Contribution à une gestion durable de structures en béton armé soumises à la pénétration des ions chlorure

Thèse de doctorat présentée et soutenue publiquement par

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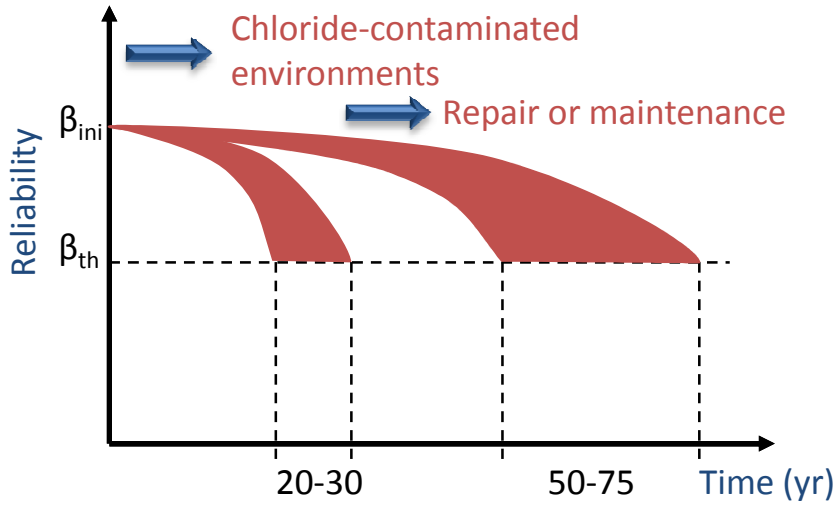
Introduction

Reliability of RC structures in chloride-contaminated environments



Problems with maintenance of corroding RC structures:

- There are no reliable models →
  - to assess the performance during the operational life and
  - to establish optimal management strategies
- Currently → corrective repair is carried out when visible signs of deterioration appear
  - the expenditures cannot be predicted during the life-cycle and
  - structural safety can be seriously compromised when repair is not undertaken

Introduction

Questions of the owners/operators:

- How much chloride ingress will affect structural integrity?
- How and when inspection and repair should be undertaken?
- How to determine a sustainable maintenance strategy?

MAREO

Maintenance and REpair of concrete coastal structures: risk-based Optimization

durabiNet

Durable Transport Infrastructure in the Atlantic Area-Network

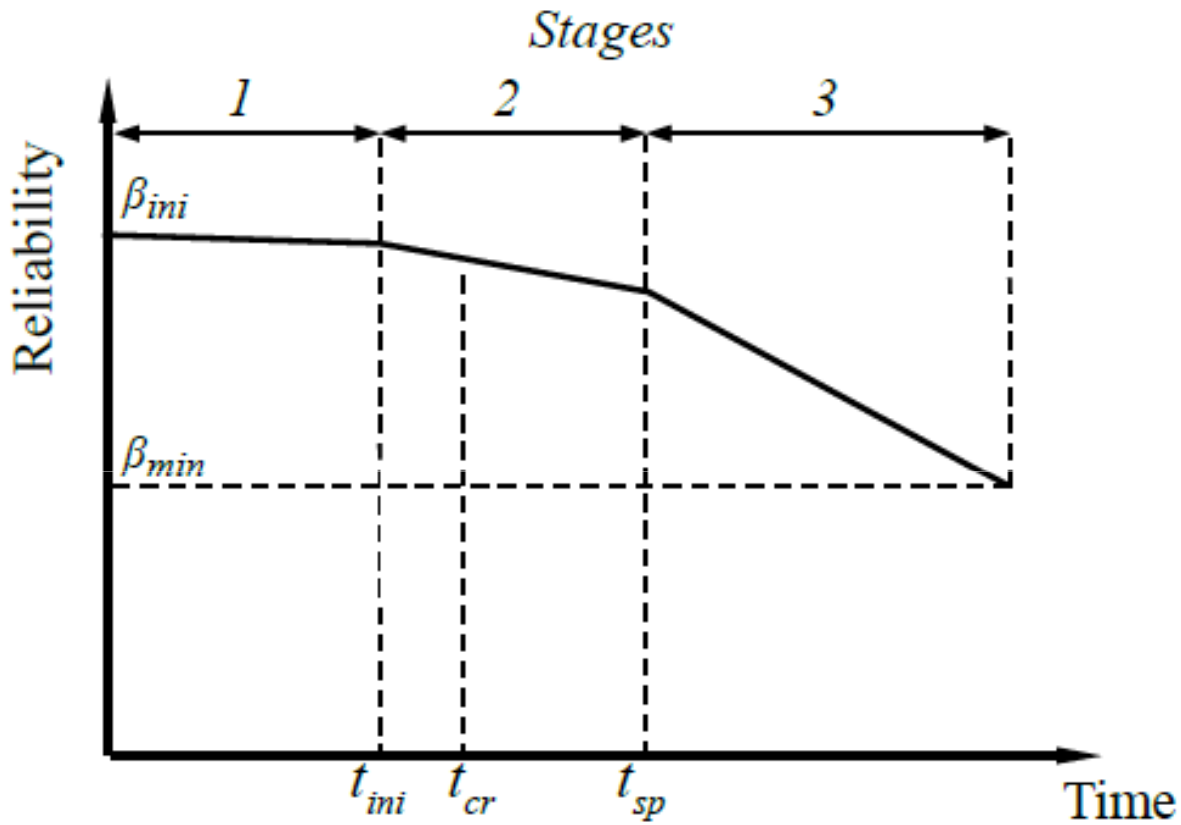
Objectives:

1. To define the approach more appropriate to deal with this problem based on a literature review
2. To choice and to implement a comprehensive model of chloride penetration
3. To introduce the deterioration model into an appropriate probabilistic framework to account for the uncertainties related to the deterioration phenomenon
4. To formulate a methodology for optimizing the performance of maintenance strategies
5. To include environmental constraints in the decision-making process to evaluate the sustainability of maintenance strategies

Outline

1. RC deterioration and maintenance
2. Probabilistic modeling of chloride ingress
3. Optimal management of corroding RC structures
4. Sustainability of maintenance strategies
5. Closure

Life-cycle of corroding RC structures



Stages of the life-cycle

1. Corrosion immunity
2. Active corrosion
3. Corrosion after severe concrete cracking

Deterioration and maintenance modeling

Approaches for modeling deterioration and maintenance actions [van Noortwijk and Frangopol,. 2004]:

1. Failure rate function
2. Markov model
3. Stochastic process
4. Time-dependent reliability index

Failure rate function

- indicates the frequency with which a structure/component fails and is computed in terms of the lifetime distribution
  - → useful in problems where the states "functioning" and "failed" are well-defined
  - → difficulties in defining failure for civil engineering problems → loss of serviceability, local failure (ULS) or total collapse
  - → structures or structural components can be in different states

Markov model

- structural conditions are discretized in various states
  - → widely used in management of civil engineering systems (e.g., PONTIS, KUBA-MS)
  - → effects deterioration, inspection and maintenance can be easily modeled
  - → based on visual inspection or expert judgment
  - → reliability is not directly incorporated

Deterioration and maintenance modeling

Stochastic process (gamma process)

- Deterioration at time t → power law –i.e., at^b for a, $b > 0$
- COV → constant
  - → simplified tool for optimizing the maintenance of critical components or prioritizing maintenance of structural networks when the mathematical properties of the stochastic process are well-known
  - → it only focuses on one component, one failure mode and one uncertainty (COV of the deterioration process)

Time-dependent reliability index

- Purpose → to minimize costs by ensuring an optimal level of safety
  - → incorporation of the uncertainties related to material properties, environmental actions, load, inspection, repair, etc.
  - → consideration of various limit states (i.e., ultimate or serviceability) and failure modes
  - → the effects of maintenance are difficult to estimate
  - → time consuming

Selected approach → Markov model

Conceptual framework of the proposed management strategy

Definition of failure

- How to define failure? (collapse, loss of serviceability, loss of capacity, …)
- After discussion with the stakeholders (MAREO project)
  - failure → corrosion initiation

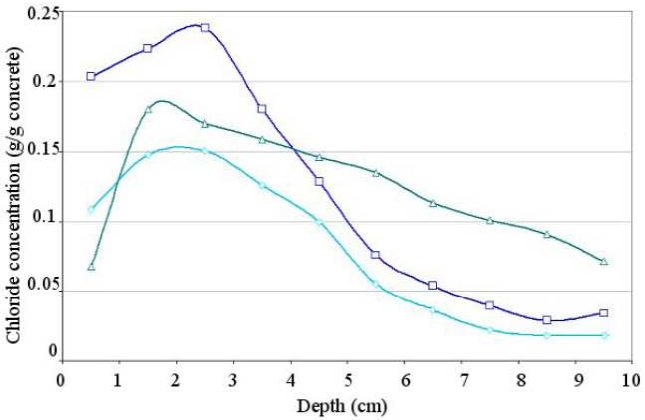
Repair criterion

- The structure is repaired before corrosion initiation
- Motivation/advantages
  - Inspection and repair actions → based on a measurable parameter
  - The decay of structural safety is minimized → repair is carried out before corrosion initiation
  - Practical point of view → the replacement of reinforcing bars is few

