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Statens vegvesen
Norwegian Public Roads Administration

Maintenance Optimization for Bridge Manangement

- Modelling of condition-based inspection and deterministic maintenance delay

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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 Availablity Analysis: Implication on Modelling due to Subsea Conditions (cooperated with DNV GL, with the use of ExtendSim)

Work experience：

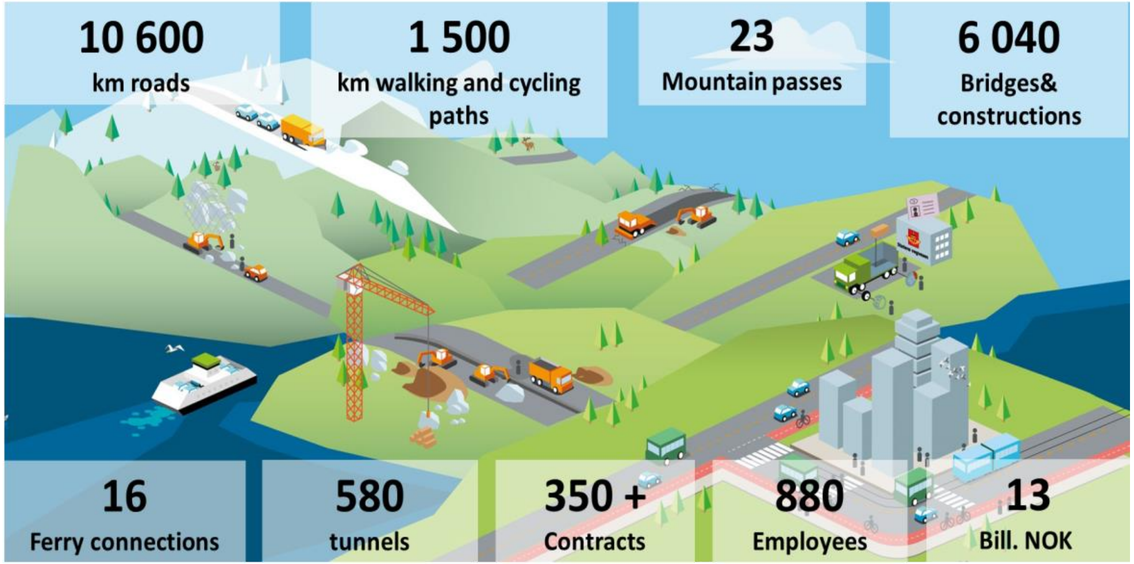
- 2018.04 – 2020.08 Safety Engineer in FAW-Volkswagen.
  - Management over special equipment (arrange periodical inspections)
  - Risk management (data collection, daily inspections)

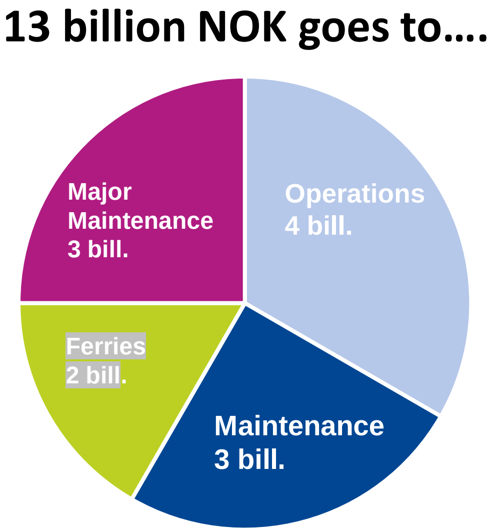
New Journey

- 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.

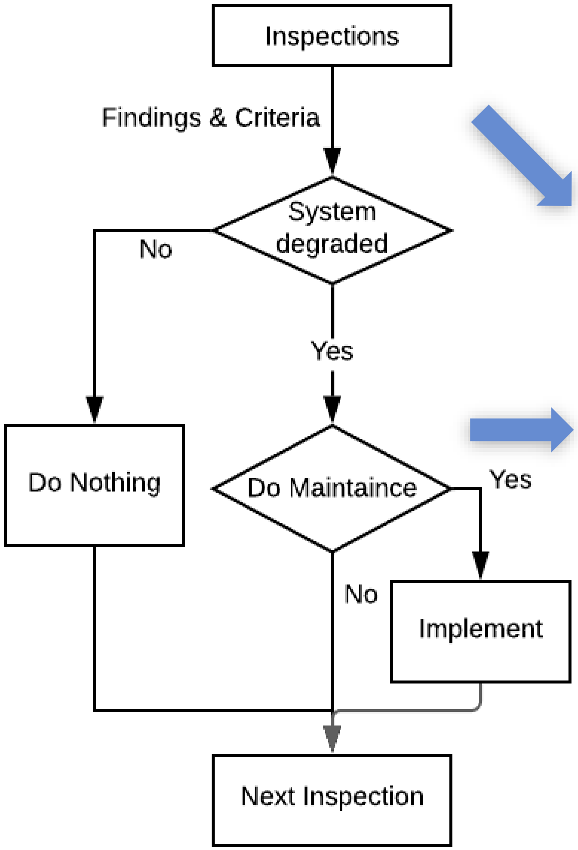




Source: (Trond Andersen, 2020)

