 are the same, i.e. 110, 25, 48 and 52 years for the abutment/pier, asphalt, bearing and deck, respectively. There values are calculated as follows:

$$E[T_{rs}] = \mu_{rs} = 1 + \sum_{k \neq s} P_{rk} \cdot \mu_{ks}, \tag{11}$$

where $E[T_{rs}] = \mu_{rs}$ is the expected time required to reach CS s starting from CS r ($r \neq s$) for the first time and P_{rk} is the probability of transition to CS k from CS r.

The transition probabilities were determined using Equation (12) and the q values in Table 12. The expected time required to go from CS 1 to 5 for each structural unit and the corresponding linear deterioration rate are also given in Table 12.

$$P = \begin{bmatrix} q_1 & 1-q_1 & 0 & \cdots & 0 & 0 \\ 0 & q_2 & 1-q_2 & \cdots & 0 & 0 \\ 0 & 0 & q_3 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & q_{S-1} & 1-q_{S-1} \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix}, \tag{12}$$

where S is the number of CSs considered.

Deterioration is modelled in the JRM by assuming that there is linear deterioration through each of the CSs. It is

Table 4. Cost models (2/2).

Cost	Formula	Parameters	Parameter's description
Noise	$I_{\mathrm{N}} = p \cdot UC_{\mathrm{dBA}} \cdot L\mathrm{eq}$	P	Number of affected persons
		UC_{dBA}	Cost per decibel, per person
		L_{eq}	The energy equivalent continuous noise gauge
	$L_{\mathrm{eq}} = 10\log\left(1/cap \cdot \sum_{w=1}^{2}\left(F_{wz}10^{0.1Lw}\right)\right)$	v	Speed
		F_{wz}	Number of each vehicle type
	$L_w = 10\log\left(10^{L_{wA}+\Delta L_S/10} + 10^{L_{wR}+\Delta L_B/10}\right)$	L_w	Noise strength
		w	Vehicle type
		L_{wA}	Motor noise for vehicle type
		L_{wR}	Roll noise for vehicle type
		ΔL_s	Change in motor noise due to slope
		ΔL_B	Change in roll noise
Air Pollution	$I_{\mathrm{AP}} = I_{PM10}^{FZ}$	I_{PM10}^{FZ}	Costs of PM10 emission
	$I_{\mathrm{PM10}}^{\mathrm{Fz}} = s \cdot DTV \cdot \sum_{w=1}^{W}\left(\mu_w \cdot T_v^w \cdot \frac{UC_{PM10}^w}{T_{avg}^w}\right)$	μ_w	Percentage of vehicles type w
		T_v^w	Fuel usage per vehicle type
		UC_{PM10}^w	Average unit cost of air pollution
		T_{avg}^w	Fuel used on average
Climate change	$I_{\mathrm{CO_2}} = s \cdot \mathrm{DTV} \cdot \left(\sum_{w=1}^{W}\mu_w \cdot T_v^w \cdot \gamma_w\right) \cdot UC_{\mathrm{CO_2}}$	$UC_{\mathrm{CO_2}}$	Unit cost of CO_2
		μ_w	Percentage of vehicles of type
		T_v^w	Fuel consumption of vehicles per vehicle type
		γ_w	Ratio of kg CO_2 per-litre fuel determined per vehicle type

assumed that each structural unit begins in CS 1 and enters CS 2 once the triggering condition for CS 2 is met. The expected time to go from new to entering CS 5 and the amount of condition lost per year are given in Table 12. The linear deterioration rate for each structural unit was determined as

$$\gamma_j = \frac{S-1}{E[T_{rs}]}, \tag{13}$$

where S is the maximum number of CSs considered for structural unit j. Here, r is 1 and s equals $\#_S$.

The values of the performance indicators and the costs associated with each structural unit being in each CS when no intervention is executed are given in Table 13. As changes in the condition of the structural units *abutments* and *bearings* have no effect on the performance of the bridge as a whole, the costs are considered to be the same for all CSs. Examples of the values of the performance indicators and the costs associated with each structure performance state are given in Table 14. These are the average costs associated with each structure performance state, i.e. taking into consideration that when the bridge is in a structure performance state that the condition of each structural unit can vary, e.g. when the asphalt is considered to be in CS 2, its condition can be anywhere between 2.00 and 2.99.

For all methodologies, the values of the performance indicators related to each structural unit when the CSs of all other structural units are in CS 1 (Table 13) are not additive. In many cases, their addition would lead to an overestimation of the value of the performance indicator for the bridge and, therefore, an overestimation of the

Table 5. Base units used in the models in Table 4.

Parameter	Symbol	Value	Units	Source
Travel time unit cost	UC_{TT}	26.24	CHF/h	VSS (2007)
Truck fuel unit cost	$UC_{\mathrm{F,truck}}$	0.595	CHF/l	Keller and Zbinden (2004)
Car fuel unit cost	$UC_{\mathrm{F,car}}$	0.544	CHF/l	Keller and Zbinden (2004)
Cost of property damage	UC_{property}	46,300	CHF/event	ASTRA (2003)
Cost of injury	UC_{injury}	301,300	CHF/event	ASTRA (2003)
Cost of fatality	UC_{fatality}	3,742,200	CHF/event	ASTRA (2003)
People affected by noise	ρ	15	#	Observation
Noise cost	C_{db}	118	CHF/db/person	ECOPLAN (2004)
Air pollution cost (truck)	$C_{\mathrm{AP,truck}}$	0.151	CHF/km	ECOPLAN (2007)
Air pollution cost (car)	$C_{\mathrm{AP,car}}$	0.024	CHF/km	ECOPLAN (2007)
CO_2 emission (truck)	γ_{truck}	2.647	kg/l	ECOPLAN (2007)
CO_2 emission (car)	γ_{car}	2.404	kg/l	ECOPLAN (2007)
Climate cost per kg CO_2	UC_{CO2}	0.051	CHF/kg	ECOPLAN (2007)
Discount rate	λ	2	%/year	–

Table 6. The equations and variables used to take into consideration the costs during the execution of interventions considered (1/2).

