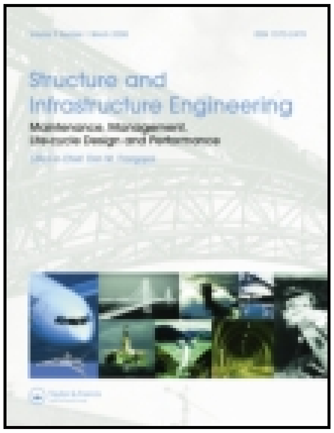

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Methodology for determination of financial needs of gradually deteriorating bridges with only structure level data

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Bridge managers, as other infrastructure managers, are increasingly required to justify the financial resources they need to perform preventative maintenance on bridges. This requires a demonstration of the current state of their bridges and the consequences if the preventative maintenance is not performed. The consequences can be expressed in terms of additional costs to the owner if unacceptable levels of failure risk are avoided. These demonstrations are complicated by the fact that many managers have only basic data with respect to the condition of their bridges, how deterioration processes will affect their bridges and on the type, cost and effectiveness of the interventions that will need to be performed on their bridges in the future. This, in many cases, makes it difficult to show that optimal intervention strategies are being followed and results in a less than convincing argument for the use of taxpayers' money. When less than the required funding is received, managers are forced to follow less than optimal intervention strategies, i.e. short term savings are exchanged for, often unknown, increased future costs. In this paper a general methodology is given that is currently being used in practice in Switzerland and France to determine the lowest cost intervention strategies of bridges with respect to gradual deterioration processes, their financial needs and the consequences, in terms of condition, if they are not followed. It is used when either sufficient detailed element level information or tools are not available to conduct such an analysis based on element level data. At a minimum, the methodology provides a way for managers to structure their technical knowledge and make logical, sound and repetitive estimates of required future financial resources. Additionally, however, it can be used to verify the base assumptions, e.g. speed of deterioration, used to make the estimates. As opposed to other methodologies used in similar situations, this methodology allows consideration of the uncertainty in the input parameters. An example is used to illustrate the type of results obtained using this methodology with normally existing data, as well as some potential uses of the results.

Keywords: bridge management; consequences of inadequate funding; financial needs; gradual deterioration

Introduction

Bridges require significant financial resources to build. In the short term, after they are built they require relatively little financial resources, if any, to maintain. In the medium to long term, assuming there are no changes in use, such as increased traffic loads, and no extreme events, such as earthquakes, the financial resources required to maintain bridges vary considerably depending on, among other things, the bridge type, the material of construction used, and the intervention strategy being followed. For example, one generic intervention strategy is to do nothing to a bridge until there is an unacceptable probability of bridge failure and then replace it, and another is to protect a bridge regularly against the processes of deterioration that affect it, e.g. painting a steel bridge at regular intervals so there is only a negligible probability that the bridge will experience any significant corrosion. The former strategy will require no financial resources in the medium term to maintain. The latter will require financial resources in the medium term to replace the protective coating of the structure. Both of these intervention strategies, however, are valid and neither necessarily results in a negative impact on the bridge users.

The choice between these intervention strategies, and all others, depends on the type and speed of the deterioration processes affecting the bridges, and the cost and effectiveness of the interventions. Taking these parameters into consideration, it is the task of managers to determine and execute the optimal intervention strategies, i.e. the strategies that ensure that the bridges provide an adequate level of service for the lowest long term costs. It is, however, in some cases desirable to follow strategies that do not result in the lowest long term costs, e.g. when it is known that the bridges will be decommissioned or during times of exceptionally tight budgets when it is decided that the

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required financial resources are better used elsewhere. When the bridges are to be kept in service in the long term, however, any deviation from the optimal intervention strategies results in an increase in the total required financial resources.

Although many bridge managers know in general which intervention strategies are optimal in the long term for their bridges, the infinite number of exact possibilities renders them unsure that the optimal intervention strategies have indeed been determined and are being executed. This uncertainty coupled with external pressure to reduce short term maintenance costs is making it necessary to demonstrate both numerically and systematically the intervention strategies that are indeed least expensive, their costs and the expected condition of the bridges if they are executed, as well as to quantify the consequences if they are not.

These demonstrations are complicated by the fact that many bridge managers have only basic data with respect to the condition of their bridges, how deterioration processes will affect their bridges and the interventions that will have to be performed on their bridges in the future. This, in many cases, makes it both impossible to show that optimal intervention strategies are being followed and results in a less than convincing argument for the use of taxpayers' money. When bridge managers receive less than the required financial resources, they are forced to follow less than optimal intervention strategies, i.e. short term savings are exchanged for, often unknown, increased future costs.

In this paper a general methodology is given that is currently being used in practice in Switzerland and France to determine the lowest cost intervention strategies for bridges with respect to gradual deterioration processes, their financial needs and the consequences, in terms of condition, if they are not followed. A distinction is made between gradual deterioration processes, which are manifest under normal inspection regimes, and sudden deterioration process, which are latent under normal inspection regimes, as the planning of interventions with respect to these two types of processes are fundamentally different. The methodology is used when either sufficient detailed element level information or tools are not available to conduct such an analysis based on element level data. It is similar to those used in state-of-the-art, but far more data intensive, management systems such as KUBA (Hajdin 2008), the Quebec Bridge Management System (Ellis *et al.* 2008) and PONTIS (Cambridge Systematics 2001).

At a minimum, the methodology provides a way for managers to structure their technical knowledge and make logical, sound and repetitive estimates of required future financial resources. Additionally, however, it can be used to verify the base assumptions, e.g. speed of deterioration, used to make the estimates. As opposed to other methodologies used in similar situations, this methodology allows consideration of the uncertainty in the input parameters.

An example is used to illustrate the type of results obtained using this methodology with normally existing data, as well as some potential uses of the results.

Literature

As there is an increasing need to make the above mentioned predictions with only basic data, numerous researchers and consultants have developed various methodologies with which to make them, in particular Adey *et al.* (2006b), Imhof *et al.* (2007), Yamamoto *et al.* (2008) and Zonto *et al.* (2008).

Both Adey *et al.* (2006b) and Zonto *et al.* (2008) proposed methodologies to be used associating the condition of bridge with an equivalent age and modelling deterioration deterministically. In these methodologies the intervention costs are linked directly to condition states for each bridge type and include only agency costs. Since agency costs are correlated with bridge and intervention types, and change depending on bridge condition, they are estimated for all condition states of each bridge type, using expert opinion, based on the experience of the experts with unit costs, bills of quantities and parametric cost estimating models. Costs, such as user costs, that are not correlated with bridge and intervention types are not included.

The methodology used by Imhof *et al.* (2007) evaluates different intervention strategies by making assumptions with respect to the interventions that would be performed at specific bridge ages, modelling deterioration of the bridges deterministically as the advancement of each bridge through each condition state one year at a time, and modelling the effect of interventions deterministically where the bridge condition is assumed to be improved to a specific time of a predefined condition state.[1] Assumptions are made with respect to the number of bridges from an investigated bridge stock that will have interventions and the time of these interventions for each intervention strategy. The optimal intervention strategy is the least expensive of the investigated strategies over an investigated time period.

Yamamoto *et al.* (2006) select intervention strategies for individual bridges and calculate life-cycle costs. Both deterioration and improvement are modelled deterministically. The optimal intervention strategy is the one that yields the least costs over a specified period of time.

