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Cost Benefit of Monitoring

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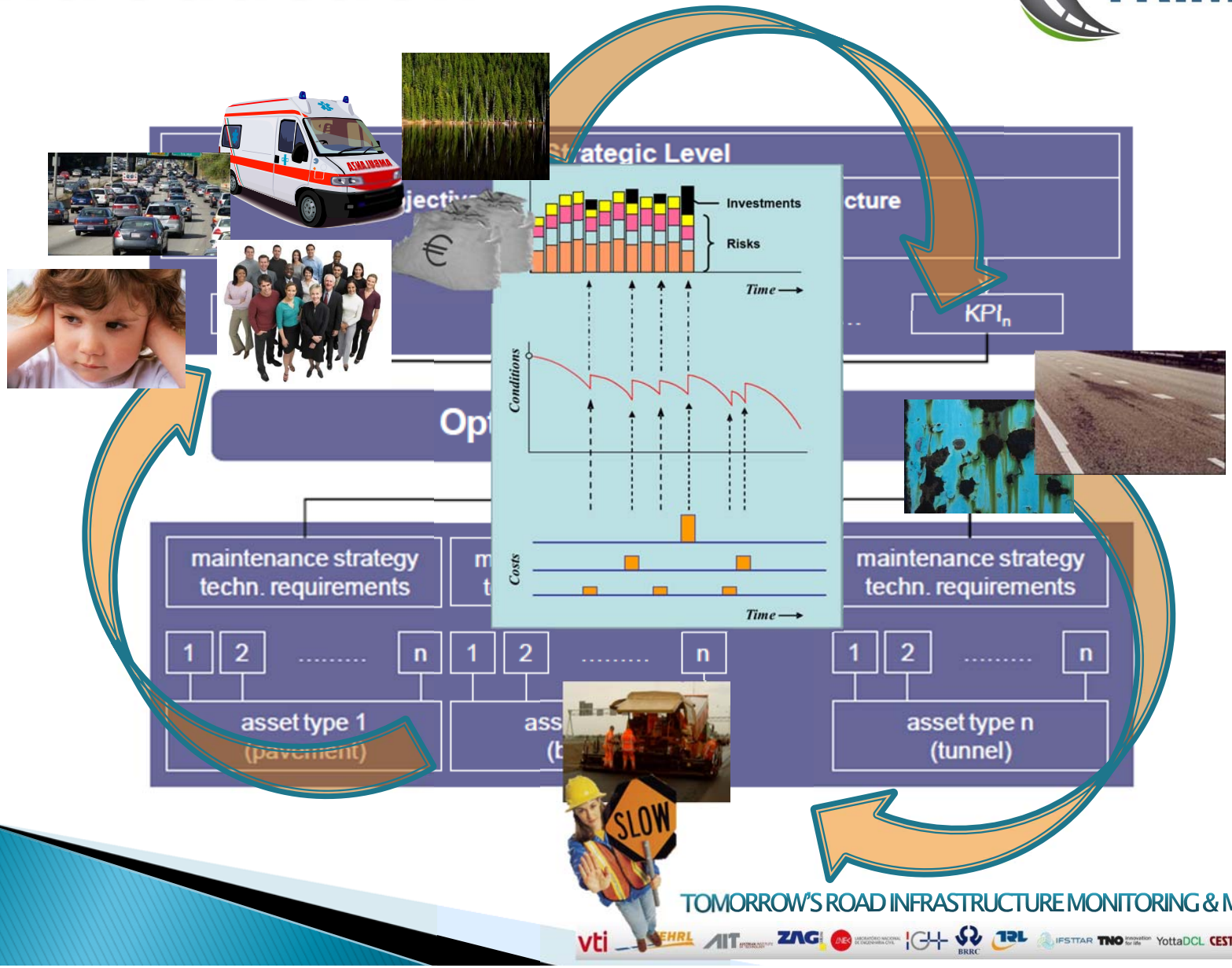
TOMORROW'S ROAD INFRASTRUCTURE MONITORING AND MANAGEMENT

Task

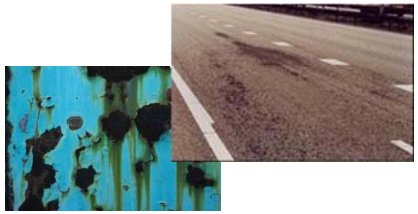
- Objective:
  - **Develop SCBA model to assess** life cycle costs and benefits of different maintenance scenarios – especially scenarios **with different or without monitoring systems**
  - Support decision making when designing monitoring schemes

Introduction



Introduction

- EUSL
  - Availability
  - Safety
  - Environment
  - …



- Condition
  - Rutting
  - Skid Resistance
  - Longitudinal Evenness
  - …

- Actions
  - Do nothing
  - Remixing
  - Renewal
  - …

Introduction

- Costs
  - Action related
  - Condition related
  - Penalty
  - …

denoted $C_{a.user}. \dots . C_{c.env}. C_q$

.

