Repair Scenarios Generation at Arbitrary Time in Bridge Maintenance

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ABTRACT: Minimizing life cycle cost (LCC) of bridge system while retaining healthy maintenance service level is a crucial task for bridge asset managers. Searching for optimized repair scenario for a bridge having different characteristics in different environments is a key to accomplish the task. This paper proposes a concept to generate all possible maintenance scenarios automatically during predicting degree of deterioration. The scenario that gives the lowest LCC with satisfied service level will be considered as an optimized repair scenario. The basic timing to repair is decided at the time just before deterioration state will be shifted to more severe level. However, there is no proof that repairing action in early point can give a better solution. Considering repairing timing at arbitrary time in scenario generation is an issue to discuss in this paper. Balance between computing time and effectiveness is also in discussion.

KEYWORDS: Bridge, Life cycle cost, maintenance, scenario

1. INTRODUCTION

Maintaining a system of bridges to be within a specified level by low cost is a critical issue especially in developed countries where a number of aged bridges are numerous. The solution can be sought by implementing a bridge management system (BMS) as a tool for decision-making. BMS that is designed to adopt mechanistic approach in deterioration prediction has advantage on repair scenarios consideration. One of the reasons is that the repair effects can be straightforwardly modeled based on physical phenomena.

The repair scenario is defined as a pattern of what-to-repair and when-to-repair for a whole lifespan of the bridge while keeping the bridge in satisfied maintenance level. What-to-repair refers to a single or a combination of two or more repair methods that has different effects (protective, corrective, or both) on the deterioration progress. It does not limit to only repair method, but also replace or rebuilt. When-to-repair is a point in time where the repair event occurs.

Figure 1 shows, for example, three different repair scenarios employing different repair methods and repair timing. Each of the repair scenarios gives a corresponding life cycle cost (LCC) that is calculated from summation of all repair events. It is one of important indexes to determine effectiveness of the scenarios. However, to find the optimized scenario that suit the bridge that is under an arbitrary deteriorative environment needs many predefined scenarios in consideration. A number of possible

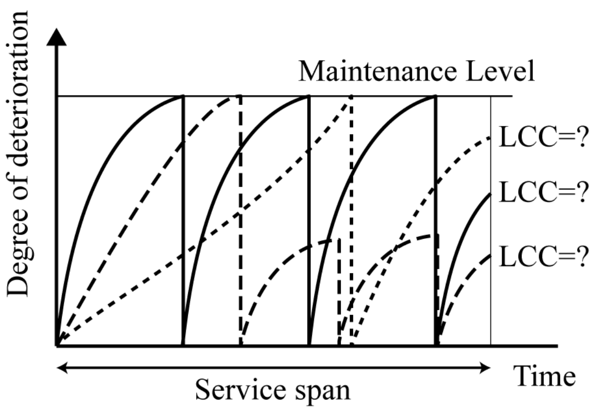


Figure 1: Comparison between different repair scenarios that give different life cycle cost

repair scenarios can be vast when the bridge is in severe environment or several repair methods are in consideration. As a result, repair budget cannot be reduced since only a limited number of scenarios can be considered by asset manager. To tackle with this issue, the author proposed a calculation algorithm that automatically generates all possible scenarios when the bridge condition, external environment, maintenance policy, available repair methods, etc. are defined, Nattakorn 2012.

The proposed algorithm generates all possible repair scenarios by considering the following when-to-repair events, figure 2.