Stakeholder	Label 1	Label 2	Level	Methodology	Variable	Equation
Owner	Intervention	Labour	Element	SOP	$UIV_{j,t}^{\varphi,i}(s)$	(2)
				SPM	$C_{j,i,sps-cs}^{is}$	(4)
				JRM	So, Sj, Vj	(9)
		Material	Element	SOP	$UIV_{j,t}^{\varphi,i}(s)$	(2)
				SPM	$C_{j,i,sps-cs}^{is}$	(4)
				JRM	Vj	(9)
		Equipment	Element	SOP	$UIV_{j,t}^{\varphi,i}(s)$	(2)
				SPM	$C_{j,i,sps-cs}^{is}$	(4)
				JRM	So, Sj, Vj	(9)
User	Travel time	Work	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)
		Leisure	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)
	Vehicle operation	Operation	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)
		Maintenance	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)
	Accident	Property damage	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)
		Injury	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)
		Death	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$, $UC_{i,sps-d}^{is,int}$	(7), (8)
				JRM	Vj	(9)

costs. An example of the approximations of these values for each methodology is given in Table 15. For the JRM, the minimum and maximum values are given.

These are not identical for all three methodologies due to how the methodologies allow for the consideration of the condition of multiple structural units. The deviations required in determining the costs for the SOP and JRM are due to the fact that the methodologies force the costs related to each structural unit to be additive. For example, in structural performances state 130, the value of the performance indicator is 2, which resulted from both deck and asphalt overlay (i.e. 2 and 2). In SOP and JRM, the value of the performance indicator for each structural unit is considered independently of other structural units and the additional costs are summed (i.e. 32,187 + 451 + 451) (see Table 15). In the SPM, the value of the performance indicator is the maximum value (i.e. 2) of the performance indicator in this structural performance state; therefore, only one additional cost is caused by combining the structural units (i.e. 32,187 + 451). This is not the case for the SPM, where there is no such requirement.

4.4. *Improvement*

The possible interventions to be executed on each structural unit are given in Table 16. The costs due to the execution of an intervention on a structural unit are considered independent of the condition of the other structural units and whether or not an intervention is executed simultaneously on other structural units. The impacts related to the bridge indirectly through the use of the bridge and how this use is perturbed during the execution of the intervention are estimated using the duration of the intervention, the situational characteristics, e.g. traffic flow, and the equations given in Tables 3 and 4.

Table 7. The equations and variables used to take into consideration the costs during the execution of interventions considered (2/2).

Stakeholder	Label 1	Label 2	Level	Methodology	Variable	Equation
Public (direct and indirectly affected)	Accident	Property damage	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$,	(7)
					$UC_{i,sps-d}^{is,int}$	(8)
				JRM	Vj	(9)
		Injury	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$,	(7)
					$UC_{i,sps-d}^{is,int}$	(8)
				JRM	Vj	(9)
		Death	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$,	(7)
					$UC_{i,sps-d}^{is,int}$	(8)
				JRM	Vj	(9)
	Noise	Noise	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$,	(7)
					$UC_{i,sps-d}^{is,int}$	(8)
				JRM	Vj	(9)
	Air pollution	PM10	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$,	(7)
					$UC_{i,sps-d}^{is,int}$	(8)
				JRM	Vj	(9)
	Climate	CO_2	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,int}$,	(7)
					$UC_{i,sps-d}^{is,int}$	(8)
				JRM	Vj	(9)

Improvement is modelled in both the SOP and SPM by assuming that the execution of an intervention restores the structural unit to CS 1 with a 100% probability, that is the additional deterioration that may happen within the time period that the intervention is executed is negligible. The impacts related to the execution of an intervention are assumed to be the same irrespective of the amount of time a structural unit has been in a CS, e.g. a patching intervention would cost 9500 CHF, take 3 days and restore the abutment to CS 1 both if the abutments structural unit had just entered CS 3, or if it was just about to enter CS 4 from CS 3.

Improvement is modelled in the JRM by assuming that the execution of an intervention restores the structural unit to CS 1. The interventions corresponding to each of the discrete CSs comprised the fixed and variable portions of costs and durations (Table 18).

The large discrepancies that can be seen in Table 16, e.g. the owner costs due to crack sealing of the amount, which is 7000 CHF for the SOP & SPM and between 17,786 and 30,572 CHF for the JRM, are due to the linear relationship that must be assumed when using the JRM. The best fit linear regression models for the owner costs of interventions in CSs 2, 3 and 4 were used (see Figures 2–5). Although this overestimates the costs associated with interventions that would be executed in CS 1 and underestimates the costs associated with interventions that would be executed in CS 5, it was selected as most interventions were expected to be executed in CSs 2, 3 and 4, and therefore the closeness to the values of the actual costs was consider the most important.

4.5. *Candidate life-cycle activity profiles*

The candidate life-cycle activity profiles evaluated in the search for the optimal one were slightly different for each methodology. They are explained in the following sections.

4.5.1. *SOP*

Using the SOP, the candidate life-cycle activity profiles were constructed by combining all feasible interventions related to each structural unit with the interventions on the

Table 8. The equations and variables used to take into consideration the costs between the execution of interventions considered (1/2).