Maintenance strategy

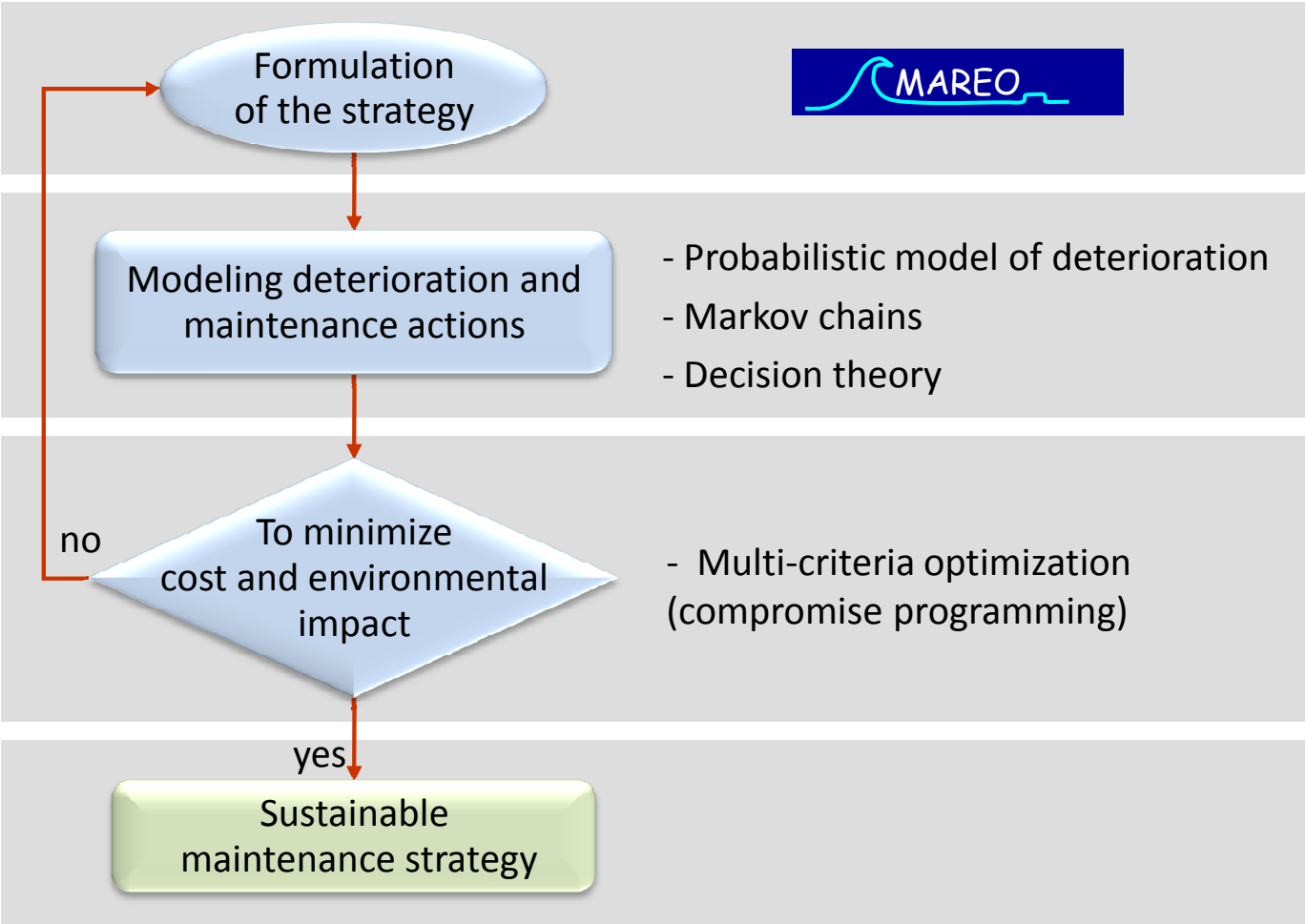
- Stages of the maintenance strategy

  1. Periodic inspection: chloride profiles → concrete cores



  2. Repair:
     - Demolition of the polluted concrete → Hydrodemolition
     - Cover rebuilding → several construction techniques

General description of the proposed approach



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Modeling chloride penetration

The adopted model of chloride ingress takes into account the interaction between three phenomena [Saetta et al., 1993]:

- Chloride penetration

$$\frac{\partial C_{fc}}{\partial t} = \underbrace{\mathrm{div}\left(D_c^* \vec{\nabla}\left(C_{fc}\right)\right)}_{\text{diffusion}} + \underbrace{\mathrm{div}\left(D_h^* C_{fc} \vec{\nabla}\left(h\right)\right)}_{\text{convection}}$$

with

$$D_c^* = \frac{D_{c,ref} f_1(T) f_2(t) f_3(h)}{1 + (1/w_e)\left(\partial C_{bc}/\partial C_{fc}\right)}$$

- Humidity diffusion

$$\frac{\partial w_e}{\partial t} = \frac{\partial w_e}{\partial h}\frac{\partial h}{\partial t} = \mathrm{div}\left(D_h \vec{\nabla}\left(h\right)\right)$$

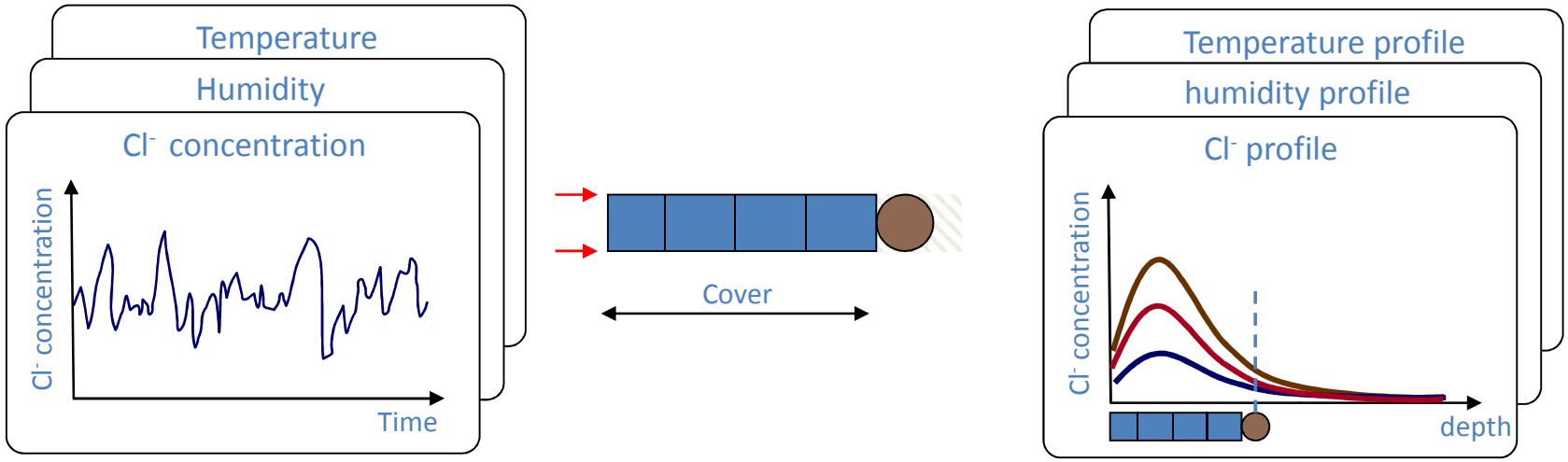
- Heat transfer

$$\rho_c c_q \frac{\partial T}{\partial t} = \mathrm{div}\left(\lambda \vec{\nabla}\left(T\right)\right)$$

Modeling chloride penetration

Numerical approach

- Spatial solution → finite element method
- Integration in time → Crank-Nicolson finite difference method
- Modeling → Fortran



Advantages with respect to the simplified Fick's model:

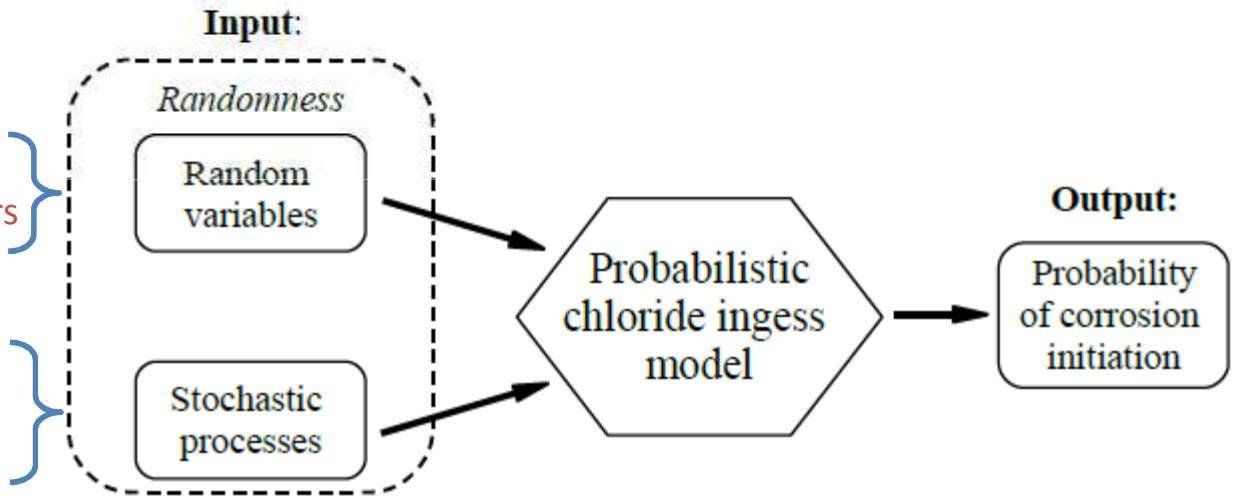
- input variables C_{env} , h_{env} and T_{env} → time-dependent or stochastic
- chloride binding
- chloride flow in two-dimensions and in unsaturated conditions

Probabilistic framework for reliability analysis

Probabilistic approach:

- material properties
- model and its parameters

- environmental actions (temperature, humidity, chloride concentration)



Probabilistic framework for reliability analysis

Instantaneous probability of corrosion initiation:

$$p_{corr}(t) = \mathrm{P}[g(\mathbf{X}, t) \leq 0] = \int_{g(\mathbf{X},t)\leq 0} f_{\mathbf{X}}(\mathbf{x}) dx_1 \ldots dx_n$$

Structural condition to define the limit state function:

- Serviceability limit state → probability of corrosion initiation

$$g(\mathbf{X}, t) = C_{th}(\mathbf{X}) - C_{ct}(\mathbf{X}, t)$$

Reliability method:

- Monte Carlo simulation and Latin Hypercube sampling

Time-invariant random variables

Random variables related to chloride penetration

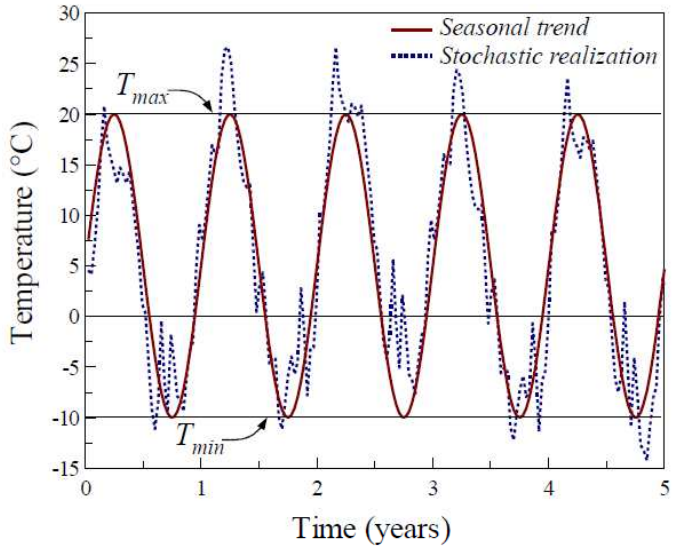
- Ordinary Portland concrete
- w/c = 0.5
- unsaturated conditions