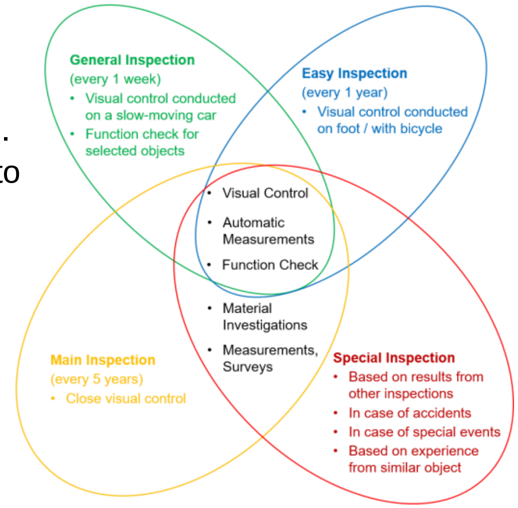
2. Maintenance management in NPRA

2.1 Maintenance Strategy in NPRA



- **Requirements**

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



- **Periodic Inspections**

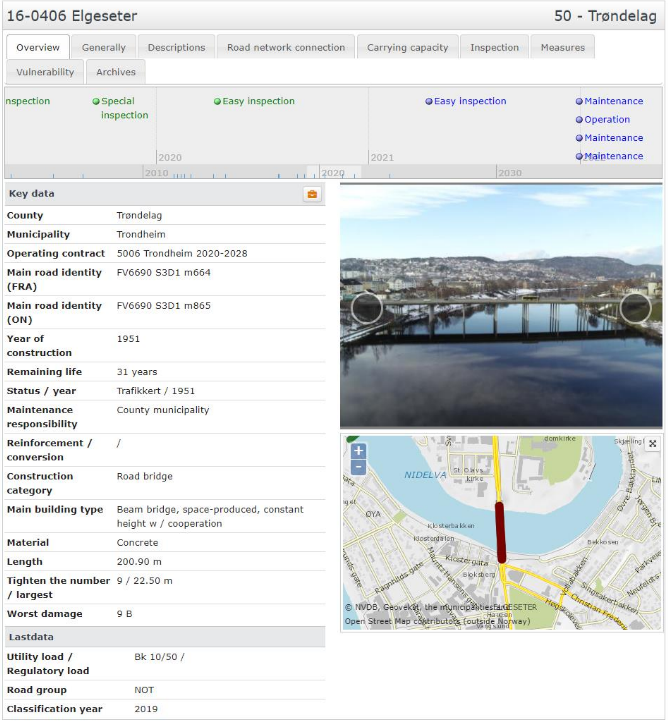
Through inspections, the road network would be monitored in order to detect deviations.

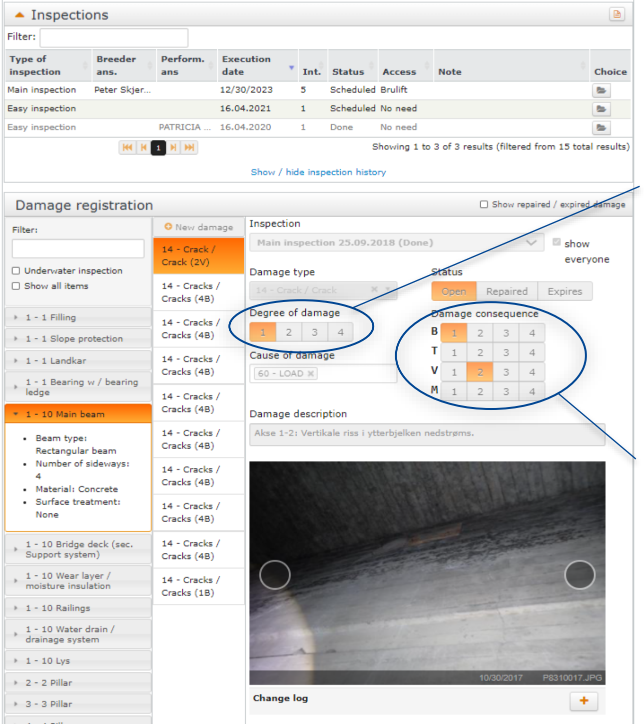
- **Condition Classification**

Level	Degree of damage	Maintenance action
1	Small damage	No action
2	Medium damage	Conducted within 4 -10 years
3	Major damage	Conducted within 1 - 3 years
4	Critical damage	Conducted within half year

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.