Stakeholder	Label 1	Label 2	Level	Methodology	Variable	Equation
Owner	Intervention	Labour	Element	SOP	$UIV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	*N/A*	–
				JRM	hj	(9)
		Material	Element	SOP	$UIV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	*N/A*	–
				JRM	hj	(9)
		Equipment	Element	SOP	$UIV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	*N/A*	–
				JRM	hj	(9)
User	Travel time	Work	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)
		Leisure	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)
	Vehicle operation	Operation	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)
		Maintenance	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)
	Accident	Property damage	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)
		Injury	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)
		Death	Bridge	SOP	$IV_{j,t}^{\varphi,i}(s)$	(3)
				SPM	$UC_{i,sps-pi}^{is,no-int}$,	(7)
					$UC_{i,sps-d}^{is,no-int}$	(8)
				JRM	Vj, hj	(9)

other structural units in the first 5-year period, using the following rules:

- If an intervention of type 1 or 2 is to be executed on the deck, then also execute an intervention of type1 on the asphalt.
- If an intervention of type 1 (seal cracks) or 2 (repair spalls and seal cracks) is to be executed on the deck, then also execute the intervention of type 1 (seal cracks) on the abutment if it is in CS 2.
- If an intervention of any type is executed on a bridge element then also execute an intervention of the type that corresponds to the CS of the bearing.

Only the structural units on which an intervention was not executed were considered to be candidates for intervention in the second time interval. The structural units on which an intervention was not executed in the first or second period were considered to have an intervention in the third period. It was assumed that at least one intervention was executed on each structural unit in the first three time intervals. These interventions were assumed to repeat until year 75. This deviation from the explanation of the SOP above was done so that a life-cycle activity profile could be developed and compared with those developed using the other methodologies. This deviation does not affect how the methodology takes into consideration element- or structure-level costs and, therefore, does not affect the evaluation of the methodologies. Although these candidates' life-cycle activity profiles are fewer in number than those that are theoretically analysed using the SPM and the JRM, this is thought to lead at most to a specific intervention being executed one time interval earlier or later.

4.5.2. *SPM*

Using SPM, only one candidate life-cycle activity profile was considered directly. The optimal element intervention

Table 9. The equations and variables used to take into consideration the costs between the execution of interventions considered (2/2).

Stakeholder	Label 1	Label 2	Level	Methodology	Variable	Equation
Public (direct and indirectly affected)	Accident	Property damage	Bridge	SOP	$IV^{\varphi,i}_{j,t}(s)$	(3)
				SPM	$UC^{is,no-int}_{i,sps-pi}$, $UC^{is,no-int}_{i,sps-d}$	(7) (8)
				JRM	Vj, hj	(9)
		Injury	Bridge	SOP	$IV^{\varphi,i}_{j,t}(s)$	(3)
				SPM	$UC^{is,no-int}_{i,sps-pi}$, $UC^{is,no-int}_{i,sps-d}$	(7) (8)
				JRM	Vj, hj	(9)
		Death	Bridge	SOP	$IV^{\varphi,i}_{j,t}(s)$	(3)
				SPM	$UC^{is,no-int}_{i,sps-pi}$, $UC^{is,no-int}_{i,sps-d}$	(7) (8)
				JRM	Vj, hj	(9)
	Noise	Noise	Bridge	SOP	$IV^{\varphi,i}_{j,t}(s)$	(3)
				SPM	$UC^{is,no-int}_{i,sps-pi}$, $UC^{is,no-int}_{i,sps-d}$	(7) (8)
				JRM	Vj, hj	(9)
	Air pollution	PM10	Bridge	SOP	$IV^{\varphi,i}_{j,t}(s)$	(3)
				SPM	$UC^{is,no-int}_{i,sps-pi}$, $UC^{is,no-int}_{i,sps-d}$	(7) (8)
				JRM	Vj, hj	(9)
	Climate	CO_2	Bridge	SOP	$IV^{\varphi,i}_{j,t}(s)$	(3)
				SPM	$UC^{is,no-int}_{i,sps-pi}$, $UC^{is,no-int}_{i,sps-d}$	(7) (8)
				JRM	Vj, hj	(9)

Table 10. Deterioration processes and indicators.

Structural unit	Deterioration processes	Deterioration indicators
Concrete deck	Freeze–thaw and corrosion of reinforcements	Cracking, signs of rust from reinforcements, spalling and delamination
Concrete abutments/piers	Freeze–thaw and carbonation-induced corrosion of reinforcements	Cracking, spalling, signs of rust and corrosion on the element and irregularities on the upper side
Asphalt overlay	Failure of binder, weathering of aggregates	Surface distresses and irregularities consist of longitudinal and transversal unevenness, and reduced friction
Bearings	Fatigue and weathering	Cracking in the pins, splitting, tears and displacement of rockers
Steel girder	Fatigue, weathering and corrosion	Discoloration, lost protective cover granular formations, and section loss

strategies were determined by investigating all possible element intervention strategies. The candidate life-cycle activity profile was then determined as the average time to intervention for each structural unit adjusted to take into consideration the initial condition of the structural units.

4.5.3. JRM

Using the JRM, the candidate life-cycle activity profiles were determined by determining the optimal intervention times for groups of structural units (Equations (9) and (10)) on which it is feasible to execute interventions simultaneously. These intervention times were then combined for the groups of structural units making up the entire bridge to give the candidate life-cycle activity profiles.

4.6. *The optimal life-cycle activity profiles*

The optimal life-cycle activity profile is the one that results in the lowest total costs as follows:

$$C_{T,\omega} = \sum_{t=0}^{75} \sum_{i=1}^{I} C_{i,\omega}(t) \cdot \frac{1}{(1+\lambda)^t}, \tag{14}$$

Table 11. Description of condition states for each structural unit.