Although all of these approaches allow bridge managers to obtain an idea of what the optimal intervention strategies are, one of their weaknesses is that deterioration and improvement must be modelled deterministically. Forcing deterioration and improvement to be modelled deterministically makes it difficult to determine the optimal intervention strategy accurately, and eliminates the ability to take into consideration uncertainty or variation in these models, which is often desired. In addition, from an operational point of view, it makes it more difficult for multiple experts to agree on input values. The herein presented methodology alleviates these problems.

Basis of methodology

Classification

As it is rarely reasonable on the management level to make predictions for bridges individually, a model must be constructed that allows the classification of the bridges. The model to be used depends on what is to be predicted, but often bridges that exhibit similar general characteristics, like function, material of construction, extent and location, can be grouped together as a bridge type. Such a classification allows limitation of the number of possible interventions and intervention strategies that need to be considered. An example, in tabular form, for bridges is shown in Table 1 using the number and surface area of the bridges. Special care is required to ensure that the classification is orthogonal and that the classification is sufficiently detailed so that precise future predictions can be made.

Condition

Condition states

In order to assess the physical condition of a bridge, condition states are used. An example of condition states is given in Table 2. In this example, the condition state 1 represents a condition where there is no damage, or only superficial damage. Each subsequent condition state represents a condition with increasing quantities and severities of damage. Condition state 5 represents a condition where there is alarming damage. A bridge is said to be in a condition state when it has at least one of the listed damage indicators and nothing more serious, i.e. listed as a damage indicator of a higher condition state. A bridge does not have to have all of the listed damage indicators to be in the condition state.

Table 1. Example tabular display of the classification of bridges.

No.	Function	Principal construction material	No.	Deck surface area [m^2]
1	Rail bridge	Concrete	33	1215
2		Masonry	287	42,121
3		Metal	37	5188
4		Composite	85	3423
5	Road bridge	Concrete	25	6386
6		Masonry	85	4548
7		Metal	8	281
8		Composite	16	796
Total			576	63,958

Extent of damage

When an entire bridge is initially considered to be in a single condition state, which is sometimes an outcome of bridge inspections, the percentage of the bridge in each condition state is estimated. This estimation is required in order to increase the accuracy of cost estimates as interventions are normally only performed on the parts of the bridge that specifically require intervention.

The percentages used for each bridge type are contained in an extent of damage matrix for each bridge type (an example is shown in Table 3). For example, when an entire concrete bridge is classified in condition state 2 (bold), it is supposed that on average 35% of the bridge is actually in condition state 1, 60% in condition state 2, 5% in condition state 3 and 0% in condition state 4 and 5.

Deterioration

Processes

Bridges experience both gradual deterioration processes, which are manifest under normal inspection regimes, and sudden deterioration process, which are latent under normal inspection regimes. The significance of each type of deterioration in the estimation of intervention costs depends on many factors related to the specific network and the specific deterioration processes at work. How deterioration is estimated, however, is fundamentally different when bridges are affected by gradual and sudden deterioration processes. In many cases, however, in the long term the majority of intervention costs can be attributed to gradual deterioration processes. Bridge deterioration due to a gradual deterioration process can be modelled in a reliable systematic manner using the presented methodology if the deterioration processes at work meet the following criteria:

- Deterioration is continuous and predictable and permits classification of bridges into condition states.

Table 2. Example of condition states for reinforced concrete bridges.

Condition state	Condition description	General description of damage	Damage indicators
1	Good	None/insignificant	Concrete elements: Small superficial cracks, no indication of corrosion, no or few humid zones Bearings: No indication of corrosion or damage
2	Acceptable	Minor	Concrete elements: Small cracks due to the corrosion of the reinforcement, some rust spots, some humid zones but no leaching of the concrete. Bearings: Some indication of corrosion or damage
3	Damaged	Significant	Concrete elements: Some calcium deposits along concrete cracks, some spalling of concrete with less than 10% of reinforcement exposed, insignificant loss of cross section area of the reinforcement, humid zones with leaching of the concrete. Bearings: Medium amount of corrosion and damage
4	Poor	Extensive	Concrete elements: Significant calcium deposits along concrete cracks, spalling of concrete with less than 25% of exposed reinforcement, occurrence of pitting corrosion, large humid zones with leaching of concrete. Bearings: Significant corrosion, including corroded support plates and anchoring connections
5	Alarming	Safety is endangered. Interventions are required before the next planned inspection.	Concrete elements: Extensive spalling of concrete with more than 25% of exposed reinforcement, significant loss of cross sectional area of the reinforcement, advanced pitting corrosion occurring, large humid zones with leaching of concrete. Bearings: Advanced corrosion, seized bearings, anchoring connections heavily deteriorated

Table 3. Extent of damage matrix for concrete bridges.

Indicated condition state of the structure	Percentage of the structure suspected to be in each condition state				
	1	2	3	4	5
1	90	10	0	0	0
2	**35**	**60**	**5**	**0**	**0**
3	10	40	45	5	0
4	5	15	35	40	5
5	0	5	15	60	20

- Damage due to the deterioration process can be discovered and inspected with relatively little effort, i.e. the process is manifest under the inspection regime.
- Interventions can be assigned to each bridge based on its condition state.
- Relationships between the extent of intervention and the extent of damage are easily discernable.

An example of gradual deterioration processes that fulfil these criteria are given in Table 4.

Model

Markov deterioration matrices are used to model the deterioration process. A Markov deterioration matrix gives the probability that a bridge or a part of a bridge will change condition state within a specified period of time, often taken as the time between two main inspections. The example of a Markov deterioration matrix shown in Equation (1) is based on a five condition state model, as shown in Figure 1.

$$\begin{array}{c} \\ CS_1 \\ CS_2 \\ CS_3 \\ CS_4 \\ CS_5 \end{array} \begin{array}{c} \begin{array}{ccccc} CS_1 & CS_2 & CS_3 & CS_4 & CS_5 \end{array} \\ \left\{ \begin{array}{ccccc} 1-(p_{12}+p_{13}+p_{14}+p_{15}) & p_{12} & p_{13} & p_{14} & p_{15} \\ & 1-(p_{23}+p_{24}+p_{25}) & p_{23} & p_{24} & p_{25} \\ & & 1-(p_{34}-p_{35}) & p_{34} & p_{35} \\ & & & 1-(p_{45}) & p_{45} \\ & & & & 1 \end{array} \right\} \end{array} \tag{1}$$

In Equation (1) Ip_{ij} is the transition probability from condition state i in year t to condition state j in year $t+1$. For example, column 1 row 1 shows the probability of part of a bridge being in condition state 1 at $t+1$ if it is in condition state 1 at time t. Note the $p_{ij}=0$ for $i>j$. This imposes the constraint that bridges cannot improve in condition.

The probability to be in condition state j in year $t+1$, is the sum of all of the transition probabilities as shown in Equation (2):

$$p_j^{t+1} = \sum_{i=1}^{j} p_{ij} \cdot p_i^t \tag{2}$$

where p_i^t is the probability to be in condition state i in year t.

Interventions

Types

The development of intervention strategies for each bridge type requires the determination of the possible intervention types for each bridge type in each condition state, their unit costs (based on a standard unit) and their effectiveness. The activities that are likely to be performed with respect to each intervention type should be explicitly noted in order to increase the accuracy of the estimates of the unit costs. Example intervention types are:

(1) Do nothing.
(2) Rehabilitation.
(3) Renewal.
(4) Replacement.