Physical problem	Variable	Unit	Distribution	Mean	COV
Chloride ingress	$D_{c,ref}$	m^2/s	log-normal	$3 \cdot 10^{-11}$	0.20
	U_c	kJ/mol	beta [32;44.6]	41.8	0.10
	m_c		beta [0;1]	0.15	0.30
Humidity diffusion	$D_{h,ref}$	m^2/s	log-normal	$3 \cdot 10^{-10}$	0.20
	α_0		beta [0.025;0.1]	0.05	0.20
	n		beta [6;16]	11	0.10
Heat transfer	λ	W/(m°C)	beta [1.4;3.6]	2.5	0.20
	c_q	J/(kg°C)	beta [840;1170]	1000	0.10
	ρ_c	kg/m^3	normal	2400	0.20
Corrosion initiation	C_{th}	wt% cem.	normal	0.48	0.30
	c_t		normal truncated	nominal	0.25

Stochastic processes

Stochastic model of weather (humidity and temperature):

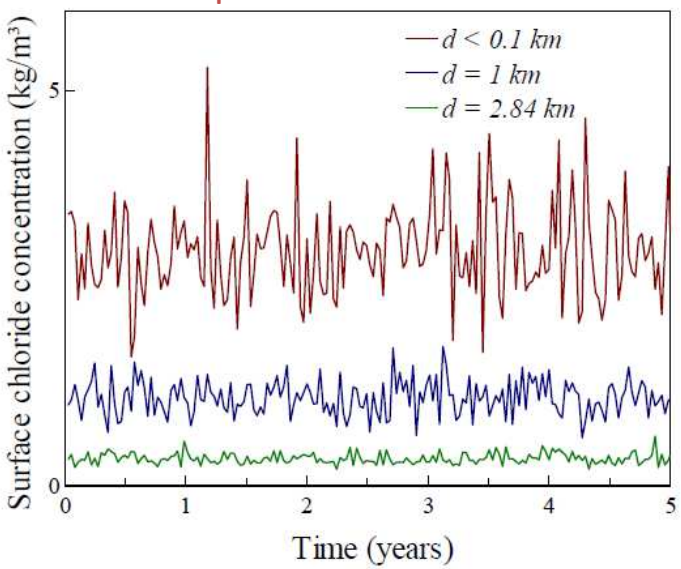
- Karhunen-Loève expansion
  - Seasonal trend
  - Global warming



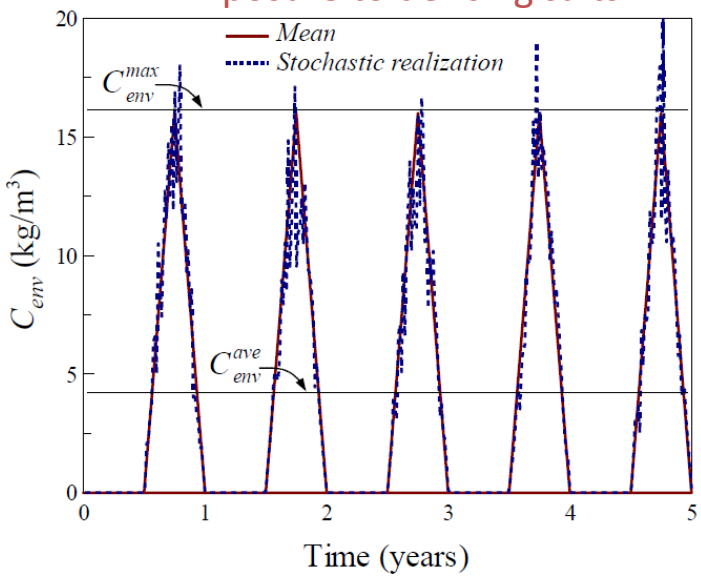
Stochastic model of environmental chloride concentration

- Uncorrelated log-normal fluctuations

Exposure to sea



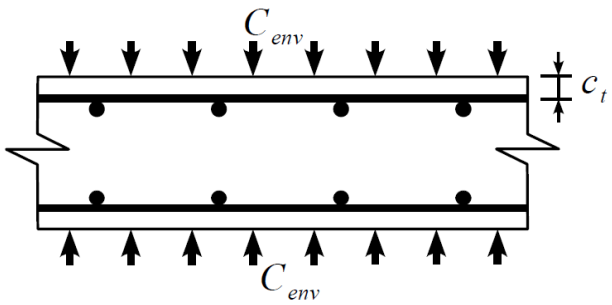
Exposure to de-icing salts



Example: influence of global warming on corrosion initiation time

Objective:
To study the influence of real weather conditions on both the probability of corrosion initiation and the lifetime reduction

Description of the example:



Basic assumptions:

- Structure placed in an unsaturated environment
- Concrete made with 400 kg/m^3 of OPC with 8% of C_3A and w/c = 0.5
- Isotherm of Langmuir: α_L = 0.1185 and β_L = 0.09

Studied environments:

Climate	Temp. (ºC)	RH
Continental: middle latitudes far from the sea	-10 to 20	0.6 to 0.8
Oceanic: middle latitudes close from the sea	5 to 25	0.6 to 0.8
Tropical: equatorial latitudes close to the sea	20 to 30	0.7 to 0.9

Example: influence of global warming on corrosion initiation time

Parameters to simulate global warming:

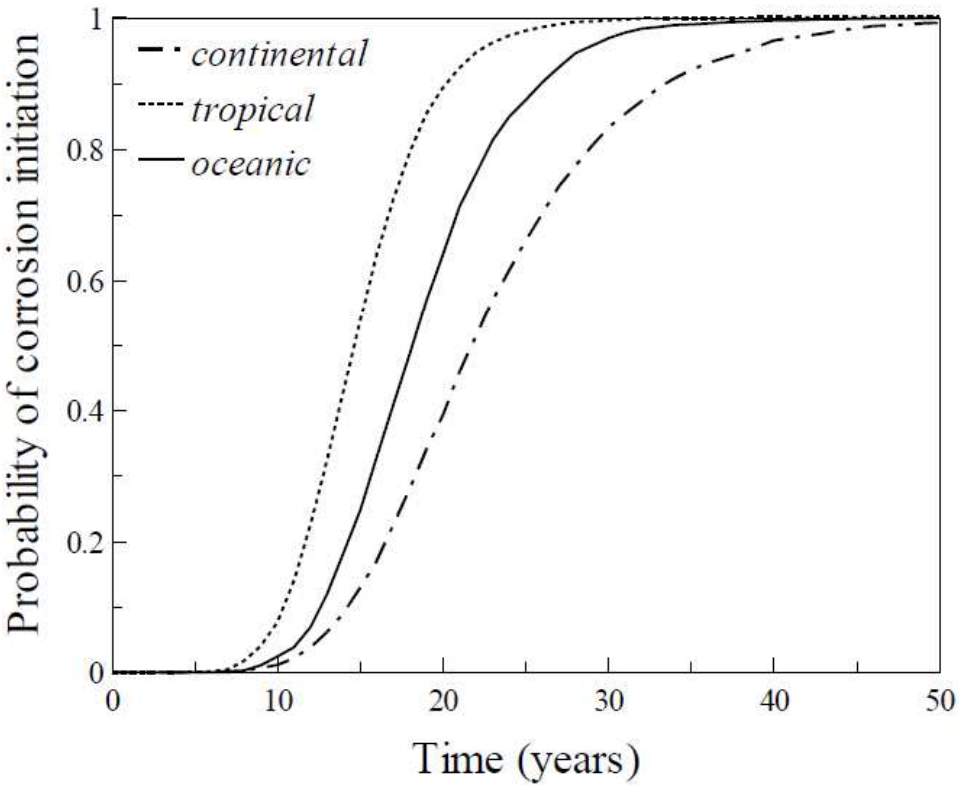
Scenario	Characteristics[1]	Δt_a[1]	Δh_a[2,3,4]
Without	climate change is neglected	0 ºC	0
Expected	use of alternative and fossil sources of energy, birthrates follow the current patterns and there is no an extensive employ of clean technologies	2.5 ºC	0.05
Pessimistic	vast utilization of fossil sources of energy, appreciable growth of population and there are no policies to develop and to share the use of clean technologies	6.5 ºC	0.10

References

1. IPCC. Climate change 2007: The physical science basis. contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Technical report, Intergovernmental Panel on Climate Change; 2007.
2. Allen MR and Ingram WJ. Constraints on future changes in climate and the hydrologic cycle. Nature 2002;419:224-32.
3. Vuille M, Bradley RS, Werner M and Keimig F. 20th century climate change in the tropical Andes: observations and model results. Climatic Change 2003;59:75-99.
4. Sperling FN, Washington R and Whittaker RJ. Future climate change of the subtropical north Atlantic: implications for the cloud forests of Tererife. Climatic Change 2004;65:103-23.