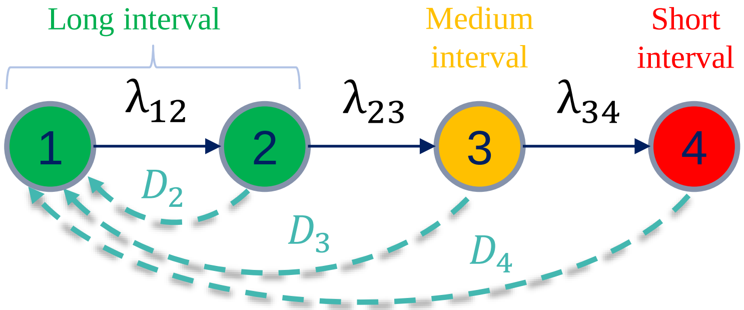
Modelling of condition-based inspections

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

Modelling of deterministic maintenance delays

3. Modelling process

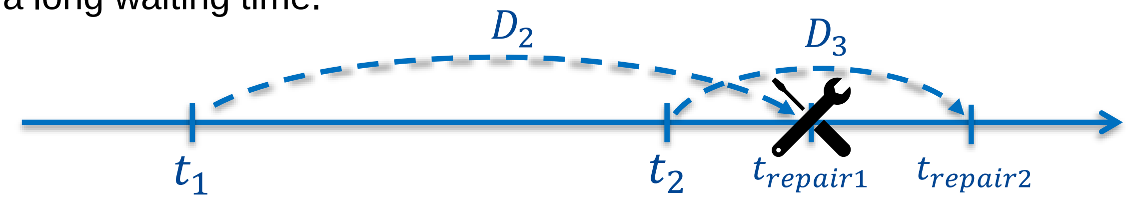
3.1 Modelling Assumptions



1. The system is subjected homogeneous poison process.

$$\boldsymbol{P}(t + \Delta t) = \boldsymbol{P}(t) \cdot e^{\boldsymbol{A}\Delta t}$$

2. The inspections are condition-based, the intervals between inspections are either τ_L , τ_M or τ_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

$$\mathbf{P}_i^{\mathrm{L},m}(t) = Pr(\text{system in state } i \cap \text{current regime is } \tau_{\mathrm{L}} \cap \text{cycle is } m)$$

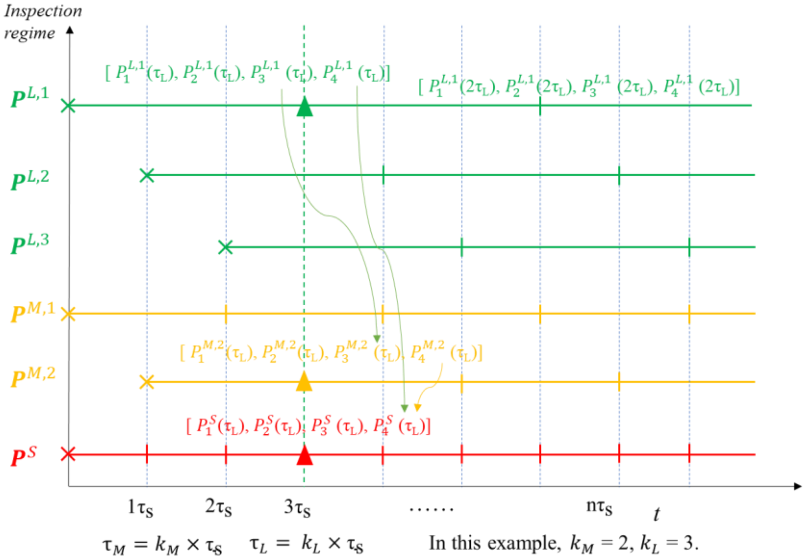
$$\mathbf{P}_i^{\mathrm{M},n}(t) = Pr(\text{system in state } i \cap \text{current regime is } \tau_{\mathrm{M}} \cap \text{cycle is } n)$$

$$\mathbf{P}_i^{\mathrm{S}}(t) = Pr(\text{system in state } i \cap \text{current regime is } \tau_{\mathrm{S}})$$

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

$m = [1, k_L]$, $n = [1, k_M]$, distinguish different long and medium P-vector.

