TU1406
COST ACTION

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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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ESF provides the COST Office through a European Commission contract

COST is supported by the EU Framework Programme

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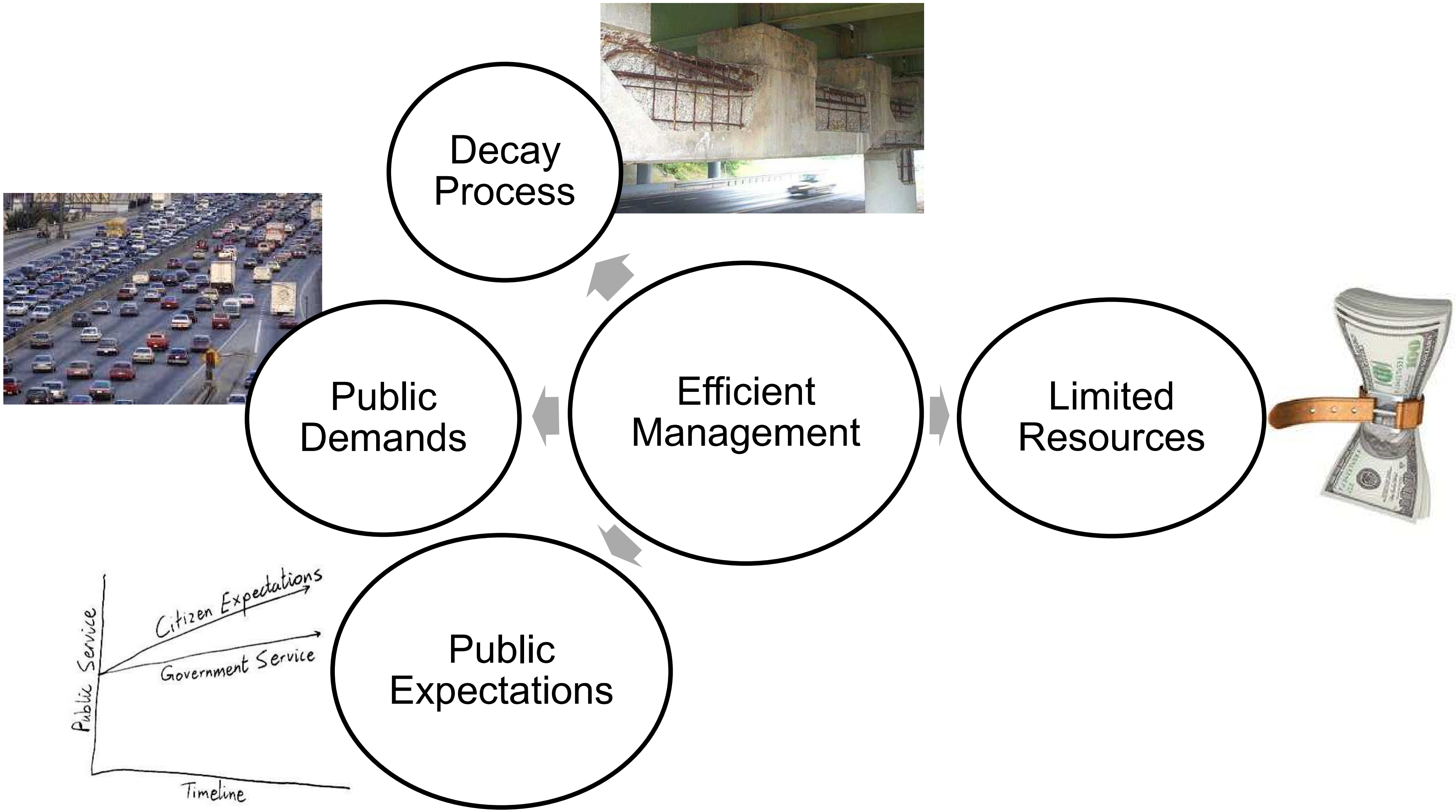
OUTLINE

- 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

- Denysiuk, R., Fernandes, J., Matos, J. C., Neves, L. C., Berardinelli, U. (2016) “A computational framework for infrastructure asset maintenance scheduling”, Structural Engineering International, Journal of IABSE, Volume 26, Number 2, pp. 94-102(9), May 2016. (doi: 10.2749/101686616X14555428759046);
- Hudson, W. R., Haas, R., Uddin, W. (2003). Public Infrastructure Asset Management. McGraw-Hill, New York;
- Van der Lei, T., Herder, P., Wijnia, Y. (2012). Asset Management. The State of the Art in Europe from a Life Cycle Perspective. Springer, Netherlands.

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

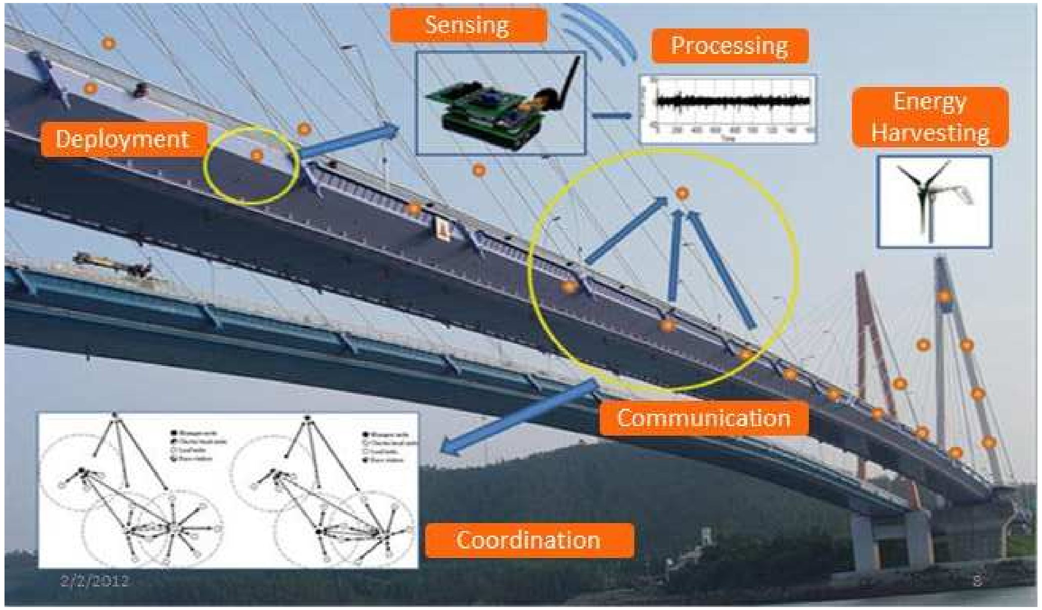


Key Performance Indicators, why and what to do with them?

- 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?

Very Good Performance !!!

But sometimes Bad 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?

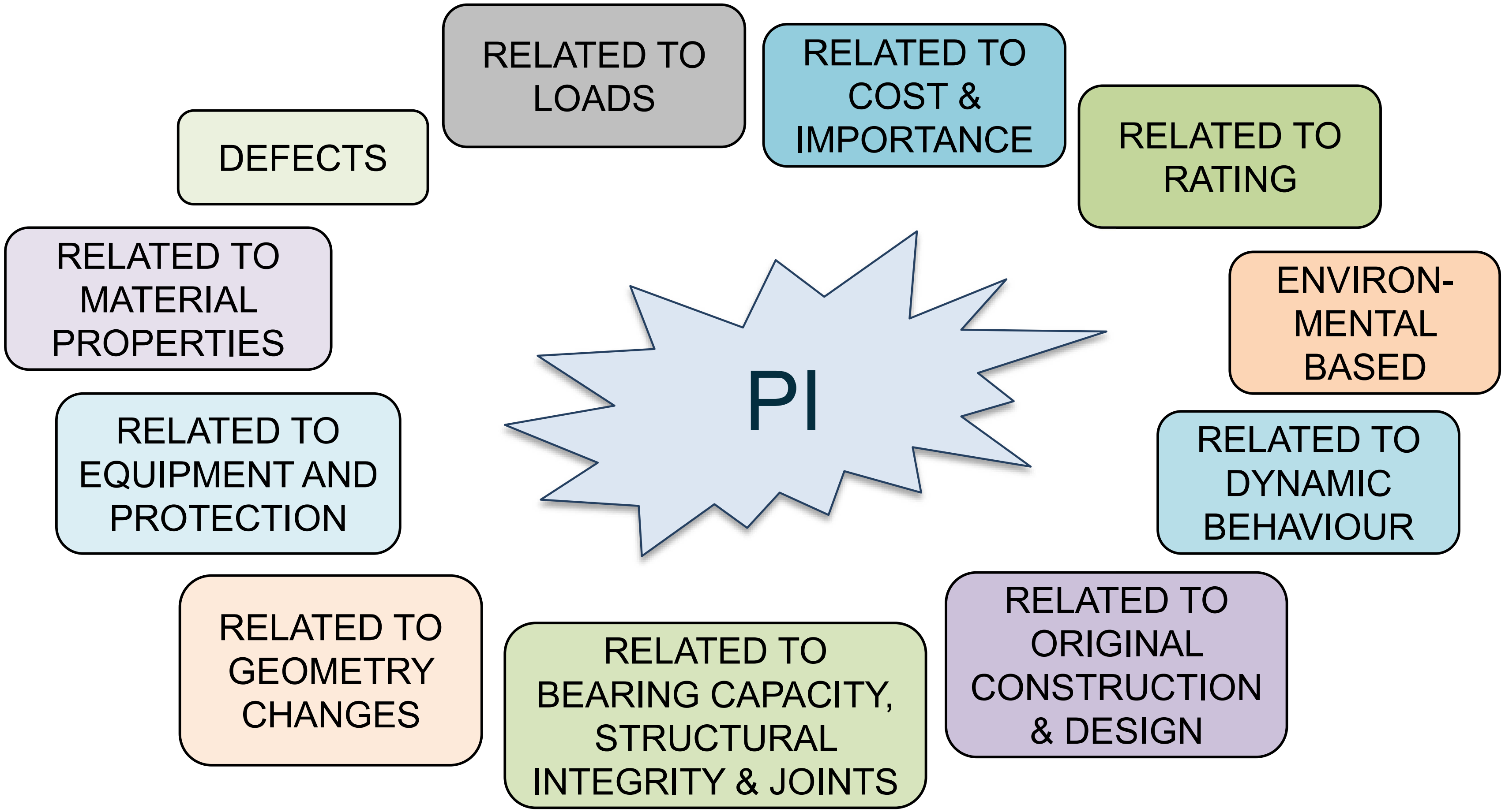
Is Crack Width an indicator?