Structural unit	CS	Condition	Description of condition on entry
Abutments /pier	1	Good	No sign of rust
	2	Acceptable	Minor spots of rust and/or spalling and thin cracks less than 2.5-mm wide
	3	Damaged	Major spots of rust and/or spalling and thin cracks
	4	Poor	Major spots of rust and/or spalling and section loss of reinforcement less than 10%
	5	Alarming	Section loss of reinforcement more than 10%
Asphalt overlay	1	Good	$0 < I_2$[a] and I_3 and $I_4 \leq 1$
	2	Acceptable	$1 < (I_2$ or I_3 or $I_4)$ and $(I_2$ and I_3 and $I_4) \leq 2$
	3	Damaged	$2 < (I_2$ or I_3 or $I_4)$ and $(I_2$ and I_3 and $I_4) \leq 3$
	4	Poor	$3 < (I_2$ or I_3 or $I_4)$ and $(I_2$ and I_3 and $I_4) \leq 4$
	5	Alarming	$4 < (\mathrm{I}_2$ or I_3 or $\mathrm{I}_4)$
Bearings	1	Good	No signs of rust and cracking
	2	Acceptable	Minor cracking and tears less than 5% of the surface area
	3	Damaged	Cracking and tears more than 5% of the surface area
	4	Poor	Cracking and tears and rotation of the rockers less than 10%
	5	Alarming	Cracking, displacement and rotation of the rockers more than 10%
Concrete deck	1	Good	No signs of reinforcement corrosion
	2	Acceptable	Thin cracks less than 1 mm wide
	3	Damaged	Spalling with no visible reinforcement
	4	Poor	The section loss of reinforcement less than 10%
	5	Alarming	Section loss of reinforcement more than 10%
Steel girder[b]	1	Good	Limited discoloration less than 25%
	2	Acceptable	Discolouration and loosing protective cover less than 10%
	3	Damaged	Granular formations less than 10% and lost protective cover between 10% and 15% of the surface area
	4	Poor	Lost protective cover between 15% and 25%, and section loss between 5% and 10% of the surface area
	5	Alarming	Lost protective cover more than 25% and section loss more than 10%

[a] I_2 is the longitudinal unevenness, I_3 is the transversal unevenness and I_4 is the surface friction of the asphalt overlay taken from (VSS, 2003).
[b] Due to the low deterioration rate, the steel girder deterioration was neglected for the example bridge.

where $C_{i,\omega}(t)$ is the costs of cost type i, calculated as

$$C_{i,\omega}(t) = \sum_{j=1}^{J} C_{\mathrm{int}\,j,t} + \sum_{i=1}^{I} \left\{ \sum_{k=1}^{K} \left(C_i\left(PI_{k,br,t}\right) \cdot (1-\tau_t) + C_i\left(PI_{k,dt,t}\right) \cdot \tau_t \right) \right\}, \tag{15}$$

where $C_{\mathrm{int}\,j,t}$ is the cost of executing intervention *int* on structural unit j at time t, $C_i(PI_{k,br,t})$ is the cost of cost type i that corresponds to the value of performance indicator k at time t. $PI_{k,t}$ is estimated based on the expected condition of the structural unit at time t, $C_i(PI_{k,dt,t})$ is the cost of cost type i that corresponds to the condition of the detour, τ_t is the expected intervention duration at time t.

If there is more than one structural unit on which an intervention is to be executed within a time interval, it is considered that the interventions are executed simultaneously.

Table 12. Deterioration, transition probabilities, expected life and linear deterioration rates.

	Structural unit			
	Abutments	Asphalt	Bearings	Deck
Expected life	110 years	25 years	48 years	52 years
q_1	0.967	0.821	0.868	0.848
q_2	0.920	0.830	0.880	0.837
q_3	0.947	0.826	0.879	0.860
q_4	0.981	0.904	0.930	0.970
Linear rate (CS/years)	0.0364	0.1600	0.0833	0.0769

4.7. Results

The optimal life-cycle activity profiles and their total costs are given in Tables 19–21 and Table 22, respectively. As expected, it can be seen from Tables 19–21 that the optimal life-cycle activity profiles are not the same, but they do have both similarities and differences. One similarity is that none contain interventions in the first time interval, and there are in most cases at least one time interval between interventions. Another similarity is that they include some of the same types of interventions. For example, the optimal life-cycle activity profiles determined using the SOP and SPM both include patching and crack sealing interventions on the asphalt, crack sealing on

Table 13. Performance indicator values and costs for each structural unit in each condition state if all other structural units are in condition state 1 when no intervention is executed.

		Travel time		Vehicle operation		Accident[b]	
Structural unit	CS	PI[a]–I_2	Cost	PI–I_2 & I_4	Cost	PI–I_4	Cost
Abutments	1–5	1	33,454	1	32,187	1	5922
Asphalt overlay	1	1	33,454	1	32,187	1	5922
	2	2	33,454	2	32,638	2	6720
	3	3	33,454	3	33,089	3	7628
	4	4	40,145	4	34,429	4	8507
	5	5	50,182	5	36,214	5	9084
Bearings	1–5	1	33,454	1	32,187	1	5922
Deck	1–4	1	33,454	1	32,187	1	5922
	5	1	33,454	2	32,638	1	5922

[a] Performance indicator.
[b] The change in condition of the structural units was assumed to have no effect on the noise, amount of air pollution or climate costs.

the abutment, and that spalls and cracks should be repaired on the bridge deck.