A) At the initial state

B) When protection life of repair method ends

C) Before the deterioration state shifts to more severe level

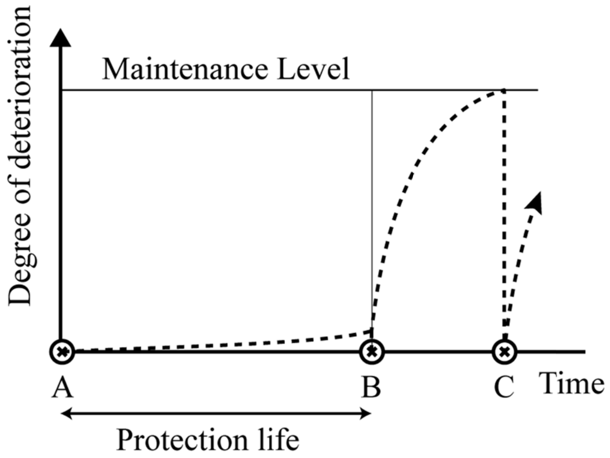


Figure 2: Repairing timing in scenario generation algorithm

At the initial state where the bridge construction is just completed, some protective repair methods can be applied (e.g., cathodic protection is applied at initial state, figure 2). After the protection life of the repair method ends, it needs to be decided what to do next. The last event is triggered at just before the degree of deterioration will shift to the next deterioration state. For example, if cracking in concrete bridge is beyond the maintenance level, it is necessary to repair the bridge before the cracking occurs. Repairing after cracking causes the repair cost to shift to higher level due to necessity of fixing the cracks. The event C at just before deterioration state shifting is set to keep the bridge condition always under the maintenance level as long as possible to prolong the service life. This assumption may be true if repair cost for a specific method does not vary on degree of deterioration. It is also true to say that instead of repair at just before the state changes, repairing at earlier arbitrary time may give a cheaper solution, figure 3.

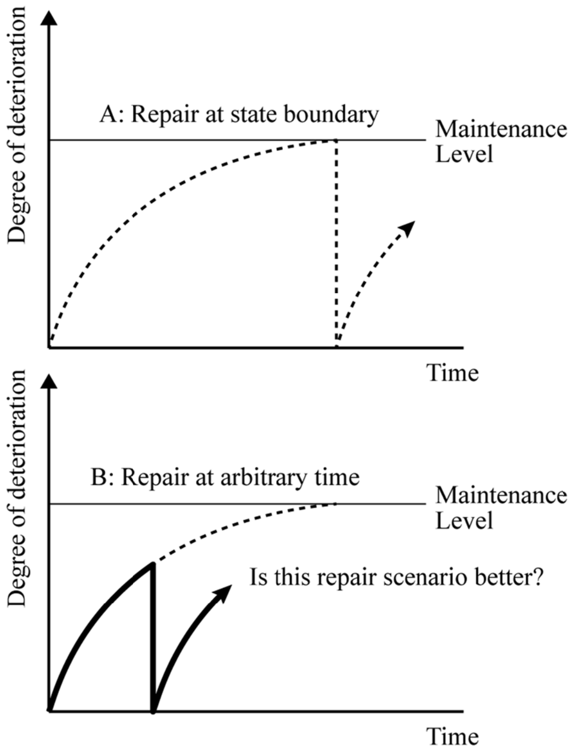


Figure 3: Repairing at arbitrary time (before reaching the maintenance level)

This paper considers the repair timing at arbitrary time in repair scenarios generation. As a result, more scenarios that are possible can be in consideration, which gives a scientific proof to the question in figure 3.

2. SCENARIO GENERATION

This section describes the concept of basic scenario generation and its application to add repair trigger at arbitrary time.

2.1 Basic of scenario generation

Figure 4 shows a diagram of generating the maintenance scenarios for a single bridge. The left side represents the bridge condition prediction (degree of deterioration) for a specified maintenance scenario, while the right side represents a so-called scenario list to manage what scenario is now being calculated, what scenario will be next in the queue, and which scenario calculation is finished. The scenario list sequentially supplies an unfinished scenario (as a current scenario) to the left side to calculate deterioration and apply repair effects at the specified trigger accordingly. The trigger can be the condition limit trigger or timer trigger. Such an unfinished scenario will be extended (to be a finished scenario) to cover the bridge lifespan while calculating degree of deterioration. The finished current scenario will be then removed from the scenario list, which LCC can be then calculated by summing all repair events during the bridge lifespan.

