Optimizing Infrastructure Solutions

Effects of carbonation on the lifetime of concrete structures and updating by Bayesian networks

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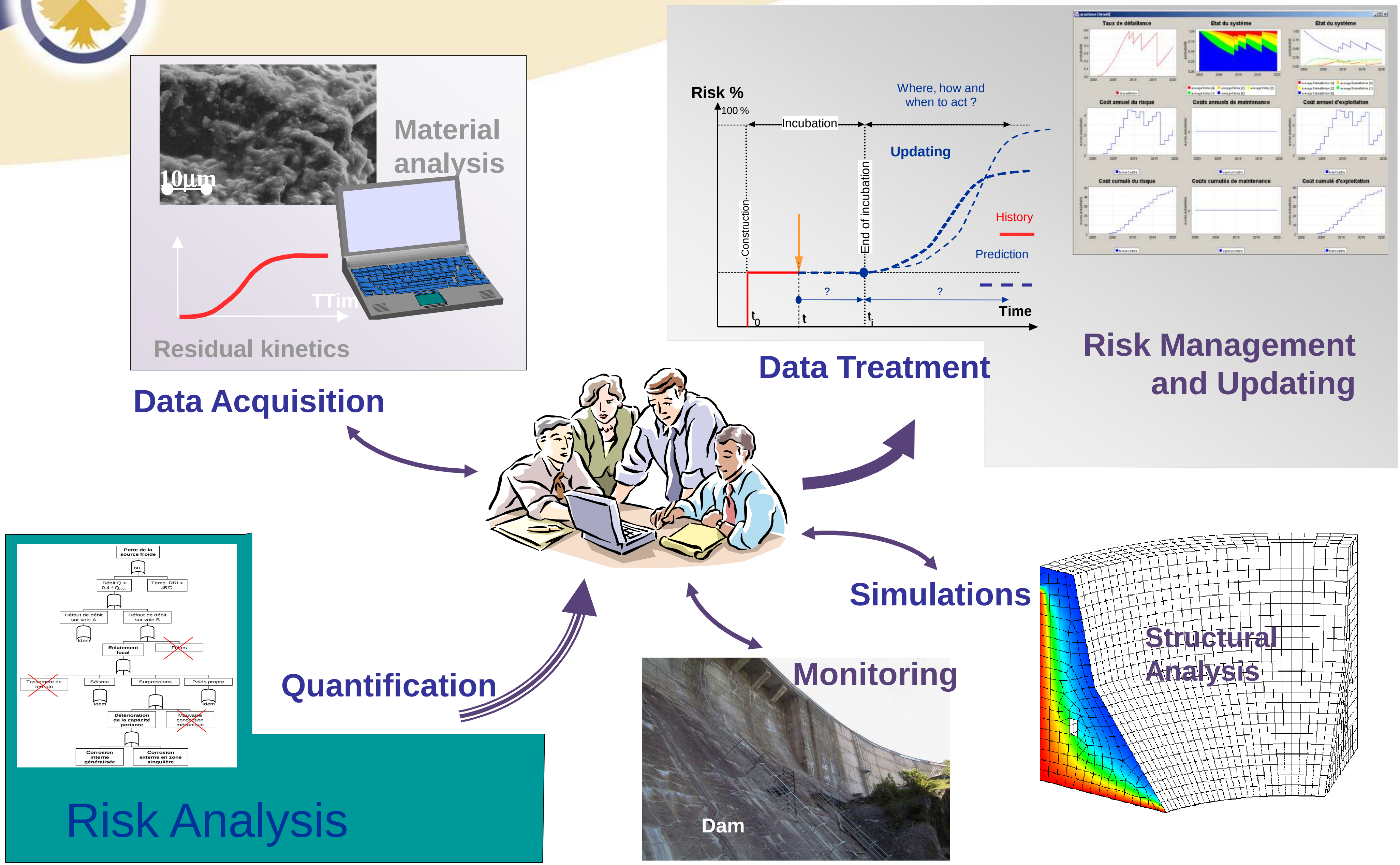
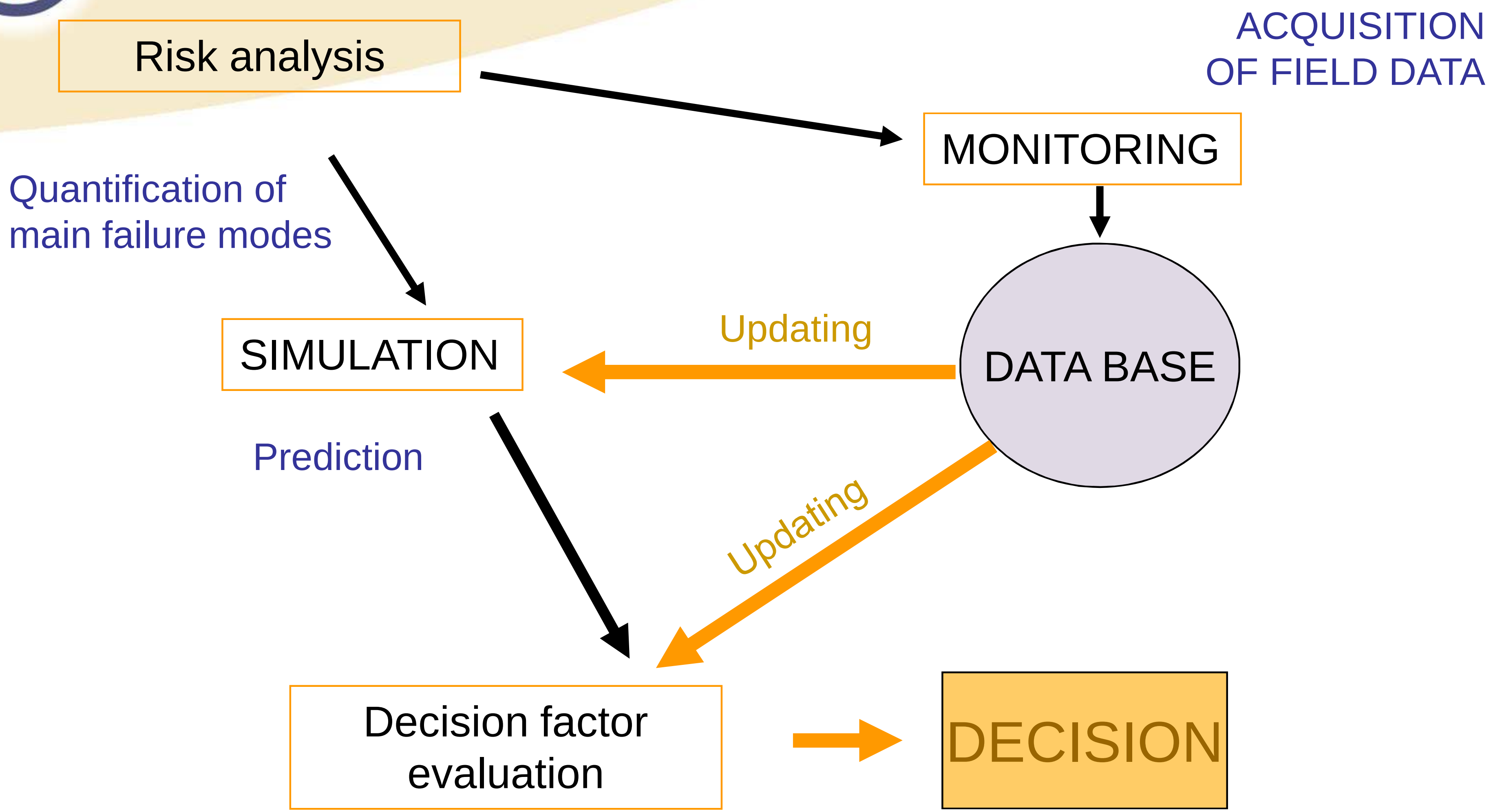
DECISION MAKING: INTEGRATION OF KNOWLEDGE