Example: influence of global warming on corrosion initiation time

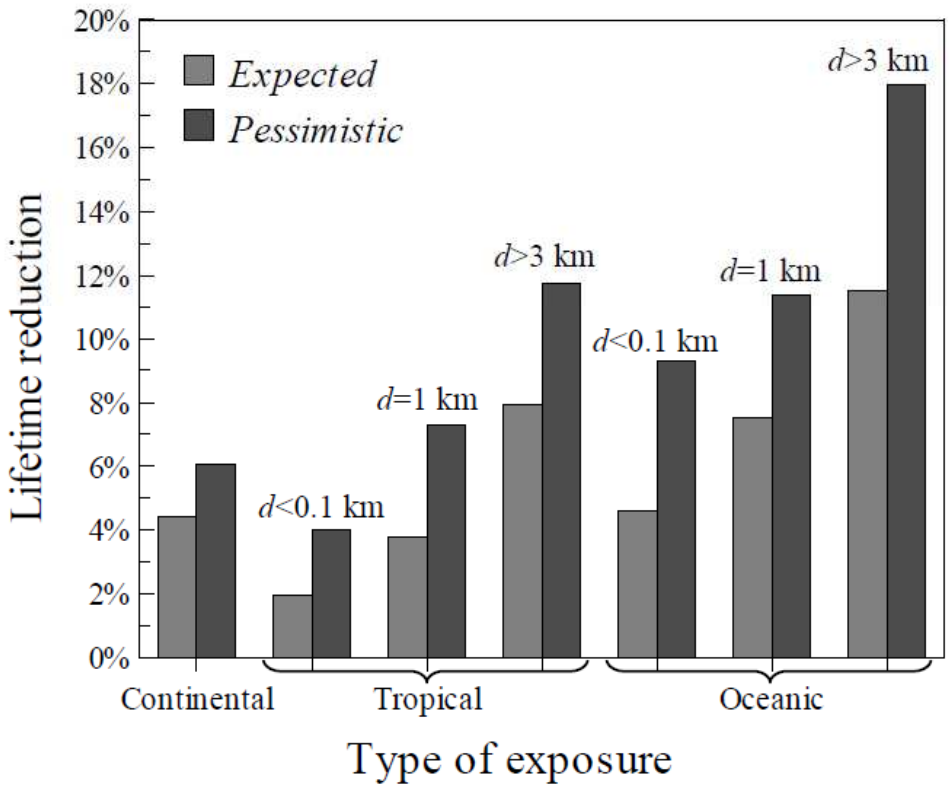
Effect of type of exposure



- highest p_{corr} → marine environments
- model → the interaction between chloride penetration and weather

Example: influence of global warming on corrosion initiation time

Lifetime reduction induced by global warming



- Lifetime reductions take as reference the case without global warming:
  - 2 to 12% → expected scenario
  - 4 to 18% → pessimistic scenario
- Results → implementation of countermeasures

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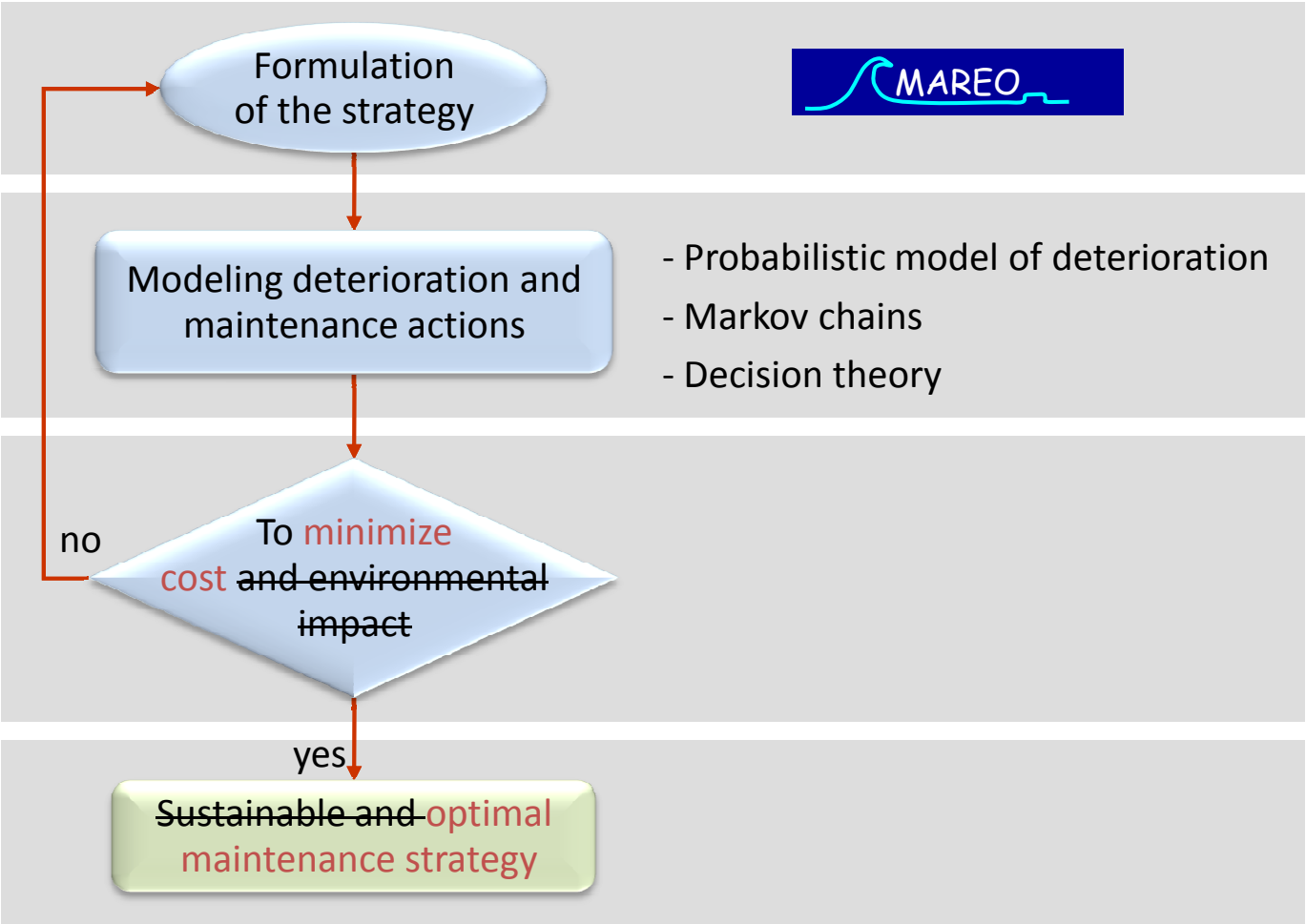
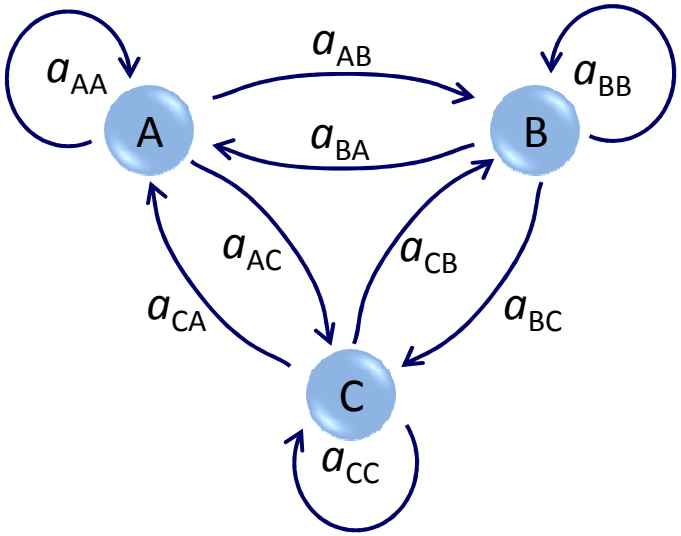


Modeling deterioration, inspection and maintenance actions

- Markov process



- Chapman-Kolmogorov → to predict a future state by knowing the present state:

$$\mathbf{q}(t) = \mathbf{q}_{ini} \cdot \mathbf{P}^t$$

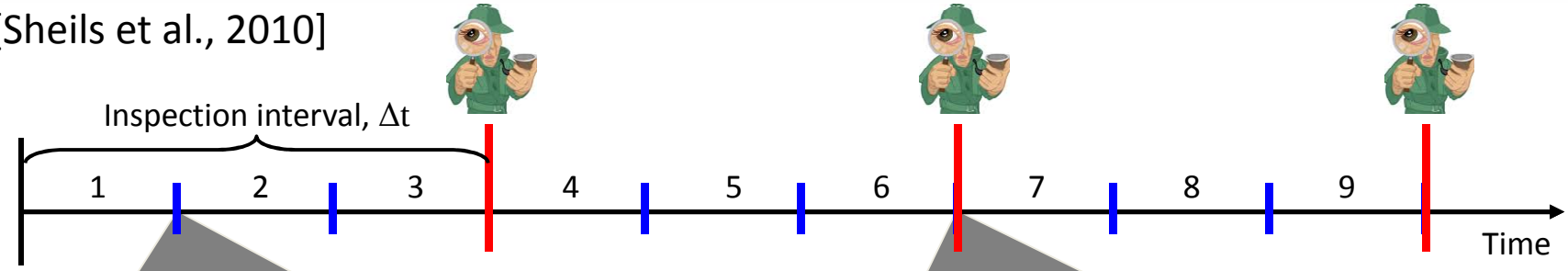
Deterioration, inspection and maintenance

- Variable of interest → chloride concentration at the cover depth

- Modeling → Matlab [Sheils et al., 2010]

Modeling deterioration, inspection and maintenance actions

[Sheils et al., 2010]



Year between inspections

$$\mathbf{P}^{be} = \begin{bmatrix} a_{ij} & a_{ij} & a_{ij} & \cdots & a_{ij} \\ a_{ij} & a_{ij} & a_{ij} & \cdots & a_{ij} \\ a_{ij} & 0 & a_{ij} & \cdots & a_{ij} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{ij} & 0 & 0 & \cdots & a_{ij} \end{bmatrix}$$

Assessment of $\mathbf{P}^{be}$

- growth matrix $\mathbf{P}^{gr}$
- Failure probability (corrosion initiation)

Inspection year

$$\mathbf{P}^{in} = \begin{bmatrix} a_{ij} & a_{ij} & a_{ij} & \cdots & a_{ij} \\ a_{ij} & a_{ij} & a_{ij} & \cdots & a_{ij} \\ a_{ij} & 0 & a_{ij} & \cdots & a_{ij} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{ij} & 0 & 0 & \cdots & a_{ij} \end{bmatrix}$$

Assessment of $\mathbf{P}^{in}$

- growth matrix $\mathbf{P}^{gr}$
- Failure probability (corrosion initiation)
- inspection results → PGA and PWA

Estimation of the growth matrix

- Discretization of the chloride concentration at the cover depth

State j	1	2	3	4	5	6	7	8	9	10
Minimum (kg/m^3)	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6
Maximum (kg/m^3)	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0

- Simulations → histogram of the chloride concentration at the cover depth and at a given time

$$\widehat{q}_j(t) = \frac{n_j(t)}{N}$$

where $n_j(t)$ is the number of observations in the state j measured at time t and N is the total number of simulations

