COST ACTION TU1406
QUALITY SPECIFICATIONS FOR ROADWAY BRIDGES,
STANDARDIZATION AT A EUROPEAN LEVEL

Training School - Stockholm
Performance-based assessment of Existing Road Bridges
12th – 16th September, 2016
KTH Royal Institute of Technology
Stockholm, Sweden

The use of KPIs for a Sustainable Bridge Management

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OUTLINE

• Key Performance Indicators, why and what to do with them?
• How should we establish a Quality Control Plan?
• Why use Bridge Management Systems?
• Predicting Performance ... and taking decisions!

References
Key Performance Indicators, why and what to do with them?
Key Performance Indicators, why and what to do with them?

- We need to accurately assess/monitor our bridges ...
- We need to have comparing measures for decision ...
Key Performance Indicators, why and what to do with them?

- And what do you obtain from the assessment / monitoring?

Crack width
Displacements
Frequency
Etc.

- Should we declare these measurements / findings as bridge performance indicators? So what is performance?
Key Performance Indicators, why and what to do with them?

But sometimes Bad Performance ...

Very Good Performance !!!

And what was the Decision Making?
Key Performance Indicators, why and what to do with them?

- And what is an indicator?

Is LDL and HDL cholesterol an indicator?
Is Crack Width an indicator?

- Something measurable, quantifiable?
- For which there is a target value, a goal, available?
- Which is valid for ranking / decision purposes?

- And what is a performance indicator?
Key Performance Indicators, why and what to do with them?

- But we have several sources of Performance Indicators:
Key Performance Indicators, why and what to do with them?

• Which complement each other ...

• So we will have a database of Performance Indicators

• We have different levels indicators (@ component, system and networking)

• And we will group them in the so-called Key Performance Indicators (KPIs)

And how to compute those KPIs?
Key Performance Indicators, why and what to do with them?

<table>
<thead>
<tr>
<th>Safety, Reliability, Security</th>
<th>KPI</th>
<th>total rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>rating (1-5)</td>
<td>weighting</td>
</tr>
<tr>
<td>crack width</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>corrosion</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>lack of bolts</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>support damage</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>drainage system</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>fungus appearance (wooden elements)</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>bugs attack (wooden elements)</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>rotting (wooden elements)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>overweight traffic</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>sediment accumulation</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>vandalism</td>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>total rating</td>
<td>2.33</td>
<td></td>
</tr>
</tbody>
</table>
Key Performance Indicators, why and what to do with them?
How should we establish a Quality Control Plan?

Ayurveda Blood Chemical Chemistry Test

<table>
<thead>
<tr>
<th>Substance</th>
<th>Patient Value</th>
<th>Normal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphates</td>
<td>76.00 mg/ahmv</td>
<td>15 - 20 mg/ahmv</td>
</tr>
<tr>
<td>Phosphates [Total]</td>
<td>60.00 Gramm/ahmv</td>
<td>60 - 80 Gramm/ahmv</td>
</tr>
<tr>
<td>Chloride</td>
<td>46.00 mg/ahmv</td>
<td>55 - 75 mg/ahmv</td>
</tr>
<tr>
<td>Potassium</td>
<td>60.00 mg/ahmv</td>
<td>28 - 48 mg/ahmv</td>
</tr>
<tr>
<td>Sodium</td>
<td>110.00 mg/ahmv</td>
<td>40 - 58 mg/ahmv</td>
</tr>
<tr>
<td>Calcium</td>
<td>24.00 mg/ahmv</td>
<td>39 - 50 mg/ahmv</td>
</tr>
<tr>
<td>Iodine</td>
<td>10.00 mg/ahmv</td>
<td>40 - 60 mg/ahmv</td>
</tr>
<tr>
<td>Iron</td>
<td>76.00 mg/ahmv</td>
<td>30 - 60 mg/ahmv</td>
</tr>
<tr>
<td>Copper</td>
<td>53.00 mg/ahmv</td>
<td>30 - 55 mg/ahmv</td>
</tr>
<tr>
<td>Magnesium</td>
<td>52.00 mg/ahmv</td>
<td>25 - 40 mg/ahmv</td>
</tr>
<tr>
<td>Ammonia</td>
<td>46.00 mg/ahmv</td>
<td>26 - 40 mg/ahmv</td>
</tr>
<tr>
<td>Uric acid</td>
<td>28.00 mg/ahmv</td>
<td>50 - 60 mg/ahmv</td>
</tr>
<tr>
<td>Creatinine</td>
<td>72.00 mg/ahmv</td>
<td>40 - 60 mg/ahmv</td>
</tr>
<tr>
<td>Urea</td>
<td>15.00 mg/ahmv</td>
<td>10 - 30 mg/ahmv</td>
</tr>
</tbody>
</table>

(Values within BOX are in NORMAL LIMIT)

In this report, shown values higher are considered higher and lower is considered lower.