Example activities that are likely to be performed for each intervention type for concrete bridges can be seen in Table 5. Of course, a renewal intervention can also contain the activities of a rehabilitation intervention, and a replacement intervention can also contain the activities of a rehabilitation and a renewal intervention.

Table 4. Examples of a gradual deterioration process that can be modelled in a reliable, systematic manner.

Material of construction	Deterioration process
Concrete	Corrosion of the concrete reinforcement
Composite	Corrosion of the metal components and the concrete reinforcement
Masonry	Chemical and physical deterioration of mortar and bricks due to water infiltration and freeze–thaw cycles
Metal	Corrosion

Effectiveness

Since interventions do not always result in a like new structure, the effectiveness of the interventions types is modelled. The effectiveness of interventions is presented in vector form. The vectors give the probability of a bridge of each bridge type being classified in each condition state at the beginning of the next analysis period following the intervention.

When no data is available from which to determine intervention effectiveness, which is often the case, it is determined based on expert opinion. An example of effectiveness vectors is given in Table 6. In the shown example, if part of a bridge is in condition state 4 before an intervention and a renewal intervention is performed there is a 90% chance that it will be

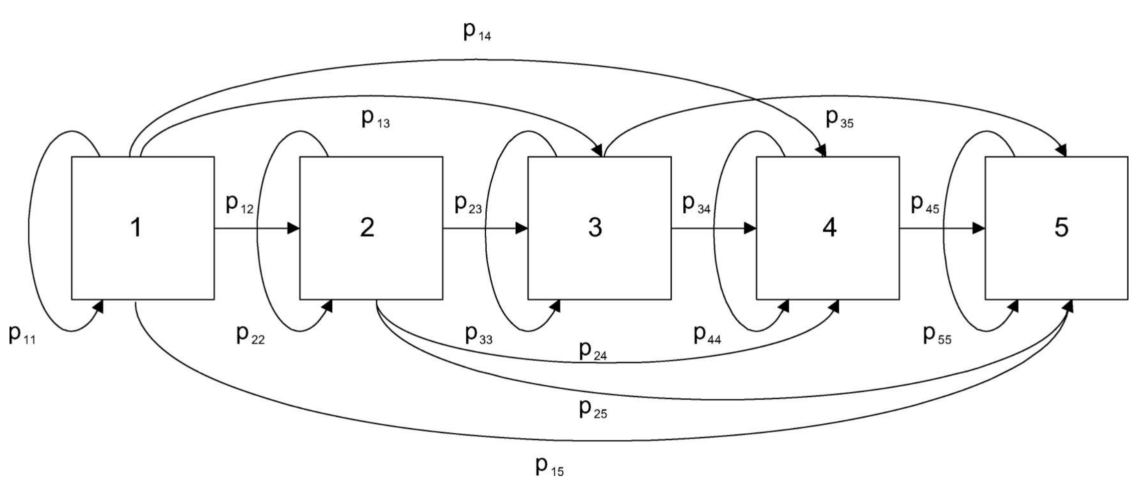

Figure 1. Transition probabilities for a 5 state model.

classified in condition state 1, and 10% chance that it will be classified in condition state 2, at the beginning of the next analysis period.

Unit costs

The cost of interventions is estimated through the multiplication of the unit costs per m^2 with the bridge surface area as shown in Equation (3). The unit costs can be determined using available data and expert opinion. An example of unit costs associated with interventions on a bridge is given in Table 6. The unit costs considered are agency costs, although it is possible to take into consideration certain types of user costs.

$$C_t = \sum_j \sum_i UC_{ij} * A_{ij} \tag{3}$$

where C_t is the cost in year t; UC_{ij} is the unit costs of interventions for bridge type j in condition state I; and A_{ij} is the area of bridge type j in condition state i.

Table 5. Example activities for each intervention type for concrete bridges.

Preservation intervention	Description of activities
Do nothing	–
Rehabilitation	Replacement of the waterproofing
	Restoration of parts of the drainage system
	Improvement or replacement of construction joints
	Repair of the reinforced concrete
	Renewal of any finishing
Renewal	Improvement or replacement of construction joints
	Replacement total or partial of the supports
	Renewal of the drainage system
	Replacement of the guard rails
	Strengthening of one or more structural elements
Replacement	Replacement of part or all of the structure

Strategies

An intervention strategy is comprised of the interventions that are to be performed as soon as a bridge is in a specific condition state. The interventions that comprise the optimal intervention strategies are the ones that if done when a part of a bridge is in each condition state will result in the lowest long term costs. These interventions are calculated based on evaluation of all possible combinations using linear programming methods. Example optimal intervention strategies are given in Table 7. The shown intervention strategy indicates that nothing should be done when part of a bridge is in condition state 1, 2 or 3, that a rehabilitation should be done when part of a bridge

Table 6. Example of effectiveness vectors and unit costs of interventions.

Condition state	Effectiveness vectors						Unit costs CHF/m^2
	Interventions	CS1	CS2	CS3	CS4	CS5	
3	Rehabilitation	0.80	0.20	0	0	0	350
	Renewal	0.95	0.05	0	0	0	700
	Replacement	1	0	0	0	0	3500
4	Rehabilitation	0.75	0.25	0	0	0	550
	Renewal	**0.90**	**0.10**	**0**	**0**	**0**	**1000**
	Replacement	1	0	0	0	0	3500
5	Rehabilitation	0.60	0.40	0	0	0	3500
	Renewal	0.85	0.15	0	0	0	3500
	Replacement	1	0	0	0	0	3500

Table 7. Example optimal intervention strategies.

Bridge type	Condition state				
	1	2	3	4	5
Reinforced concrete	Do nothing	Do nothing	Do nothing	Rehabilitation	Replacement
Pre-stressed concrete	Do nothing	Do nothing	Do nothing	Rehabilitation	Replacement
Masonry	Do nothing	Do nothing	Do nothing	Rehabilitation	Replacement
Composite	Do nothing	Do nothing	Rehabilitation	Rehabilitation	Replacement
Metal	Do nothing	Do nothing	Rehabilitation	Rehabilitation	Replacement

is in condition state 4 and if part of a bridge is in condition state 5 than it should be replaced.

Benefit/cost ratio

The prioritisation of interventions when sufficient financial resources are not available to perform all of the required interventions is determined based on the benefit/cost ratio of the interventions. The costs of the interventions are determined by multiplying the bridge surface area that requires intervention according to the investigated intervention strategy, and the unit costs per m^2 of each corresponding intervention. The benefits are estimated as the difference between the long term costs for a reference strategy (e.g. CS1 – Do nothing, CS2 – Do nothing, CS3 – Do nothing, CS4 – Do nothing, and to do what is optimal in CS5, either Rehabilitation, Renewal or Replacement) minus the long term costs of the optimal intervention strategy plus the actual intervention costs. This is shown mathematically in Equation (4). The actual costs of the intervention are added to the numerator so that the results are always greater than 1, allowing an incremental benefit/cost analysis to be used (Farid *et al.* 1994).

$$B/C = \frac{(C^l_{IS-R} - C^l_{IS-O}) + C_t}{C^l_{IS-0}} \qquad (4)$$

where C_t is the cost in year t; C^l_{IS-O} is the long term costs of the optimal intervention strategy; and C^l_{IS-R} is the long term costs of the reference intervention strategy.