- 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)

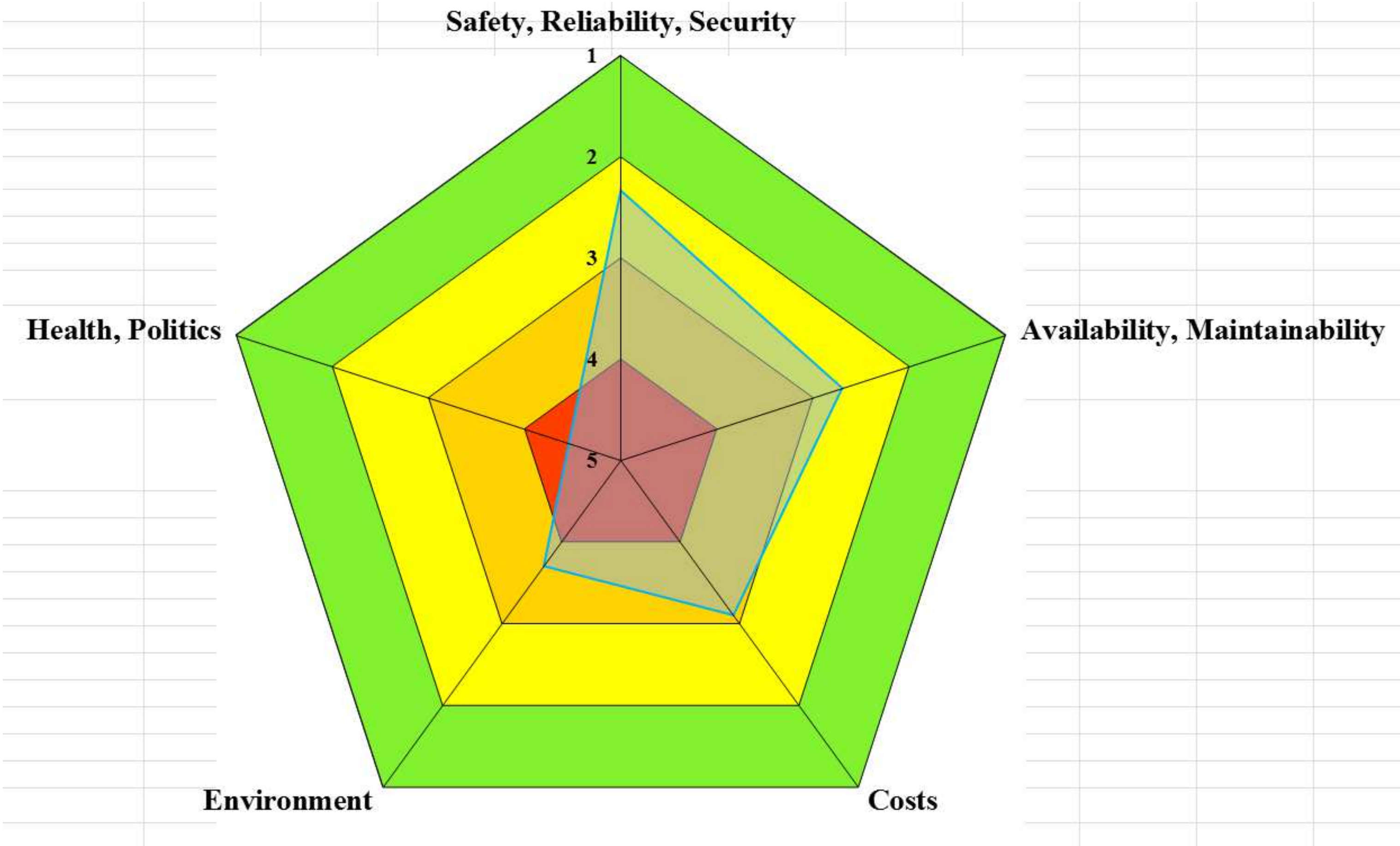
And how to compute those KPIs ?

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

Safety, Reliability, Security		
PI	**rating (1-5)**	**weighting**
crack width	2	0,8
corrosion	3	0,5
lack of bolts	5	0,3
support damage	2	1
drainage system	2	0,8
fungus appereance (wooden elements)	3	0,5
bugs attack (wooden elements)	5	0,3
rotting (wooden elements)	2	1
overweight traffic	1	1
sediment accumulation	2	0,8
vandalism	3	0,8
	total rating	**2,33**

KPI	total rating
Safety, Reliability, Security	2,33
Availability, Maintainability	2,69
Costs	3,10
Environment	3,70
Health, Politics	#DIV/0!

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



How should we establish a Quality Control Plan?

Kanak Polytherapy Clinic And Research Center

Ayurveda Blood Chemical Chemistry Test

Ayurvedic BLOOD TEST is done by AYUSH BLOOD METER ; Developed by KPCARC, Kanpur

	Patient Value		Normal Value	
Sulphates	70.00	mg/ahmv	15 - 20	mg/ahmv
Phosphates [Total]	60.00	Gramm/ahmv	60 - 80	Gramm/ahmv
Chloride	46.00	mg/ahmv	55 - 75	mg/ahmv
Pottassium	60.00	mg/ahmv	25 - 45	mg/ahmv
Sodium	110.00	mg/ahmv	40 - 55	mg/ahmv
Calcium	24.00	mg/ahmv	35 - 50	mg/ahmv
Iodine	106.00	mg/ahmv	40 - 60	mg/ahmv
Iron	76.00	mg/ahmv	30 - 60	mg/ahmv
Copper	43.00	mg/ahmv	30 - 55	
Magnesium	52.00	mg/ahmv	25 - 40	
Ammonia	40.00	mg/ahmv	25 - 40	
Uric acid	28.00	mg/ahmv	50 - 60	
Creatine	72.00	mg/ahmv	45 - 60	
Urea	19.00	mg/ahmv	18 - 30	

(Values within BOX are in NORMAL Li

In this Report Shown Values
HIGHER is Considered LOWER and
LOWER is considered HIGHER

WARNING: Above Patient Data & Readings have gained after Patient's BLOOD,Examined by AYUSH 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 the other purposes. Blood Test can be affected by Season, Thermal situation, Stage of Fast / Starvation, Hunger, Thirst, Physical and Mental Exertion.

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[199]

SHAKIL AHMAD 33 YRS 10/11/2014 ABCT1

67/70, Bhoosatoli Road, Bartan Bazar, Kanpur-1

The performance indicators ….

And the Goals ….

	Patient Value		Normal Value	
Sulphates	70.00	mg/ahmv	15 - 20	mg/ahmv
Phosphates [Total]	60.00	Gramm/ahmv	60 - 80	Gramm/ahmv
Chloride	46.00	mg/ahmv	55 - 75	mg/ahmv

How should we establish a Quality Control Plan?

And with a BRIDGE ???

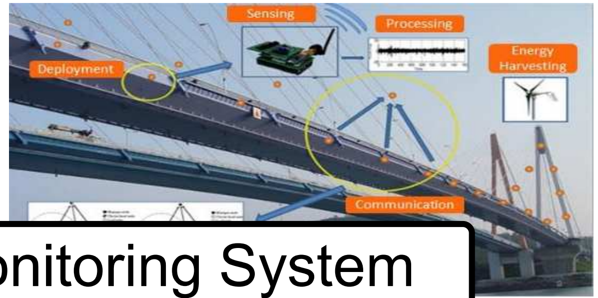
Key Performance Indicators, why and what to do with them?

The performance indicators ….

And the Goals ….

Safety, Reliability, Security							
PI	Level	Performance indicator PI if	PI belongs to the Key Peformance Indicator(s)	Assessment	applicable/ not applicable	rating (1-5)	weighting
	Component Level (CL) System Level (SL) Network Level (NL)	Measurable? {Quantifiable?; Target value available?; Valid for ranking purposes?; Allow decision with economic implications?} (YES/No)	Reliability (R), Availability (A), Maintainability (M), Safety (S), Security (Se), Environment (E), Costs (C), Health (H), Politics (P), Rating/Inspection (I)	Threshold (T = …..) Goal (G = ….) Rating (R = ….)			
crack length	CL	yes, tech	yes, I, S			2	0,8
crack orientation	CL	yes, tech	yes, I, S	degrees		3	0,5
crack width	CL	yes, tech, sust	yes, I, S, D			5	0,3
~~cracks distance~~ crack spacing	CL	yes, tech	yes, I,S			2	1
due to settlement, due to crumbling of concrete,…	SL	yes, sust	yes, I, S			2	0,8

How should we establish a Quality Control Plan?