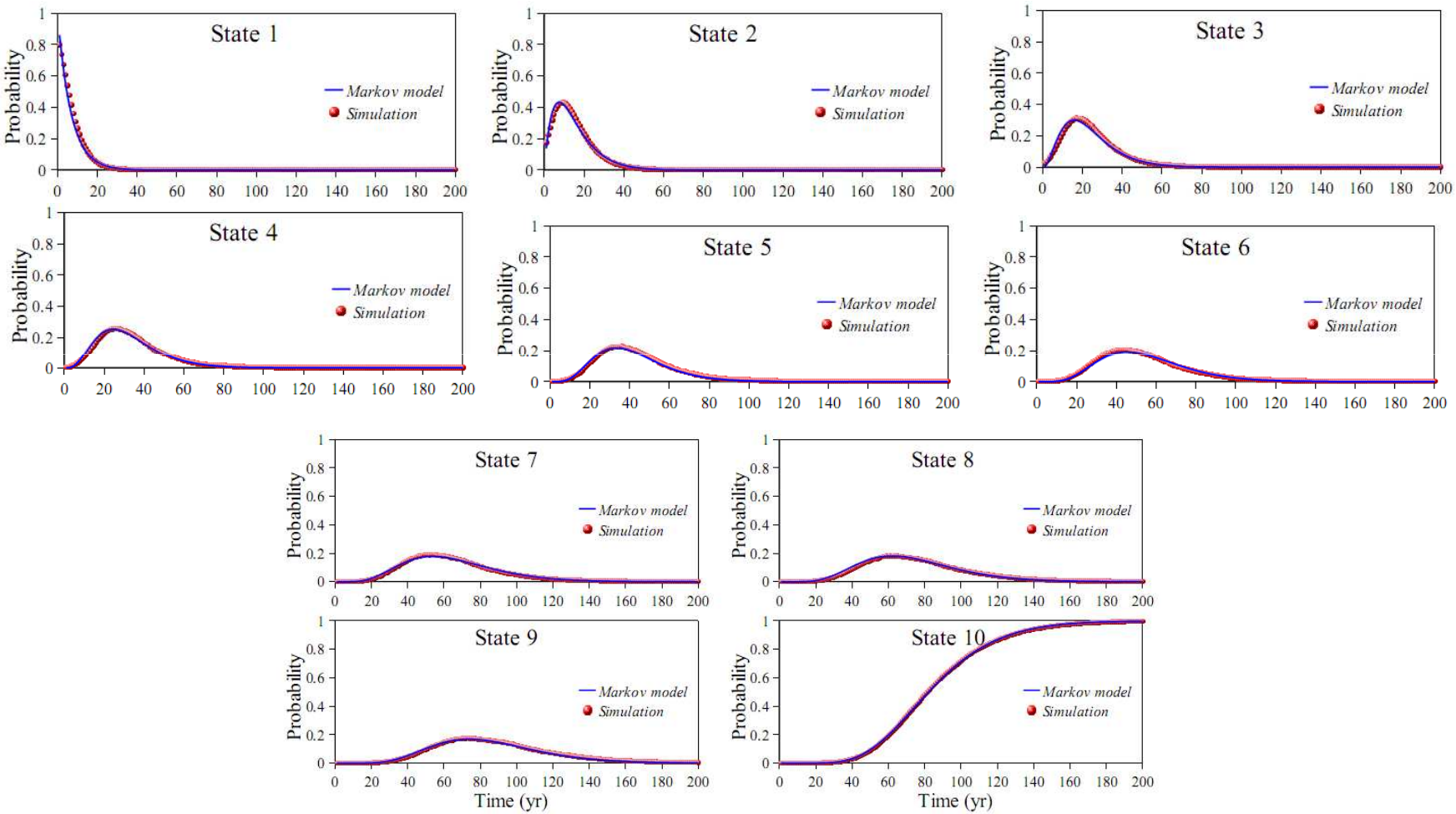
- Transition probabilities **a** → multi-objective optimization

$$\begin{cases} \min_{\mathbf{a}} \max_{\mathbf{F}} \mathbf{F}(\mathbf{a}) = (f_1(\mathbf{a}), f_2(\mathbf{a}), \ldots, f_M(\mathbf{a}))^T \\ \text{u.c. } a_{ij} \geq 0 \text{ and } \sum_{j=0}^{\infty} a_{ij} = 1 \end{cases}$$

where → $$f_j(\mathbf{a}) = \sum_{t=0}^{t_{ana}} (\underbrace{\widehat{q}_j(t)}_{\text{Simulation}} - \underbrace{q_j(t,\mathbf{a})}_{\text{Markov}})^2$$

Estimation of the growth matrix

Results of the optimization: discrete probabilities with time



Inspection results – imperfect measurement

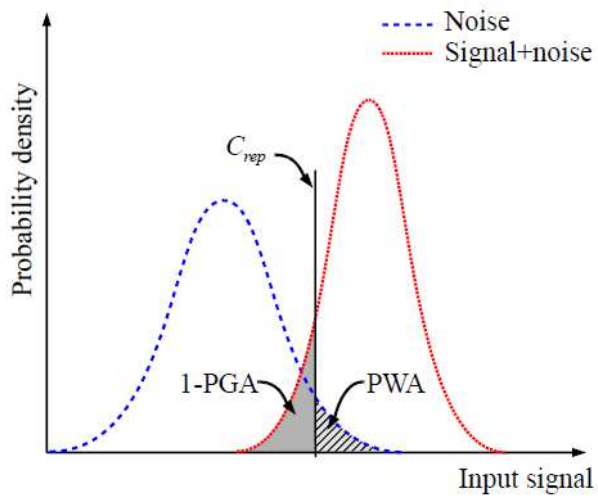
PGA and PWA

- Probability of good assessment (PGA)

$$\mathrm{PGA} = \mathrm{P}(\widehat{C}(\mathbf{X}) \geq C_{rep} | C(\mathbf{X}) \geq C_{rep})$$

- Probability of wrong assessment (PWA)

$$\mathrm{PWA} = \mathrm{P}(\widehat{C}(\mathbf{X}) \geq C_{rep} | C(\mathbf{X}) < C_{rep})$$



Assessment of PGA and PWA

- characterization of the noise → experimental tests [Bonnet et al., 2009]
  - Generalized extreme value distribution (K_η= 0.016, σ_η= 9.3·10^{-5} and μ_η= -8.4·10^{-5} in kg/kg of concrete)
- characterization of the signal → simulations
  - Log-normal distribution
- probability of good assessment → FORM
- probability of wrong assessment:

$$\mathrm{PWA} = 1 - \exp\left(-\left[1 + K_\eta\left(\frac{C_{rep} - \mu_\eta}{\sigma_\eta}\right)\right]^{-1/K_\eta}\right)$$

Cost analysis

- Markov model → stabilized number of defects in each state [Sheils et al., 2010]

- Expected total cost

$$\underbrace{E[C_T]}_{\text{Total}} = \underbrace{E[C_I]}_{\text{Inspection}} + \underbrace{E[C_R]}_{\text{Repair}} + \underbrace{E[C_F]}_{\text{Failure}}$$

  - Only agency (direct) costs
  - Expected costs computed on an annual basis → annual expenditures of the agency

- Inspection cost

$$E[C_I] = E[n_I] C_0 k_I$$

where n_I is the annual number of inspections and

k_I is a coefficient to estimate the inspection cost as function of the initial cost of construction, C_0

Cost analysis

- Repair cost

$$\mathrm{E}[C_R] = C_0 k_R \sum_{i=1}^{M} \mathrm{E}[n_R(i)]$$

where n_R is the annual number of repairs and

k_R is a coefficient to estimate the repair cost as function of C_0

- Failure cost

$$\mathrm{E}[C_F] = \mathrm{E}[C_{F1}] + \mathrm{E}[C_{F2}] \begin{cases} \mathrm{E}[C_{F1}] = C_0 k_F \sum_{i=1}^{M} \mathrm{E}[n_{F1}(i)] & \text{between inspections} \\ \mathrm{E}[C_{F2}] = C_0 k_F \sum_{i=1}^{M} \mathrm{E}[n_{F2}(i)] & \text{at inspection years} \end{cases}$$

where n_{F1} and n_{F2} are the annual number of failures between inspections and at inspection years, respectively; and

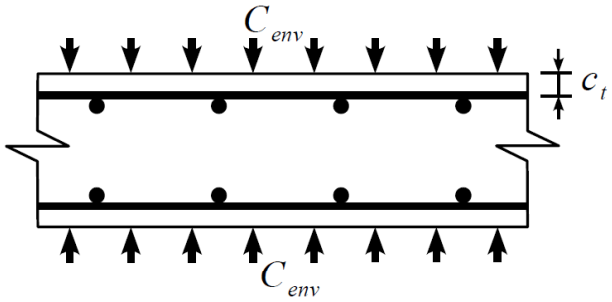
k_F is a coefficient to estimate the failure cost as function of C_0

Illustrative example

Objective:
To illustrate the proposed methodology studying the influence of the inspection interval on expected costs

Description of the example:

- 100 structural components placed in an unsaturated environment
- Temperature → 5 to 25ºC
- Relative humidity → 0.6 to 0.8
- μC_{env} = 6 kg/m^3 and COV=0.2
- Discretization into M = 10 states