Agency rules

Since it is not desired to perform interventions on the same bridges every year, and it is not desired to perform interventions on very small parts of bridges, agency rules are used in the building of work programmes. Some example agency rules are:

- Interventions must be performed when more than 5% of the surface area of a bridge is considered to be in condition state 5 (to ensure negligible failure risks).
- If less than 5% of the surface area of a bridge requires an intervention according to the intervention strategy to be followed, no intervention is performed (to ensure interventions are not performed on very small parts of bridges).
- If more than 5% of the surface area of a structure requires an intervention according to the intervention strategy to be followed, than interventions for all parts of the bridge that are in condition states 3, 4 and 5 are performed (to

Table 8. Steps for the development of financial needs and structural condition on the network level.

Step	Description
1	Estimate the percentage of bridges in each condition state for each bridge type at time $t = 0$.
2	Determine the optimal intervention strategy for each bridge type
3	Select the intervention strategy i to be performed (optimal, minimal or user defined).
4	Determine the interventions to be performed at time t (based on actual or expected structural condition).
5	Sum the financial needs of all necessary interventions at time t.
6	Estimate the distribution of structural condition for each bridge type at time $t = t + 1$.
7	Repeat steps 4 to 7 (with $t = t + 1$) until the structural condition prediction and financial needs for the implementation of intervention strategy i over the investigated time period is determined.
8	Repeat steps 3 to 8 until the structural condition predictions and financial needs for each of the intervention strategies over the investigated period are determined.
9	Display of the structural condition predictions and the financial needs for each intervention strategy over the investigated time period.

Table 9. Steps for the development of financial needs and structural condition on the project level.

Step	Description
1	Determine the financial needs of each intervention on each bridge under the assumption that the selected intervention strategy is followed.
2	Determine the benefit of the interventions for each bridge in year t.
3	Selection of the bridges where interventions will be performed when the benefit/cost ratios are maximised, in year t.
4	Predict the effect of the interventions on the bridge condition $t = t + 1$.
5	Repeat steps 1 to 4 until the work program for the desired period of time is completed, $t = x$.
6	Estimate the percentage of bridges for each bridge type that are in each condition state immediately following the work programme, $t = x$.
7	Determine the interventions to be performed at $t = x$ based on the structural condition.
8	Addition of the financial needs for each of the interventions at $t = x$.
9	Determine the percentage of bridges of each bridge type in each condition state at $t = x + 1$.
10	Repeat steps 7 to 9 (with $t = t + 1$) until the structural condition predictions and the financial needs for the implementation of the selected intervention strategy over the investigated time period is determined.
11	Repeat steps 6 to 10 until the condition states and the financial needs of for all intervention strategies to be investigated are determined.

ensure a sufficient return period between interventions). The interventions to be performed in this case must be defined (Adey *et al*. 2006a).

Predictions

The steps for the determination of the financial needs and structural condition for the optimal intervention strategies using the basis presented above on the network level (without consideration of specific work programs or budget restrictions) and project level (with consideration of specific work programs and budget restrictions) are shown in Tables 8 and 9, respectively.

Example results

This section provides an example of the results from the application of the explained methodology and how the results can be used to determine the most suitable budget scenario. Four budget scenarios[2] (Table 10) and three types of intervention strategies were investigated, i.e. optimal, minimal and user defined[3] (Table 11) for the bridges presented in Table 12. Although determined, the information for each bridge (condition state and extent of damage) and for each bridge type (transition probabilities to model deterioration, intervention types, and intervention effectiveness and unit costs) are not presented here due to space restrictions and as they do not substantially increase understanding of the methodology.

Network level

The required financial resources and the resulting condition of the bridges for the three types of intervention strategies, on the network level, are shown in Figure 2. These estimates are seen as theoretically optimal as opposed to those on the project level that deviate from being theoretically optimal due to budget constraints and the agency rules used to construct work programmes.

It can be seen in Figure 2 that if the optimal intervention strategies for all bridge types are followed 20.3 million CHF is required to perform the interventions in year 1. This amount is substantially reduced in the following year and then increases slowly to 3.1 million CHF. This large initial expenditure is due to the existing condition of the bridges, where many of them, even if indicated to be in condition state 2 actually have parts in condition state 3 and 4, condition states where an intervention should be performed following the investigated intervention strategies. Performing these interventions will result in the following changes in the percentage of the bridge stock in each condition state (Figure 2):

- 33.2% in condition state 1 instead of the present 60.8%.
- 42.1% in condition state 2 instead of the present 26.5%.
- 24.0% in condition state 3 instead of the present 9.3%.
- 0.7% in condition state 4 instead of the present 2.4%.
- 0.0% in condition state 5 instead of the present 0.9%.

Table 10. Example: Budget scenarios.

Scenario	Budget constraints (10^6 CHF/year)			
	Year 1	Year 2	Year 3	Years 4–10
0	–	–	–	–
1	3.0	4.0	5.0	6.0
2	4.5	4.5	4.5	4.5
3	3.0	3.0	3.0	3.0

Table 12. Example: Surface area (m^2) and condition state of bridges.

Bridge type	Condition state					
	1	2	3	4	5	Total
Reinforced concrete	91,609	47,811	17,639	4,172	25	161,256
Pre-stressed concrete	19,275	0	3159	0	0	22,434
Composite	98	1680	2241	154	0	4172
Metal	25,965	9211	7644	1237	552	44,608
Masonry	2024	1938	1346	74	574	5956
Total	138,970	60,640	32,028	5637	1151	238,426

Table 11. Example: Intervention strategy types.

Strategy type	Condition state				
	1	2	3	4	5
Optimal	Optimal	Optimal	Optimal	Optimal	Optimal
Minimal	Do nothing	Do nothing	Do nothing	Do nothing	Optimal
User defined	Do nothing	Do nothing	Do nothing	Rehabilitation	Renewal