WARNING: Above Patient Data & Readings have been gained after Patient's BLOOD examined by AVUSH BLOOD METER device, which is a new invention in Ayurvedic Medical System. Errors are possible in Data & Readings, therefore it is advisable to Ayurvedic Physician to correlate the Diagnosis with the Clinical symptoms and Syndromes. The above Blood Test readings are only for helping Ayurvedic Physician for approaching Disease Diagnosis and not for other purposes. Blood Test can be affected by Season, Thermal situation, Stage of Fast / Starvation, Hunger, Thirst, Physical and Mental Exertion.

SHAKIL AHMAD 33 YRS
6/7/10, Bhossalp Road, Bantin Bazar, Kanpur - 2

And the Goals ....
How should we establish a Quality Control Plan?

And with a BRIDGE??
**Key Performance Indicators, why and what to do with them?**

---

### Safety, Reliability, Security

<table>
<thead>
<tr>
<th>PI</th>
<th>Level</th>
<th>Performance indicator PI if</th>
<th>PI belongs to the Key Performance Indicator(s)</th>
<th>Assessment</th>
<th>applicable/ not applicable</th>
<th>rating (1-5)</th>
<th>weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>crack length</td>
<td>CL</td>
<td>yes, tech</td>
<td>yes, I, S</td>
<td></td>
<td>2</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>crack orientation</td>
<td>CL</td>
<td>yes, tech</td>
<td>yes, I, S</td>
<td>degrees</td>
<td>3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>crack width</td>
<td>CL</td>
<td>yes, tech, sust</td>
<td>yes, I, S, D</td>
<td></td>
<td>5</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>crack-distance crack spacing</td>
<td>CL</td>
<td>yes, tech</td>
<td>yes, I, S</td>
<td></td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>due to settlement, due to crumbling of concrete...</td>
<td>SL</td>
<td>yes, sust</td>
<td>yes, I, S</td>
<td></td>
<td>2</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

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The performance indicators .......

And the Goals .......

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COST ACTION TU1406  
SLIDE 14
How should we establish a Quality Control Plan?

- Visual Inspection
- NDT Testing
- Monitoring System

Performance Indicator → Performance Goal → Quality Control Plan
How should we establish a Quality Control Plan?

**COMPONENT LEVEL**

1. **DAMAGE DEGREE & EXTENSION** (PI)
2. **DAMAGE ASSESSMENT** (PG, PI)
3. **ELEMENT FUNCTIONALITY** (PG, PI)

**SYSTEM LEVEL**

1. **IMPORTANCE OF BRIDGE ELEMENT** (PI)
2. **BRIDGE CONDITION ASSESSMENT** (PG, PI)

**NETWORK LEVEL**

1. **+ BRIDGE IMPORTANCE IN THE NETWORK** (PI)
2. **PRIORITY REPAIR RANKING** (PG, PI)
3. **QUALITY CONTROL PLAN** (PG)

Crucial for optimal QC and Management
Why use Bridge Management Systems?

A Bridge Management System is used to store the performance indicators data and the quality control plans of the bridge network …
Why use Bridge Management Systems?

And why having the DATA, if we do not use such DATA?

*It is agreed among the bridge community that advanced BMSs incorporating predictive models, maintenance effects and costs, and optimization tools should be used for decision making …*
Why use Bridge Management Systems?

DATA WAREHOUSE

Inventory  Condition Evaluation

ANALYSIS

Predictive Model  Decision-Making Process

REPORTING

Traditional BMSs

Advanced BMSs
Predicting Performance ... and taking decisions!

Small but timely renewal investments save money

- Poor Asset Management ($60m total): Let asset deteriorate, then replace
- Smart Asset Management ($40m total): Make timely investments throughout asset life

[Ministry of Ontario, 2014]
Predicting Performance ... and taking decisions!

List of predicted models that can be used ...