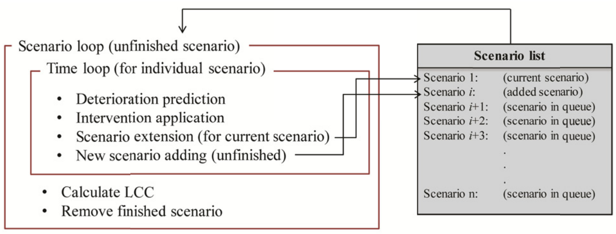


Figure 4: Concept of scenario generation process

Figure 5 shows the way that maintenance scenarios are generated and updated in the scenario list from the beginning of calculation, first and second generation steps. $m_{x,y}$ represents a repair method where x is repair sequence counting starts from zero, and y is available repair methods at the current deterioration state (from method 1 to j_0). t_z in the trigger column is the repair trigger of the corresponding intervention method $m_{x,y}$ where t_I is at the initial state and t_m is a condition boundary of the maintenance level. Each m and t are written by

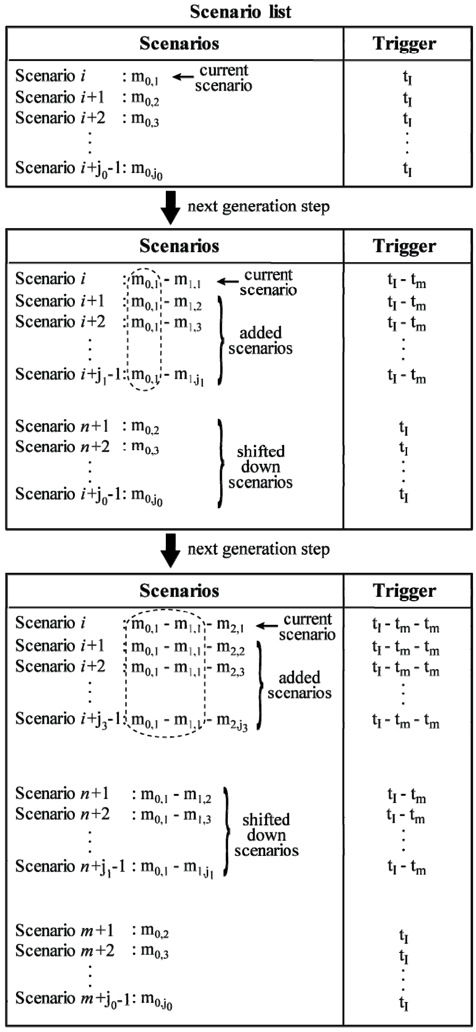
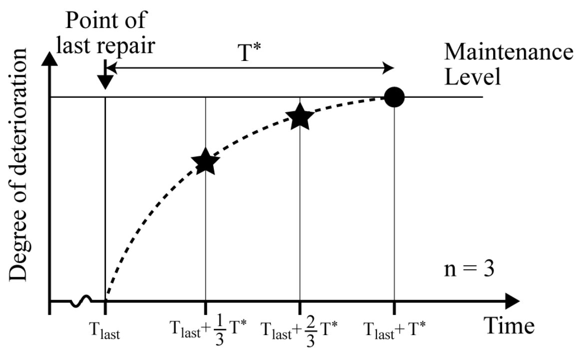


Figure 5: Scenario generation process in the scenario list

hyphen separation, e.g. m_1 - m_2 - m_3 and so on to represent the order of execution temporally. At the beginning of scenario calculation, applicable repair methods and trigger are added into the scenario list, figure 5(top). When the deterioration state of the bridge has reached the maintenance limit before lifespan of the bridge ends, new set of scenarios will be generated and added into the scenario list, figure 5(middle and bottom). From the base current scenario, applicable repair methods will be added to form a group of inheritance scenarios and their triggers. The previously generated scenarios other than the current scenario are then shifted down for later calculation. This process continues until all scenarios are processed.