$i = [1,4]$, represent different state,



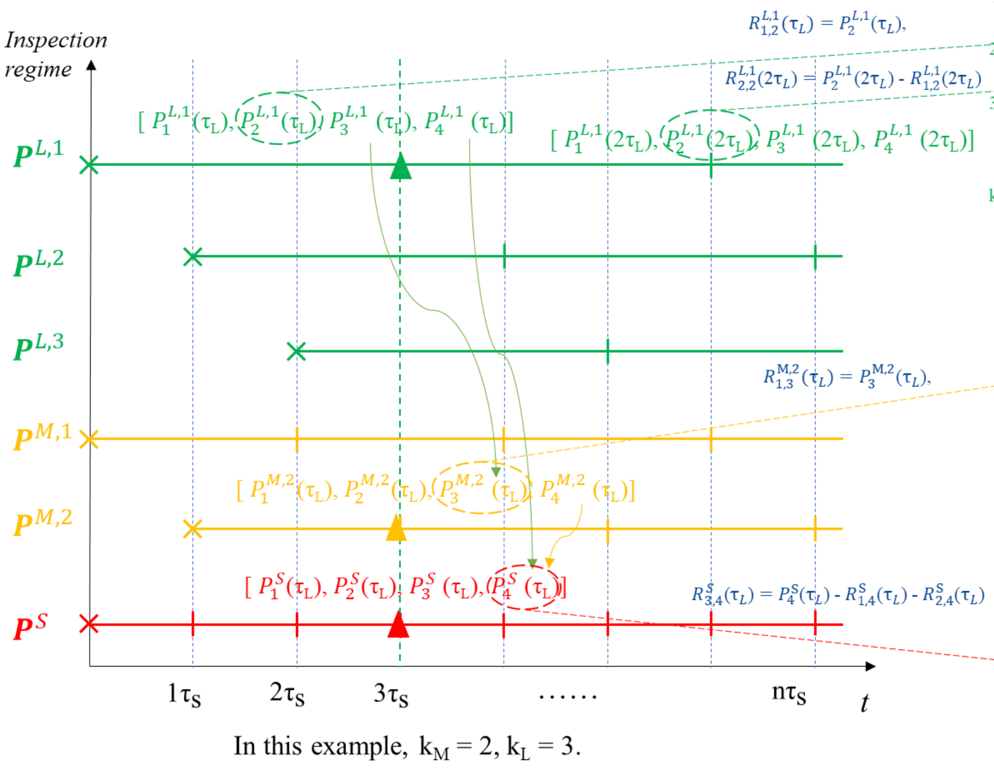
For long inspection regime, when $t = \tau_L + (m-1)\tau_S, 2\tau_L + (m-1)\tau_S, \ldots, k\tau_L + (m-1)\tau_S$:

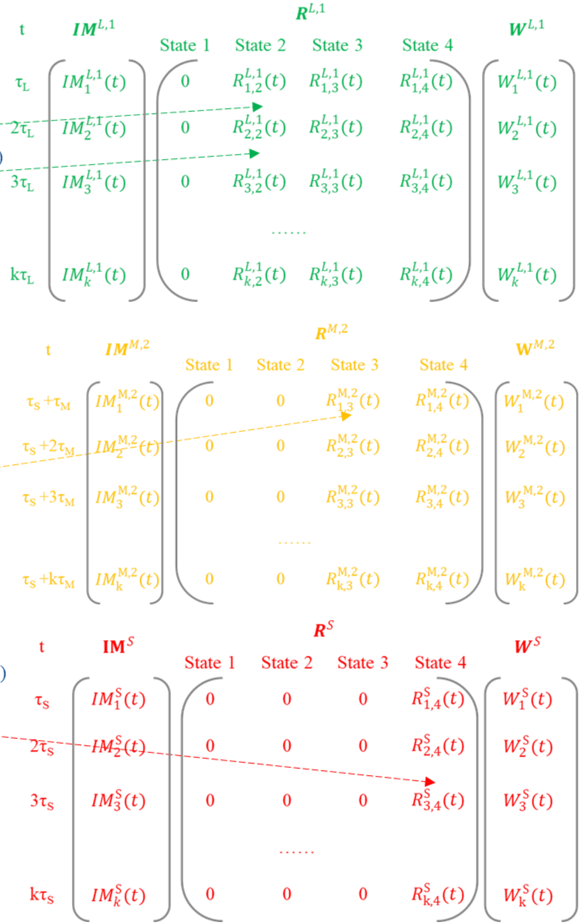
$$\mathbf{P}_3^{\mathrm{M},n}(t^+) = \mathbf{P}_3^{\mathrm{M},n}(t^-) + \mathbf{P}_3^{\mathrm{L},m}(t^-),$$
$$\mathbf{P}_4^{\mathrm{S}}(t^+) = \mathbf{P}_4^{\mathrm{S}}(t^-) + \mathbf{P}_4^{\mathrm{L},m}(t^-),$$

$$\mathbf{P}_1^{\mathrm{L},m}(t^+) = \mathbf{P}_1^{\mathrm{L},m}(t^-),$$
$$\mathbf{P}_2^{\mathrm{L},m}(t^+) = \mathbf{P}_2^{\mathrm{L},m}(t^-),$$
$$\mathbf{P}_3^{\mathrm{L},m}(t^+) = 0,$$
$$\mathbf{P}_4^{\mathrm{L},m}(t^+) = 0$$