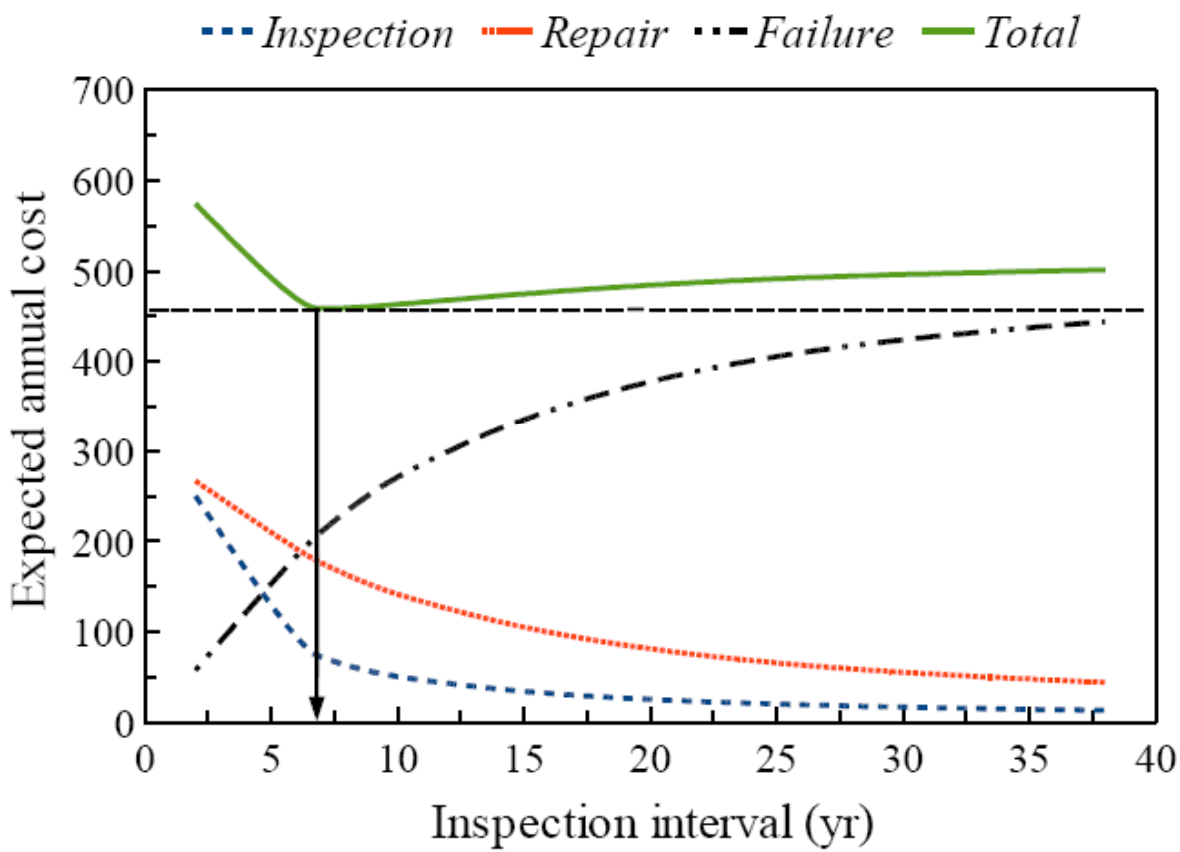


Cost models → average expenditures Port of Nantes – S.-Nazaire MAREO project

Parameter	Value
Initial cost, C_0	1000
Inspection coefficient, k_I	0.005
Repair coefficient, k_R	0.15
Failure coefficient, k_F	0.30

Illustrative example

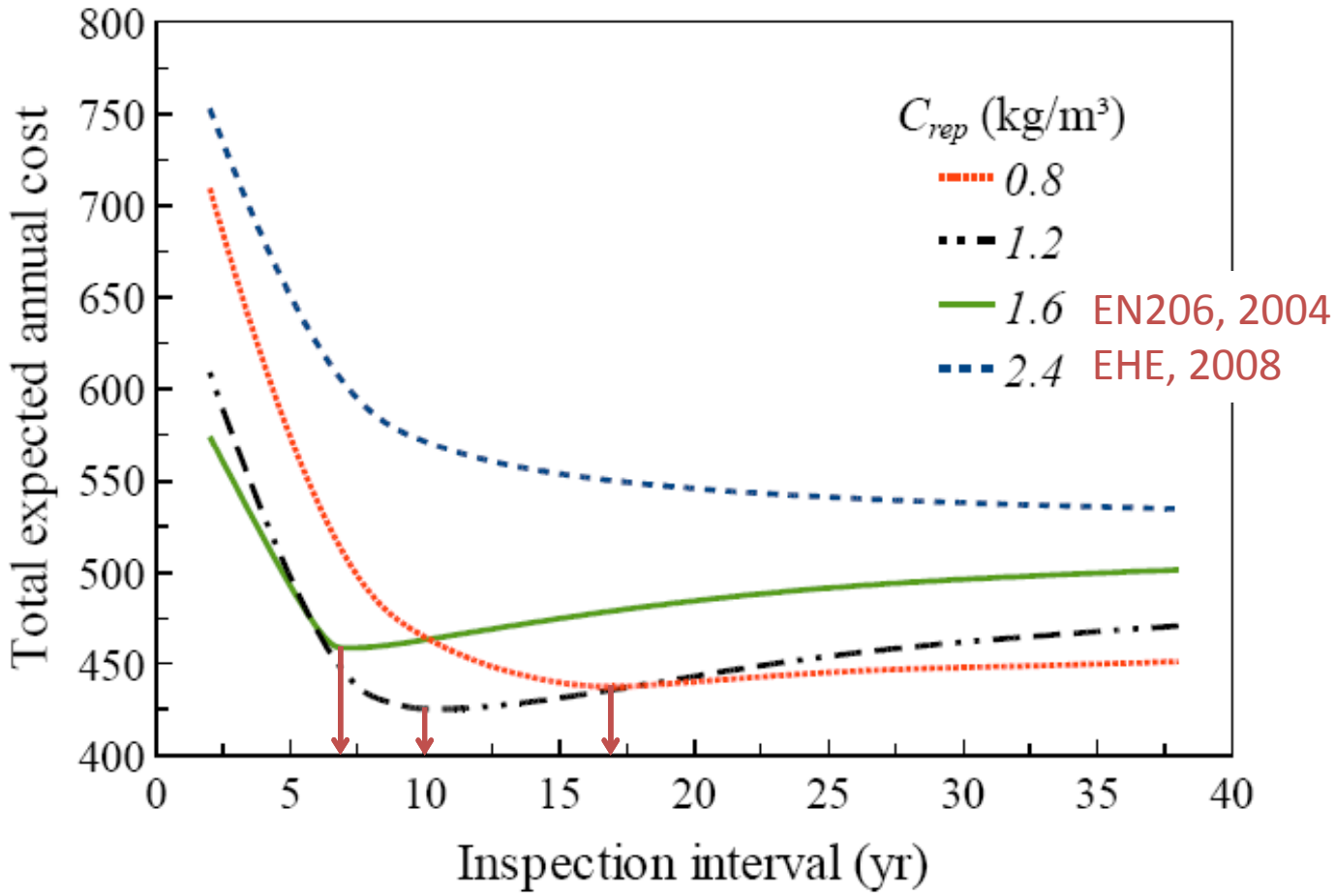
Effect of the inspection interval on expected annual costs



- E[C_I] and E[C_R] ↓ when Δt ↑
- E[C_F] ↑ when Δt ↑
- Optimal total Inspection interval → 7 years

Illustrative example

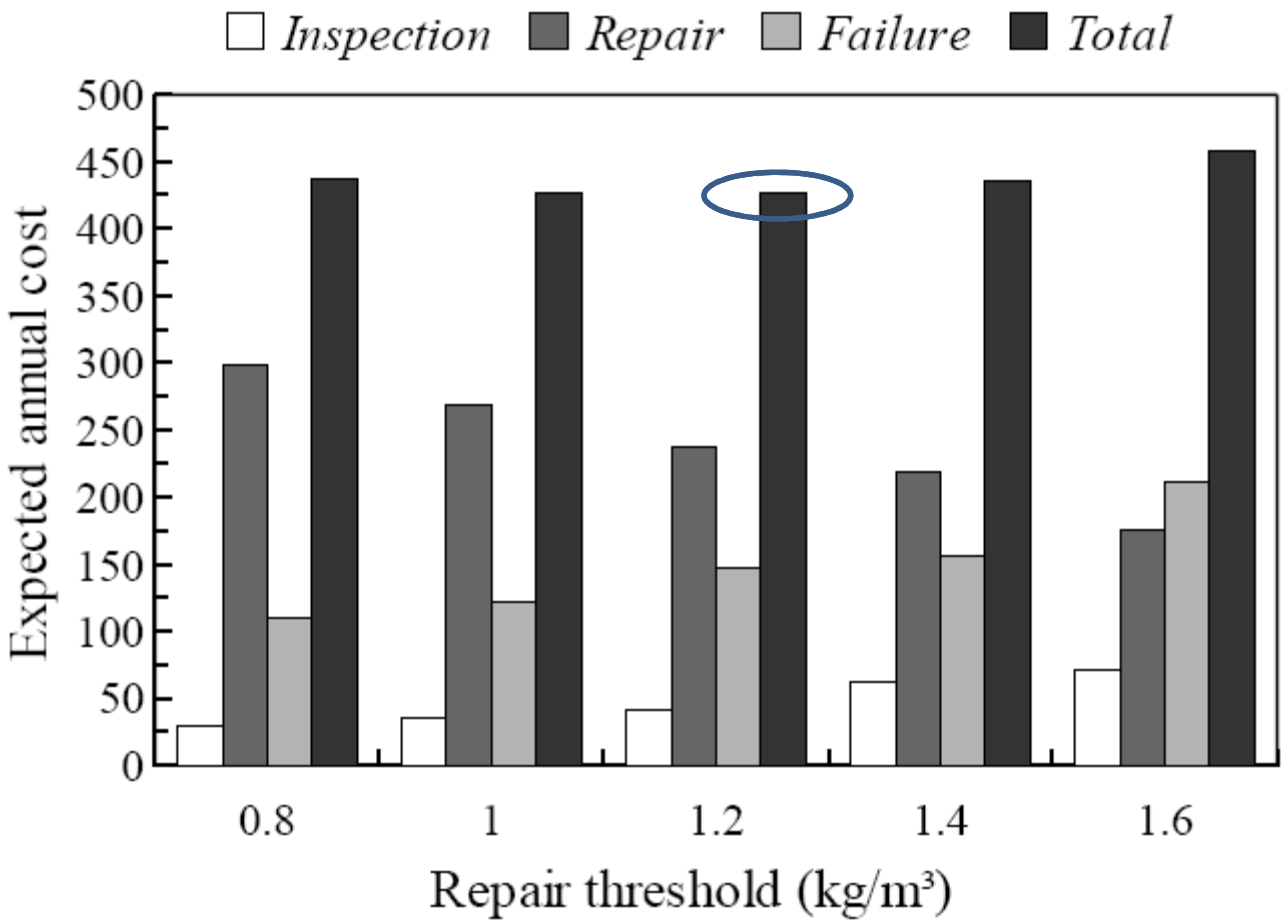
Influence of the repair threshold C_{rep} on the total cost



- E[C_T] sensitive to the repair threshold
- For repair thresholds < 1.6 kg/m³, there is Δt_{opt} that minimizes cost
- The repair threshold → defined for a particular problem

Illustrative example

Influence of the repair threshold C_{rep} on the expected annual cost



- E[C_I], E[C_F] ↑ and E[C_R] ↓ when the repair threshold ↑
- Optimal repair threshold → 1.2 kg/m^3