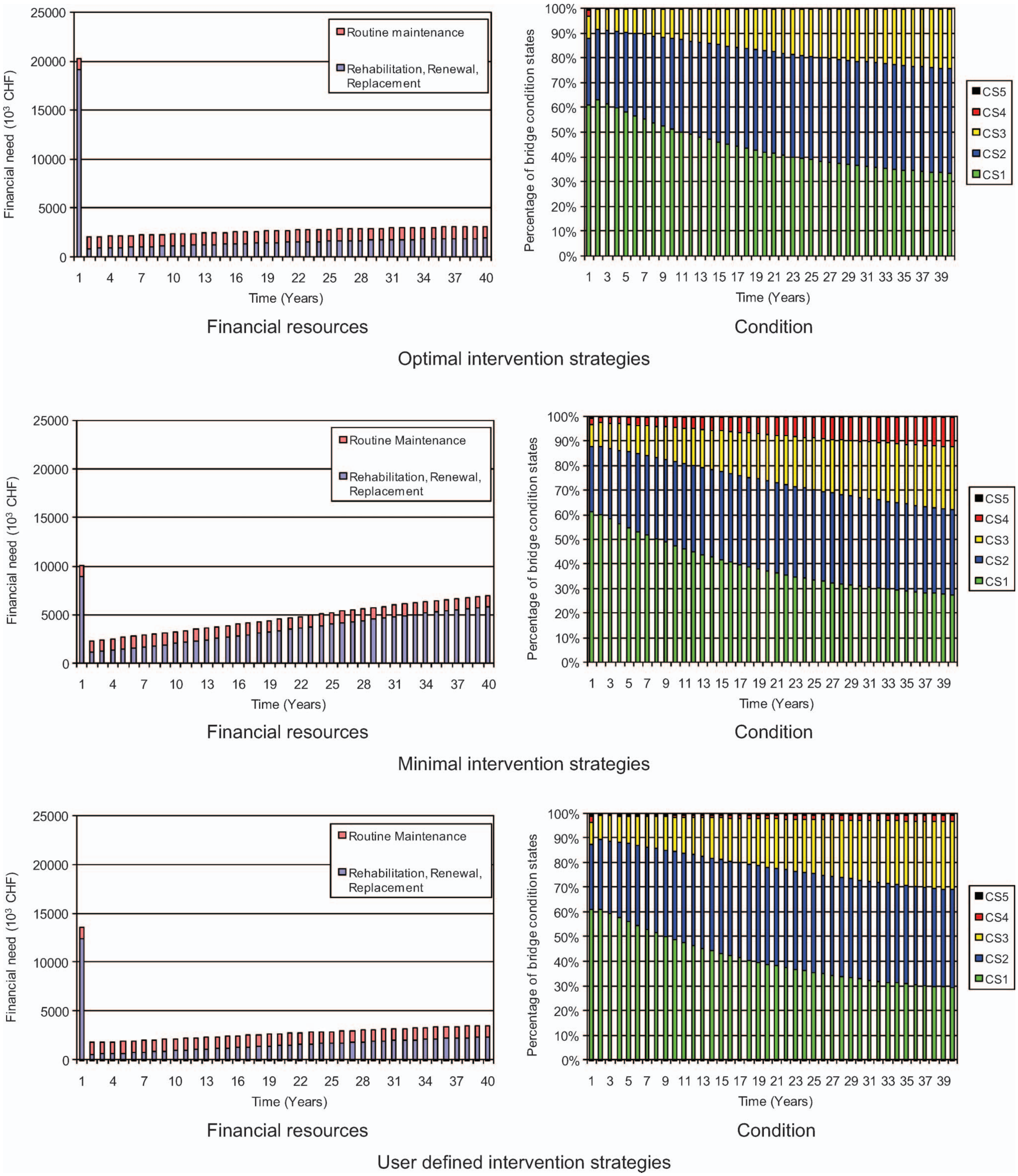

Figure 2. Network level: Required financial resources and resulting bridge condition.

With this information it is possible to make comparisons between intervention strategies to demonstrate that the optimal intervention strategies result in the long term in the lowest annual costs and the best condition. For example, it can be seen that although the optimal intervention strategies require in year 1 101% more financial resources than the minimal (20.3 vs. 10.1 Mio. CHF) and 49% more than the user defined (20.3 vs. 13.6 Mio. CHF) intervention strategies, that they require annually in the long term, i.e. year 40, only 55% (3.1 vs. 6.9 Mio. CHF) and 14% (3.1 vs. 3.6 Mio. CHF) of the financial resources required by the minimal and user-defined intervention strategies, respectively. It can also be seen that the optimal intervention strategies result in a smaller percentage of bridges being in condition state 4 and 5 (Table 13) than the minimal and user defined intervention strategies (0.7% compared to 12.6% and 3.1%, respectively.).

Project level

On the project level the presented methodology allows the development of work programs consisting of candidate bridges for intervention and determination of the impact of this work program on future bridge condition and costs. A sample of the candidates to be included in the first year of the work programs under each budget scenario for each intervention strategy, in this example, are shown in Table 14. The effects of the complete 10 year work program on the required financial resources and future bridge condition are shown in Figures 3 to 6. From such graphs, the yearly variations in costs can be seen. For example, when the optimal intervention strategies are being followed and there are no budget restrictions, i.e. Scenario 0, it is suggested to allocate approximately 18 million CHF in year 1,[4] 6 million in year 2 and nothing in years 3 through 7, in addition to that required for routine maintenance. It can be seen for scenario 1 that the 18 million CHF required is not available to be allocated due to budget restrictions and therefore that the ever increasing amount of work is pushed into the years where enough funding is available, i.e. years 3-7. The spike in costs that occurs following the work programs is due to the alleviation of the agency rules in the methodology in year 11. The results for all four scenarios are summarised in Table 15.

Table 13. Example: Long term condition distribution.

Condition state	Intervention strategies		
	Optimal	Minimal	User defined
1	33.2	27.1	29.2
2	42.1	34.6	39.9
3	24.0	25.6	27.8
4	0.7	12.0	3.0
5	0.0	0.6	0.1

Comparison of results

Optimal

If the optimal interventions strategies are followed scenario 0 is the least expensive scenario over 11 years (50.3 instead of 52.7, 52.7 or 54.7 $\times$ 10^6 CHF) and over 40 years (128 instead of 130, 130 or 132 $\times$ 10^6 CHF). The difference over 40 years, however, is small since the optimal intervention strategies without budget constraint are followed after the 10 year work programme. This indicates that the exact year of intervention is not of great significance if a bridge provides an adequate level of service. Scenario 1, however, results in the best condition of the bridges immediately after the work program (87.4% in condition states 1 and 2). This happens because the scenarios with budget restrictions that are not too severe have the effect of postponing some interventions a few years. By having these interventions later in the work programme, instead of earlier, the bridges are in a better condition immediately following the work programme as they have had less time to deteriorate. Scenario 3 results in the worst condition after the work programme because there is insufficient funding in the first 10 years to perform all of the required interventions. It, therefore, also has the largest intervention

Table 14. Example: Sample of work programme.

Bridge identifier	Bridge type	Surface area (m^2)	Benefit of optimal intervention strategy (10^3 CHF)	Cost of intervention strategy (10^3 CHF)	Benefit/cost ratio	Scenario			
						0	1	2	3
B-006	Reinforced concrete	1932	7049	927	7.6	Yes	No	No	No
B-015	Pre-stressed concrete	3159	9541	971	9.8	Yes	No	Yes	No
B-023	Reinforced concrete	1685	6147	809	7.6	Yes	No	No	No
B-028	Metal	1065	3492	327	10.7	Yes	Yes	Yes	Yes
B-032	Metal	552	3194	844	3.8	Yes	No	No	No
B-038	Metal	1691	5546	520	10.7	Yes	Yes	Yes	Yes
B-052	Metal	284	1346	209	6.5	Yes	No	No	No
B-067	Metal	443	2103	326	6.5	Yes	No	No	No
B-117	Reinforced concrete	243	533	58	9.1	Yes	No	No	No
B-118	Reinforced concrete	74	161	18	9.1	Yes	No	No	No