NDT Testing

Visual Inspection

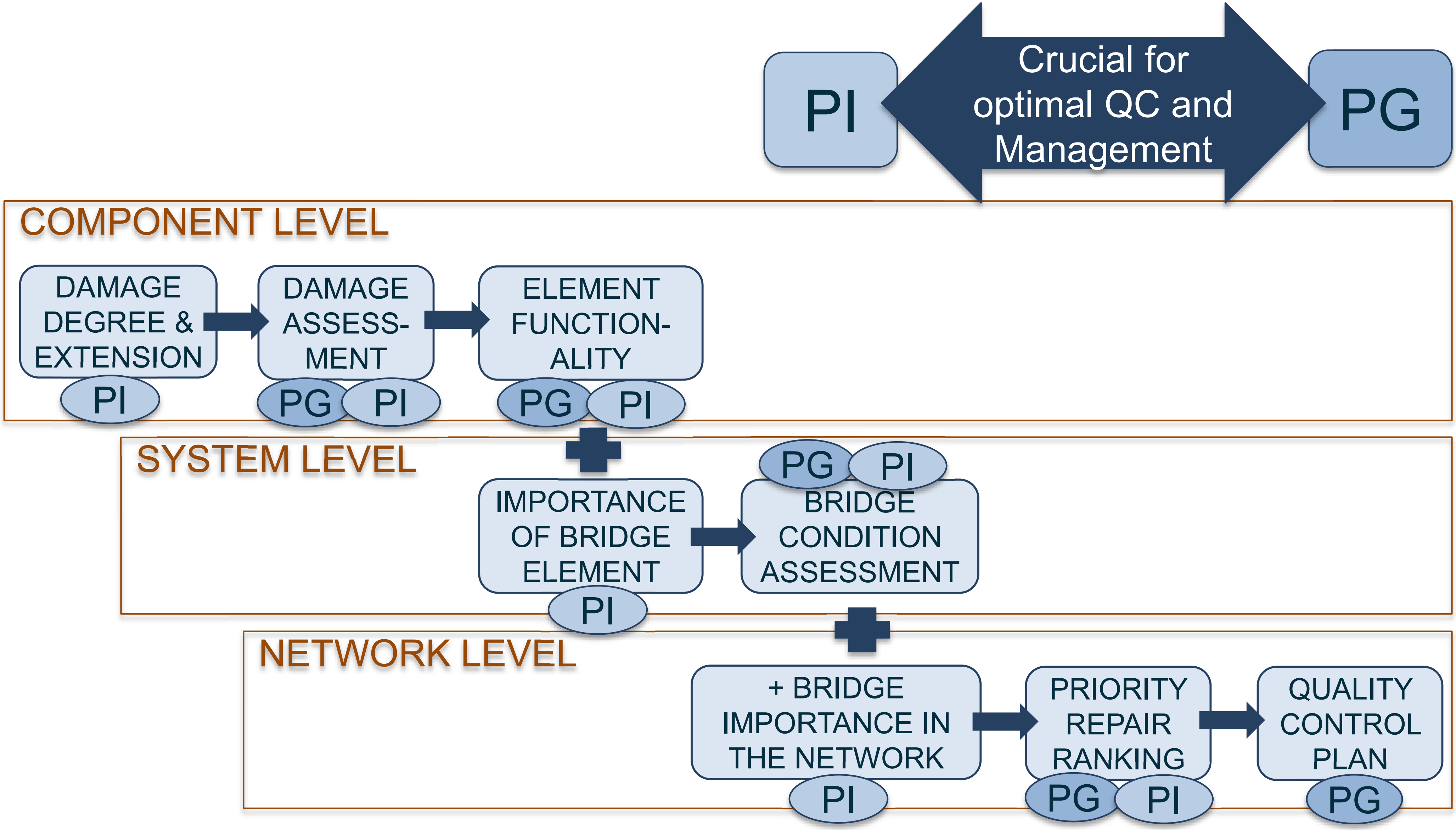
Monitoring System

Performance Indicator

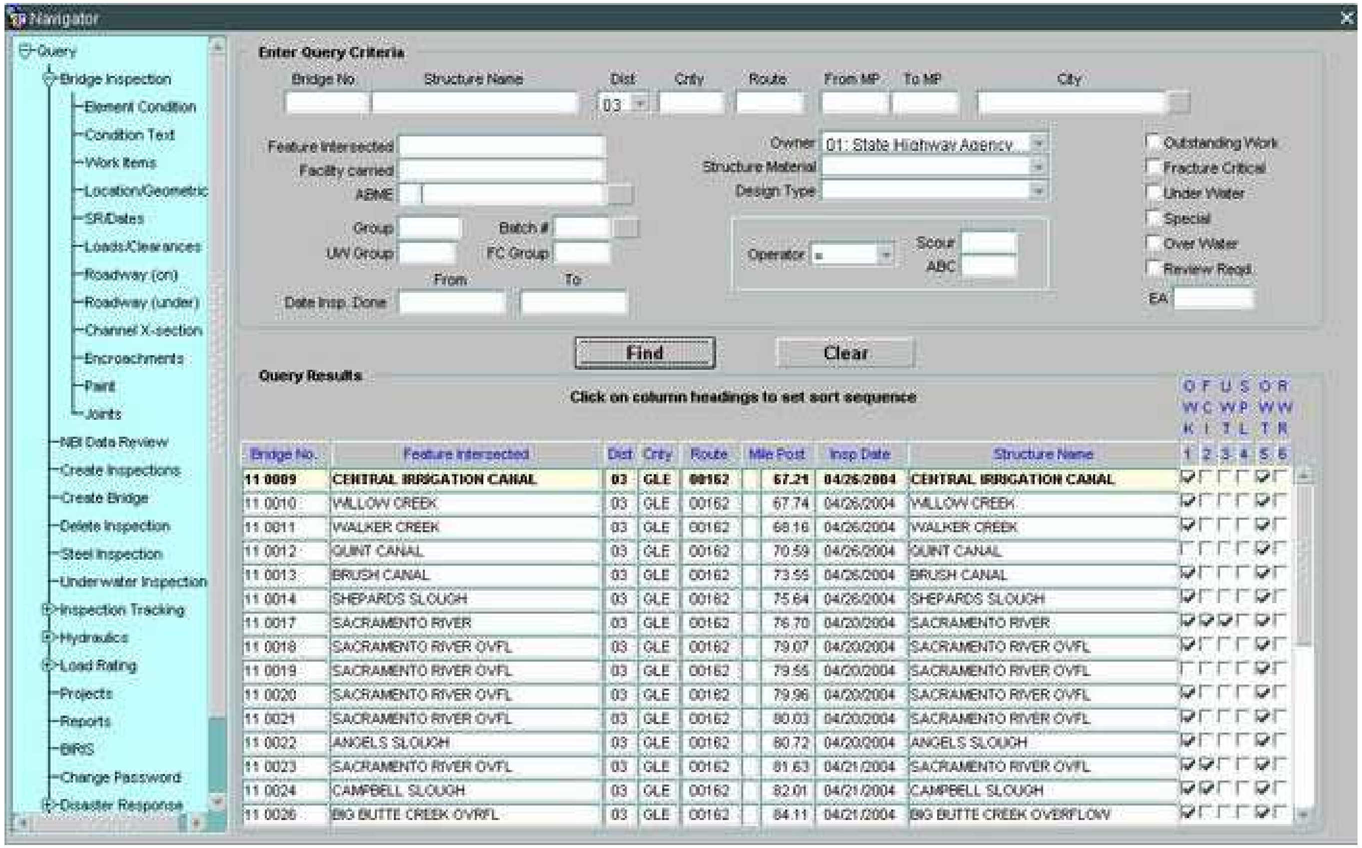
Performance Goal

Quality Control Plan

How should we establish a Quality Control Plan?



Why use Bridge Management Systems?

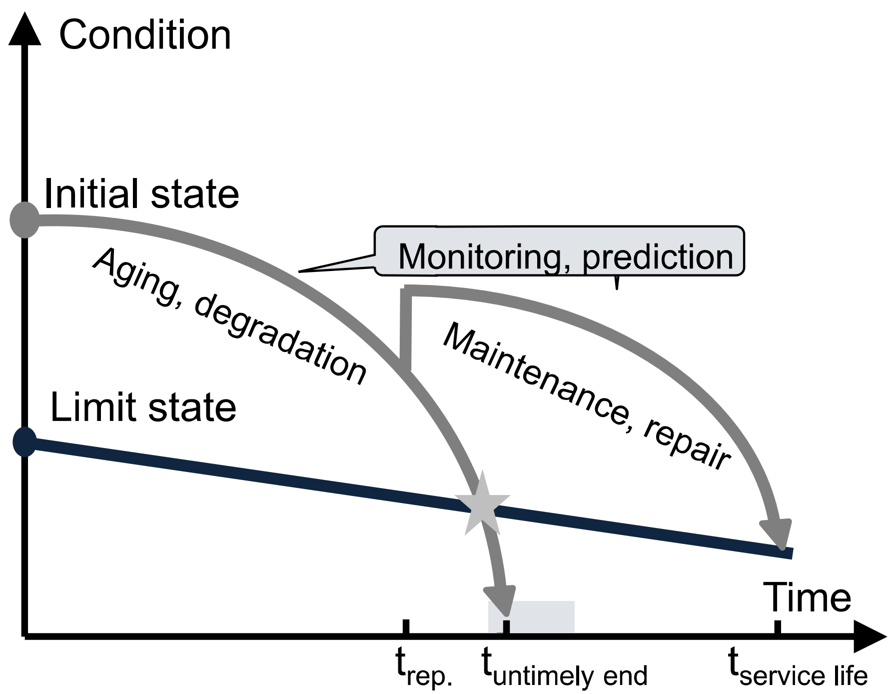


A Bridge Management System is used to store the performance indicators data and the quality control plans of the bridge network …