- EUSL
  - Availability
  - Safety
  - Environment
  - …

denoted $X_1. \dots . X_E$

$\Delta X_1. \dots . \Delta X_E$

- Condition
  - Rutting
  - Skid Resistance
  - Longitudinal Evenness
  - …

denoted $s_1. \dots . s_K$

$\Delta\, s_1. \dots . \Delta s_K$

- Actions
  - Do nothing
  - Remixing
  - Renewal
  - …

denoted $a_0. a_1. \dots . a_A$

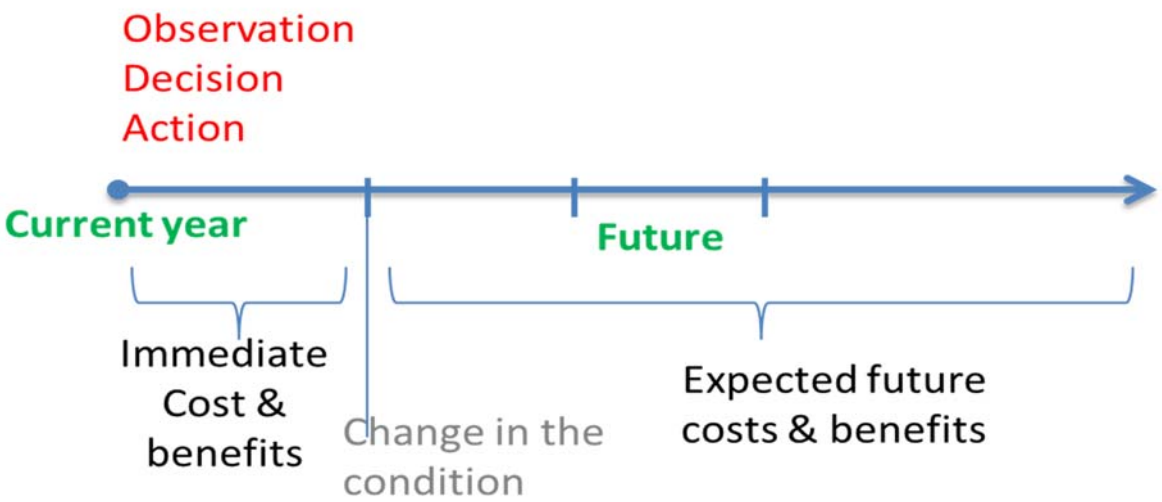
Problem description

X EUSL
s Condition
a Action

X, s

a

$X, s \mid a \qquad X', s' \mid X, s, a$



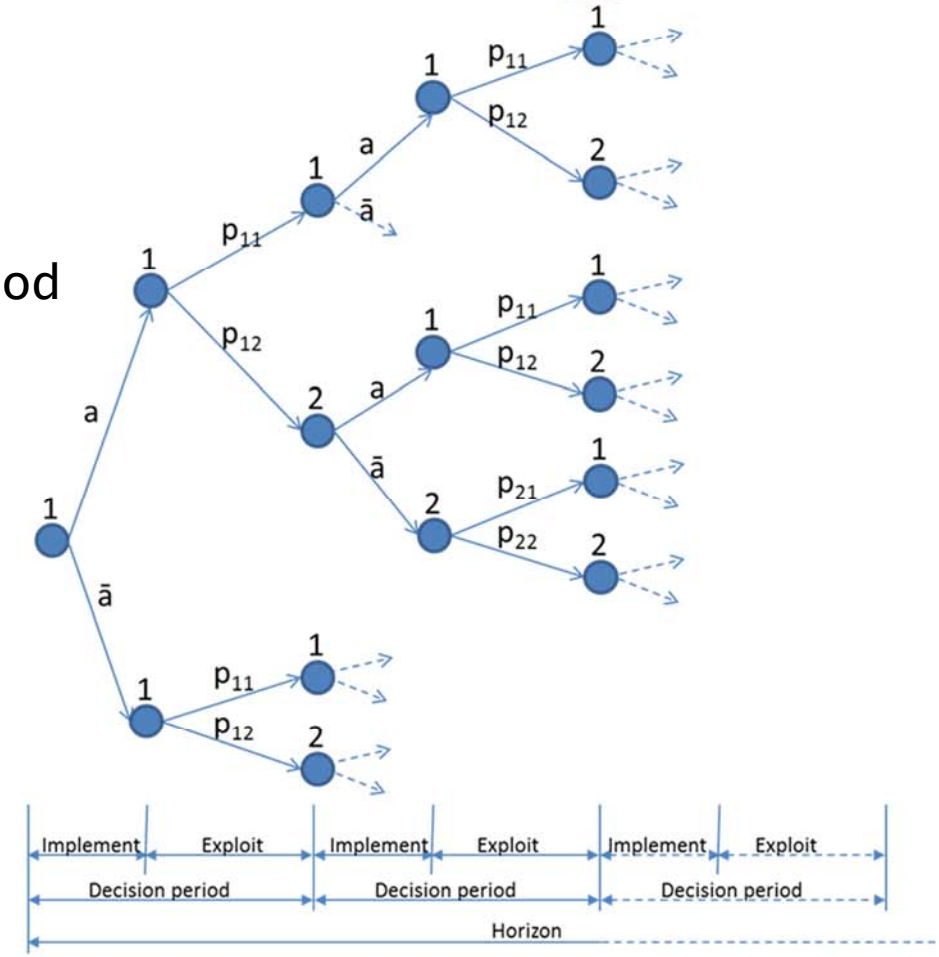
Problem description

SIMPLE EXAMPLE
what can/will happen (see figure)
when we have:

Repetitive decision periods
decision at beginning of period
e.g. each year

2 Actions
a repair
ā do nothing

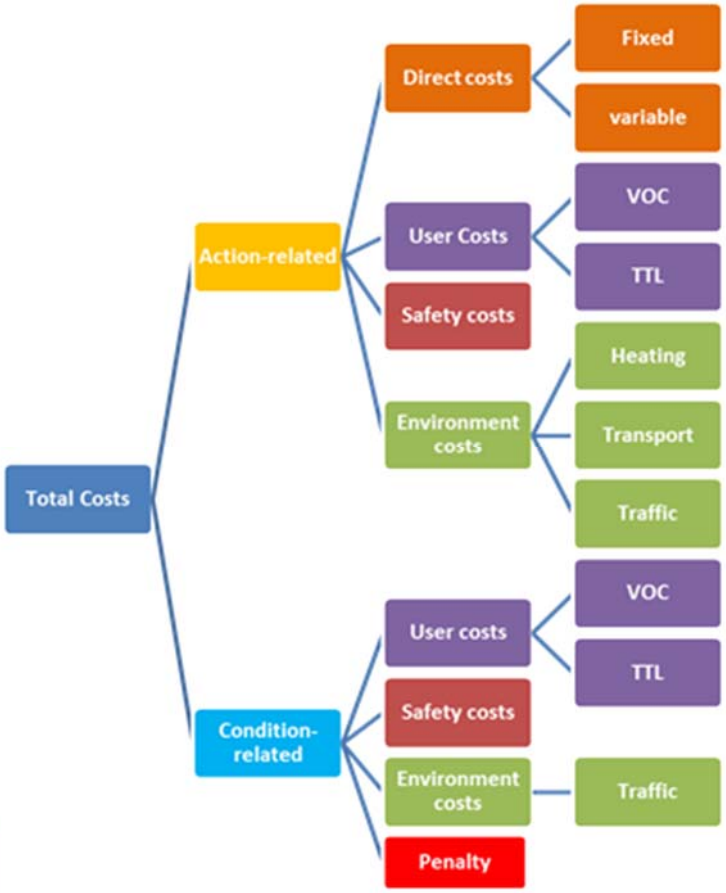
2 States (conditions)
1 good
2 bad

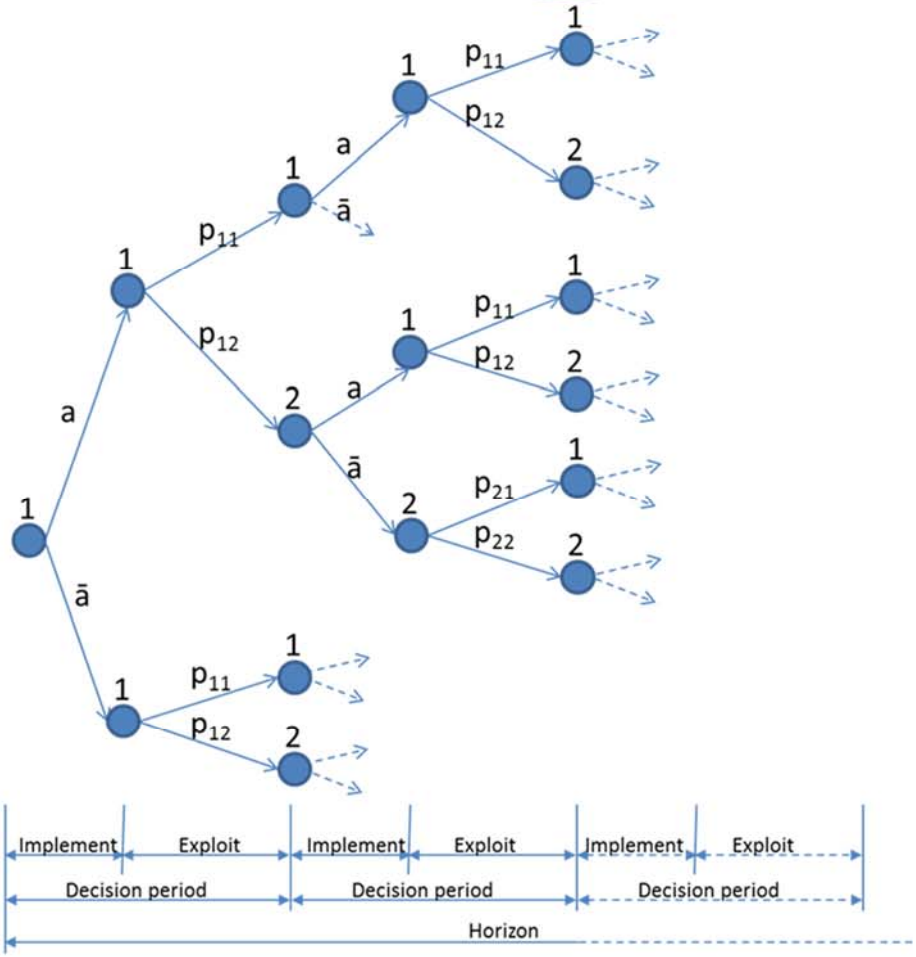


Degradation
Transition probabilities
p_{ij} probability to change from state i to state j within a period