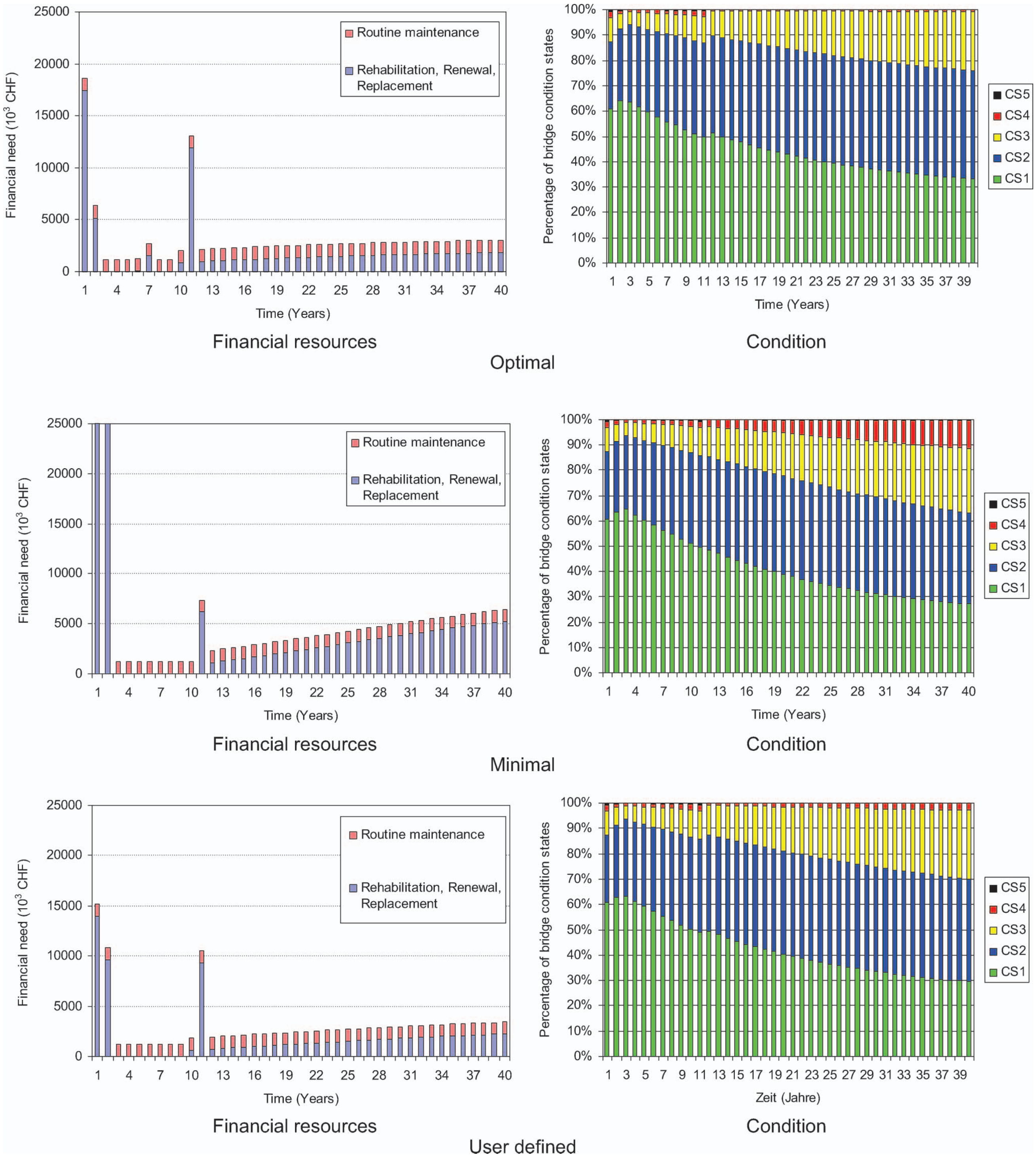

Figure 3. Scenario 0: Evolution of required financial resources and bridge condition.

deficit, immediately following the work programme (24.7 instead of 13.0, 12.6 or 12.8 $\times$ 10^6 CHF).

This information clearly shows that if the optimal intervention strategies are to be followed that there should be no budget constraints as this results in the least required financial resources and bridges that are in a good, although not the best, condition following the work programme.

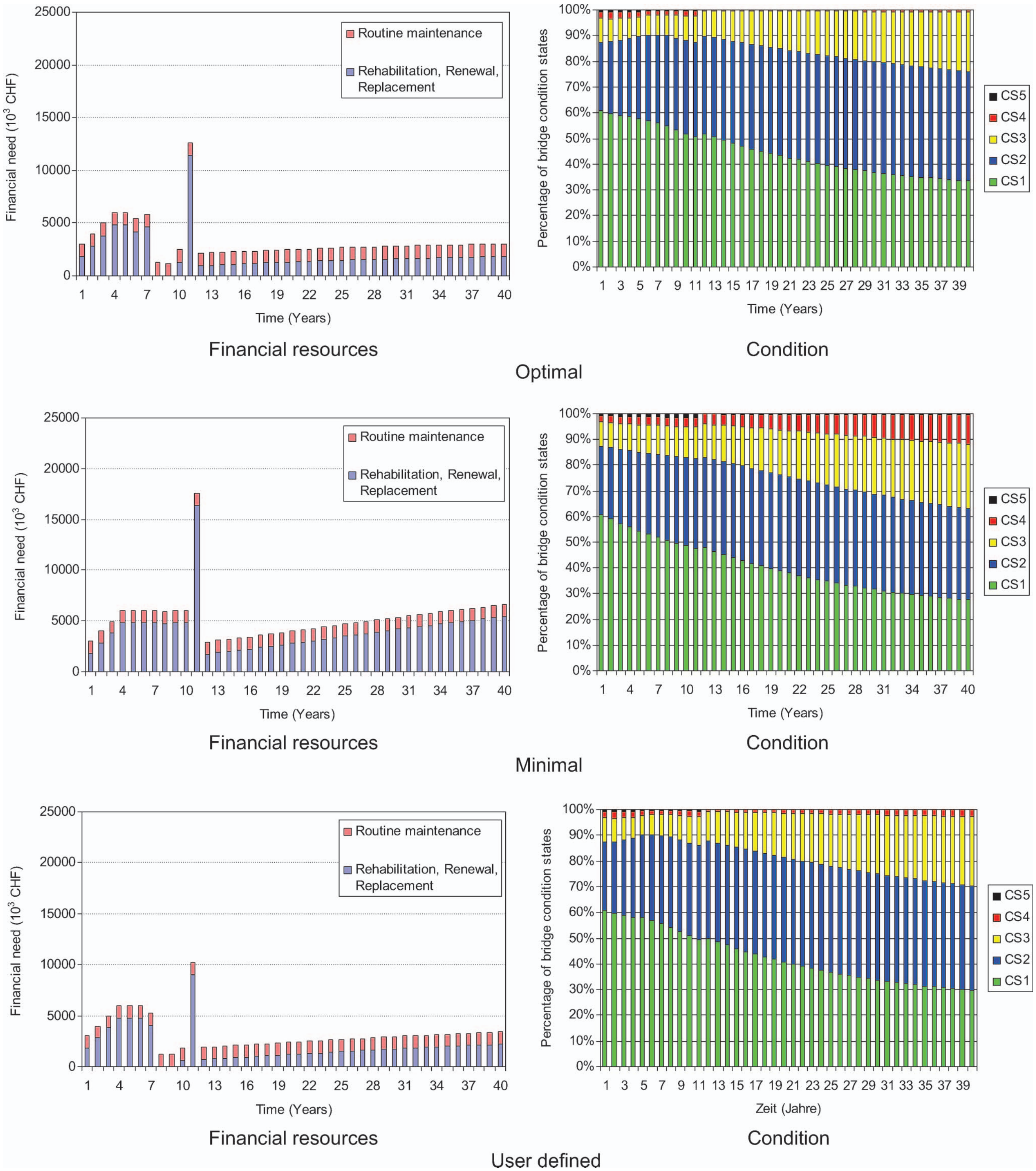

Figure 4. Scenario 1: Evolution of required financial resources and bridge condition.