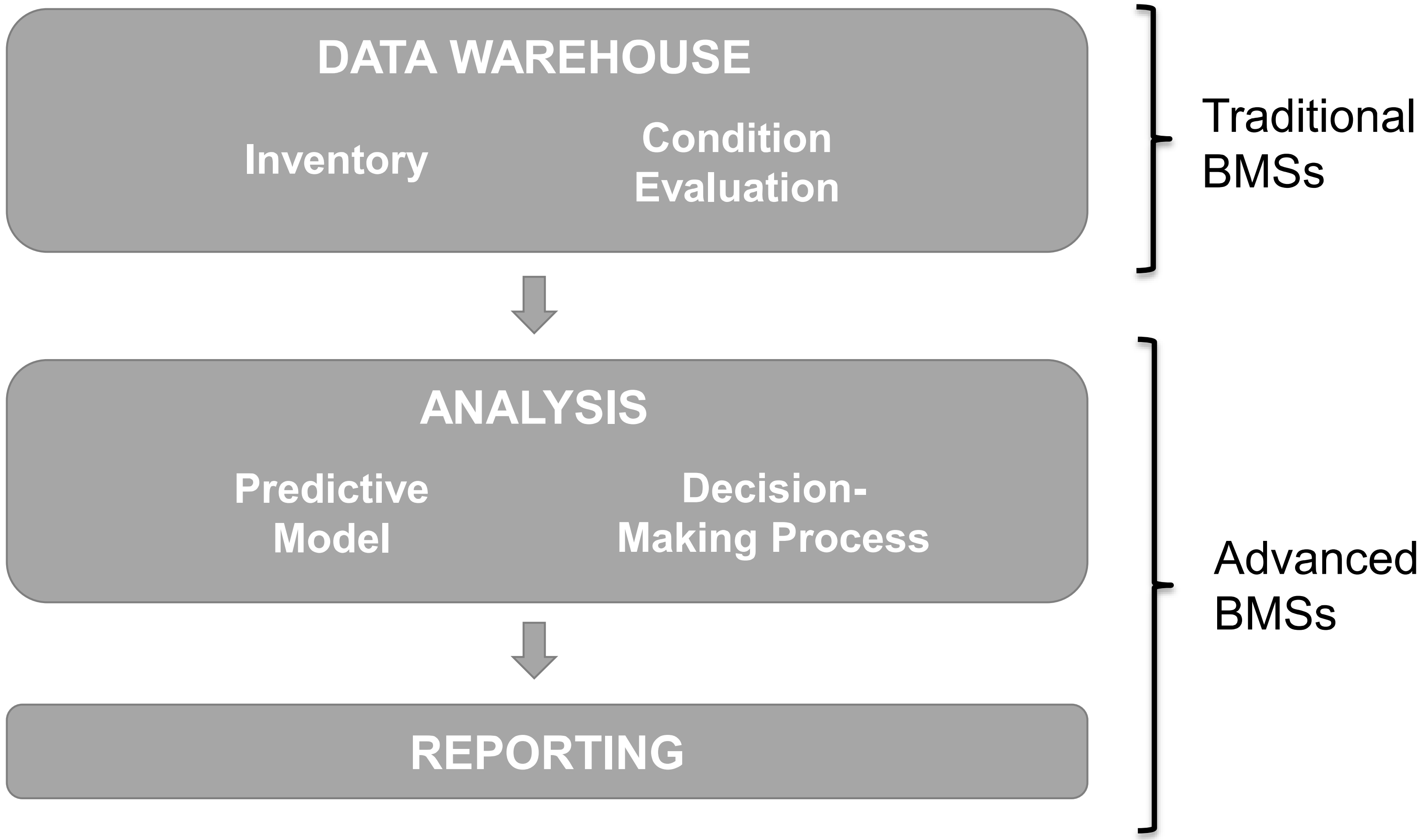
Why use Bridge Management Systems?

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

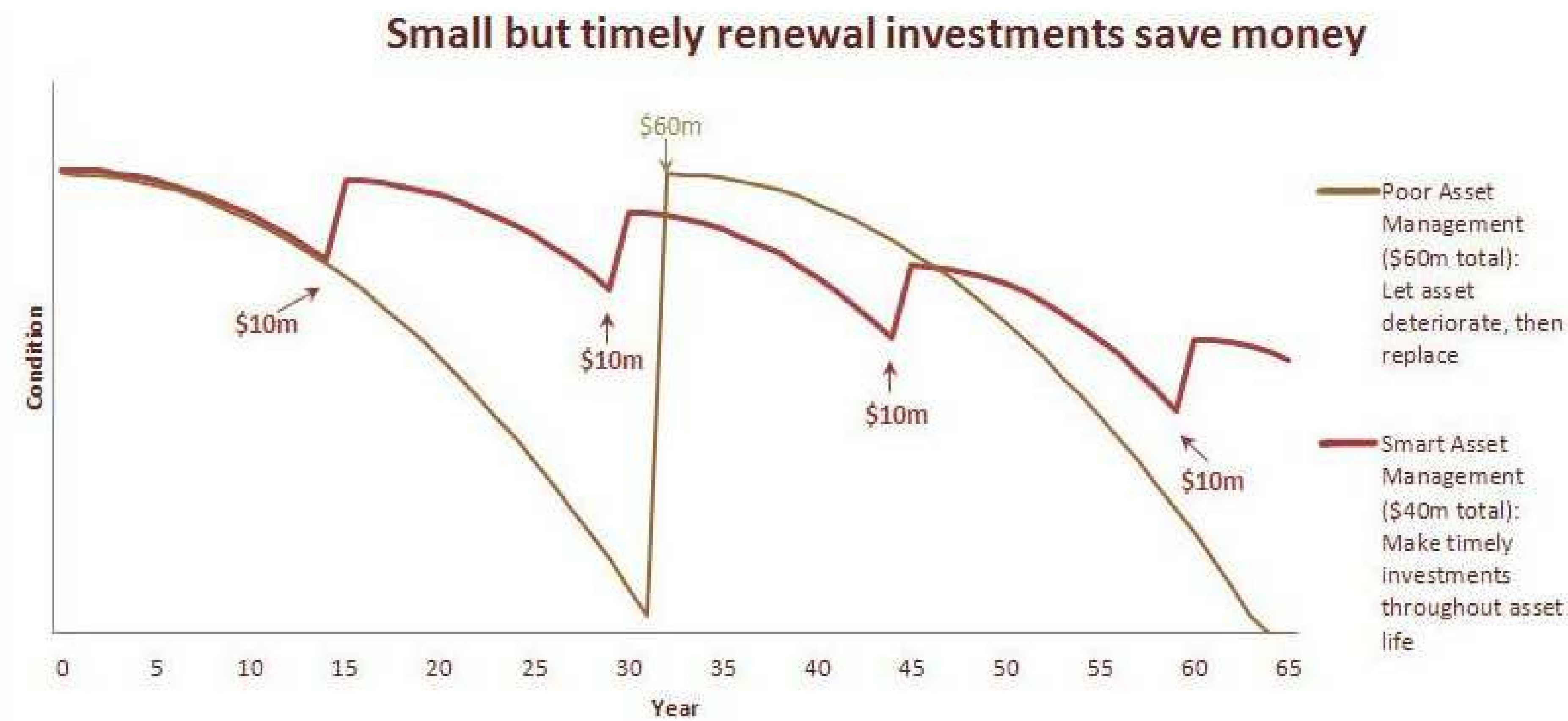
It is agreed among the bridge community that advanced BMSs incorporating predictive models, maintenance effects and costs, and optimization tools should be used for decision making …



Why use Bridge Management Systems?



Predicting Performance ... and taking decisions!



[Ministry of Ontario, 2014]

Predicting Performance ... and taking decisions!

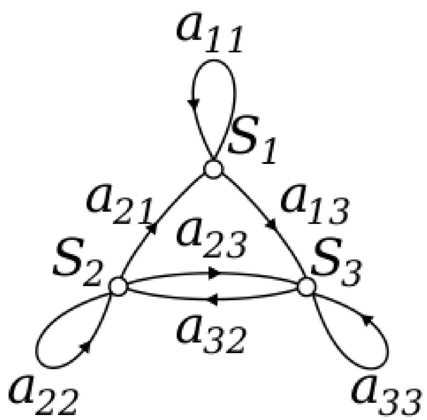
List of predicted models that can be used …

- *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:

$$P\left[q_t = S_j \middle| q_{t-1} = S_i, q_{t-2} = S_k, \dots, q_1 = S_1\right]$$

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

$$P\left[q_t = S_j \middle| q_{t-1} = S_i, q_{t-2} = S_k, \dots, q_1 = S_1\right] = P\left[q_t = S_j \middle| q_{t-1} = S_i\right]$$

Predicting Performance ... and taking decisions!

Discrete Markov Model

The transition state probabilities are then represented by:

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

$$\begin{cases} a_{ij} \geq 0 \\ \sum_{j=1}^{N} a_{ij} = 1 \end{cases}$$

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_{ii} 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 $p(t_f)$.

$$p(t_f) = p(t_i) \times P\,, \qquad p(t) = [p_1 \quad p_2 \quad \cdots \quad p_n]$$

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_{ij} 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.

$$\theta_i = q_{ii} = -\sum_{j \neq i} q_{ij} \quad with \quad i = 1,..,N$$

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

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

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:

$$Q = \begin{bmatrix} -0{,}0893 & 0{,}0893 & 0 & 0 & 0 \\ 0 & -0{,}0125 & 0{,}0125 & 0 & 0 \\ 0 & 0 & -0{,}0034 & 0{,}0034 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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:

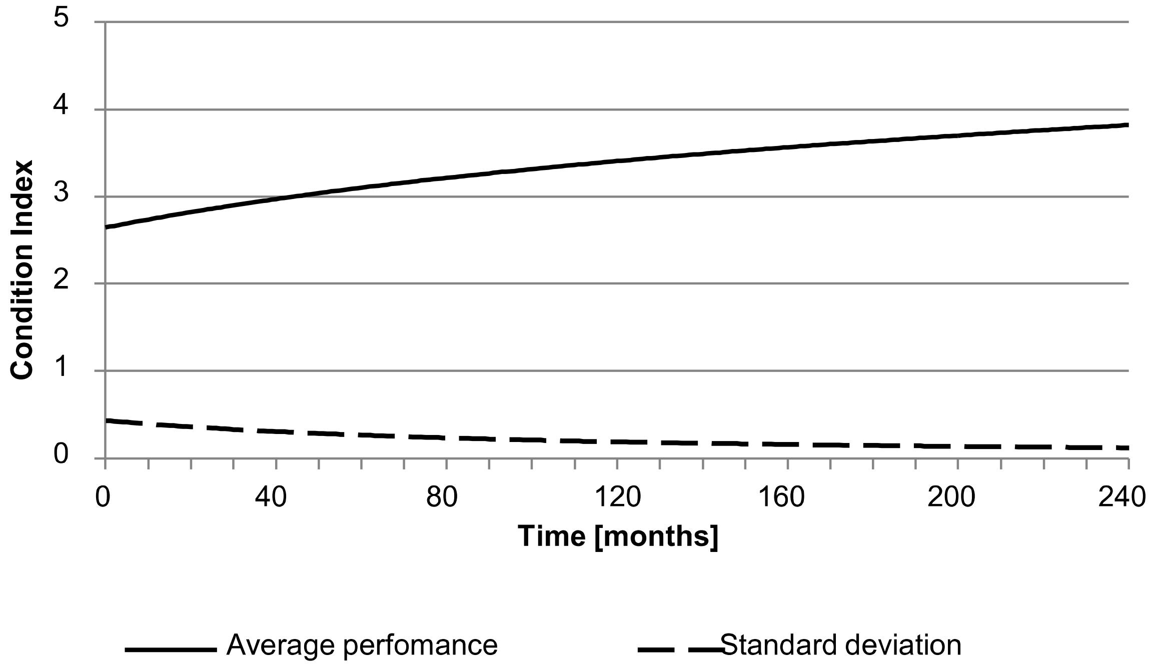
$$Q = \begin{bmatrix} -0{,}1038 & 0{,}1038 & 0 & 0 & 0 \\ 0 & -0{,}0082 & 0{,}0082 & 0 & 0 \\ 0 & 0 & -0{,}0025 & 0{,}0025 & 0 \\ 0 & 0 & 0 & -0{,}0010 & 0{,}0010 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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

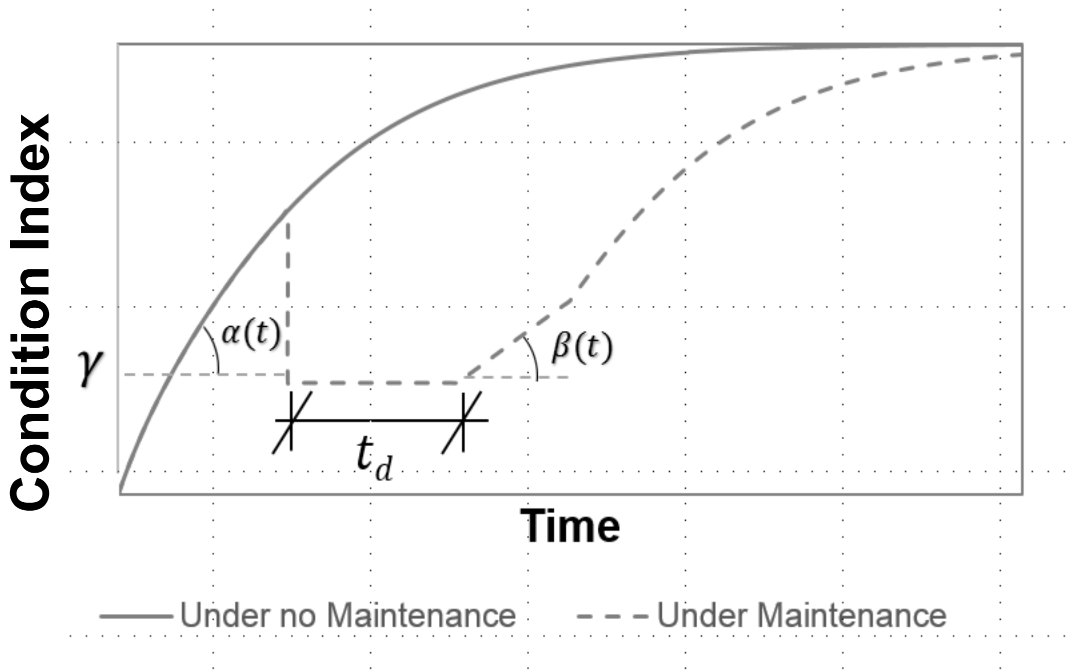
In order to assess the performance evolution, it is computed the transition probabilities P_{ij} for the four possible initial conditions, and a Δt = 240 months (time horizon) is considered in the analysis.



Predicting Performance ... and taking decisions!

Intervention Effects

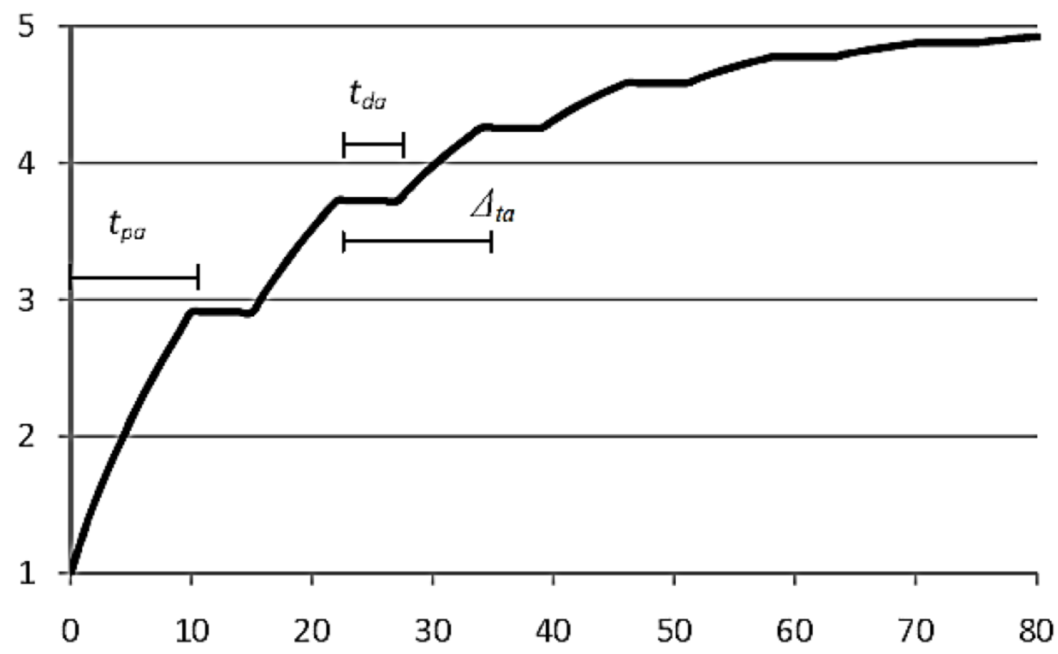
In general, the impact of na intervention in a system performance is modelled by one (or more than one) of the following effects: (i) Improvement in performance at time of application (Y); (ii) Delay in deterioration for a period of time after application (t_d); (iii) Reduction in deterioration rate for a period of time after application (δ: β(t) = α(t) x δ).



Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

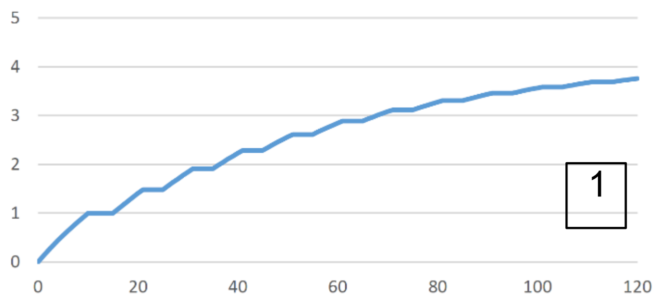
- Time of first application (t_{pa});
- Time interval between applications (Δ_{ta});
- Time delay of each application (t_{da}).

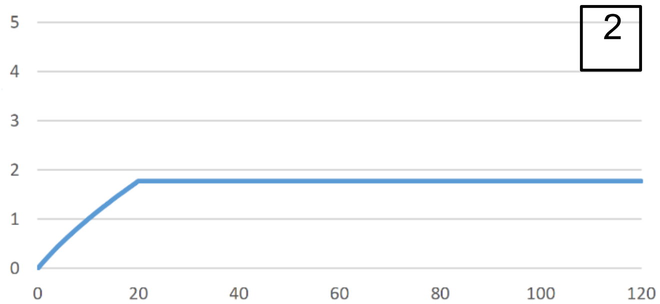


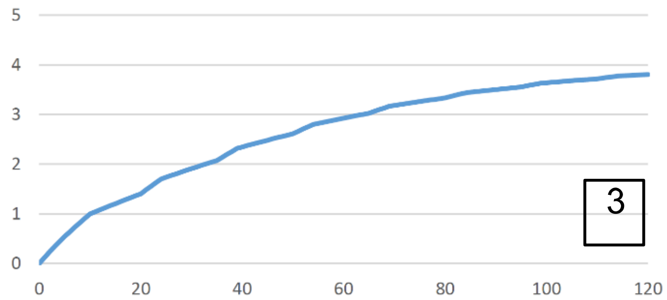
Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

Scenario	t_{pa}	Δ_{ta}	t_{da}	δ
1	10	12	5	-
2	20	5	5	-
3	10	15	10	50 %







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:

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

$p(t = 10) = [0{,}29 \quad 0{,}50 \quad 0{,}14 \quad 0{,}06 \quad 0{,}01 \quad 0]$

(month 10-15)

Matrix *I*

$$C_{(t=[10-15])} = \begin{bmatrix} 0{,}29 \\ 0{,}50 \\ 0{,}14 \\ 0{,}06 \\ 0{,}01 \\ 0 \end{bmatrix}^T * \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} = 1$$

Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Preventive Interventions

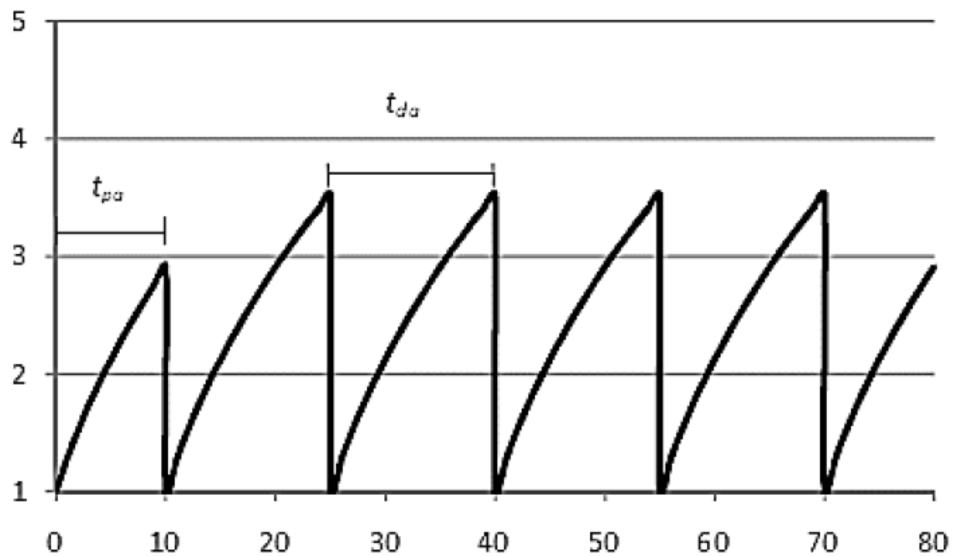
- The deterioration rate reduction implies to multiply the transition rates (θ) by a reduction factor (δ):

$$\theta_i = \begin{bmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix} = \begin{bmatrix} 0{,}062 \\ 0{,}032 \\ 0{,}067 \\ 0{,}033 \\ 0{,}001 \end{bmatrix} * (1-\delta) = \begin{bmatrix} 0{,}031 \\ 0{,}015 \\ 0{,}029 \\ 0{,}011 \\ 0{,}001 \end{bmatrix}$$

Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

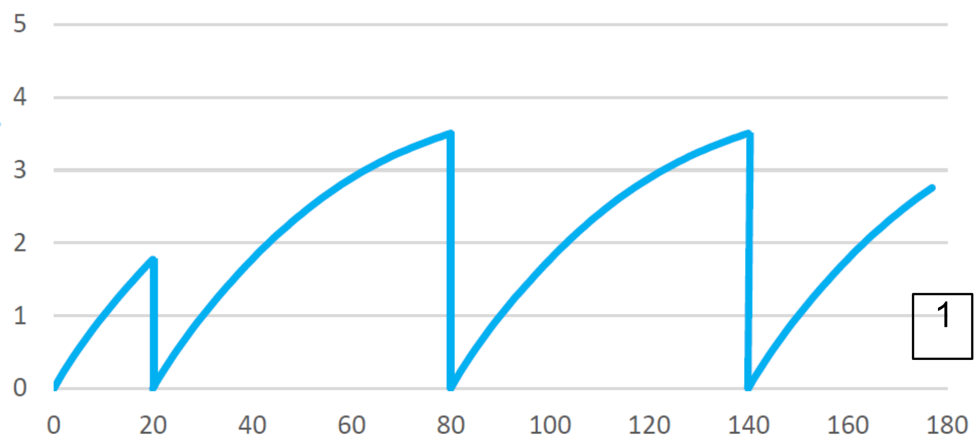
- It also considers the target performance (I_T) at time of application.

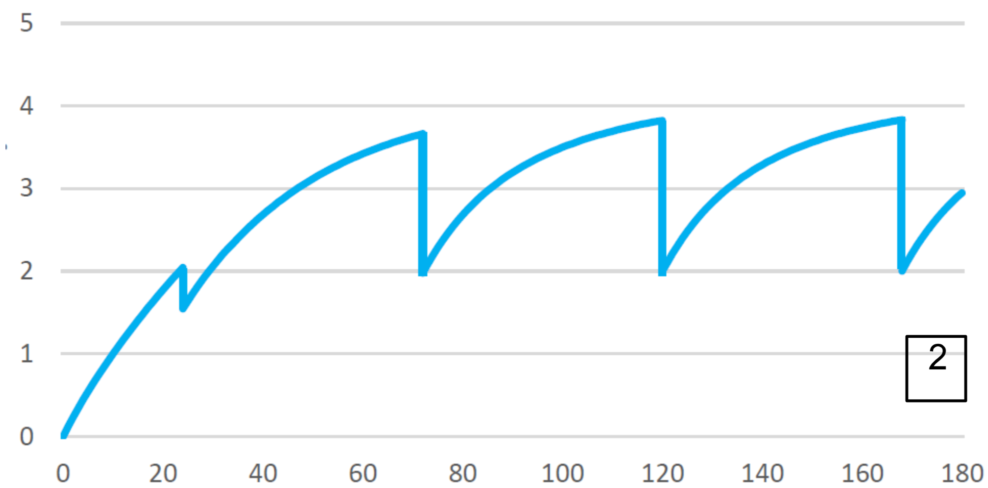


Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

Scenario	t_{pa}	Δ_{ta}	I_T
1	20	60	0
2	24	48	2





Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

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

$$C_t = [C_1 \quad C_2 \quad C_3 \quad C_4 \quad C_5]$$

- 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)

$$p(t = t_{pa}) = [0{,}09 \quad 0{,}41 \quad 0{,}21 \quad 0{,}22 \quad 0{,}07 \quad 0]$$

$$p(t = 20) = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

$$C_{t=20} = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0] * \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} = 0$$

Predicting Performance ... and taking decisions!

Intervention Effects – Time-Based Corrective Interventions

- Scenario 2 (month 72)

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

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

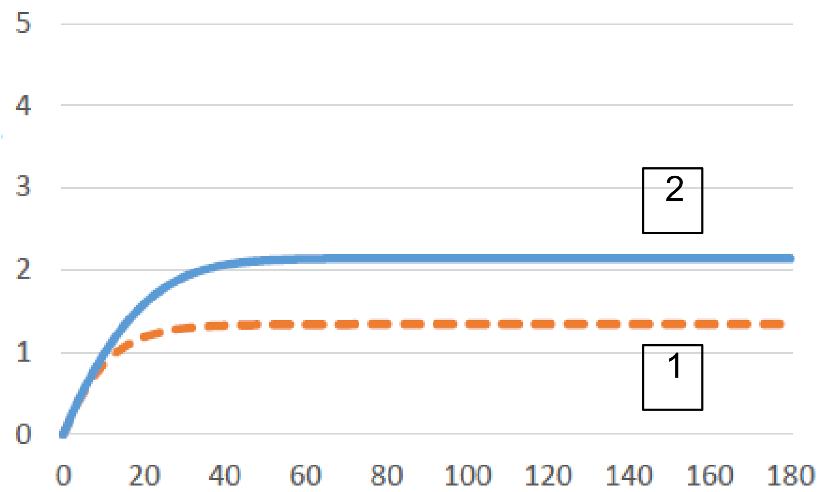
$$p(t_{depois} = 72)(2) = 1 - 0 - 0{,}02 = 0{,}98$$

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.

Scenario	I_R	I_T
1	3	1
2	4	1



Predicting Performance ... and taking decisions!

Intervention Effects – Condition-Based Corrective Interventions

- Scenario 1

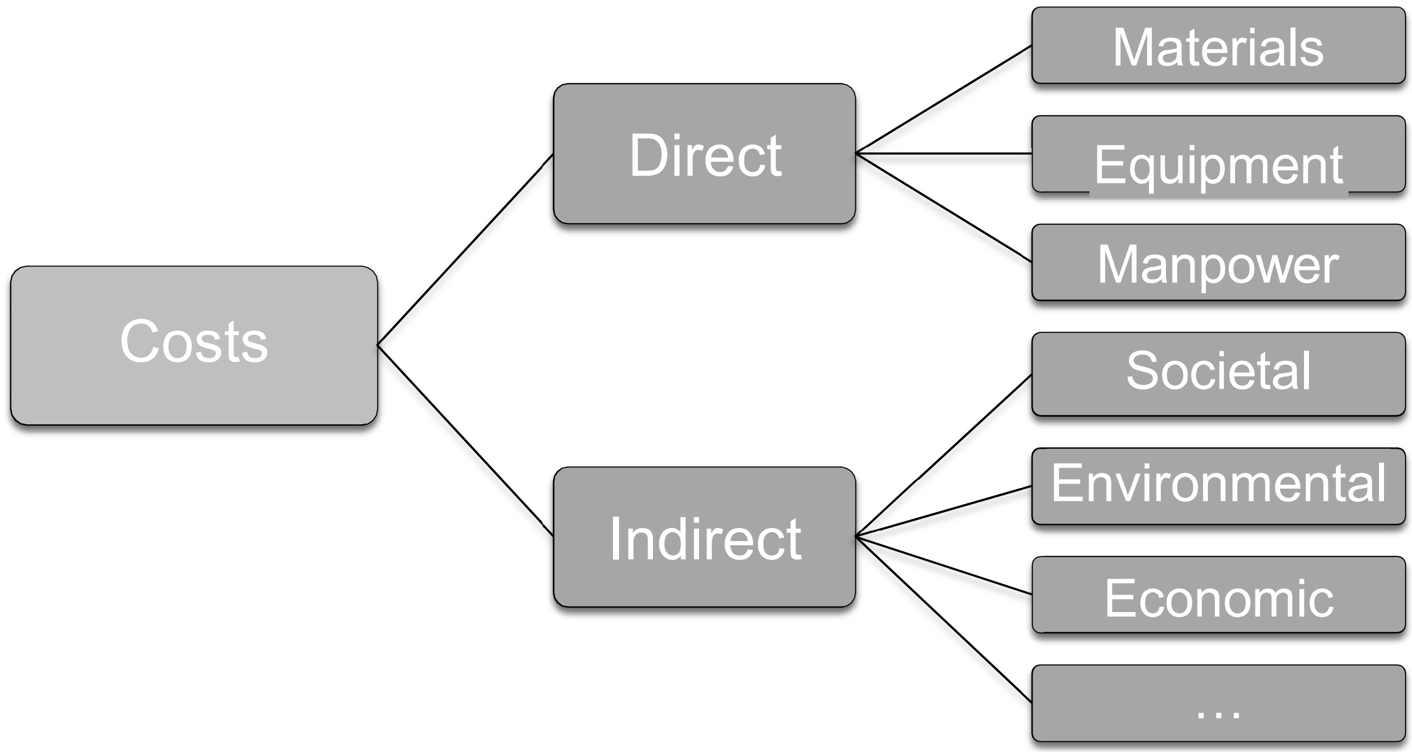
$$p(t=19) = [0{,}10 \quad 0{,}63 \quad 0{,}25 \quad 0 \quad 0 \quad 0]$$

$$p(t=20) = [0{,}10 \quad 0{,}61 \quad 0{,}26 \quad \boxed{0{,}03} \quad 0 \quad 0]$$

$$p(t=20) = [0{,}10 \quad 0{,}64 \quad 0{,}26 \quad 0 \quad 0 \quad 0]$$

Predicting Performance ... and taking decisions!