- Poisson processes (for purely aleatory behaviors, e.g. safety guards);
- Weibull processes (when no data or few data is available)
- **Markov model** (widely used, with success in most cases);
- Semi-Markov model (recommended e.g. for fatigue);
- Hidden-Markov model (when data is available – big data);
- Artificial neural-networks (when data is available, and some correlations between variables are already known);
- Bayesian networks (when the conditional probabilities are known or can be established);
- etc.
Predicting Performance ... and taking decisions!

Markov Model

- Stochastic method, whose probability distribution in future state prediction depends only on its current state (memory less);
- Markov processes are state transition systems, that may vary in temporal space (discrete – Markov Chain - or continuous), represented by probability vectors.

Discrete Markov Model

Consider a system that, at each time instant, can be in any state from a set of $N$ states ($S_1$, $S_2$, ..., $S_N$), being in this case $N = 3$. The state change at discrete time periods is defined by a set of probabilities, being the time instant designated by $t = 1, 2, ...$, and the time state $t$ by $q_t$. 
Predicting Performance ... and taking decisions!

Discrete Markov Model

The probability of a system being in any state is then given by:

\[ P[q_t = S_j | q_{t-1} = S_i, q_{t-2} = S_k, ..., q_1 = S_1] \]

In a first order Markov chain this probability only depends from the current and previous state:

\[ P[q_t = S_j | q_{t-1} = S_i, q_{t-2} = S_k, ..., q_1 = S_1] = P[q_t = S_j | q_{t-1} = S_i] \]
Predicting Performance ... and taking decisions!

Discrete Markov Model

The transition state probabilities are then represented by:

\[
a_{ij} = P[q_t = S_j | q_{t-1} = S_i], \quad 1 \leq i, j \leq N
\]

Being the state transition probabilities matrix given by:

\[
P = \begin{bmatrix}
    a_{11} & a_{12} & \cdots & a_{1j} \\
    a_{21} & a_{22} & \cdots & a_{2j} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{i1} & a_{i2} & \cdots & a_{ij}
\end{bmatrix}
\]

Being for a predicted time \( t \), \( a_{ij} \) the probability of a specific system that, presently, is in state condition \( i \), transit to state \( j \) at then end of \( t \), and \( a_{ij} \) the probability that, in the homologous period, the equipment stay in the initial condition state.
Predicting Performance ... and taking decisions!

Discrete Markov Model

As this is a degradation model (that do not consider maintenance actions) it is reasonable that the system cannot have natural improvements, being the state transition probabilities $a_{ij}$, with $i > j$, null. Additionally, in Markov matrixes, state transitions are always sequential, which means that state transition probabilities between non sequential states should be also null.

$$P = \begin{bmatrix}
a_{11} & a_{12} & \cdots & 0 \\
0 & a_{22} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & a_{ij}
\end{bmatrix}$$
Predicting Performance ... and taking decisions!

Discrete Markov Model

The state transition probabilities can be thus defined as the number of transitions divided by a specific time unit, being estimated by the quotient between the number of elements that transit from state $i$ to state $j$, $n_{ij}$, in a specific time frame, and the number of elements which initial state was $i$, $n_i$.

$$a_{ij} = \frac{n_{ij}}{n_i}$$

Once the probability vector $p(t_i)$, related to the various condition states in an initial time instant $t_i$, is known, it is possible to predict the future performance for a final instant $t_f$, obtaining thus the final probabilities vector $p(t_f)$.

$$p(t_f) = p(t_i) \times P, \quad p(t) = [p_1 \ p_2 \ \ldots \ p_n]$$
Predicting Performance ... and taking decisions!

Continuous Markov Model

Unlike discrete Markov chains, in which a time constant between different condition states is assumed, continuous Markov model consider that state transitions are completely aleatory being a continuous stochastic process with time. In this situation, the main objective is the definition of the intensity matrix, $Q$, that represent the transition time-independent rates between the different states.

\[
Q = \begin{bmatrix}
q_{11} & q_{12} & \cdots & q_{1j} \\
q_{21} & q_{22} & \cdots & q_{2j} \\
\vdots & \vdots & \ddots & \vdots \\
q_{i1} & q_{i2} & \cdots & q_{ij}
\end{bmatrix}
\]
Predicting Performance ... and taking decisions!

Continuous Markov Model

In this case the transition rates between states can be computed through:

$$q_{ij} = \frac{n_{ij}}{\sum \Delta t_i}$$

Being $n_{j}$ the number of elements that transit from state $i$ to $j$, and $\sum \Delta t_i$ the sum of time intervals between observations from initial state $i$.