2.2 Repairing at arbitrary time

The repair event at arbitrary time occurred when degree of deterioration reaches the maintenance level. In addition to the basic scenario to repair at just before reaching the maintenance level (filled circle in figure 6), the same repairing method to be executed at early time is inherited as new scenarios (filled stars). The repair events are set in discrete divisions in between the point of the last repair to the current point that has the period of T^*. The period T^* is divided into n subdivisions that is set by asset manager. The inherited scenarios for repairing at arbitrary time have the same repair sequence as that of the current scenario, but only the repair triggers are different, see the scenario list in figure 6. The capital T in the trigger represents time trigger in contrast to the small t as deterioration condition trigger. When the time trigger T is reached in the time loop of deterioration prediction, the corresponding repair event occurs by applying the physical repair effects to the current deterioration condition. At this point in each inherited scenarios, the same process to generate the scenarios at arbitrary time continues until the time loop reaches the bridge lifespan, figure 7. This makes a combination of repair events, which logarithmically increases with value of n. This implies that setting larger value of n may give a more precise scenario planning, but will cost for calculation time. In addition, it is strongly related to the accuracy of the deterioration prediction model, which the precise scenarios calculated are not applicable when error of the prediction model is unavoidable.



Scenarios		Trigger
★→ Scenario i : $m_{0,1}$ - $m_{1,1}$	← current scenario	t_I - t_m
★→ Scenario i+1 : $m_{0,1}$ - $m_{1,1}$	added arbitrary time scenarios	t_I - $T_{last}+\frac{1}{n}T^*$
⋮		⋮
★→ Scenario i+n-1 : $m_{0,1}$ - $m_{1,1}$		t_I - $T_{last}+\frac{n-1}{n}T^*$
Scenario n+1 : $m_{0,1}$ - $m_{1,2}$	shifted down scenarios	t_I
Scenario n+2 : $m_{0,1}$ - $m_{1,3}$		t_I
⋮		⋮
Scenario $i+j_0$-1 : $m_{0,1}$ - m_{1,j_1}		t_I

Figure 6: Scenario generation for the repair event at arbitrary time

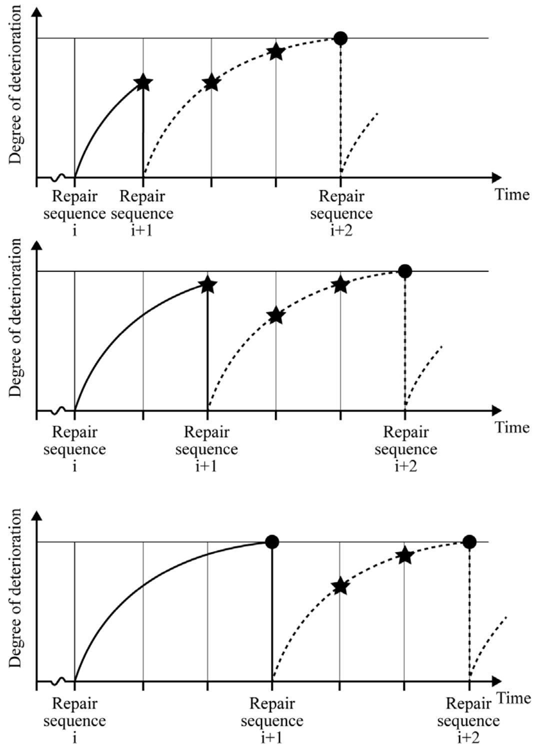


Figure 7: Inherited repair scenarios from n=3 divisions

3. ANALYSIS EXAMPLES AND DISCUSSION

This section illustrates the tradeoff analysis between LCC optimization, bridge condition, and calculation time of a bridge under various environmental conditions (airborne chloride flux: 100, 200, 300, 500, and 800 mg/dm^2.yr). A normal concrete bridge is assumed with the following analysis parameters: cover thickness = 5cm, w/c = 55%, rebar size = 19 mm, compressive strength = 30 N/mm^2, and Modulus of elasticity = 26,000 N/mm^2.