Intervention Costs



Predicting Performance ... and taking decisions!

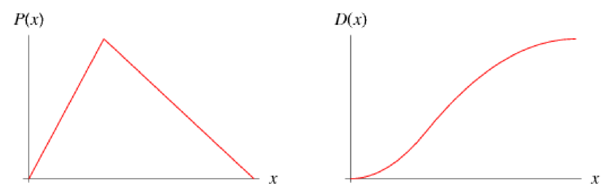
Uncertainty in Quantification of Effects and Costs

… Lack of knowledge
… Natural variability
… Model uncertainties

Probabilistic approach

⬇

Probability distributions



⬇

Triangular distribution

⬇

Parameters definition → Intuition / Expert opinion / Engineering Judgement → Questionnaire

Predicting Performance ... and taking decisions!

Examples of Interventions on Roadway Bridge

Preventive MA		t_d [year]	δ [-]	γ [-]	Cost [-]
MA1	Cleaning of surrounding areas	[1, 1.5, 2]	-	-	10
MA2	Paint concrete surface, in localized areas	[4, 6, 8]	[0.3, 0.4, 0.5]	-	50

Corrective MA		t_d [year]	δ [-]	γ [-]	Cost [-]
MA3	Paint concrete surface, in general	[10, 12, 15]	[0.5, 0.6, 0.7]	[1, 1, 2]	1000
MA4	Crack sealing by injection resin based on epoxy	[3, 4, 6]	[0.3, 0.4, 0.5]	-	400
MA5	Repair of plaster coating	[0.5, 1.5, 3]	[0.7, 0.8, 0.9]	-	150

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 → Overall asset performance (PI)

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

→ Life-cycle maintenance cost (TC)

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

Time value of money

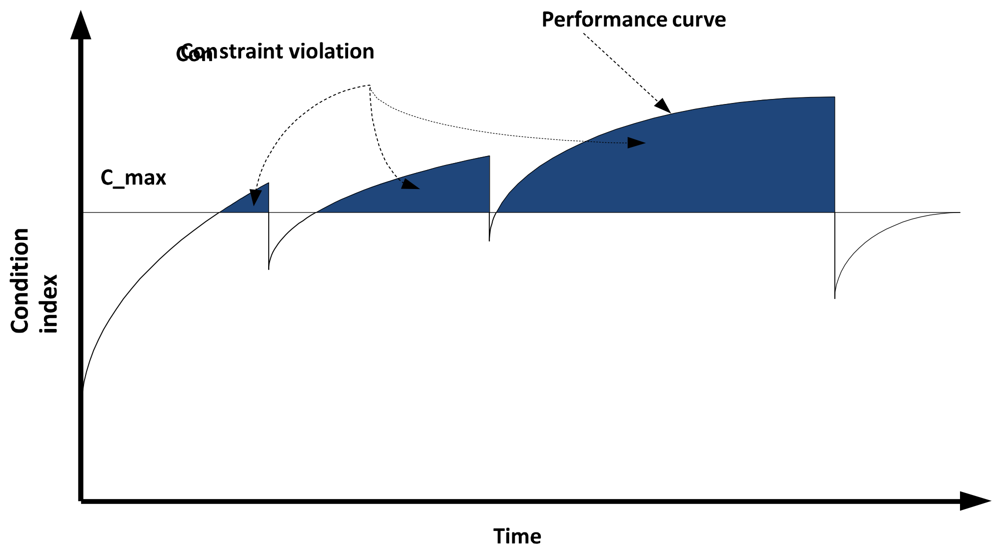
- Constraints → Threshold value → Assure a proper level of service

$$C_{i,j} \le C_{\epsilon}, \forall i \in \{1, \dots, N\} \wedge \forall j \in \{1, \dots, T\}$$

Predicting Performance ... and taking decisions!

Decision-making

… Optimization model



Objective Function and Constraints

Optimization Algorithm (e.g. NSGA II)

Algorithm 1 NSGA–II

```
1: g ← 0;
2: initialization: P;
3: repeat
4:     g ← g + 1;
5:     R ← matingSelection(P);
6:     Q ← variation(R);
7:     P ← environmentalSelection(P ∪ Q);
8: until the stopping criterion is met
9: output: P;
```

Predicting Performance ... and taking decisions!

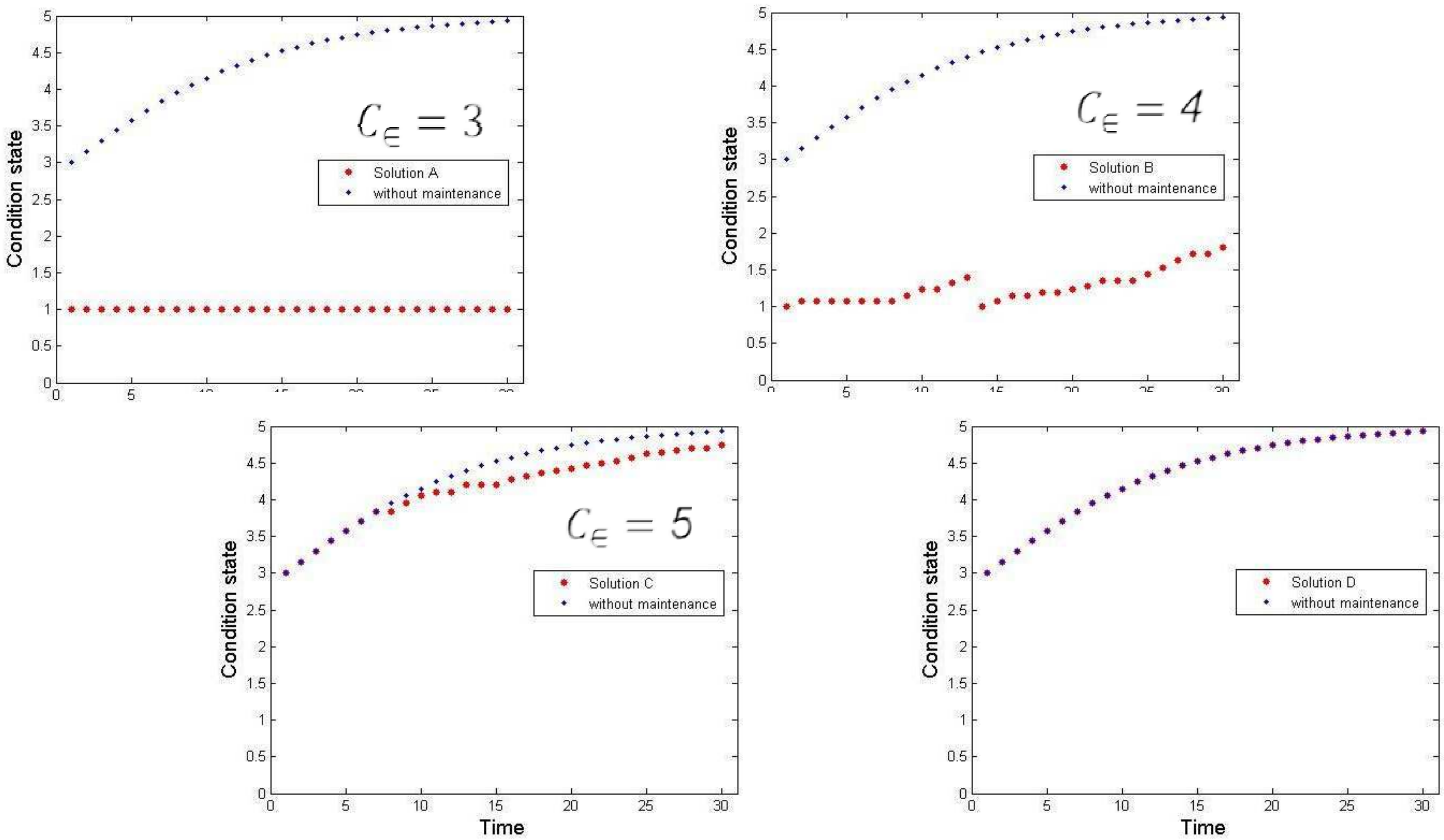
Decision-making on Roadway Bridge

Solution	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
A	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3
B	MA3	MA2	MA2	MA2	MA2	MA2	MA2	NA	NA	MA2	NA	NA	MA2	MA3	NA
C	NA	NA	NA	NA	NA	NA	MA2	NA	NA	MA1	MA2	NA	MA2	MA2	NA
D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Solution	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25	Year 26	Year 27	Year 28	Year 29	Year 30	Cost
A	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	MA3	16141
B	MA2	MA1	MA2	MA1	MA1	NA	MA2	MA2	NA	NA	NA	NA	MA2	NA	NA	4024
C	MA1	MA1	MA1	MA1	MA1	MA1	MA1	NA	NA	MA1	MA1	NA	MA2	NA	MA2	460
D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0

Predicting Performance ... and taking decisions!

Decision-making on Roadway Bridge



Predicting Performance ... and taking decisions!

TU1406 COST ACTION   IABSE

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

TRAINING SCHOOL
STOCKHOLM
Performance-based assessment of existing road bridges
September 12-16, 2016
KTH Royal Institute of Technology
Stockholm, Sweden

Performance Indicators on Asset Management Tool

Predicting Performance ... and taking decisions!

