Maintenance Optimization for Bridge Management

- Modelling of condition-based inspection and deterministic maintenance delay

By Tianqi Sun
Main Supervisor: Jørn Vatn
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Agenda

1. Background
2. Maintenance Management in NPRA
3. Modelling process
4. Conclusion and future work
1. Background
1.1 About myself

Education background:
• 2011 – 2015 Bachelor in Safety Engineering from China
• 2015 – 2017 Master in RAMS from NTNU
  – Thesis: Production Availability Analysis: Implication on Modelling due to Subsea Conditions (cooperated with DNV GL, with the use of ExtendSim)

Work experience:
• 2018.04 – 2020.08 Safety Engineer in FAW-Volkswagen.
  – Management over special equipment (arrange periodical inspections)
  – Risk management (data collection, daily inspections)

New Journey
• 2020.09 – present Ph.D. Candidate at MTP, NTNU
1.2 About the project

- NPRA is in charge of a large number of road constructions, while the complicated geographic conditions in Norway increase the challenge;
- **Maintenance cost** contributes almost half of the total expenses;
- The proportion of budget allocated to reactive maintenance kept increasing.

**Diagram:**
- 10,600 km roads
- 1,500 km walking and cycling paths
- 23 Mountain passes
- 6,040 Bridges & constructions
- 16 Ferry connections
- 580 tunnels
- 350 + Contracts
- 880 Employees
- 13 Bill. NOK

**Legend:**

**Source:** (Trond Andersen, 2020)
2. Maintenance management in NPRA
2.1 Maintenance Strategy in NPRA

- **Requirements**
  - Described in regulations & handbooks.
  - Operation & maintenance actions to ensure the satisfaction of them.

- **Periodic Inspections**
  Through inspections, the road network would be monitored in order to detect deviations.

- **Condition Classification**

<table>
<thead>
<tr>
<th>Level</th>
<th>Degree of damage</th>
<th>Maintenance action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Small damage</td>
<td>No action</td>
</tr>
<tr>
<td>2</td>
<td>Medium damage</td>
<td>Conducted within 4 - 10 years</td>
</tr>
<tr>
<td>3</td>
<td>Major damage</td>
<td>Conducted within 1 - 3 years</td>
</tr>
<tr>
<td>4</td>
<td>Critical damage</td>
<td>Conducted within half year</td>
</tr>
</tbody>
</table>
2.2 Maintenance Management for bridges

- According to NPRA’s Handbook *V441 Inspection Handbook for Bridges* and *R411 Management, Operation and Maintenance of Bridges*.

- Inspections and maintenance actions are recorded in detail for each bridge.

Degree of damage:
1 – Small
2 – Medium
3 – Major
4 – Critical

Damage consequence:
B – Structure capacity
T – Traffic safety
V – Maintenance cost
M – Environment
2.3 Problem Statement

• With such large stock of bridges, it is sometimes difficult to follow all inspection plans due to limited budget and resources. NPRA is suffering from many backlogs and would like to investigate a more efficient inspection strategy.

Modelling of condition-based inspections

• Currently, NPRA adopts condition-based delays before the implementation of repairs.

Modelling of deterministic maintenance delays
3. Modelling process
3.1 Modelling Assumptions

1. The system is subjected homogeneous poison process.

\[ P(t + \Delta t) = P(t) \cdot e^{A\Delta t} \]

2. The inspections are condition-based, the intervals between inspections are either \( \tau_L \), \( \tau_M \) or \( \tau_S \), where \( \tau_L = k_L\tau_S \) and \( \tau_M = k_M\tau_S \).

3. All inspections are perfect.

4. There are condition-based deterministic delays before the implementation of repairs, \( D_2 \), \( D_3 \), \( D_4 \) for system in state 2, 3, 4.

5. All repairs are perfect and conducted instantaneously.

6. If the system is found at a more deteriorated state during an inspection but the repair from the original plan is earlier than the rescheduled repair, the system will follow the original plan to avoid a long waiting time.
3.2 Modelling of condition-based inspections

- Based on lecture notes from Maintenance Optimization
- Consider only the deterioration
- We define several P-vectors to simulate different inspection regimes

\[ P^{L,m}_i(t) = Pr(\text{system in state } i \cap \text{current regime is } \tau_L \cap \text{cycle is } m) \]

\[ P^{M,n}_i(t) = Pr(\text{system in state } i \cap \text{current regime is } \tau_M \cap \text{cycle is } n) \]

\[ P^S_i(t) = Pr(\text{system in state } i \cap \text{current regime is } \tau_S) \]

L, M, S denote long, medium and short inspection regimes respectively.

\[ m = [1, k_L], \quad n = [1, k_M] \]

\[ i = [1, 4], \text{ represent different state,} \]

For long inspection regime, when

\[ t = \tau_L + (m - 1)\tau_S, 2\tau_L + (m - 1)\tau_S, \ldots, k\tau_L + (m - 1)\tau_S: \]

\[ P_{3}^{M,n}(t^{+}) = P_{3}^{M,n}(t^{-}) + P_{3}^{L,m}(t^{-}), \quad P_{4}^{L,m}(t^{+}) = P_{4}^{L,m}(t^{-}), \]

\[ P_{2}^{L,m}(t^{+}) = P_{2}^{L,m}(t^{-}), \quad P_{3}^{m}(t^{+}) = 0, \]

\[ P_{4}^{L,m}(t^{+}) = 0 \]
3.3 Modelling of deterministic maintenance delay

➢ The IM vectors, R matrices and W vectors

In this example, \( k_M = 2 \), \( k_L = 3 \).
3.3 Modelling of deterministic maintenance delay

➢ Modelling process, example with long inspection regime.