3.3 Modelling of deterministic maintenance delay

➢ **The IM vectors, R matrices and W vectors**





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 $= \tau_L + (m-1)\tau_S, 2\tau_L + (m-1)\tau_S, \ \dots,$ $k\tau_L + (m-1)\tau_S$, we have:

$$\mathbf{IM}_k^{\mathrm{L},m}(t^+) = 1$$

Due to the assumption of perfect inspection

$$\mathbf{R}_{k,2}^{\mathrm{L},m}(t^+) = \mathbf{P}_2^{\mathrm{L},m}(t^-) - \sum_{u=0}^{k-1} \mathbf{R}_{u,2}^{\mathrm{L},m}(t)$$

- **At each integration**

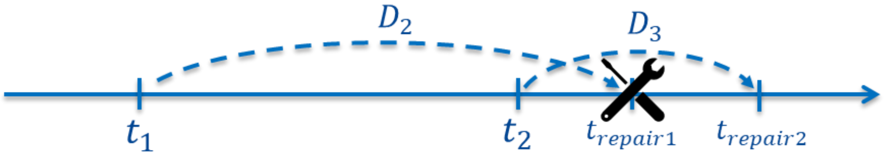
$$\mathbf{W}(t^+) = \mathbf{W}(t^-) + \Delta t, \qquad \forall \mathbf{IM}(t^-) = 1$$

To model system deterioration while waiting for maintenance

$$\mathbf{R}(t + \Delta t) = \mathbf{R}(t) \cdot e^{\mathbf{A}\Delta t}$$

3.3 Modelling of deterministic maintenance delay

- **Treatment of Special case**



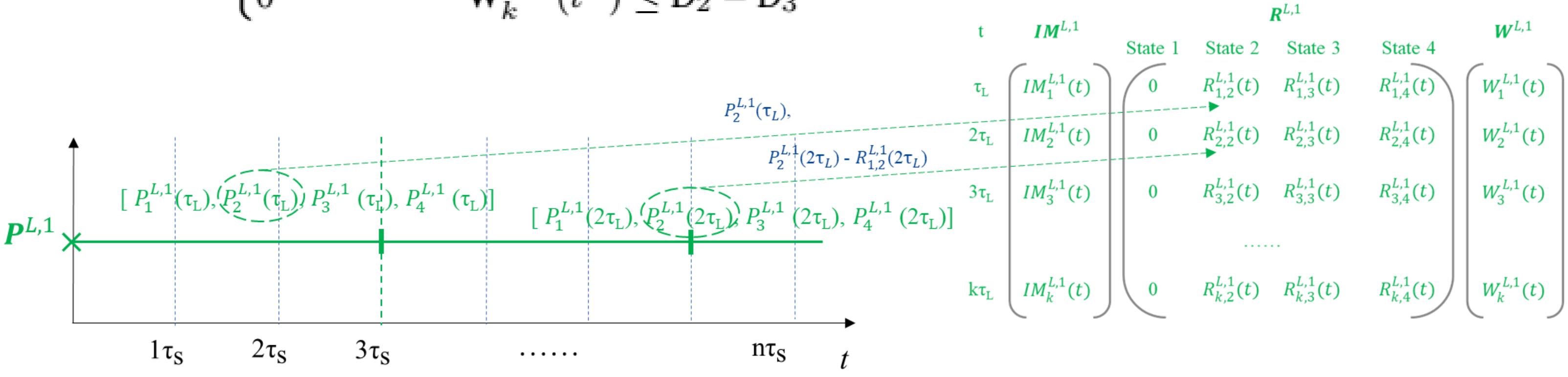
"old" deterioration

$$q_3^{L,m}(t^+) = \begin{cases} \dfrac{R_{k-1,3}^{L,m}(t^-)}{P_3^{L,m}(t^-)} & W_k^{L,m}(t^+) > D_2 - D_3 \\ 0 & W_k^{L,m}(t^+) \le D_2 - D_3 \end{cases}$$

