European Commission

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TRIMM

# Cost Benefit of Monitoring

Willy Peelen – TNO

TOMORROW'S ROAD INFRASTRUCTURE MONITORING AND MANAGEMENT

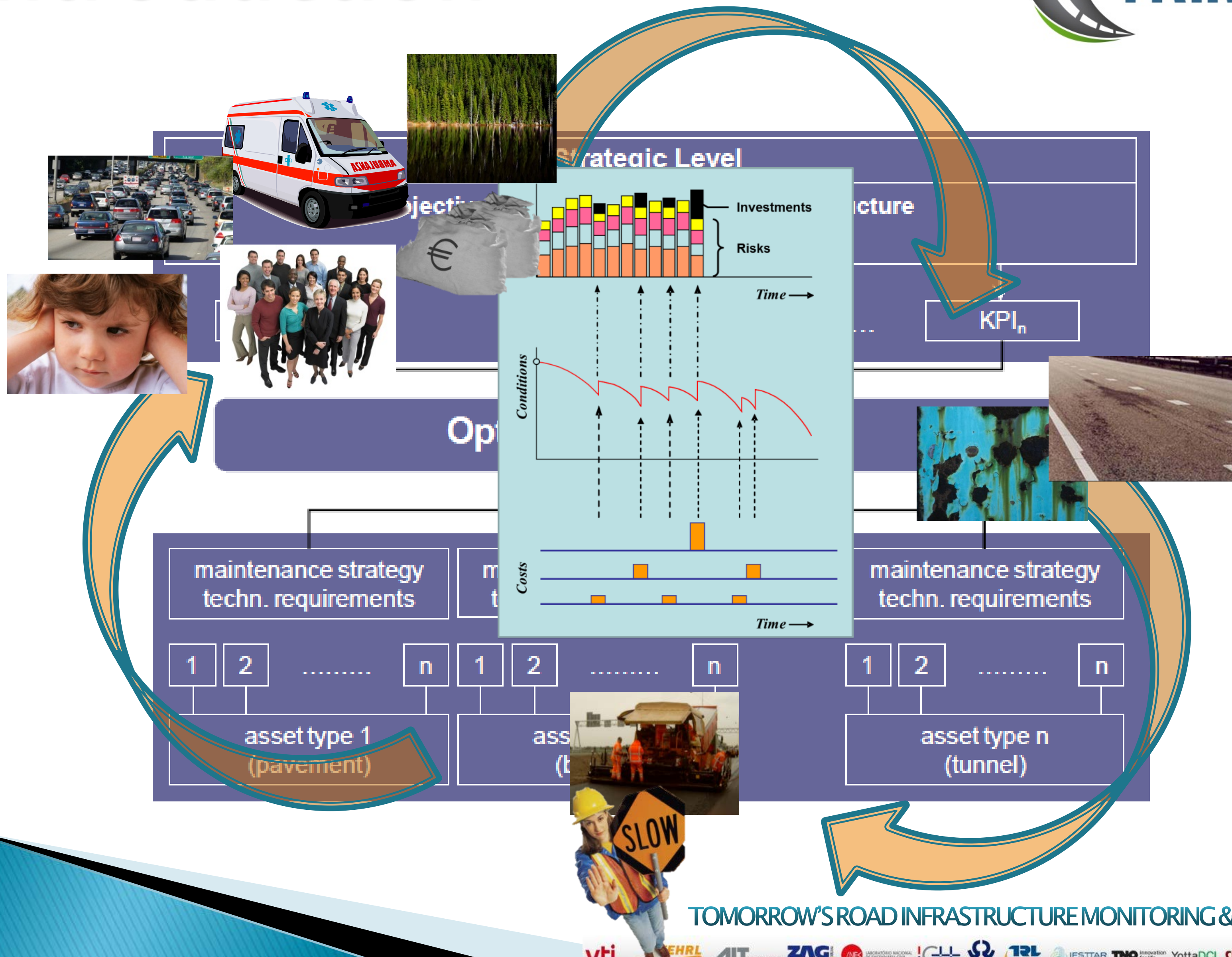
# Task

- 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 $a_0. a_1. \dots . a_A$

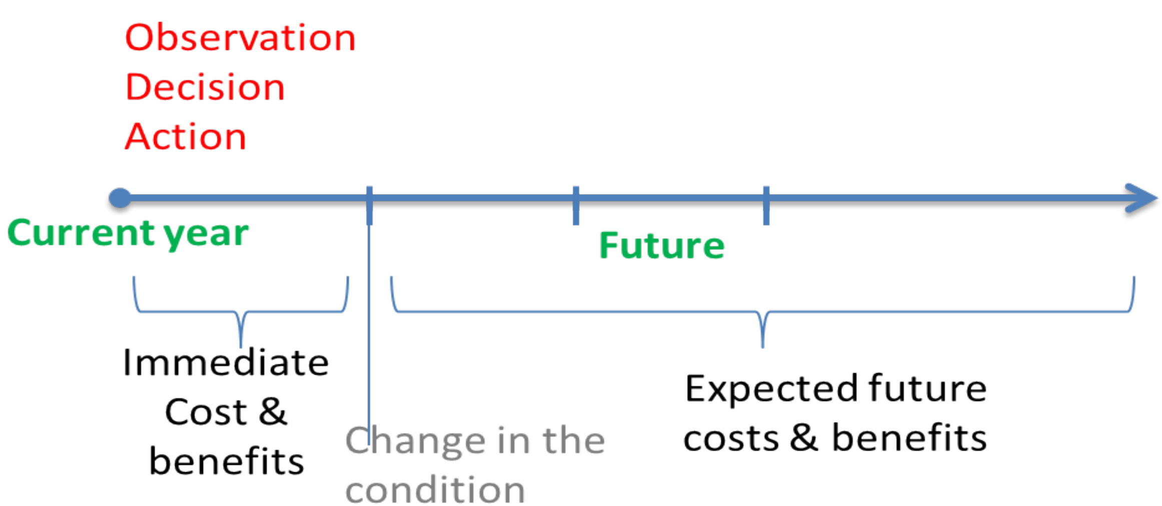