Problem description

SIMPLE EXAMPLE
what implications would this have





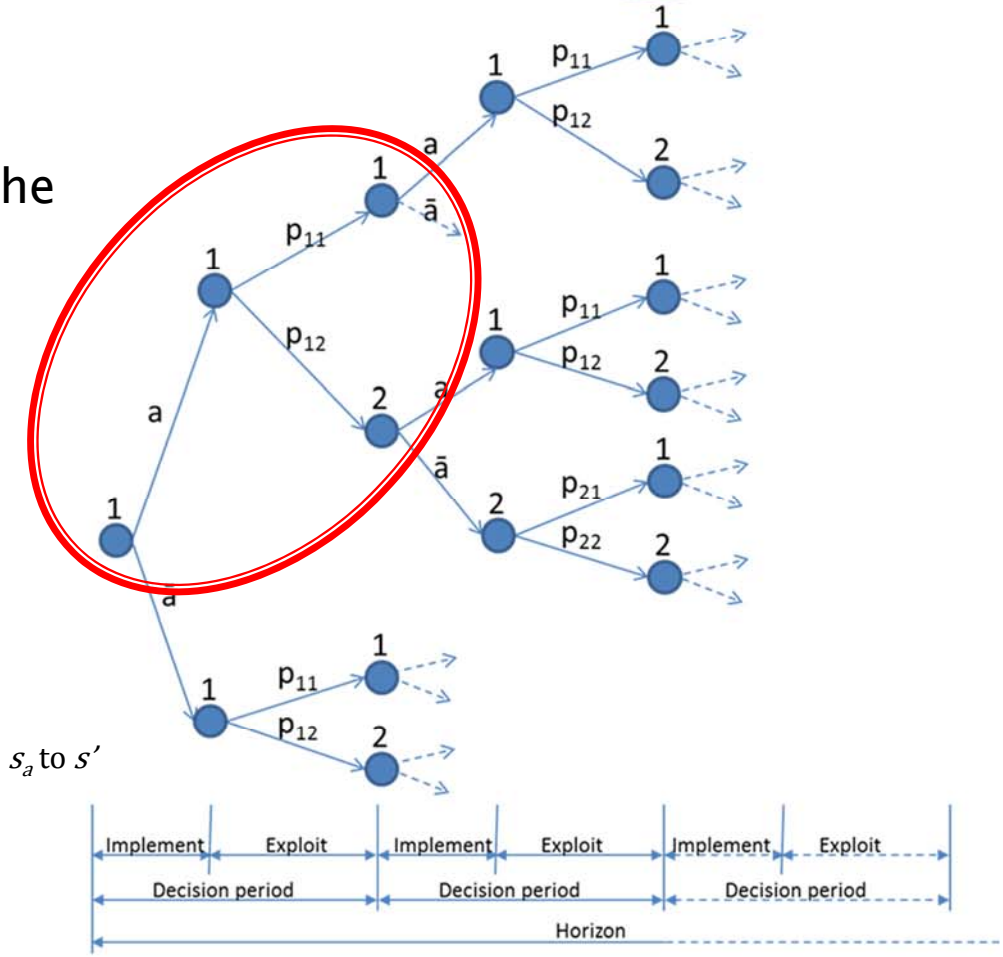
Cost Benefit Analysis

SIMPLE EXAMPLE
Planning/decisions

Noting the repetitive character of the branches. we get

$$V(s) = C_{implement}(a) + \sum_{s' \in S} p^{a}_{s_a s'} \left(C_{exploit}(s_a, s') + \lambda V(s') \right)$$

s condition at beginning of period
s' condition at end of period
s_a condition as a result of the action
λ discount for future costs
$p^{a}_{s_a s'}$ transition probability (after action a) to move from state s_a to s'
$V(s)$ cost associated with a node from the tree
$C_{exploit}(s_a, s')$ costs (risk) of exploitation
$C_{implement}(a)$ costs of implementing an action a



Which enables cost optimisation and maintenance scenarios

Cost Benefit Analysis

Markov Decision Proces (MDP)

$$C^{a^*}(X, s, \hat{a}) = \min_{a=a_0.a_1.....a_A} c_{action}(a, l) + c_{ind_action}(a(s))$$