Total deterioration

$$P_3^{L,m}(t^+) = P_3^{L,m}(t^-) \cdot q_3^{L,m}(t^+),$$
$$P_3^{M,n}(t^+) = P_3^{L,m}(t^-) \cdot (1 - q_3^{L,m}(t^+))$$
$$P_4^{L,m}(t^+) = P_4^{L,m}(t^-) \cdot q_4^{L,m}(t^+),$$
$$P_4^{M,n}(t^+) = P_4^{L,m}(t^-) \cdot (1 - q_4^{L,m}(t^+))$$

$$R_{k-1,3}^{L,m}(t^+) = \begin{cases} R_{k-1,3}^{L,m}(t^-) & W_k^{L,m}(t^+) > D_2 - D_3 \\ 0 & W_k^{L,m}(t^+) \le D_2 - D_3 \end{cases}$$



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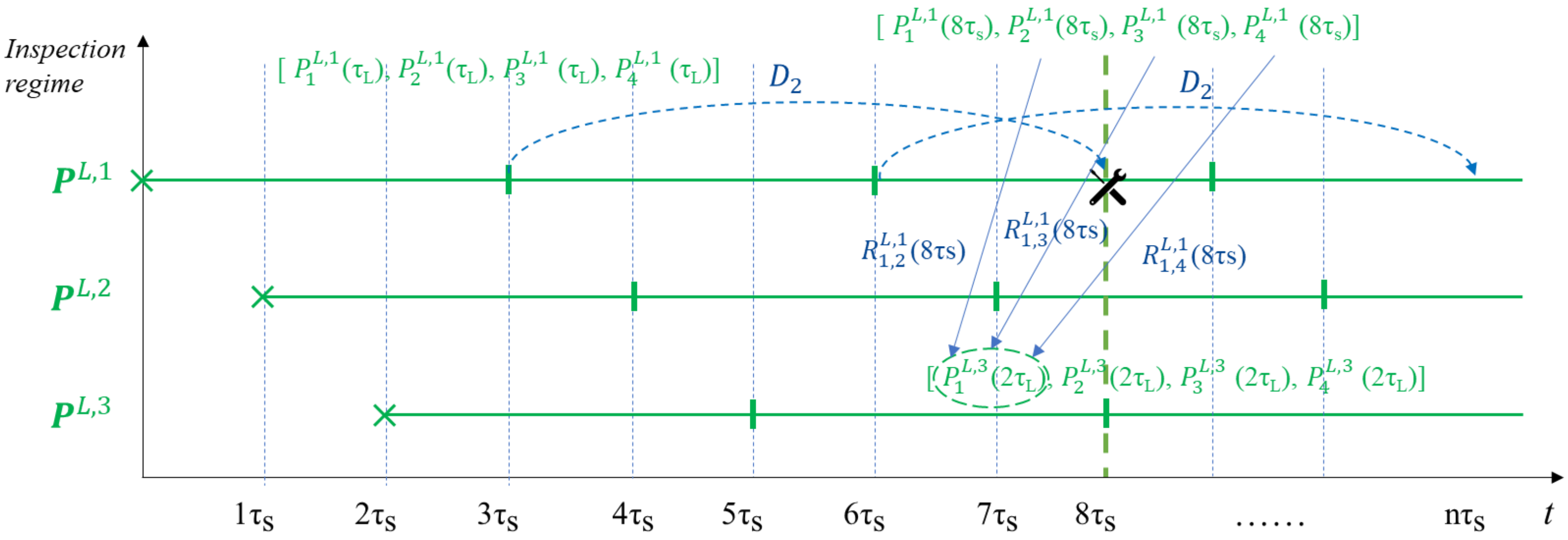
3.3 Modelling of deterministic maintenance delay

- **Count waiting time and conduct repair**



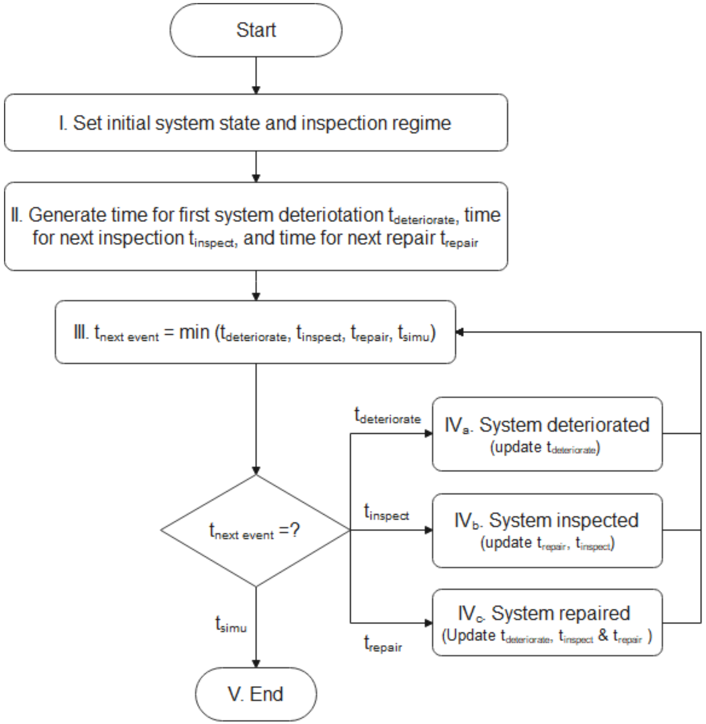
$$\mathbf{P}_1^{\mathrm{L},m}(t^+) = \mathbf{P}_1^{\mathrm{L},m}(t^-) + \sum_{\mathbf{W}_i^{\mathrm{L},m'}(t^-)=\mathrm{D}_2} \mathbf{R}_{i,j}^{\mathrm{L},m'}(t^-), i=[1, \frac{t^-}{\tau_\mathrm{L}}], j=[2,4]$$