# Problem description

$X$ EUSL
$s$ Condition
$a$ Action

$X, s$

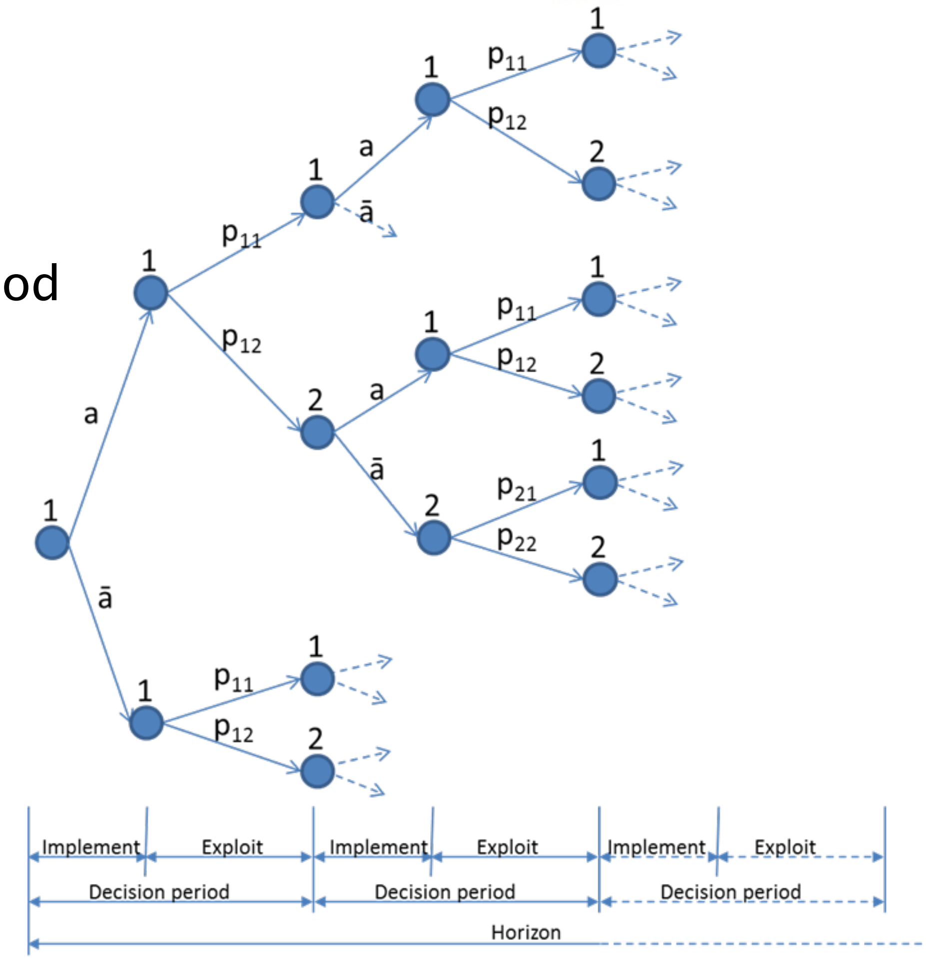
$a$

$X, s \mid a$ → $X', s' \mid X, s, a$



# 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

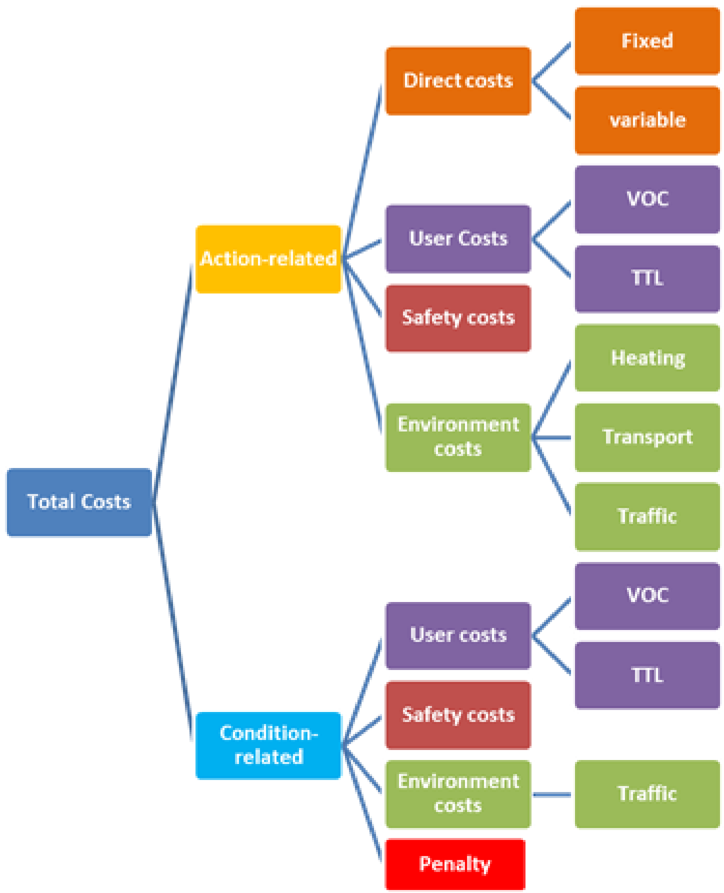
2 Actions
- a repair
- ā do nothing

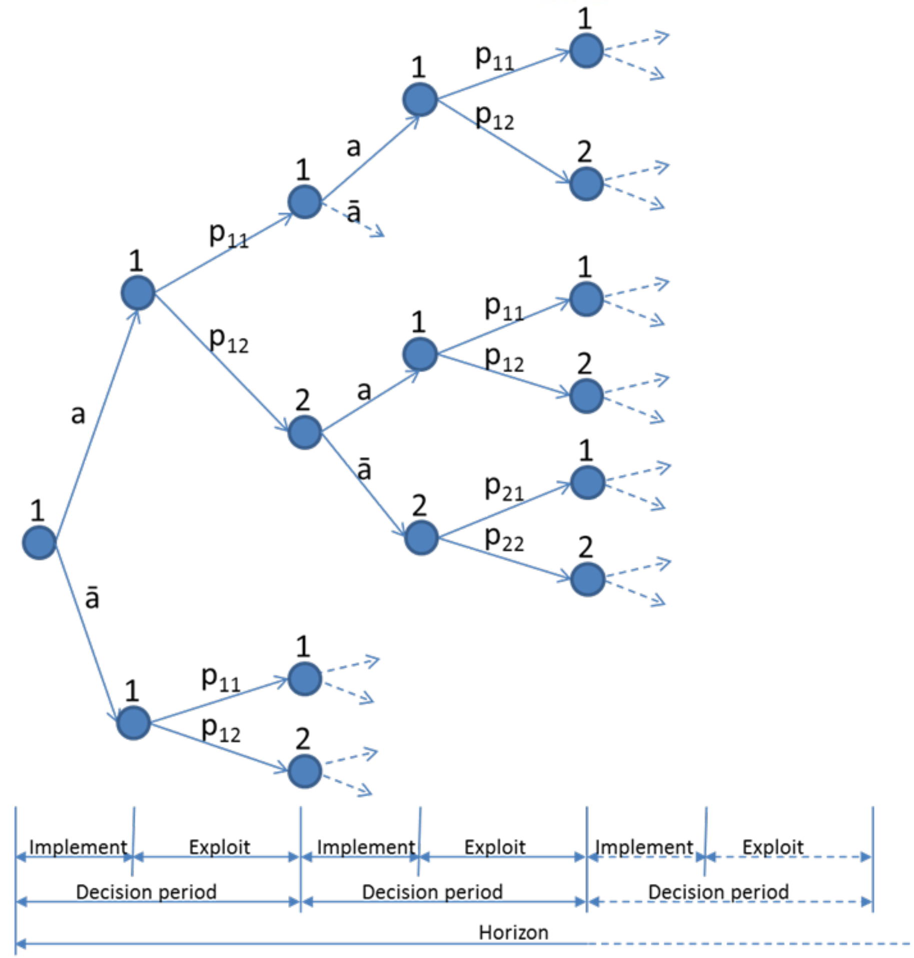
2 States (conditions)