One difference is that the optimal life-cycle activity profile determined using the SPM, includes more interventions on structural units (SPM: 23 vs. SOP: 7 and JRM: 8) and a higher number of days of bridge closure, (SPM: 58 days, and SOP: 28 and JRM: 24), than those determined using the SOP and JRM. Another difference is that no intervention is proposed systematically. For example, although the optimal life-cycle activity profile determined using the SOP and the JRM include only the reparation of joints and minor crack sealing, the one determined using the SPM includes the patching, major crack sealing and repair joints of the asphalt structural unit.

It can be seen from Table 22 that the total costs associated with each optimal life-cycle activity profile, although close, are different (SOP: 3,609,760; SPM: 3,580,709; JRM: 3,517,366). It can also be seen that the least total costs were predicted by the JRM, the highest costs between interventions were predicted by the SPM and the highest total costs during interventions were predicted by the SOP.

Table 14. The actual performance indicator values and cost values for each structural performance state when no intervention is executed.

	Condition states				Travel time		Vehicle operation		Accident[b]	
SPS[a] number	Abutment	Asphalt overlay	Bearing	Deck	PI–I_4	Cost	PI–I_2	Cost	PI–I_4	Cost
1	1	1	1	1	1	33,454	1	32,187	1	5922
2	1	1	1	2	1	33,454	1	32,187	1	5922
…	…	…	…	…	…	…	…	…	…	…
4	1	1	1	4	1	33,454	1	32,187	1	5922
5	1	1	1	5	1	33,454	2	32,638	1	5922
…	…	…	…	…	…	…	…	…	…	…
6	1	2	1	1	2	33,454	2	32,638	2	6720
…	…	…	…	…	…	…	…	…	…	…
126	1	2	1	4	2	33,454	2	32,638	2	6720
130	1	2	1	5	2	33,454	2	32,638	2	6720
…	…	…	…	…	…	…	…	…	…	…
254	1	3	1	4	3	33,454	3	33,089	3	7628
255	1	3	1	5	3	33,454	3	33,089	3	7628
…	…	…	…	…	…	…	…	…	…	…
374	5	3	5	4	3	33,454	3	33,089	3	7628
375	5	3	5	5	3	33,454	3	33,089	3	7628
…	…	…	…	…	…	…	…	…	…	…
624	5	5	5	4	1	50,181	5	36,213	1	9083
625	5	5	5	5	2	50,181	5	36,213	2	9083

[a] Structure performance state.
[b] The change in condition of the structural units was assumed to have no effect on the amount of air pollution or climate costs.

Table 15. An example of the performance indicator values and impact values for each structural performance state.

	Condition states				SOP		Actual (SPM)		JRM	
SPS number	Abutment	Asphalt overlay	Bearing	Deck	PI–I_2	Cost	PI–I_2	Cost	PI–I_2	Cost
1	1	1	1	1	1	32,187	1	32,187	1	32187
2	1	1	1	2	1	32,187	1	32,187	1–2	32,187–32,216
…	…	…	…	…	…	…	…	…	…	…
4	1	1	1	4	1	32,187	1	32,187	1–2	32,272–32,300
5	1	1	1	5	1–2	32,638	2	32,638	2	32,300
…	…	…	…	…	…	…	…	…	…	…
6	1	2	1	1	2–1	32,638	2	32,638	1–2	32,187–32,851
…	…	…	…	…	…	…	…	…	…	…
126	1	2	1	4	2–1	32,638	2	32,638	1–2	32,243–32,936
130	1	2	1	5	2–2	33,089	2	32,638	1–2	32,272–32,964
…	…	…	…	…	…	…	…	…	…	…
254	1	3	1	4	3–1	33,089	3	33,089	1–3	32,908–33,600
255	1	3	1	5	3–2	33,540	3	33,089	2–3	32,964–33,628
…	…	…	…	…	…	…	…	…	…	…
374	5	3	5	4	3–1	33,089	3	33,089	1–3	32,908–33,600
375	5	3	5	5	3–2	33,540	3	33,089	2–3	32,964–33,628

5. Discussion

Three different optimal life-cycle activity profiles with three different costs were determined using the investigated methodologies, due to the different ways both element-level and structure-level costs are taken into consideration. These differences are explained in the following sections.

5.1. *Effect of structural-level cost consideration*

When the condition of an element does not affect the performance of the bridge, i.e. structure-level costs, the effect on the types of interventions included in the life-cycle activity profile between the use of the different methodologies is small. For example, all three optimal life-cycle activity profiles include an intervention of type 1 on the abutment structural unit. The differences in the times of intervention (SPM: every 30 years, SOP every 20 years and JRM every 18 years) happen because in the SOP, the use of the knowledge-based models to group interventions forces the execution of an intervention of type 1 in year 20 when the abutment structural unit is in CS 2, and in the JRM, the costs associated with the execution of interventions on grouped elements was considered to be less than the costs

Table 16. Interventions.