$$\mathbf{IM}_k^{\mathrm{L},m}(t^+)=0, \quad R_{k,2}^{\mathrm{L},m}(t^+)=0$$

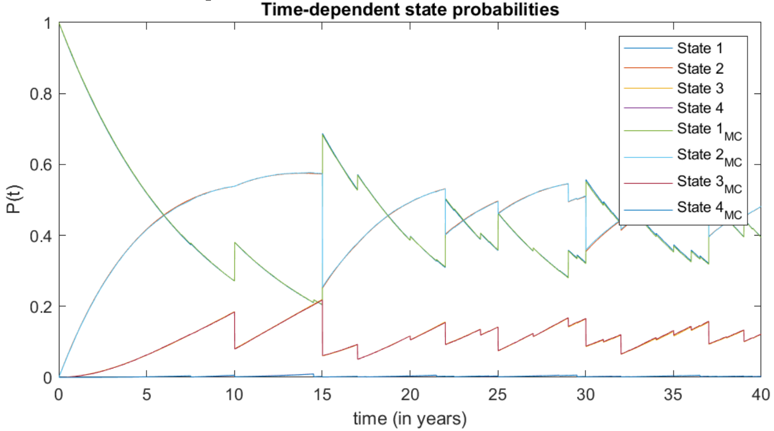
$$\forall \mathbf{W}_k^{\mathrm{L},m}(t^-)=\mathrm{D}_2$$

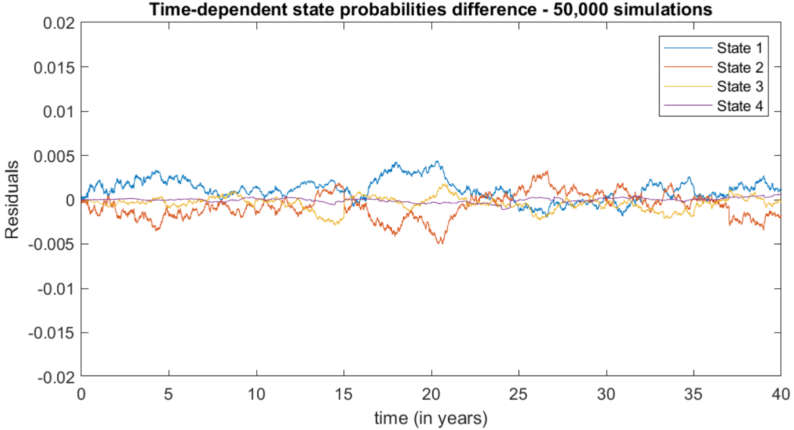
3.4 Verification with Monte Carlo Simulation