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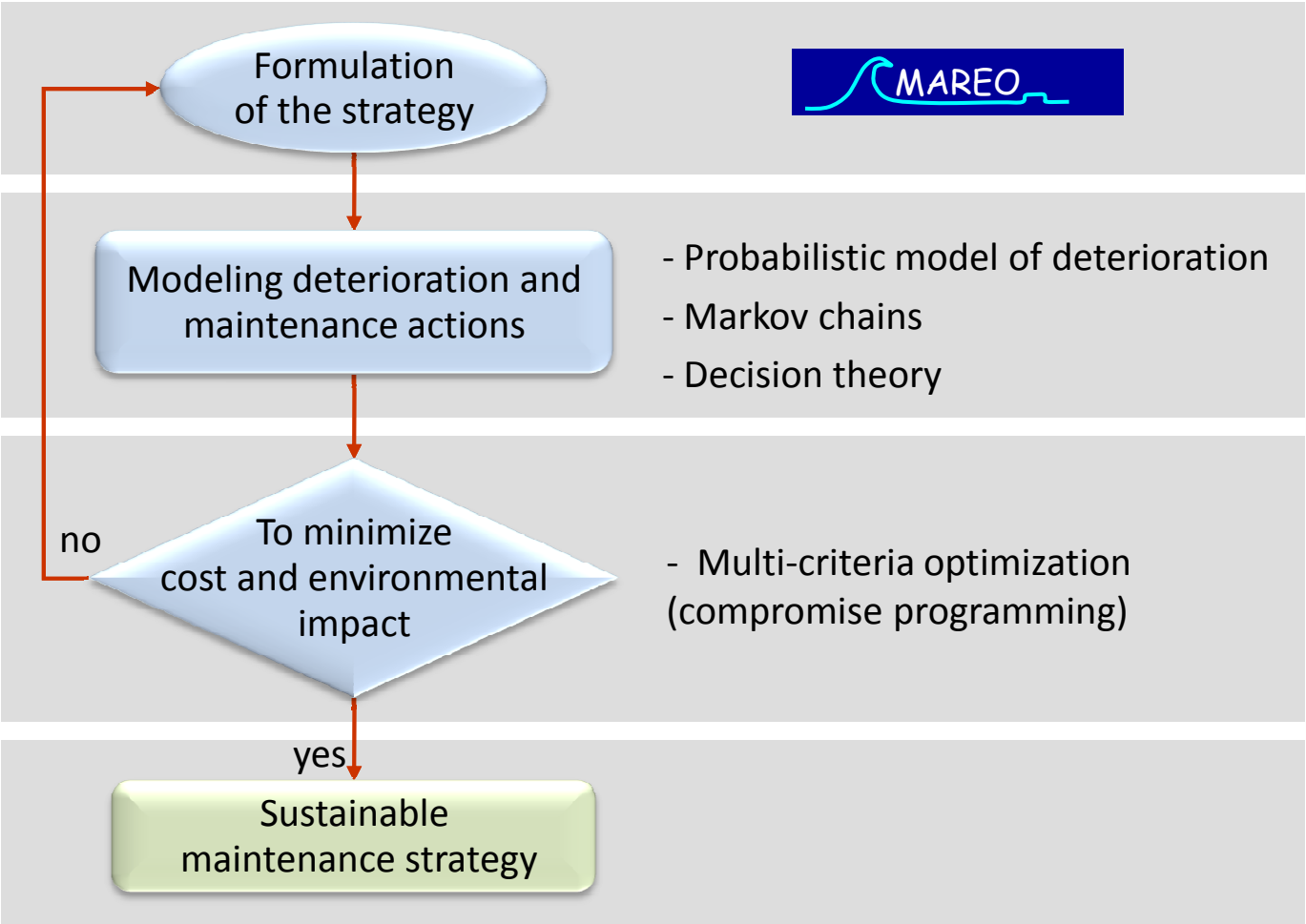
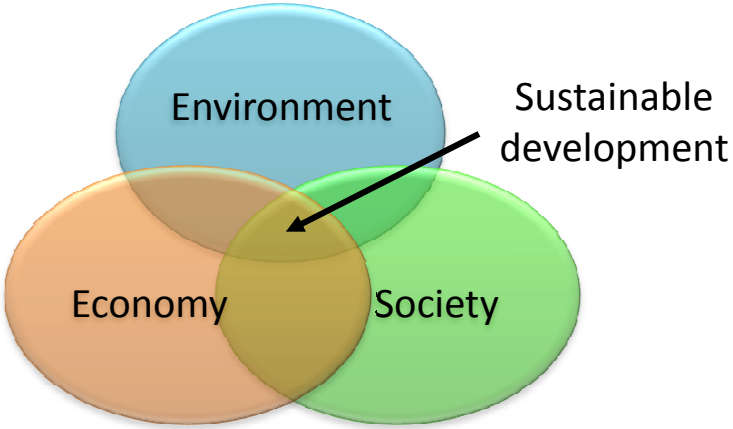


Maintenance in the framework of sustainable development

- Sustainable development [World commission on environment and development, 1987] :

  … development that meets the needs of the present without compromising the ability of future generations to meet their own needs…

- Components of sustainability → environment, economy, and society



- The evaluation of the sustainability of maintenance strategies is based on the comparison of three criteria:
  1. costs,
  2. waste generation, and
  3. CO_2 emissions

Criteria to assess the sustainability of maintenance strategies

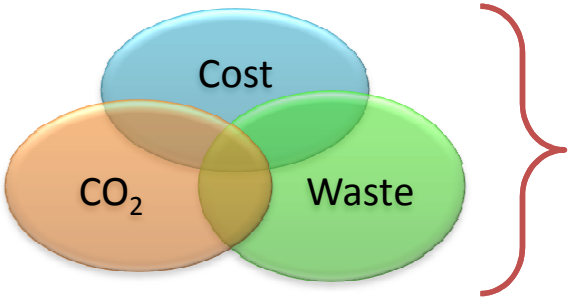
- Costs
  - Assessment → model of inspection/maintenance
  - Direct costs → inspection, repair and failure
  - Real data → port of Nantes – St.-Nazaire and MAREO project

- Waste generation
  - Concrete → 67% of waste of construction and demolition [American Institute of Architects, 1999]
  - 5% recycled
  - Assessment → waste produced during demolition and repair
  - Data→ repair on real beams (MAREO project)

- CO_2 emissions
  - Production of cement → 7% of total emissions of CO_2 [Kumar Mehta, 1997]
  - Sources:
    - production and transport of repair products
    - transport of equipment
    - transport of waste
  - Data → repair on real beams (MAREO project) and literature

Decision-making under multiple constraints

- Multi-criteria comparison:



Multi-objective optimization:
compromise programming

- Ideal solution:

$$\mathbf{f}^* = [x_1^*,\ x_2^*,\ \dots\ x_m^*]$$

- Multi-objective index:

$$\mathrm{MOI}(x) = \left[\sum_{i=1}^{m} w_i^p \left| \frac{x_i - x_i^*}{x_{i*} - x_i^*} \right|^p \right]^{1/p}$$

where w_i is the weighting factor for the optimization criterion
p indicates the importance given to deviations from the ideal solution

Case study – problem description

The Agri-foodstuffs terminal (Port of Nantes - St.-Nazaire):

- built in 1971
- Repair area → 1400 m^2

Generalized corrosion → Large-scale repair → Repair strategies → Decision criterion?

Objective:
To find a sustainable repair strategy

Description of the repair techniques

Basic repair technique → rebuilding the concrete cover by using three techniques

1. Wet shotcrete
2. Dry shotcrete
3. Formed concrete

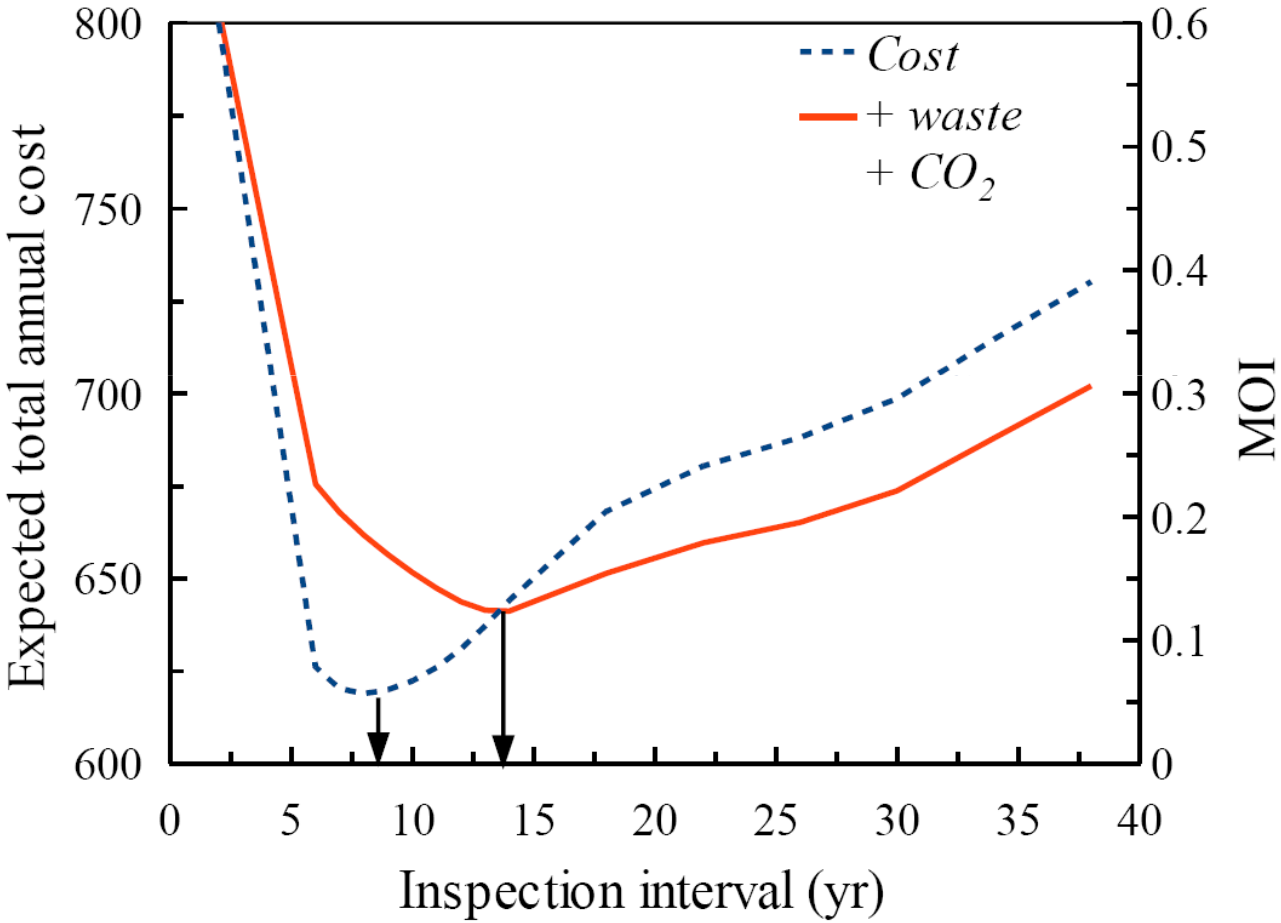
Beams after 80 years of exposure (Lorient, France)