MATLAB
The Language of Technical Computing

Denysiuk, R., Fernandes, J., Matos, J. C., Neves, L. C., Berardinelli, U. (2016) “A computational framework for infrastructure asset maintenance scheduling”, Structural Engineering International, Journal of IABSE, Volume 26, Number 2, pp. 94-102(9), May 2016. (doi: 10.2749/101686616X14555428759046).

JAVA LINK :

http://www.oracle.com/technetwork/java/javase/downloads/jre8-downloads-2133155.html

Predicting Performance ... and taking decisions!

Intensity Matrix (computation)

```
Q = 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 =

-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

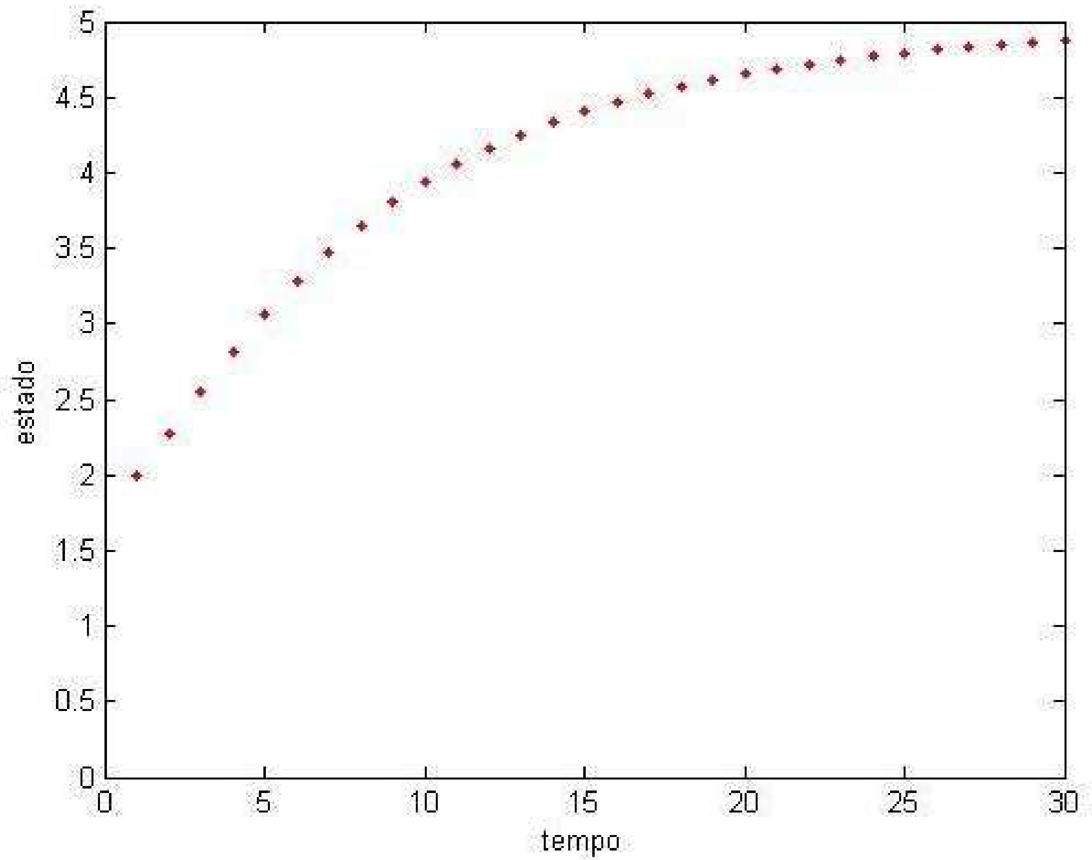
Predicting Performance ... and taking decisions!

Performance Prediction (computation)

```
%% sem ações de manutenção

% matrix 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 condição inicial
c0 = 2;
% tempo horizonte
th = 30;

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

% construir gráfico
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)

Intervention Effects →

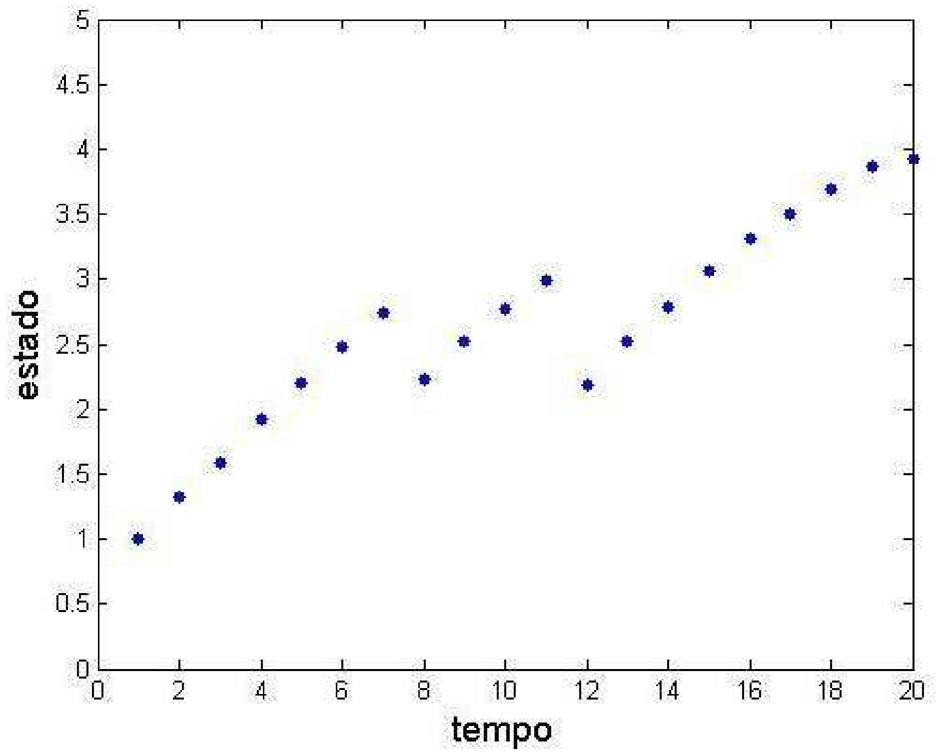
Intervention Costs →

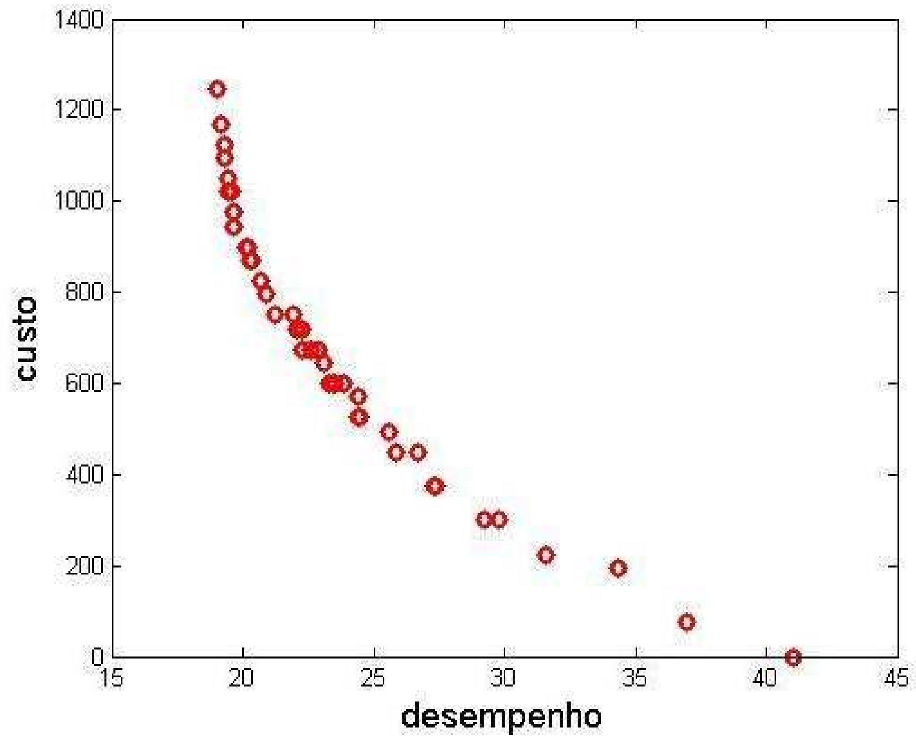
Run →

```
%% 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 -0.05219325007888024 0.05219325007888024 0.0;
    0.0 0.0 0.0 -0.05360549452068326 0.05360549452068326;
    0.0 0.0 0.0 0.0 0.0];

% 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)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	ano 1	ano 2	ano 3	ano 4	ano 5	ano 6	ano 7	ano 8	ano 9	ano 10	ano 11	ano 12	ano 13	ano 14	ano 15	ano 16	ano 17	ano 18	ano 19	ano 20
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0
4	3	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	3	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0
6	3	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0
7	0	3	0	0	0	4	0	0	3	0	0	0	0	0	0	0	0	0	0	0
8	0	3	0	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0
9	3	0	0	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0
10	3	0	0	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0
11	3	0	0	0	0	3	0	0	3	0	0	0	3	0	0	0	0	7	0	0
12	0	3	0	0	0	4	0	0	3	0	0	0	3	0	0	0	0	0	0	0
13	3	0	3	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0
14	3	0	3	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0
15	3	0	3	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0
16	3	0	3	0	0	3	0	0	3	0	0	0	3	0	0	0	0	7	0	0
17	3	3	0	0	0	4	0	0	3	0	0	0	3	0	0	0	0	0	0	0
18	3	0	3	0	0	4	0	0	3	0	0	0	3	0	0	0	0	0	0	0
19	3	0	3	0	0	4	0	0	3	0	0	0	3	0	0	0	0	0	0	0
20	3	0	3	0	0	4	0	0	3	0	0	0	3	0	0	0	0	0	0	0
21	3	0	4	0	0	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0

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COST ACTION

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