$$+ \sum_{X's'} P^{\hat{a}'}_{X\,s,X's'} \begin{pmatrix} c_{ind_{cond}}(a, X, s, X', s') + \\ c_q(a, X, s, X', s') + \\ \lambda C^a(X', s', \hat{a}') \end{pmatrix}$$

$$V(s) = C_{implement}(a) + \sum_{s' \in S} p^a_{s_a s'} \left(C_{exploit}(s_a, s') + \lambda V(s') \right)$$

s condition at beginning of period
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$C_{implement}(a)$ costs of implementing an action a

Planned strategy of actions

Cost Benefit Analysis

Year	Action	State before Action	State after Action	Monitoring Cost kEuro	Maint. Cost kEuro	EUSL Cost kEuro	Total Cost kEuro
1	DN	1	1	50	0	53.6	103.6
2	DN	1	1	2	0	53.6	55.6
3	DN	2	2	2	0	1092.4	1094.4
4	DN	2	2	2	0	1092.4	1094.4
5	DN	2	2	2	0	1092.4	1094.4
6	DN	2	2	2	0	1092.4	1094.4
7	R	3	1	2	12000	53.3	12055.3
8	DN	1	1	2	0	53.6	55.6
9	DN	1	1	2	0	53.6	55.6
10	DN	2	2	2	0	1092.4	1094.4

Net present Value

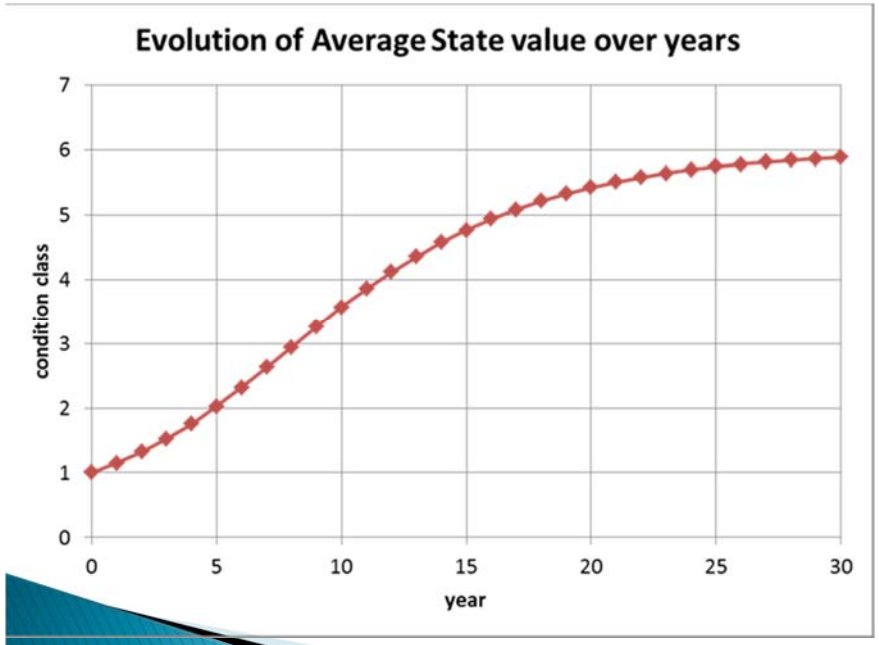
$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^{t-1}}$$