The state transitions are sequential and natural improvements in the condition are not possible. Accordingly, there is not possible more transitions when the last condition state is attained (e.g. for $N = 3$, $q_{33} = 0$). Additionally, the sum of the rates in each state should be null.

$$\theta_i = q_{ii} = -\sum_{j \neq i} q_{ij} \text{ with } i = 1, \ldots, N$$
Predicting Performance ... and taking decisions!

Continuous Markov Model

Therefore, for $N = 3$, the intensity matrix is:

$$Q = \begin{bmatrix}
-\theta_1 & \theta_1 & 0 \\
0 & -\theta_2 & \theta_2 \\
0 & 0 & 0
\end{bmatrix}$$

Being $\theta$ the transition rate between consecutive condition states. From this matrix it is then possible to obtain the Markov matrix through:

$$P_{\Delta t} = \exp(Q \times \Delta t)$$
Predicting Performance ... and taking decisions!

Performance Model of a Roadway Bridge

For continuous-time processes:

- the goal is the definition of the intensity matrix $Q$;
- represents the time independent transition probabilities between states.

For the available data, condition indicators, the intensity matrix that reflect the bridge performance, is:

$$Q = \begin{bmatrix} -0.0893 & 0.0893 & 0 & 0 & 0 & 0 \\ 0 & -0.0125 & 0.0125 & 0 & 0 \\ 0 & 0 & -0.0034 & 0.0034 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$
Predicting Performance ... and taking decisions!

Performance Model of a Roadway Bridge

A way to assess how much the model represents reality is through the computation of its maximum likelihood. For the intensity matrix, obtained likelihood is -181.92. Using an optimization tool, the solution that maximizes its likelihood is:

\[
Q = \begin{bmatrix}
-0.1038 & 0.1038 & 0 & 0 & 0 \\
0 & -0.0082 & 0.0082 & 0 & 0 \\
0 & 0 & -0.0025 & 0.0025 & 0 \\
0 & 0 & 0 & -0.0010 & 0.0010 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

The obtained value is -179.09 ( > -181.92). These vector and matrix are those that best reflect the bridge performance.
Predicting Performance ... and taking decisions!

Performance Model of a Roadway Bridge

In order to assess the performance evolution, it is computed the transition probabilities $P_{ij}$ for the four possible initial conditions, and a $\Delta t = 240$ months (time horizon) is considered in the analysis.
Predicting Performance ... and taking decisions!

Intervention Effects

In general, the impact of an intervention in a system performance is modelled by one (or more than one) of the following effects: (i) Improvement in performance at time of application ($\gamma$); (ii) Delay in deterioration for a period of time after application ($t_d$); (iii) Reduction in deterioration rate for a period of time after application ($\delta$: $\beta(t) = \alpha(t) \times \delta$).
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

- Time of first application ($t_{pa}$);
- Time interval between applications ($\Delta_{ta}$);
- Time delay of each application ($t_{da}$).
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$t_{pa}$</th>
<th>$\Delta_{ta}$</th>
<th>$t_{da}$</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>12</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>5</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>15</td>
<td>10</td>
<td>50 %</td>
</tr>
</tbody>
</table>
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

- Use of an identity matrix $I$ (instead of an intensity matrix, $Q$) to simulate deterioration delay:

$$P_{\Delta t} = \exp(Q \times \Delta t) \rightarrow P_{\Delta t} = \exp(I \times \Delta t)$$

$p(t = 10) = [0.29, 0.50, 0.14, 0.06, 0.01, 0]$ (month 10-15)

$C_{(t=[10-15])} = \begin{bmatrix}
0.29^T \\
0.50 \\
0.14 \\
0.06 \\
0.01 \\
0
\end{bmatrix} \ast \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} \ast \begin{bmatrix}
0 \\
1 \\
2 \\
3 \\
4 \\
5
\end{bmatrix} = 1$
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

- The deterioration rate reduction implies to multiply the transition rates ($\theta$) by a reduction factor ($\delta$):

\[
\theta_i = \begin{bmatrix}
\theta_0 \\
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4 \\
\end{bmatrix} = \begin{bmatrix}
0,062 \\
0,032 \\
0,067 \\
0,033 \\
0,001 \\
\end{bmatrix} \times (1 - \delta) = \begin{bmatrix}
0,031 \\
0,015 \\
0,029 \\
0,011 \\
0,001 \\
\end{bmatrix}
\]
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