- **Update IM vector**
  - Update at each inspection

- **Derive probability mass to repair R(t)**
  - Derive the value at each inspection
  - Update at each integration

- **Count waiting time W(t)**
  - Update each integration

- **At each inspection**
  
  When \( t = \tau_L + (m - 1)\tau_S, 2\tau_L + (m - 1)\tau_S, \ldots, \\ k\tau_L + (m - 1)\tau_S \), we have:

  \[
  IM_{k,m}^L(t^+) = 1
  \]

  Due to the assumption of perfect inspection

  \[
  R_{k,2}^{L,m}(t^+) = P_2^{L,m}(t^-) - \sum_{u=0}^{k-1} R_{u,2}^{L,m}(t)
  \]

- **At each integration**

  \[
  W(t^+) = W(t^-) + \Delta t, \quad \forall IM(t^-) = 1
  \]

  To model system deterioration while waiting for maintenance

  \[
  R(t + \Delta t) = R(t) \cdot e^{A\Delta t}
  \]
3.3 Modelling of deterministic maintenance delay

- Treatment of Special case

“old” deterioration

\[
q_{3,m}^{L,m}(t^+) = \begin{cases} 
R_{k-1,3}^{L,m}(t^-) & W_{k}^{L,m}(t^+) > D_2 - D_3 \\
0 & W_{k}^{L,m}(t^+) \leq D_2 - D_3 
\end{cases}
\]

Total deterioration

\[
R_{k-1,3}^{L,m}(t^+) = \begin{cases} 
R_{k-1,3}^{L,m}(t^-) & W_{k}^{L,m}(t^+) > D_2 - D_3 \\
0 & W_{k}^{L,m}(t^+) \leq D_2 - D_3 
\end{cases}
\]
3.3 Modelling of deterministic maintenance delay

- Count waiting time and conduct repair

\[
P^{L,m}_1(t^+) = P^{L,m}_1(t^-) + \sum_{w_{i,j}^{L,m}(t^-) = D_2} R^{L,m}_i(t^-), \quad i = 1, \frac{t^-}{T_L}, \quad j = 2, 4
\]

\[
IM^{L,m}_k(t^+) = 0, \quad R^{L,m}_k(t^+) = 0
\]

\[\forall W^{L,m}_k(t^-) = D_2\]
3.4 Verification with Monte Carlo Simulation

- Monte Carlo Simulation

  ![Flowchart Diagram](image)

  - Start
  - I. Set initial system state and inspection regime
    - Generate time for first system deterioration $t_{deterioration}$, time for next inspection $t_{inspection}$, and time for next repair $t_{repair}$
    - III. $t_{next\ event} = \min(t_{deterioration}, t_{inspection}, t_{repair}, t_{repair})$
  - IVa. System deteriorated (update $t_{inspection}$)
  - IVb. System inspected (update $t_{inspection}$, $t_{repair}$)
  - IVc. System repaired (update $t_{inspection}$, $t_{repair}$ & $t_{repair}$)
  - V. End

- Result comparison

  ![Graphs](image)
3.4 Verification with Monte Carlo Simulation

\[ P(t + \text{length of step}) = P(t)[e^{\lambda \Delta t}]^a \quad \text{where} \quad \Delta t = \frac{\text{length of step}}{a} \]

- Step length = 730 hour

- Step length = 73 hour
3.5. Support in decision-making

- Evaluate critical damage probability for different maintenance strategies

- Evaluate expected cost:

\[ C(t) = \text{Cost}_{\text{Inspections}} + \text{Cost}_{\text{Critical repair}} + \text{Cost}_{\text{Medium repair}} + \text{Cost}_{\text{Small repair}} \]

\[ = C_I \cdot N_I + C_{CR} \cdot N_{CR} + C_{MR} \cdot N_{MR} + C_{SR} \cdot N_{SR} \]

Where

- \( N_I \) = accumulated probability mass in different states at each inspection,
- \( N_{CR} \) = accumulated probability mass moved from state 4 to state 1,
- \( N_{MR} \) = accumulated probability mass moved from state 3 to state 1,
- \( N_{SR} \) = accumulated probability mass moved from state 2 to state 1.
4. Conclusion and Future works

• Conclusion
  – The proposed approach is capable of modelling both condition-based inspections and deterministic maintenance delay.
  – Different maintenance strategies can then be evaluated with regard to probability of critical damage and the total expected cost.

• Future works
  – In this paper, the inspections and repairs are all perfect, imperfect inspections and different levels of repairs can be further investigated later.
  – With access to NPRA’s database, investigate a better estimation of the parameters.
Thanks for your attention

Questions / comments?