Minimal

If the minimal intervention strategies are followed scenario 3 is the least expensive scenario over 11 years (52.6 instead of 98.4, 71.4 or 63.4 $\times$ 10^6 CHF) and over 40 years (198 instead of 224, 210, 205 $\times$ 10^6 CHF) (Table 15). This means that as few interventions as possible should be executed. Since there is no more advanced condition state than condition state 5, and the intervention costs do not increase with further deterioration, it is better to wait until an unacceptably large portion of a bridge is in condition state 5. Immediately following the work

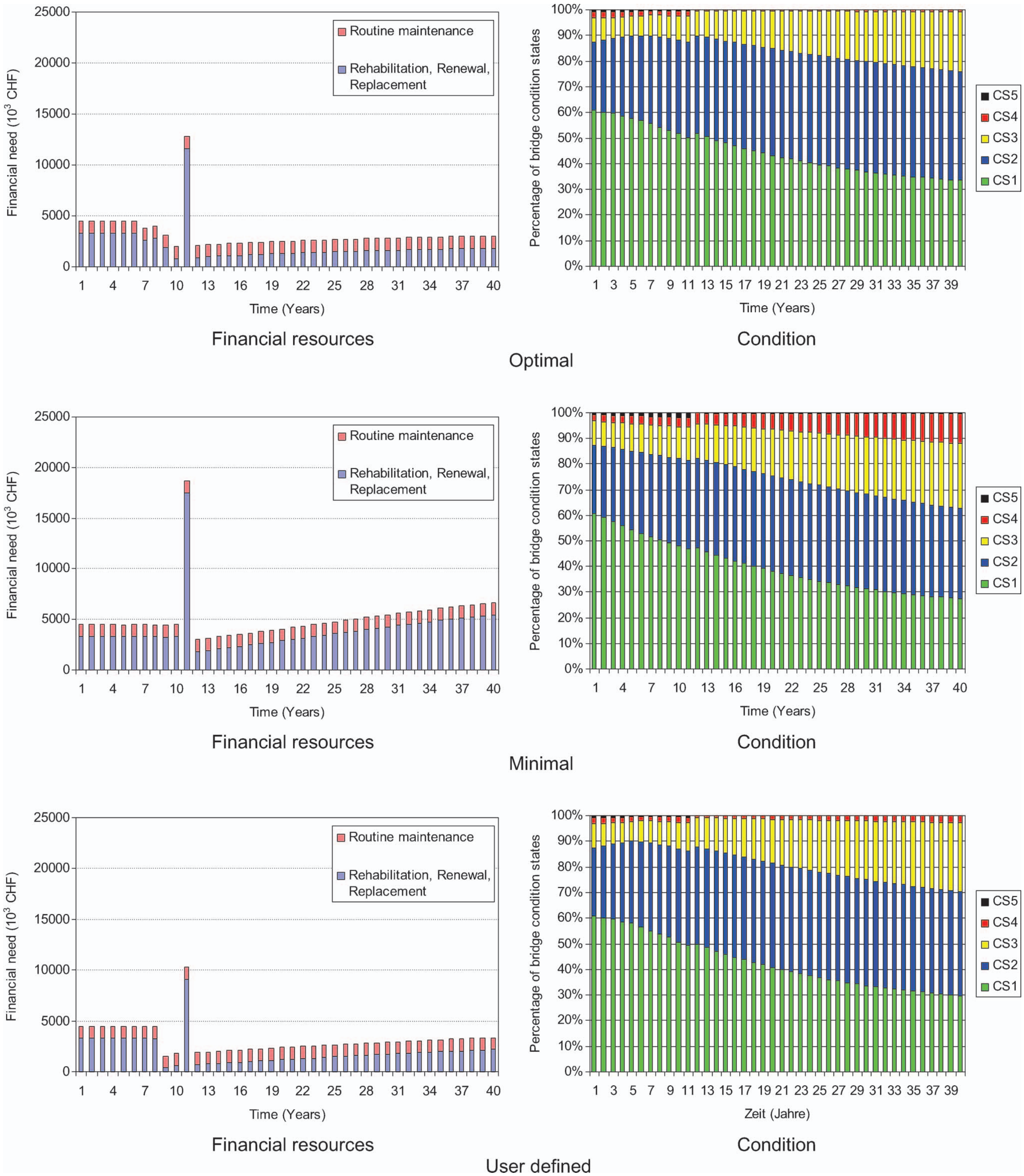

Figure 5. Scenario 2: Evolution of required financial resources and bridge condition.

programme scenario 3 results in the worst condition of the bridges (79.8% in condition state 1 and 2) and scenario 0 the best (85.7% in condition states 1 and 2).

This information shows that if the minimal intervention strategies are to be followed, and an adequate level of service is provided, then as little money as possible should be spent during the work program.