Planned strategy of actions

Monitoring

Transition Matrices:

	1	2	3	4	5	6
1	0.85	0.15	0	0	0	0
2		0.7	0.3	0	0	0
3			0.5	0.5	0	0
4				0.4	0.6	0
5					0.55	0.45
6						1



States s

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1N} \\ \vdots & \ddots & \vdots \\ p_{N1} & \cdots & p_{NN} \end{bmatrix}$$

where $p_{ij} = P\{s_{t+1} = j | s_t = i\}$

$$f_s(t) = (p_1 \ldots \ldots p_N)^T$$

with $p_i = P\{s = i\}$

$$f_s(t+m) = (P^T)^m \; f_s(t)$$

Monitoring

	1	2	3	4	5	6
1	0.85	0.15	0	0	0	0
2		0.7	0.3	0	0	0
3			0.5	0.5	0	0
4				0.4	0.6	0
5					0.55	0.45
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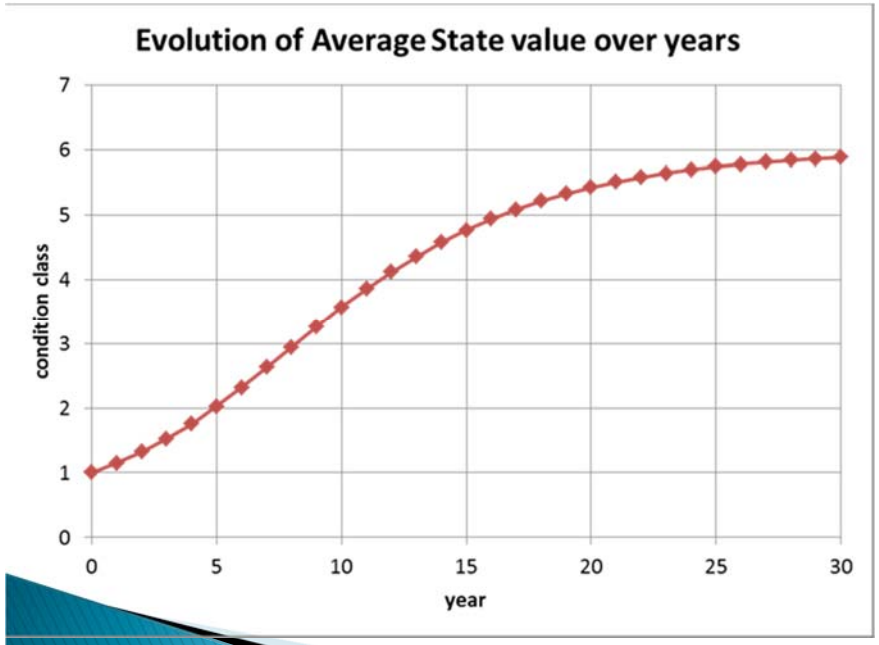


Measurements:

Year t	IRI_t	Class IRI_t	Year $t+1$	IRI_{t+1}	Class IRI_{t+1}	ΔIRI
2003	0.843	1	2004	0.991	2	0.147
2004	0.991	2	2005	1.148	3	0.157
2005	1.148	3	2006	1.221	3	0.073
2006	1.221	3	2007	1.339	3	0.118
2007	1.339	3	2008	1.453	3	0.114
2008	1.453	3				

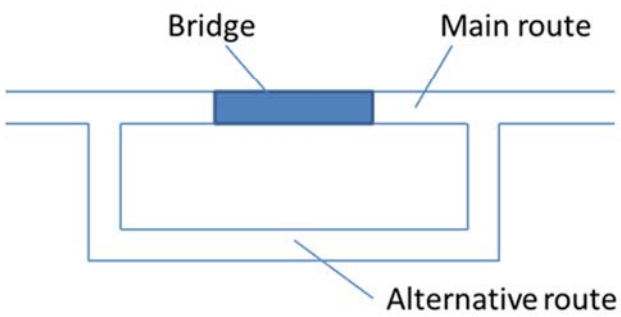
$$p_{ij} = \frac{n_{ij}}{n_i}$$

n_{ij} is the number of transitions from state i to state j within a given time period and

n_i is the total number of elements in state i before the transition

Cost Benefit Analysis

Example:



State s of bridge is monitored
Conservative upper bound is used for safety measures:

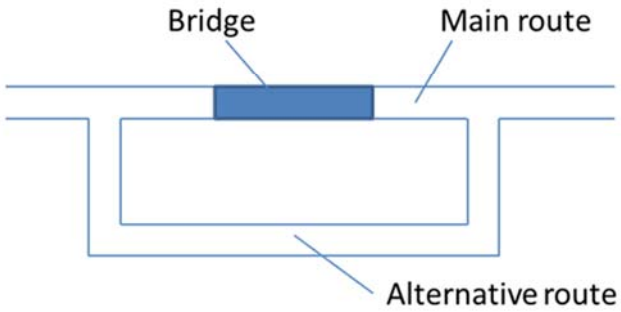
$$s^u = \mu(s) + \sigma(s)$$

When s^u exceeds the value of 3.30, heavy traffic is forced to take the alternative route, at a cost of 730 kEuro/year.
When s^u exceeds the value of 4.85, all traffic is forced to take the alternative route, which costs 3650 kEuro/year as a result of travel time los

Description	value	unit
AADT passenger cars	4000	#/day
AADT trucks and lorries	1000	#/day
distance main route	10	km
distance alternative route	30	km
unit prize for TTL	10	Euro/h
Traffic speed V	100	km/h
Period	1	Year
Horizon	25	Year
discount rate	0.035	–
λ	0.9662	–
Criterion 1 for f^u	3.3	–
Criterion 2 for f^u	4.85	–
Action cost	120000	kEuro
Initial state	1	–
State after action	1	–

Cost Benefit Analysis

Example:



2 Monitoring systems:

	1	2	3	4	5	6
1	0.859979	0.138306	0.000206	1.09E-05	0.000613	0.000885
2		0.751804	0.172779	0.027472	0.021391	0.026555
3			0.64749	0.235698	0.008101	0.108711
4				0.213994	0.007524	0.778481
5					0.105633	0.894367
6						1

Reference system

50 kEuro initial cost
2 kEuro annual cost

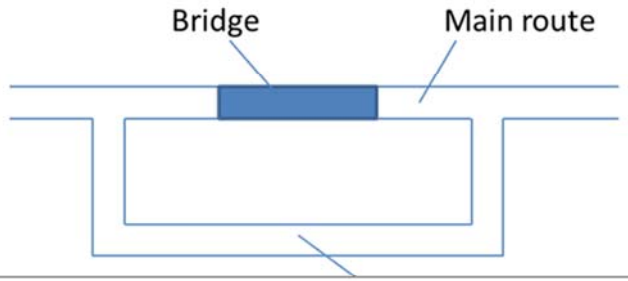
	1	2	3	4	5	6
1	0.85	0.15	0	0	0	0
2		0.7	0.3	0	0	0
3			0.5	0.5	0	0
4				0.4	0.6	0
5					0.55	0.45
6						1

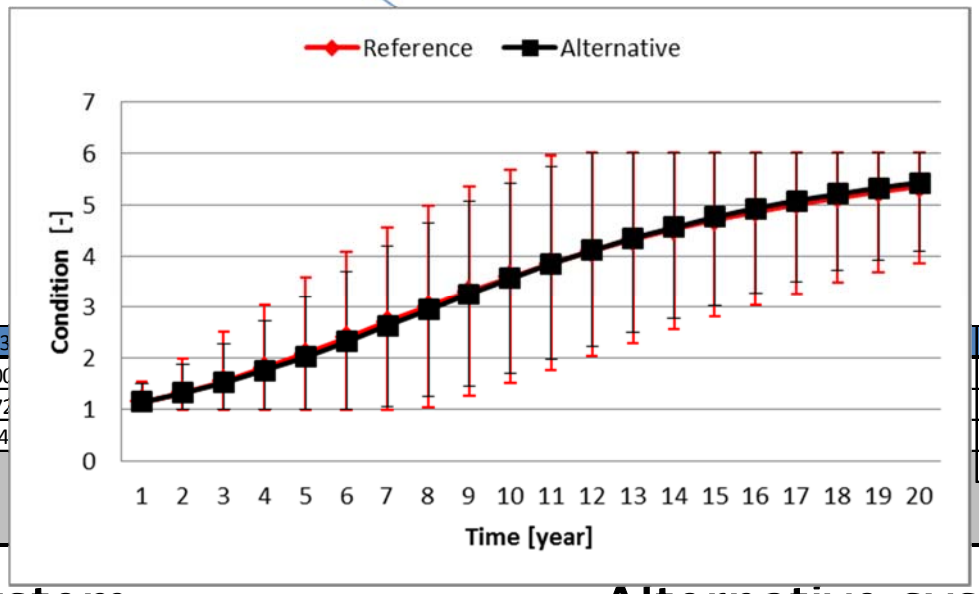
Alternative system

100 kEuro initial cost
4 kEuro annual cost

Cost Benefit Analysis

Example:





	1	2	3	4	5	6
1	0.859979	0.138306	0.000	0	0	0
2		0.751804	0.172	0	0	0
3			0.64	0.5	0	0
4				0.4	0.6	0
5					0.55	0.45
6						1

Reference system

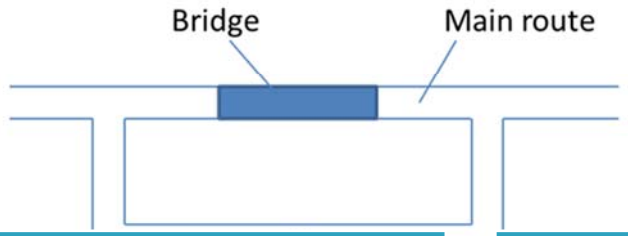
50 kEuro initial cost
2 kEuro annual cost

Alternative system

100 kEuro initial cost
4 kEuro annual cost

Cost Benefit Analysis

Example:



Reference scenario

Year	Action	State before Action	State after Action	Monit. Cost kEuro	Maint. Cost kEuro	TTL Cost kEuro	Total Cost kEuro
1	DN	1	1	50	0	53.6	103.6
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3	DN	2	2	2	0	1092.4	1094.4
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11	DN	2	2	2	0	1092.4	1094.4
12	DN	2	2	2	0	1092.4	1094.4
13	DN	2	2	2	0	1092.4	1094.4
14	R	3	1	2	12000	53.3	12055.3
15	DN	1	1	2	0	53.6	55.6
16	DN	1	1	2	0	53.6	55.6
17	DN	2	2	2	0	1092.4	1094.4
18	DN	2	2	2	0	1092.4	1094.4
19	DN	2	2	2	0	1092.4	1094.4
20	DN	2	2	2	0	1092.4	1094.4
21	R	3	1	2	12000	53.3	12055.3
22	DN	1	1	2	0	53.6	55.6
23	DN	1	1	2	0	53.6	55.6
24	DN	2	2	2	0	1092.4	1094.4
25	DN	2	2	2	0	1092.4	1094.4

Alternative scenario

Year	Action	State before Action	State after Action	Monit. Cost kEuro	Maint. Cost kEuro	TTL Cost kEuro	Total Cost kEuro
1	DN	1	1	100	0	0.0	100.0
2	DN	1	1	4	0	0.0	4.0
3	DN	2	2	4	0	109.5	113.5
4	DN	2	2	4	0	109.5	113.5
5	DN	2	2	4	0	109.5	113.5
6	DN	2	2	4	0	109.5	113.5
7	DN	3	3	4	0	1460.0	1464.0
8	DN	3	3	4	0	1460.0	1464.0
9	DN	3	3	4	0	1460.0	1464.0
10	R	4	1	4	12000	0.0	12004.0
11	DN	1	1	4	0	0.0	4.0
12	DN	1	1	4	0	0.0	4.0
13	DN	2	2	4	0	109.5	113.5
14	DN	2	2	4	0	109.5	113.5
15	DN	2	2	4	0	109.5	113.5
16	DN	2	2	4	0	109.5	113.5
17	DN	3	3	4	0	1460.0	1464.0
18	DN	3	3	4	0	1460.0	1464.0
19	DN	3	3	4	0	1460.0	1464.0
20	R	4	1	4	12000	0.0	12004.0
21	DN	1	1	4	0	0.0	4.0
22	DN	1	1	4	0	0.0	4.0
23	DN	2	2	4	0	109.5	113.5
24	DN	2	2	4	0	109.5	113.5
25	DN	2	2	4	0	109.5	113.5

Conclusions

- CBA: method based on Markov Decision process for maintenance planning
- SCBA: Extensions with respect to direct and indirect costs (social costs)
- Monitoring data: condition values and transitions (degradations)
- NPV's for comparing added value of monitoring systems
- Feasible method, although laborious
- Connecting: data↔information↔condition↔performance↔decisions↔actions
- Added value^{+} : operational maintenance planning
- Further need of performance models