- It also considers the target performance \( (I_T) \) at time of application.
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$t_{pa}$</th>
<th>$\Delta_{ta}$</th>
<th>$I_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>48</td>
<td>2</td>
</tr>
</tbody>
</table>
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

- If in instance $t_i$, the deterioration level of the element is in the range of applicability;
- Just before the application of the maintenance action, the condition state is defined through:

$$C_t = \begin{bmatrix} C_1 & C_2 & C_3 & C_4 & C_5 \end{bmatrix}$$

- After, the updated condition state vector is given by:

$$C_{t,i}^* = \begin{cases} 1, & i = \gamma \\ 0, & i \neq \gamma \end{cases}$$
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

- Scenario 1 (month 20)

\[ p(t = t_{pa}) = [0,09, 0.41, 0.21, 0.22, 0.07, 0] \]

\[ p(t = 20) = [1, 0, 0, 0, 0, 0] \]

\[ C_{t=20} = [1, 0, 0, 0, 0, 0] \times \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} = 0 \]
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

- Scenario 2 (month 72)

\[
p(t_{antes} = 72) = [0 \ 0,02 \ 0,03 \ 0,25 \ 0,67 \ 0,03]
\]

\[
p(t_{depois} = 72) = [0 \ 0,02 \ 0,98 \ 0 \ 0 \ 0]
\]

\[
p(t_{depois} = 72)(2) = 1 - 0 - 0.02 = 0.98
\]
Predicting Performance ... and taking decisions!

Intervention Effects – Condition-Based Corrective Interventions

- In this case it is only necessary to define the performance condition when the management action is applied ($I_R$) as well as the target performance ($I_T$) as there is no time parameters.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$I_R$</th>
<th>$I_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

![Graph showing intervention effects](image)
Predicting Performance ... and taking decisions!

Intervention Effects – Condition-Based Corrective Interventions

- Scenario 1

\[ p(t = 19) = [0.10, 0.63, 0.25, 0, 0, 0] \]

\[ p(t = 20) = [0.10, 0.61, 0.26, 0.03, 0, 0] \]

\[ p(t = 20) = [0.10, 0.64, 0.26, 0, 0, 0] \]
Predicting Performance ... and taking decisions!

Intervention Costs
Predicting Performance ... and taking decisions!

Uncertainty in Quantification of Effects and Costs

Probabilistic approach

\[ \downarrow \]

Probability distributions

\[ \downarrow \]

Triangular distribution

\[ \downarrow \]

Parameters definition

- Intuition
- Expert opinion
- Engineering Judgement
- Questionnaire

... Lack of knowledge
... Natural variability
... Model uncertainties
Predicting Performance ... and taking decisions!

Examples of Interventions on Roadway Bridge

<table>
<thead>
<tr>
<th>Preventive MA</th>
<th>$t_d$ [year]</th>
<th>$\delta$ [-]</th>
<th>$\gamma$ [-]</th>
<th>Cost [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA1 Cleaning of surrounding areas</td>
<td>[1, 1.5, 2]</td>
<td>-</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>MA2 Paint concrete surface, in localized areas</td>
<td>[4, 6, 8]</td>
<td>[0.3, 0.4, 0.5]</td>
<td>-</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Corrective MA</th>
<th>$t_d$ [year]</th>
<th>$\delta$ [-]</th>
<th>$\gamma$ [-]</th>
<th>Cost [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA3 Paint concrete surface, in general</td>
<td>[10, 12, 15]</td>
<td>[0.5, 0.6, 0.7]</td>
<td>[1, 1, 2]</td>
<td>1000</td>
</tr>
<tr>
<td>MA4 Crack sealing by injection resin based on epoxy</td>
<td>[3, 4, 6]</td>
<td>[0.3, 0.4, 0.5]</td>
<td>-</td>
<td>400</td>
</tr>
<tr>
<td>MA5 Repair of plaster coating</td>
<td>[0.5, 1.5, 3]</td>
<td>[0.7, 0.8, 0.9]</td>
<td>-</td>
<td>150</td>
</tr>
</tbody>
</table>
Predicting Performance ... and taking decisions!

Decision-making

... There are different decision making techniques to support wise investments

- Life-cycle cost
- Multi-criteria
- Risk-based methods
- Trade-off analysis

Safety
Socio-economic
Environmental
...
Predicting Performance ... and taking decisions!