		Methodology	SOP & SPM		JRM		
Structural unit	CS	Interventions[b]	Owner intervention cost (CHF)	Duration (days)	Owner[a] intervention cost (CHF)	Duration (days)	CS after interven-tion
Abutment/pier	2	1	7000	2	17,786–30,572	4.21–6.43	1
	3	2	9500	3	30,572–43,358	6.43–8.64	1
	4	3	61,000	7	43,358–56,144	8.64–10.86	1
	5	4	235,000	25	56,144	10.86	1
Asphalt overlay	2	1	16,800	3	13,807–23,614	2.93–4.36	1
	3	2	23,940	4	23,614–33,421	4.36–5.79	1
	4	3	30,100	6	33,421–43,228	5.79–7.21	1
	5	4	74,060	7	43,228	7.21	1
Bearing	2	1	2500	1	9907–16,814	2.36–3.21	1
	3	2	13,600	2	16,814–23,721	3.21–4.07	1
	4	3	28,000	3	23,721–30,628	4.07–4.93	1
	5	4	55,000	5	30,628	4.93	1
Deck	2	1	13,500	3	17,821–31,142	4.50–21.00	1
	3	2	19,000	4	31,142–44,463	21.00–30.50	1
	4	3	155,000	12	44,463–57,784	30.50–40.00	1
	5	4	435,000	40	57,784	40.00	1

[a] It was estimated that there is travel time costs of 1087 CHF/day, vehicle operation costs of 920 CHF/day, accident costs of 207 CHF/day, noise costs of 315 CHF/day, air pollution costs of 123 CHF/day and climate costs of 34 CHF/day were incurred every time an intervention was executed on a structural unit.
[b] The definition of intervention on each structural unit is given in Table 17.

Table 17. Definition of interventions on each structural unit.

Structural unit	Intervention type	Activities
Abutment/pier	0	Do nothing
	1	Seal concrete cracks
	2	Seal concrete cracks, patching
	3	Rehabilitation including seal concrete cracks and patching
	4	Replacement of the whole structural unit
Asphalt overlay	0	Do nothing
	1	Repair joints and minor crack sealing
	2	Patching, major crack sealing and repair joints
	3	Depth repair including patching, crack sealing and joints
	4	Replacement of the whole structural unit
Bearing	0	Do nothing
	1	Clean, paint and fill and cover cracks
	2	Fixing pins, clean, paint and fill and cover cracks
	3	Major rehabilitation including fixing pins and cracks
	4	Replacement of the whole structural unit
Deck	0	Do nothing
	1	Seal concrete cracks
	2	Repair spalls and seal concrete cracks
	3	Major rehabilitation including repairing spalls and cracks
	4	Replacement of the whole structural unit

on all elements in the group individually. In the SPM, the time of intervention is the expected time when the abutment is considered to be in CS 2.

When the entire performance of the bridge, i.e. structure-level costs, depends on the condition of one element, the variations in the optimal life-cycle activity profiles were due to the groupings of interventions within the methodologies and the linear approximations of the costs in the JRM. For example, using the SOP and the JRM, an intervention of type 1 for the asphalt structural unit was included in the optimal life-cycle activity profile at every 10 and 9 years, respectively, and using the SPM an intervention of type 2 was included every 11 years. These differences are, however, due to the grouping that occurs due to the use of the knowledge-based models in the SOP and the use of discounting in the JRM.

When the SOP is used without knowledge-based models, the intervention on the asphalt would be executed in year 8. The intervention is moved forward in time from year 8 to year 10 as it is grouped with the intervention of type 2 on the deck. When the JRM is used and the asphalt is considered alone, due to the linear approximation of the costs, an intervention of type 1 would be executed in year 7. By grouping the interventions on the asphalt, the bearings and on the deck, however, the intervention is delayed to year 9. Using the SPM the intervention on the asphalt would be executed in year 11, when the asphalt is expected to be in CS 3.

5.2. *Effect of linear approximation of element group costs in the JRM*

The effect of the linear approximation of element group costs in the JRM can result in the execution of interventions earlier (or later) than would otherwise

Table 18. Costs associated with, and durations of, interventions used in the JRM.

Structural unit	Intervention	Cost (CHF)	Duration (days)
Abutment/pier	Minor set-up	2500	1.00
	Major set-up	2500	1.00
	Variable action (per CS)	12,786	2.21
Asphalt overlay	Minor set-up	1500	0.50
	Major set-up	2500	1.00
	Variable action(per CS)	9807	1.43
Bearing	Minor set-up	500	0.50
	Major set-up	2500	1.00
	Variable action (per CS)	6907	0.86
Deck	Minor set-up	2000	1.00
	Major set-up	2500	1.00
	Variable action (per CS)	13,321	2.50

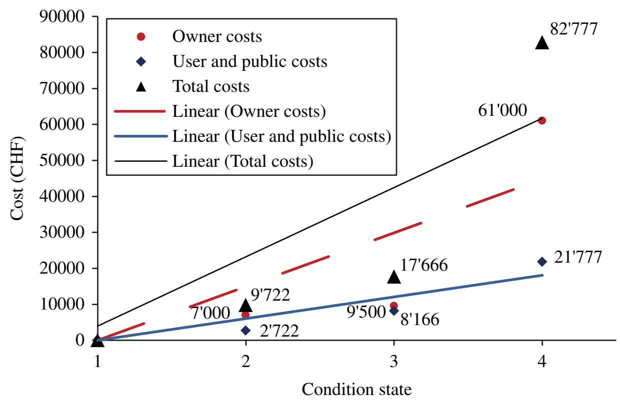

Figure 2. Costs of intervention on the abutments over the condition states.