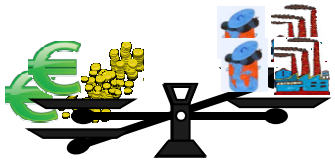
Practical aspects of the repair techniques

Criteria	Wet shotcrete	Dry shotcrete	Formed concrete
Product cost (€/kg)	0.68	0.28	0.14
Staff (people)	5	3	2
Waste generation	< 5%	> 30%	< 5%
Finished	Satisfactory	Rough	Very satisfactory

Results

Optimization of the sustainability of a given maintenance strategy

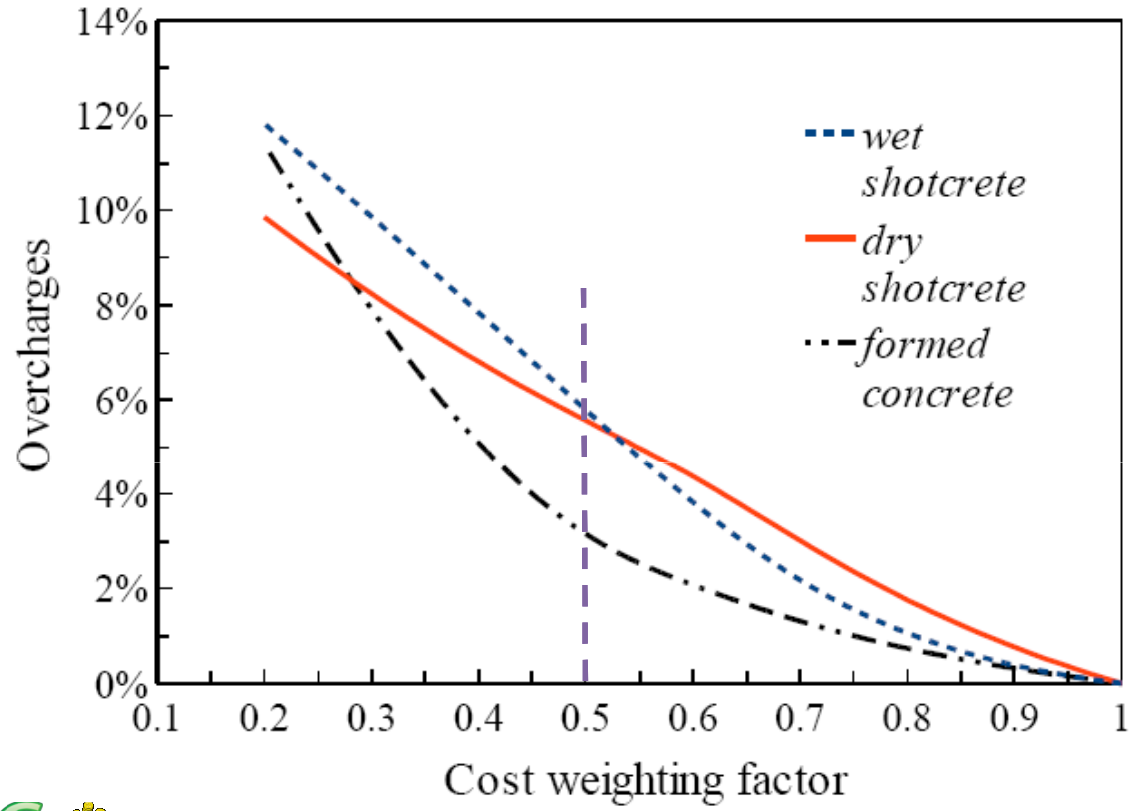




w_{cost} =0.6
w_{CO_2} =0.05
w_{waste}=0.05

Results

Optimization of the sustainability of a given maintenance strategy



For a lifetime of 50 years and a repair surface of 1000 m^2, a sustainable maintenance strategy will reduce the waste generation in 84 m^3 and the emissions in 28 tons of CO_2

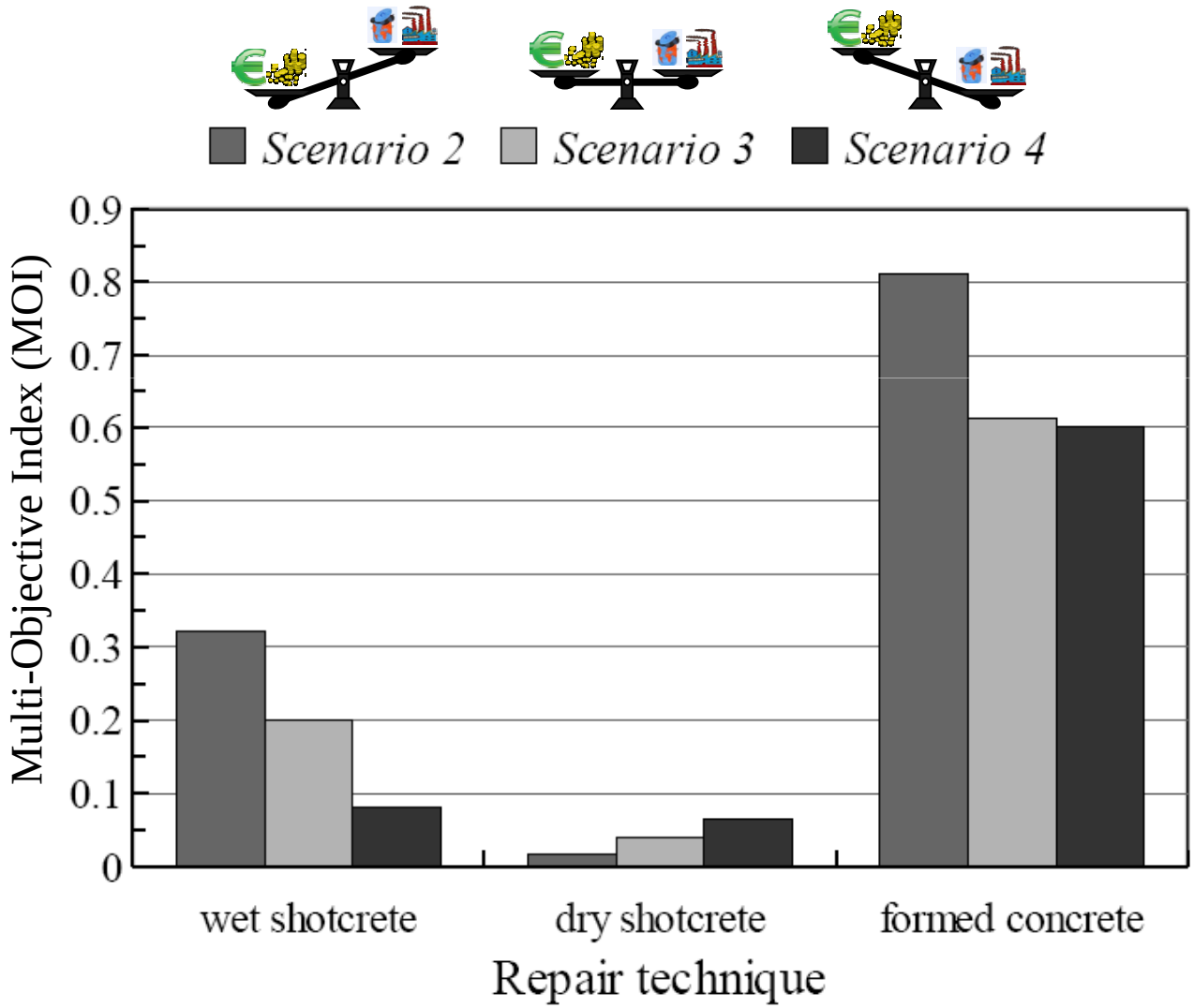
Results

Sustainable decision-making

Technique	Cost	Waste (10^3 m^3/yr)	Emissions (kg CO_2/yr)
Wet shotcrete	468	14.6	6.8
Dry shotcrete	362	16.4	7.8
Formed concrete	626	32.7	15.3

Results

Sustainable decision-making



Outline

1. RC deterioration and maintenance
2. Probabilistic modeling of chloride ingress
3. Optimal management of corroding RC structures
4. Sustainability of maintenance strategies
5. Closure

Summary and conclusions

- Probabilistic modeling of chloride penetration
  - Chloride penetration in unsaturated conditions and in two-dimensions
  - Chloride binding capacity
  - Time-dependence of T, h and C_{env}
  - Aging

- Markovian approach for modeling deterioration and maintenance actions
  - Preventive repair → reduce the reliability decay
  - Inspection → experimental measurements
  - Decision theory → effect of imperfect inspections

- Optimization of management of RC structures subjected to chloride penetration → (1) to minimize costs and (2) to ensure a level of safety

  Requirements:
  - To optimize the repair threshold C_{rep}
  - To determine an appropriate model of C_{th}
  - To improve the quality of the inspection technique

Summary and conclusions

- Sustainability of maintenance strategies → to minimize costs and environmental impact
  - Definition of criteria for sustainability analysis
  - Multi-objective optimization → sustainable maintenance strategy
  - Proposed methodology → to optimize the performance of a maintenance technique or as a tool for decision-making

Perspectives

Improvements of the model → addition of other physical phenomena, improvement of the probabilistic model and use of other inspection techniques or repair criteria

- Chloride penetration model
  - determination of model parameters for a wide range of concrete types and cement-based repair materials
  - formulation and implementation of a model that considers the kinematics between concrete cracking and chloride penetration
  - study of the influence of hourly, daily and weekly variations of temperature and humidity on chloride ingress
- Probabilistic model
  - consideration of the spatial variability of the phenomenon and the correlations between the material properties
  - characterization and modeling of error propagation in the whole deterioration process
  - consideration of the uncertainty inherent to waste generation and CO_2 emissions in the assessment of environmental impact

Perspectives

- Inspection/repair model
  - updating of transition probabilities from inspection data (Bayesian approach [Corotis et al., 2005]) and modeling of inspection based on NDT-tools
  - combination of preventive (SLS) and corrective (ULS) repair strategies during the structural lifetime to find an optimal solution in a larger time-window
  - formulation and study of the effectiveness of a management strategy that considers time-variant inspection intervals
  - integration of user costs to the analysis and assessment of the optimal inspection intervals on the basis of values other than the expected costs (i.e., [Schoefs et al., 2009])

Thank you for your kind attention!