Maintenance level is set at cracking boundary.

Figure 8 and 9 show effects of increment of *n* on the scenarios generated and calculation time.

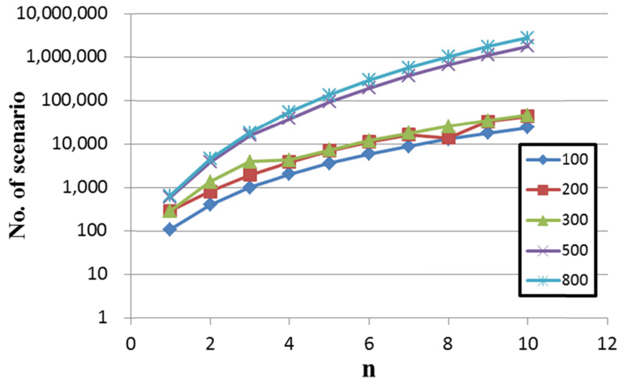


Figure 8: Increment of scenarios generated

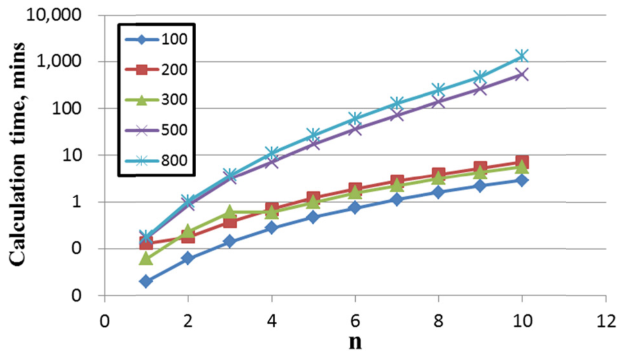


Figure 9: Increment of calculation time

It is straightforward that considering more *n* subdivision causes more scenarios in consideration as well as the calculation time. In severe environment, the bridge needs more frequent repairing, which results in more combination of maintenance scenario to consider.

Table 1 shows the best scenario of all cases. Some cases, e.g. 100 and 500 mg/dm^2.yr, retain the same maintenance scenario (but different execution time) for different *n* subdivisions. The other cases change their maintenance scheme when *n* increased to some extent. This is the new adjustment the find the lowest LCC and minimum deteriorated condition.

In the aspect of cost, figure 10 shows the changes of LCC on *n* for the best scenario of each