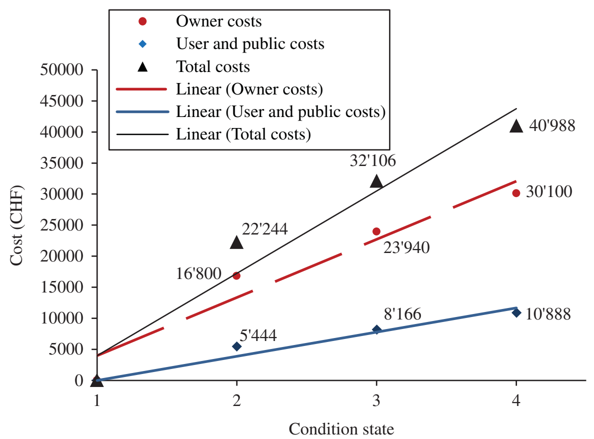

Figure 3. Costs of intervention on the asphalt over the condition states.

occur. For example, using the JRM it is proposed to execute an intervention of type 1 on the deck every 9 years, whereas using the SPM the interventions of type 2 should be executed every 13 years. The difference in the type of interventions is because of the overestimation of the costs

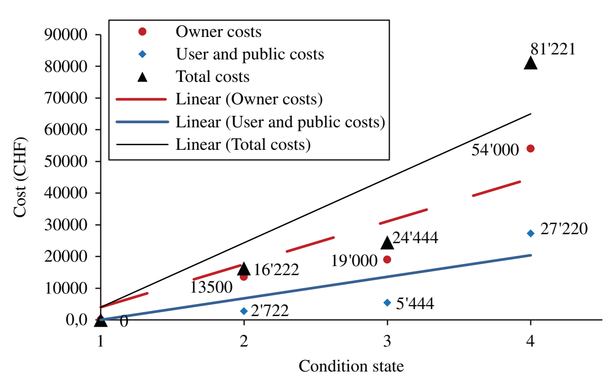

Figure 4. Costs of intervention on the deck over the condition states.

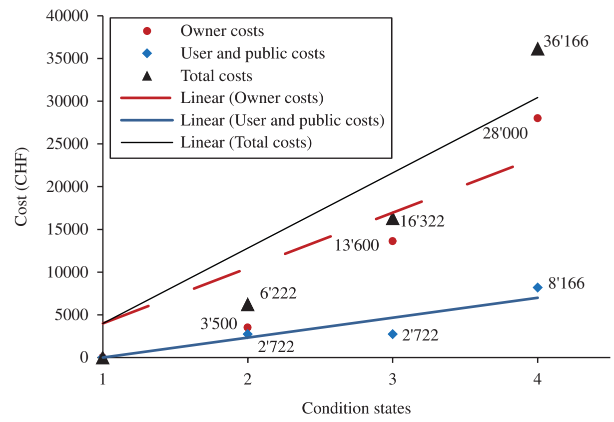

Figure 5. Costs of intervention on the bearings over the condition states.

associated with the interventions to be executed in CSs 2 and 3 using the JRM.

As the overestimation of the costs incurred during the execution of the intervention in CS 3 is much higher than the overestimation of the costs incurred during the execution of the intervention to be executed in CS 2 (Figure 4), it is more advantageous to execute interventions every time the deck is in CS 2. This would not be the case if the costs were estimated correctly. Although it is theoretically possible due to the underestimation of costs associated with an intervention in a CS that the intervention be executed later than would otherwise occur, this was not seen in this example. This would only be noticed if interventions in CS 5 were included in the life-cycle activity profiles, which in this case they were not.

Except for the interventions to be executed on the bearing, the linear approximation of the element group costs in the JRM results in an increase in the number of interventions to be executed on each element when compared with using the SPM, (SPM: asphalt every 11 years, abutment every 30 years, bearing every 7 years and deck every 13 years, JRM: every 9 years), and, therefore, a decrease in the expected costs to be incurred between the execution of interventions (SPM: 3,370,202 CHF, JRM; 3,363,715 CHF).

5.3. *Effect of knowledge-based models in the SOP on the life-cycle activity profile*

The use of knowledge-based models can force the execution of interventions earlier or later than would otherwise occur. For example, using the SOP with knowledge-based models, it is proposed to execute an intervention of type 1 on the asphalt every 10 years, when it is in CS 2, whereas using the SOP without knowledge-based models interventions of type 1 should be executed every 8 years, when it is in CS 2. In this case, an

Table 19. The optimal life-cycle activity profiles determined using each methodology (1/3).

	Year																								
Methodology	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
SOP																									
Asphalt	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Abutment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Bearing	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Deck	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Duration	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
SPM																									
Asphalt	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Abutment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bearing	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Deck	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Duration	0	0	0	0	0	0	1	0	0	0	4	0	4	1	0	0	0	0	0	0	1	4	0	0	0
JRM																									
Asphalt	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Abutment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Bearing	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Deck	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Duration	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0

intervention is executed later than it would be without the knowledge-based models because they force the execution of the intervention of type 1 on the asphalt, when it is in CS 2, when an intervention is to be executed on the deck.

Using the SOP with knowledge-based models, it is proposed to execute an intervention of type 2 on the bearings structural unit every 10 years, when it is in CS 3, whereas using the SOP without knowledge-based models, the interventions of type 2 should be executed every 13 years, when it is in CS 3. In this case, an intervention is executed earlier because the knowledge-based models in the SOP force the execution of an intervention to happen when there is an intervention on the deck.

The use of knowledge-based models in the SOP results in fewer interventions in the life-cycle activity profile than the others (SOP: 7, SPM: 23, JRM: 8), and the highest estimate of the costs to be incurred during the execution of interventions (SOP: 243,055, SPM: 210,507, JRM; 153,651). This is not surprising because as the frequency of interventions decreases, the cost due to their execution increases, when the costs for identical interventions are the same. For JRM, they were reduced.

Table 20. The optimal life-cycle activity profiles determined using each methodology (2/3).

	Year																								
Methodology	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
SOP																									
Asphalt	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Abutment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Bearing	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
Deck	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
Duration	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4
SPM																									
Asphalt	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Abutment	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bearing	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
Deck	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Duration	4	0	1	0	2	0	0	4	0	1	0	0	0	4	0	0	1	0	4	0	0	0	0	1	0
JRM																									
Asphalt	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Abutment	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bearing	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Deck	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Duration	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0

Table 21. The optimal life-cycle activity profiles determined using each methodology (3/3).