- 1 good
- 2 bad

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

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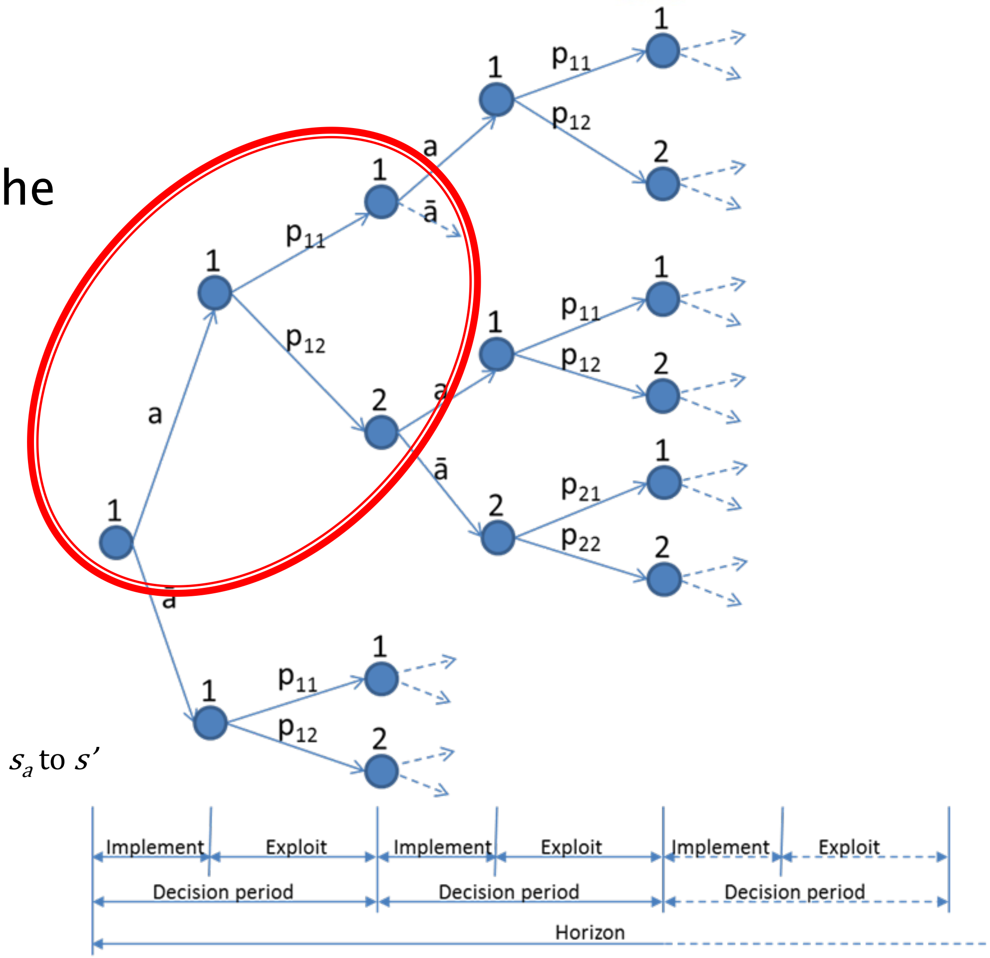
**SIMPLE EXAMPLE**
**Planning/decisions**

Noting the repetitive character of the branches. we get

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

$s$ condition at beginning of period