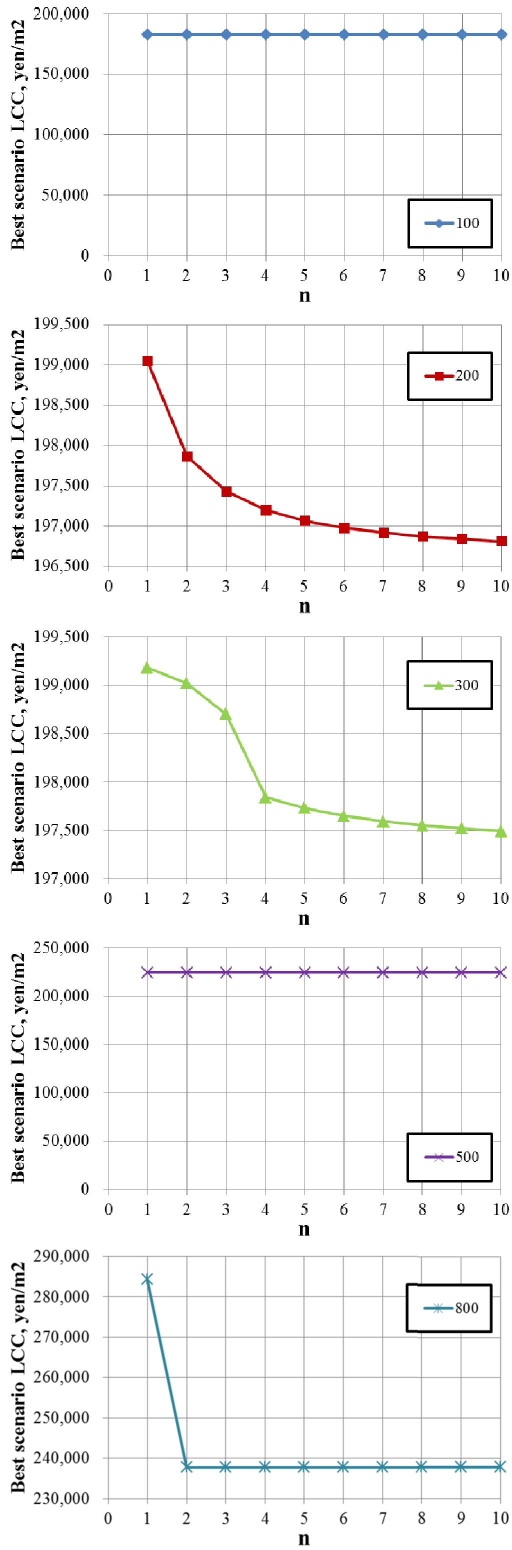


Figure 10: Changes of LCC

environmental condition. The best scenario is selected from the order of lowest LCC, number of repair events and maximum corrosion rate during lifespan. At a glance, more subdivision *n* offers decreasing tendency of LCC. Some cases are not changed, e.g. chloride flux is 100 or 800 mg/dm^2.yr, and some cases are gradually decreasing with *n*, e.g. 200 or 300 mg/dm^2.yr, and some cases decreases in a stepwise manner, e.g. 300 or 800 mg/dm^2.yr. These decreasing patterns are depending on the characteristics of the scenario. If the repair is corrective scheme (e.g. section restoration) that the repair cost is unchanged when repairing at early state, the LCC still the same unless the maintenance scenario changes to new repair pattern. Although the increment of *n* is ineffective on reducing LCC, but it has effect on reducing the degree of deterioration, figure 11. For the case of gradually decreasing, it occurs when the maintenance scenario is related with protective scheme (e.g. cathodic protection). As the repair timing shifts, the variable cost (i.e. electricity cost) can be reduced, but not in a significant scale. For the stepwise case, this occurs when the maintenance scenario has totally changed to the other pattern where the repair costs are different.

Figure 11 shows the maximum accumulated corrosion during the bridge lifespan when maintained by the best scenario. Majority of the cases have decrement tendency of maximum corrosion on the increment of *n* subdivision. This is because of the find adjustment of the LCC and the bridge condition to find an optimum point to maintain. In contrast, some cases, i.e. 200 and 300 mg/dm^2.yr, have opposite tendency. This is because of the shifting of maintenance scenario to other scheme to reduce LCC as low as possible, but there is a tread-off in increment of corrosion risk.

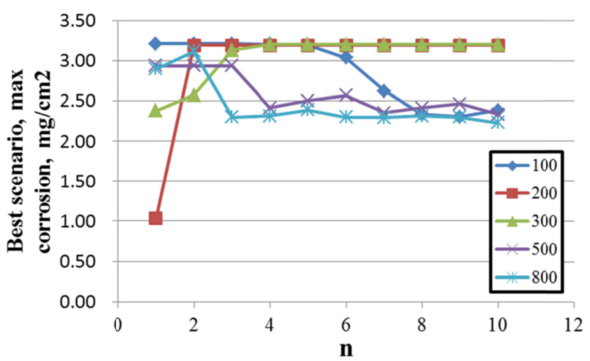


Figure 11: Maximum of corrosion rate during lifespan

Table 1: Calculated maintenance scenarios

Chloride flux = 100 mg/dm^2.yr

n	Best scenarios
1	SC(0)→SR(45.5)→SR(79)
2	SC(0)→SR(45.5)→SR(79)
3	SC(0)→SR(45.5)→SR(79)
4	SC(0)→SR(34.1)→SR(68.7)
5	SC(0)→SR(36.4)→SR(70.8)
6	SC(0)→SR(37.9)→SR(66.5)
7	SC(0)→SR(39)→SR(68.3)
8	SC(0)→SR(39.8)→SR(69.6)
9	SC(0)→SR(40.4)→SR(70.7)
10	SC(0)→SR(41)→SR(71.6)