	Year																								
Methodology	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
SOP																									
Asphalt	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Abutment	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bearing	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Deck	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Duration	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
SPM																									
Asphalt	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Abutment	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bearing	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Deck	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Duration	0	4	0	0	4	1	0	0	0	2	0	0	1	0	4	4	0	0	0	1	0	0	0	0	0
JRM																									
Asphalt	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Abutment	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Bearing	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Deck	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Duration	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0

5.4. Lowest total costs

Although the JRM found the life-cycle activity profile with the lowest total costs (SOP: 3,609,760; SPM: 3,580,709; JRM: 3,517,366), this does not yield a clear statement with respect to the best methodology, as reduced costs were used for the JRM than with the SOP and the SPM.

Table 22. Absolute total costs for the optimal life cycle activity profiles (values calculated through Equation (14)).

		Total costs (CHF)			
Cost type	Methodology	Total NPV[a] between the intervention	Total NPV during the intervention	Total	% of total
Intervention	SOP	**173,793**[b]	**178,264**	**352,337**	9.75
	SPM	173,741	133,443	307,516	8.58
	JRM	173,883	109,511	283,584	8.06
Travel time	SOP	**1,359,680**	25,046	1,384,726	38.36
	SPM	1,359,270	**29,735**	**1,389,004**	38.79
	JRM	1,357,378	17,070	1,377,448	39.16
Vehicle operating	SOP	1,324,287	20,552	1,344,839	37.26
	SPM	**1,325,523**	**24,543**	**1,350,066**	37.70
	JRM	1,323,480	13,990	1,337,470	38.02
Accident (user)	SOP	208,182	3699	211,880	5.87
	SPM	**210,581**	**4391**	**214,972**	6.00
	JRM	206,077	2521	208,598	5.93
Accident (public)	SOP	57,545	1022	58,567	1.62
	SPM	**58,208**	**1214**	**59,422**	1.66
	JRM	56,963	697	57,660	1.64
Noise	SOP	0	10,801	10,801	0.30
	SPM	0	**12,823**	**12,823**	0.36
	JRM	0	7361	7361	0.21
Air pollution	SOP	**187,280**	2820	190,100	5.27
	SPM	186,958	**3348**	**190,306**	5.31
	JRM	186,967	1922	188,889	5.37
Climate	SOP	55,938	852	56,789	1.57
	SPM	55,921	**1011**	**56,932**	1.59
	JRM	**55,966**	580	56,547	1.61
Sum	SOP	3,366,705	**243,055**	**3,609,760**	100
	SPM	**3,370,202**	210,507	3,580,709	100
	JRM	3,363,715	153,651	3,517,366	100

[a] NPV ~ net present value.
[b] The values in bold are the highest values calculated for each cost type.

5.5. Summary

With respect to the consideration of structure-level costs:

- Using the SOP, there is no consistent way to attribute the structure-level costs to the structure. It may be done manually in the first two periods, but afterwards it must be attributed in some way to the elements. As the initial interventions to be included in the first two periods are determined based on selected element intervention strategies, it would also be necessary attribute structure-level costs to the elements here if it is desired to use them to determine optimal element intervention strategies.
- Using the SPM, both element-level costs and structure-level costs can be attributed to each structure performance state. The only complication is the large number of possible structure performance states for structure made up of many elements that can be in many CSs. Fernando et al. (2012), however, showed that there is a potential way of drastically limiting the number values of the performance indicators that need to be estimated if there are many structure performance states. Although not done in the example, in line with the example illustrated in Fernando et al. (2012), it is possible to use correct models of both element-level and structure-level costs to assign costs to all structure performance states, both during and between interventions.
- Using the JRM, both element-level costs and structure-level costs can be taken into consideration if the entire structure is modelled as a single element group. One complication here is that if the entire structure is modelled as a single element group it is not possible to generate a life-cycle activity profile that includes interventions of different types. This is possible if different element groups are used, although it is at the expense of being able to correctly model the structure-level costs because the structure-level costs depend on all of the elements in the bridge. Two other complications are the large number of simulations that need to be run to ensure that there is a complete picture of the likely intervention times, and that costs must be approximated linearly through the CSs. Once the element group is determined, correct models of both element-level and structure-level costs can be used to assign costs in each period of time investigated.

Based on this analysis, it seems that the SPM is the most suitable methodology for the simultaneous consideration of element-level and structure-level costs in the determination of optimal life-cycle activity profiles.

6. Conclusions

Three methodologies were investigated to assess their suitability to take into consideration both element-level and structure-level costs in the determination of optimal life-cycle activity profiles for bridges. It was found that the SPM is the most suitable. With the SPM, correct models of both element-level and structure-level costs can be used, both during and between interventions.

This conclusion is based on the experience of working with models and is not directly derived from the results shown in the example where the JRM found the best life-cycle activity profile. This occurred because no reductions in costs were given to structural performance states in which multiple elements had interventions, in line with the example illustrated in Fernando et al. (2012).

The SPM has the additional advantage that it determines directly an optimal bridge intervention strategy, so in the future, the intervention on the bridge to be executed is known without an excessive number of simulations. Further investigation is, however, required to determine improved ways of determining the costs of each cost type to be assigned to each structure performance state over the bridge life, to determine the optimal number of structure performance states to be used to model different types of bridges as a whole, and to verify the applicability of this methodology to different types of bridges.

Notations

SOP: state of practice methodology
SPS: structure performance state methodology
JRM: joint replenishment methodology

Acknowledgements

The Cantonal Road Authority of Wallis in Switzerland is gratefully acknowledged for providing the technical information corresponding to the case study bridge considered.

Note

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