$s'$ condition at end of period
$s_a$ condition as a result of the action
$\lambda$ 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

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## 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
$s'$ condition at end of period
$s_a$ condition as a result of the action
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$p^{a}_{s_a s'}$ 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

Planned strategy of actions

# Cost Benefit Analysis

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| 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

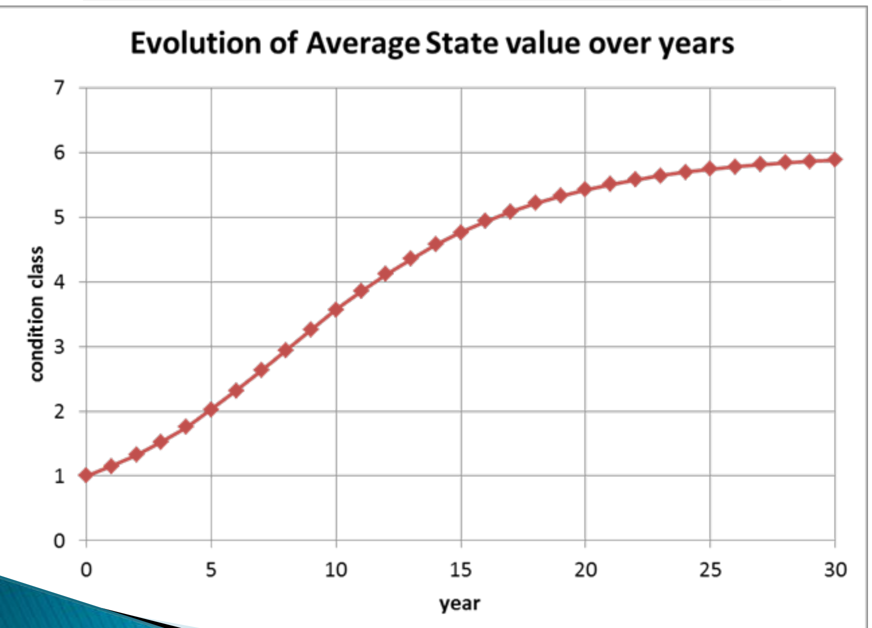
$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^{t-1}}$$