- **Monte Carlo Simulation**



- **Result comparison**

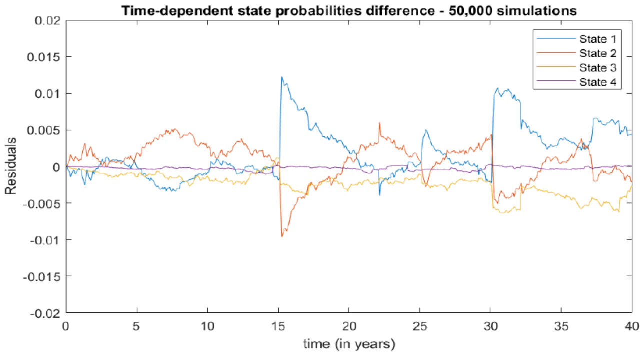


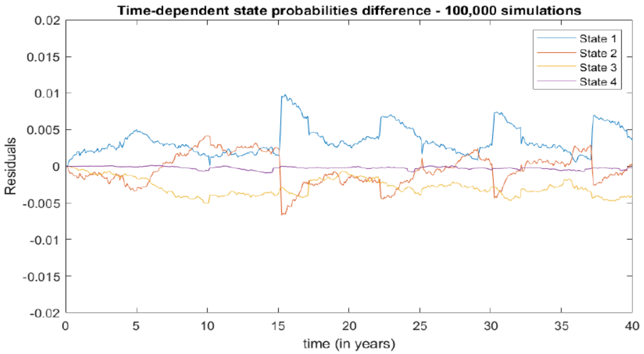


3.4 Verification with Monte Carlo Simulation

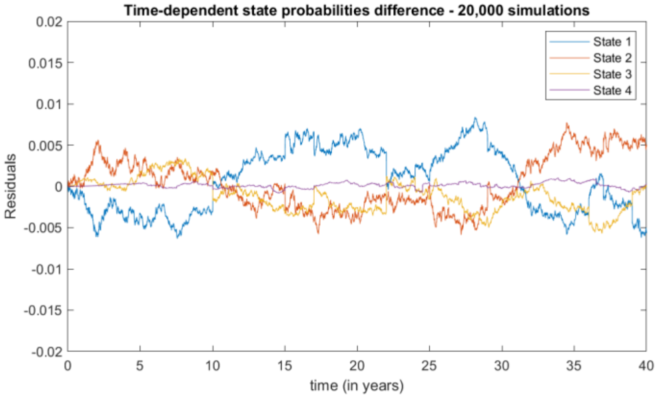
$$\mathbf{P}(t + \text{length of step}) = \mathbf{P}(t)[e^{\mathbf{A}\Delta t}]^a \quad \text{where } \Delta t = \frac{\text{length of step}}{a}$$

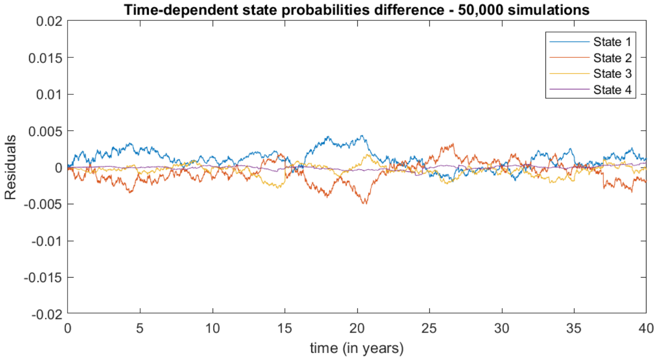
- **Step length = 730 hour**





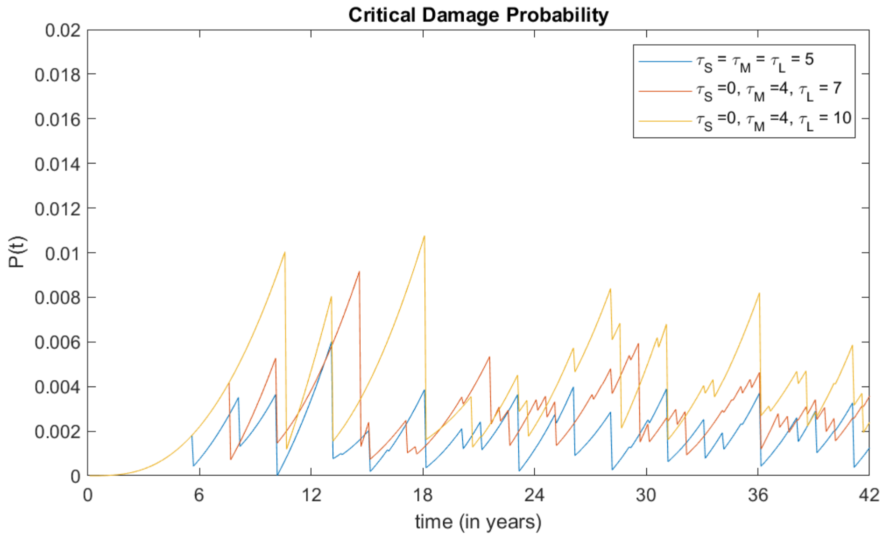
- **Step length = 73 hour**





3.5. Support in decision-making

- **Evaluate critical damage probability for different maintenance strategies**



- **Evaluate expected cost:**

$$C(t) = Cost_{Inspections} + Cost_{Critical\ repair} + Cost_{Medium\ repair} + Cost_{Small\ repair}$$
$$= C_I \cdot N_I + C_{CR} \cdot N_{CR} + C_{MR} \cdot N_{MR} + C_{SR} \cdot N_{SR}$$

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.

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Thanks for your attention

Questions / comments?