Decision-making

An Optimization Model should contain:

Efficient long term planning of maintenance actions

Ensure safe and serviceable assets at lowest possible investment

Life-cycle cost analysis

Multi-objective optimization problem
Predicting Performance ... and taking decisions!

Decision-making

... Multi-objective optimization problem, with the aim of optimal scheduling of maintenance actions for a given time horizon:

Formulation:

- Conflicting objectives

  \[ PI = \sum_{i=1}^{N} \sum_{j=1}^{T-1} \left( \frac{C_{i,j+1} + C_{i,j}}{2} \right) \Delta t_j \]

  Life-cycle maintenance cost (TC)

  \[ TC = \sum_{i=1}^{N} \sum_{j=1}^{T} \frac{cost(\cdot)}{(1 + r)^j} \]

- Constraints \[ \forall i \in \{1, ..., N\} \land \forall j \in \{1, ..., T\} \]

  \[ C_{i,j} \leq C_{\epsilon}, \forall i \in \{1, ..., N\} \land \forall j \in \{1, ..., T\} \]

  Threshold value

  Assure a proper level of service

  Time value of money
Predicting Performance ... and taking decisions!

Decision-making

... Optimization model

Algorithm 1 NSGA-II
1: $g \leftarrow 0$;
2: initialization: $P$;
3: repeat
4:  $g \leftarrow g + 1$;
5:  $R \leftarrow$ matingSelection($P$);
6:  $Q \leftarrow$ variation($R$);
7:  $P \leftarrow$ environmentalSelection($P \cup Q$);
8: until the stopping criterion is met
9: output: $P$;
Predicting Performance ... and taking decisions!

Decision-making on Roadway Bridge

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Predicting Performance ... and taking decisions!

Decision-making on Roadway Bridge

- $C_E = 3$
- $C_E = 4$
- $C_E = 5$
Predicting Performance ... and taking decisions!
Predicting Performance ... and taking decisions!


JAVA LINK:

Predicting Performance ... and taking decisions!

Intensity Matrix (computation)

\[ Q = \text{MarkovModel('dados.dat')} \]

- Date: yyyy-mm-dd
- Condition State: from 1 (best) to 5 (worst)
  Separated by ","
Predicting Performance ... and taking decisions!

Intensity Matrix (results)

\[
Q =
\begin{bmatrix}
-0.0751 & 0.0751 & 0 & 0 & 0 \\
0 & -0.0998 & 0.0998 & 0 & 0 \\
0 & 0 & -0.1481 & 0.1481 & 0 \\
0 & 0 & 0 & -0.1680 & 0.1680 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]
Predicting Performance ... and taking decisions!

Performance Prediction (computation)

```matlab
%% sem acoes de manutencao

% matriz de intensidade
Q = [-0.35536621072355506 0.35536621072355506 0.0 0.0 0.0; 0.0 -0.26264072614532066 0.26264072614532066 0.0 0.0; 0.0 0.0 -0.38035073667554344 0.38035073667554344 0.0; 0.0 0.0 0.0 -0.09810154865555702 0.09810154865555702; 0.0 0.0 0.0 0.0 0.0];

% estado de condicao inicial
c0 = 2;

% tempo horizonte
th = 30;

% calcular o desempenho futuro
s = AssetPerformance(Q, c0, th);

% construir grafico
plot(1:th, s, 'r.');
axis([0 th 0 5]);
xlabel('tempo');
ylabel('estado');
```
Predicting Performance ... and taking decisions!

Performance Prediction (results)
Predicting Performance ... and taking decisions!

Decision-making (computation)

```matlab
%% multiobjective optimization

% matriz de intensidade
Q = [-0.25289420837327026 0.25289420837327026 0.0 0.0 0.0;
    0.0 -0.06052186396042611 0.06052186396042611 0.0 0.0;
    0.0 0.0 0.0521932500788024 0.0521932500788024 0.0;
    0.0 0.0 0.0 0.0;0.05360549452068326 0.05360549452068326;
    0.0 0.0 0.0 0.0 0.00];

% estado de condição inicial
c0 = 2;

% tempo horizonte
th = 20;

% ficheiro com efeitos das ações
efeitosFile = 'acoes.xlsx';

% vetor dos custos das ações
costs = [75.00, 120.00, 500.00, 698.00, 1576.00];

% executar
[objectives, actions, states, costs] = AssetOptimization(Q, c0, th, efeitosFile, costs);
```
Predicting Performance ... and taking decisions!

Decision-making (results)
Predicting Performance ... and taking decisions!

## Decision-making (results)

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