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

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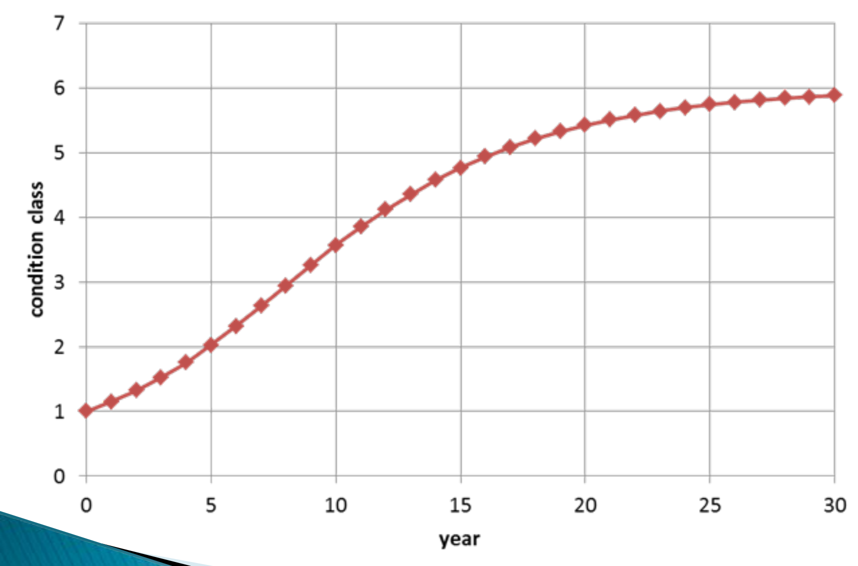
| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 0.85 | 0.15 | 0 | 0 | 0 | 0 |
| 2 | | 0.7 | 0.3 | 0 | 0 | 0 |
| 3 | | | 0.5 | 0.5 | 0 | 0 |
| 4 | | | | 0.4 | 0.6 | 0 |
| 5 | | | | | 0.55 | 0.45 |
| 6 | | | | | | 1 |




## Measurements:

| Year $t$ | $IRI_t$ | Class $IRI_t$ | Year $t+1$ | $IRI_{t+1}$ | Class $IRI_{t+1}$ | $\Delta IRI$ |
|---|---|---|---|---|---|---|
| 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

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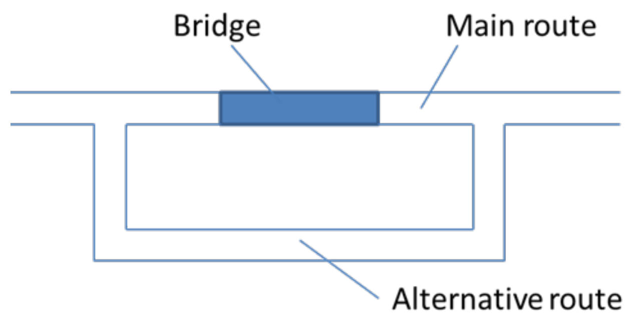
## Example:




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 | – |
| $\lambda$ | 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

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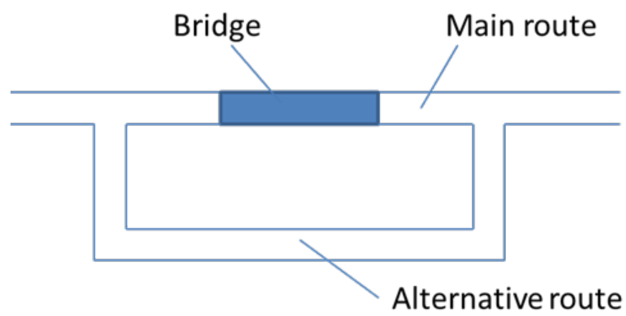
Example:




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

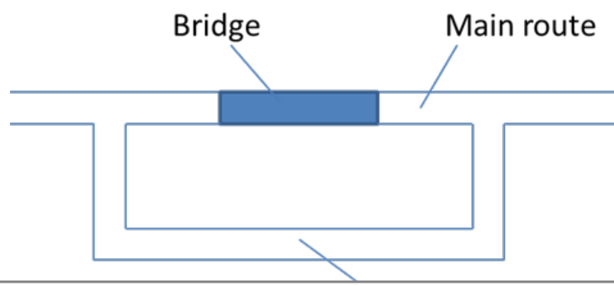
| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 0.85 | 0.15 | 0 | 0 | 0 | 0 |
| 2 | | 0.7 | 0.3 | 0 | 0 | 0 |
| 3 | | | 0.5 | 0.5 | 0 | 0 |
| 4 | | | | 0.4 | 0.6 | 0 |
| 5 | | | | | 0.55 | 0.45 |
| 6 | | | | | | 1 |

## Alternative system

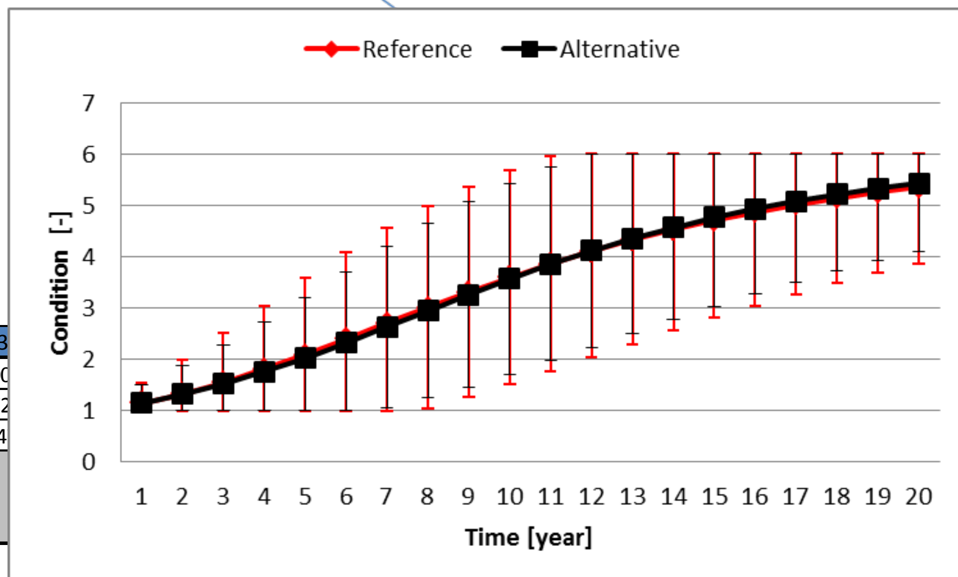
100 kEuro initial cost
4 kEuro annual cost

# Cost Benefit Analysis

Example:




| | 1 | 2 | 3 |
|---|---|---|---|
| 1 | 0.859979 | 0.138306 | 0.000 |
| 2 | | 0.751804 | 0.172 |
| 3 | | | 0.64 |
| 4 | | | |
| 5 | | | |
| 6 | | | |




| | 4 | 5 | 6 |
|---|---|---|---|
| 1 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 |
| 3 | 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

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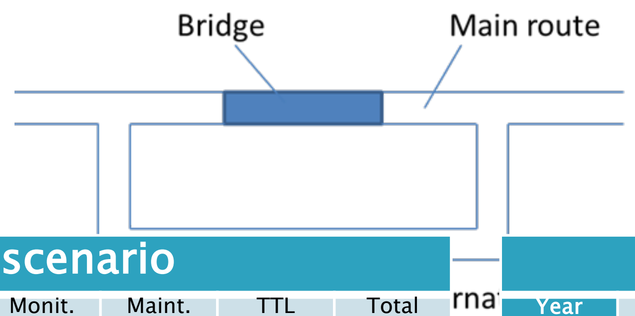
**Example:**




## 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 |
| 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 |
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| 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 |
| 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