Chloride flux = 200 mg/dm^2.yr

n	Best scenarios
1	DN(0)→CP(9.4)→CP(59.4)
2	SC(0)→SR(38)→CP(51.3)
3	SC(0)→SR(38)→CP(55.7)
4	SC(0)→SR(38)→CP(58)
5	SC(0)→SR(38)→CP(59.3)
6	SC(0)→SR(38)→CP(60.2)
7	SC(0)→SR(38)→CP(60.8)
8	SC(0)→SR(38)→CP(61.3)
9	SC(0)→SR(38)→CP(61.6)
10	SC(0)→SR(38)→CP(61.9)

Chloride flux = 300 mg/dm^2.yr

n	Best scenarios
1	DN(0)→CP(8.1)→CP(58.1)
2	DN(0)→CP(9.7)→CP(59.7)
3	DN(0)→CP(12.9)→CP(62.9)
4	SC(0)→SR(34.1)→CP(51.6)
5	SC(0)→SR(34.1)→CP(52.7)
6	SC(0)→SR(34.1)→CP(53.5)
7	SC(0)→SR(34.1)→CP(54.1)
8	SC(0)→SR(34.1)→CP(54.5)
9	SC(0)→SR(34.1)→CP(54.8)
10	SC(0)→SR(34.1)→CP(55.1)

Chloride flux = 500 mg/dm^2.yr

n	Best scenarios
1	SC(0)→CP(15.1)→SC+CP(65.1)
2	SC(0)→CP(15.1)→SC+CP(65.1)
3	SC(0)→CP(15.1)→SC+CP(65.1)
4	SC(0)→CP(15.1)→SC+CP(52.6)
5	SC(0)→CP(15.1)→SC+CP(55.1)
6	SC(0)→CP(15.1)→SC+CP(56.8)
7	SC(0)→CP(15.1)→SC+CP(50.8)
8	SC(0)→CP(15.1)→SC+CP(52.6)
9	SC(0)→CP(15.1)→SC+CP(54)
10	SC(0)→CP(15.1)→SC+CP(50.1)

Chloride flux = 800 mg/dm^2.yr

n	Best scenarios
1	DN(0)→CP(6)→SR+CP(56)
2	SC(0)→CP(12.2)→SC(37.2)→SC+CP(62.2)
3	SC(0)→CP(12.2)→SC(28.9)→SC+CP(51.1)
4	SC(0)→CP(12.2)→SC(24.7)→SC+CP(52.8)
5	SC(0)→CP(12.2)→SC(22.2)→SC+CP(54.2)
6	SC(0)→CP(12.2)→SC(28.9)→SC+CP(51.1)
7	SC(0)→CP(12.2)→SC(26.5)→SC+CP(52)
8	SC(0)→CP(12.2)→SC(24.7)→SC+CP(52.8)
9	SC(0)→CP(12.2)→SC(28.9)→SC+CP(51.1)
10	SC(0)→CP(12.2)→SC(22.2)→SC+CP(50.2)

* CP=Cathodic protection, SC=Surface coating, SR=Section restoration, DN=Do nothing

4. CONCLUSIONS

The proposed algorithm to consider maintenance triggers at arbitrary time is able to find a new maintenance scheme to reach the lowest LCC. However, the calculation time will be sacrificed to obtain a little decrement of LCC. A good balance between effectiveness of LCC reduction and calculation time should be taken case by case. For long-term planning where the process is not so urgent, increasing *n* subdivision up to 3 or 4 can be a good practice.

The fine shifting of the repair time can be advantage when considering budget constraint, where the lower-priority bridge can be shifted to other repair opportunity when the budget is insufficient.

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