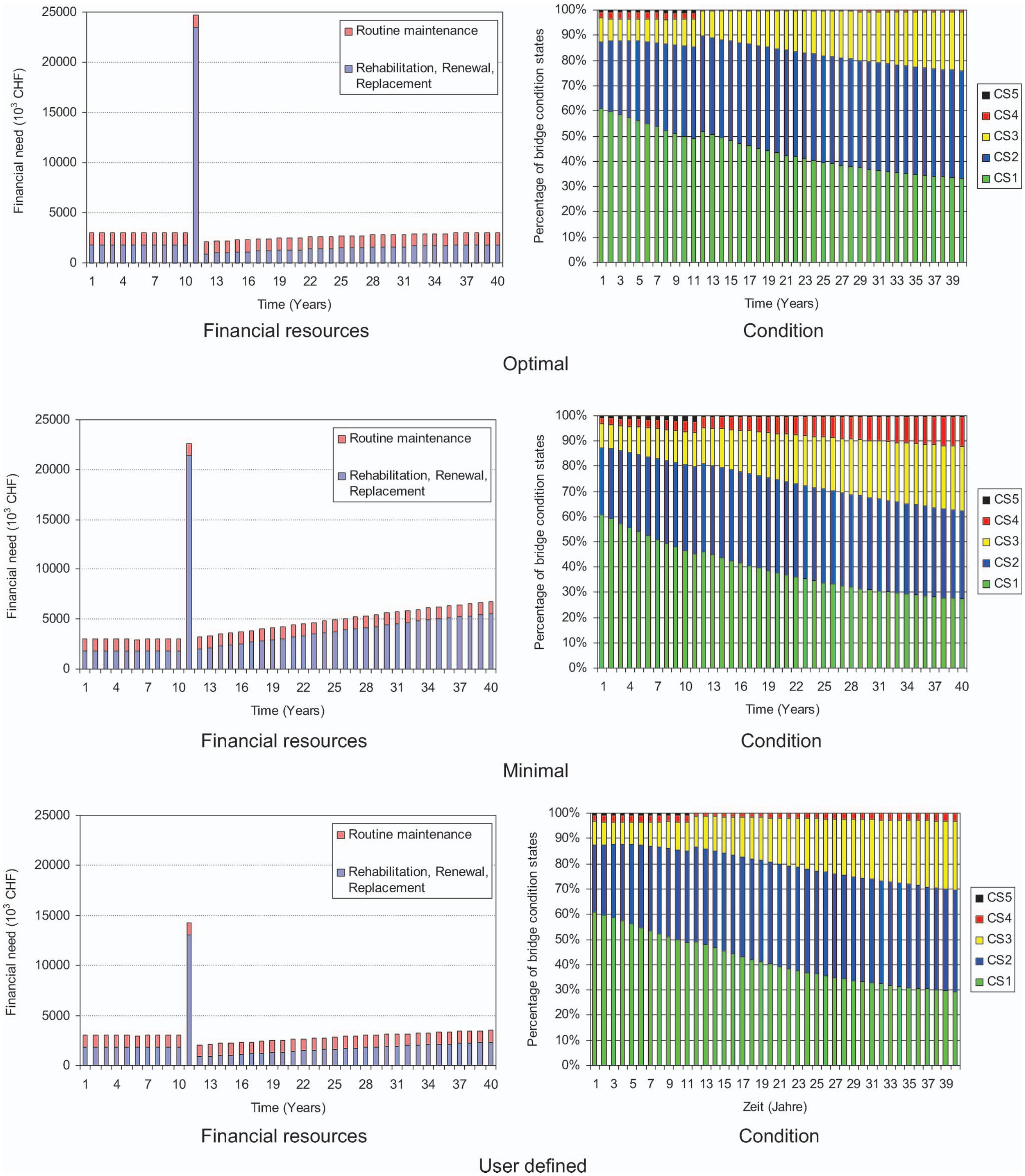

Figure 6. Scenario 3: Evolution of required financial resources and bridge condition.

User defined

If the user defined intervention strategies are to be followed scenario 3 is the least expensive scenario over 11 years (44.3 versus 47.1, 49.5, 50.1 $\times$ 10^6 CHF) and scenario 0 is the least expensive over 40 years (126 versus 128, 128, 127 $\times$ 10^6 CHF). Immediately following the work programme scenario 3 results in the worst and scenario 0 the best, condition of the bridges.

Table 15. Summary of required financial resources and resulting bridge condition.

		Costs				Condition in year 11				
Intervention strategy	Budget Scenario	Years 1–10 (10^6 CHF)	Year 11 (10^6 CHF)	Year 40 (10^6 CHF)	Years 1–40 (10^6CHF)	1 %	2 %	3 %	4 %	5 %
Optimal	**0**	**37.3**	**13.0**	3.0	**128**	**49.8**	**37.0**	10.5	2.1	0.5
	1	40.1	12.6	3.0	130	50.4	37.0	10.0	2.0	0.5
	2	39.9	12.8	3.0	130	50.4	37.0	10.0	2.0	0.5
	3	30.0	24.7	3.0	132	48.9	36.4	11.1	2.6	1.0
Minimal	0	91.1	7.3	6.4	224	49.5	36.2	11.2	2.5	0.6
	1	53.8	17.6	6.6	210	47.6	34.7	12.3	3.6	1.7
	2	44.8	18.6	6.7	205	46.7	34.6	12.9	3.8	1.9
	3	**30.0**	**22.6**	6.8	**198**	**45.3**	**34.5**	13.7	4.0	2.3
User defined	**0**	**36.7**	**10.4**	3.4	**126**	**48.9**	**36.9**	11.2	2.4	0.6
	1	39.3	10.2	3.4	128	49.5	36.8	10.8	2.3	0.6
	2	39.8	10.3	3.4	128	49.5	36.8	10.8	2.3	0.6
	3	30.0	14.3	3.5	127	48.6	36.4	11.4	2.7	0.9

The key numbers for the suggested scenario for each intervention strategy type are set in bold.

This information shows that if the user defined intervention strategies are followed that there should be no budget limit because this is the least expensive in the long term and a good condition state of the bridges immediately following the work programme is obtained.

Comparison between types of intervention strategies

Although there are only small differences between the required financial resources over 11 years and over 40 years when the optimal or the user defined intervention strategies are followed, the optimal intervention strategies do provide the lowest annual required financial resources and the best condition in the long term (75.3% of the bridges in condition state1 and 2 versus 61.7% and 69.2% for the minimal and user defined intervention strategies, respectively (Table 13)).

Discussion

Although the methodology is similar to those used in state-of-the-art, but far more data intensive, management systems, such as KUBA (Hajdin 2008), the Quebec Bridge Management System (Ellis *et al.* 2008) and PONTIS (Cambridge Systematics 2001), the necessary approximations to use only bridge level data, as opposed to element level data, mean that the results are on average less accurate than those that would be obtained from the more data intensive management systems. This is principally due to the fact that data collected on the bridge level is less exact than that collected on the element level. This happens mainly due to:

- *The mathematical modelling of the deterioration processes*. Since bridges are composed of different elements and each element can have a different deterioration processes modelling of the deterioration without consideration of the deterioration of the specific elements requires significant simplifications, which result in a corresponding loss of accuracy.
- *The determination of the condition state of the bridge*. Since the different elements that make up a bridge deteriorate at different rates there are many possible element-condition combinations, and the representation of the bridge condition in terms of five discrete condition states on the bridge level using only percentages requires significant simplifications. Because so many element-condition combinations are possible it is also practically impossible to make guidelines that would allow the systematic approximation of the damaged areas.
- *The evaluation of the intervention*. Since interventions made on the bridge must allow for, but cannot insist on, the possibility of intervention on all elements of the bridge there is a wide variation in unit costs and effectiveness vector values. If, for example, a rehabilitation intervention is foreseen this intervention would also need to include the rehabilitation of the abutments, the decks, the columns and the bearings, although it is entirely possible that the condition of only one of these elements could result in rehabilitation intervention being predicted. The use of single effectiveness vectors for interventions to be performed on a bridge requires significant simplifications.

These simplifications should be understood when using this methodology.

Conclusion

It was demonstrated in this article that the methodology presented can be used only when structure level data is available to:

- determine the lowest cost intervention strategies of bridges with respect to gradual deterioration processes under multiple budget scenarios,
- estimate the required financial resources to follow each of the investigated intervention strategies in each year of the investigated period, and
- estimate the resulting condition state of the bridges, assuming the intervention strategies are followed in each year of the investigated period.

The methodology also enables the consideration of uncertainty with respect to the speed of deterioration and the effectiveness of interventions.

As demonstrated in the example, use of the methodology also ensures that all predictions are made in a sound and logical manner, thereby ensuring that they are both easily repeatable and making it possible to easily investigate the impact of variation in the values of base parameters, such as the unit cost of an intervention type.

It is proposed that this methodology be used when either sufficient detailed element level information or tools are not available to conduct a similar analysis using element level data.

Notes

1. As deterioration is deterministically modelled each bridge is expected to spend x years in a condition state. The specific time of a condition state refers to an exact year within the time period that it is expected that the bridge will be in the condition state.
2. The financial resources available in each of the first 10 years of the 40 year analysis period.
3. The optimal intervention strategies are those that give the lowest long term costs for each structure type, if followed without budget constraint. The minimal intervention strategies are those where no intervention is performed unless a part of the bridge is in condition state 5, and then the optimal intervention is performed. The user defined interventions are those where no intervention is performed until a part of the bridge is in condition state 4, and then a rehabilitation intervention is performed, and if a part of the bridge is in condition state 5 a renewal intervention is performed.
4. The difference between the network and project level predictions is due to multiple bridges having surface areas requiring intervention that are below 5% of the structure. With the agency rules these structures do not have interventions on the project level, whereas they do on the network level.

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