Risk management associated to ageing

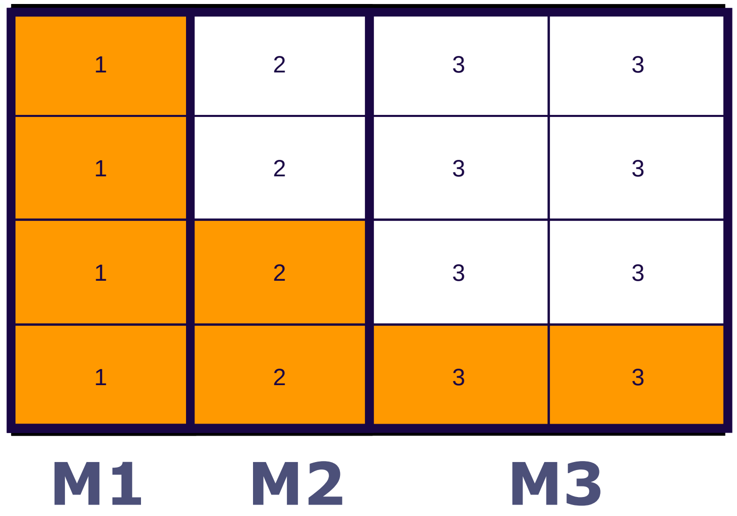


Predictive maintenance
Cost estimation
Optimisation of maintenance decision

UPDATING:
better management of uncertainty

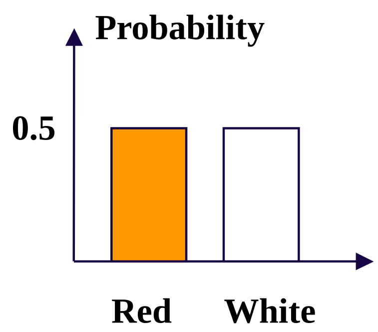
BAYESIAN APPROACH
Basic principles

Factory: 3 machines : M1, M2, M3
Production: white and red parts
(Color C: discrete variable)



Probabilities to have white or red parts:

P(C=white)= ½
P(C=red)= ½

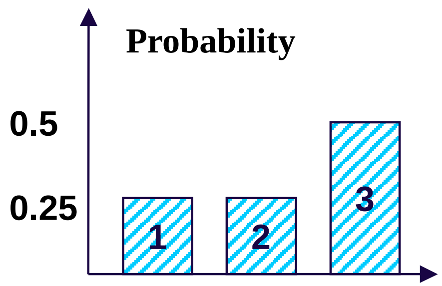


- Conditional probabilities :

P(C=red|M1) = 1
P(C=red|M2) = ½
P(C=red|M3) = ¼

- A priori : origin of the part

P(M1) = P(M2) = ¼
P(M3) = ½



BAYESIAN APPROACH
Basic principles

- A priori: origin of the part

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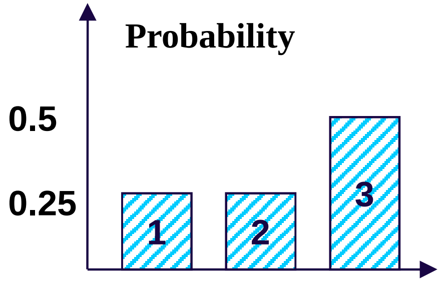
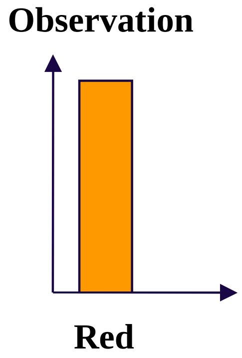


Prior

- Observation : red piece picked



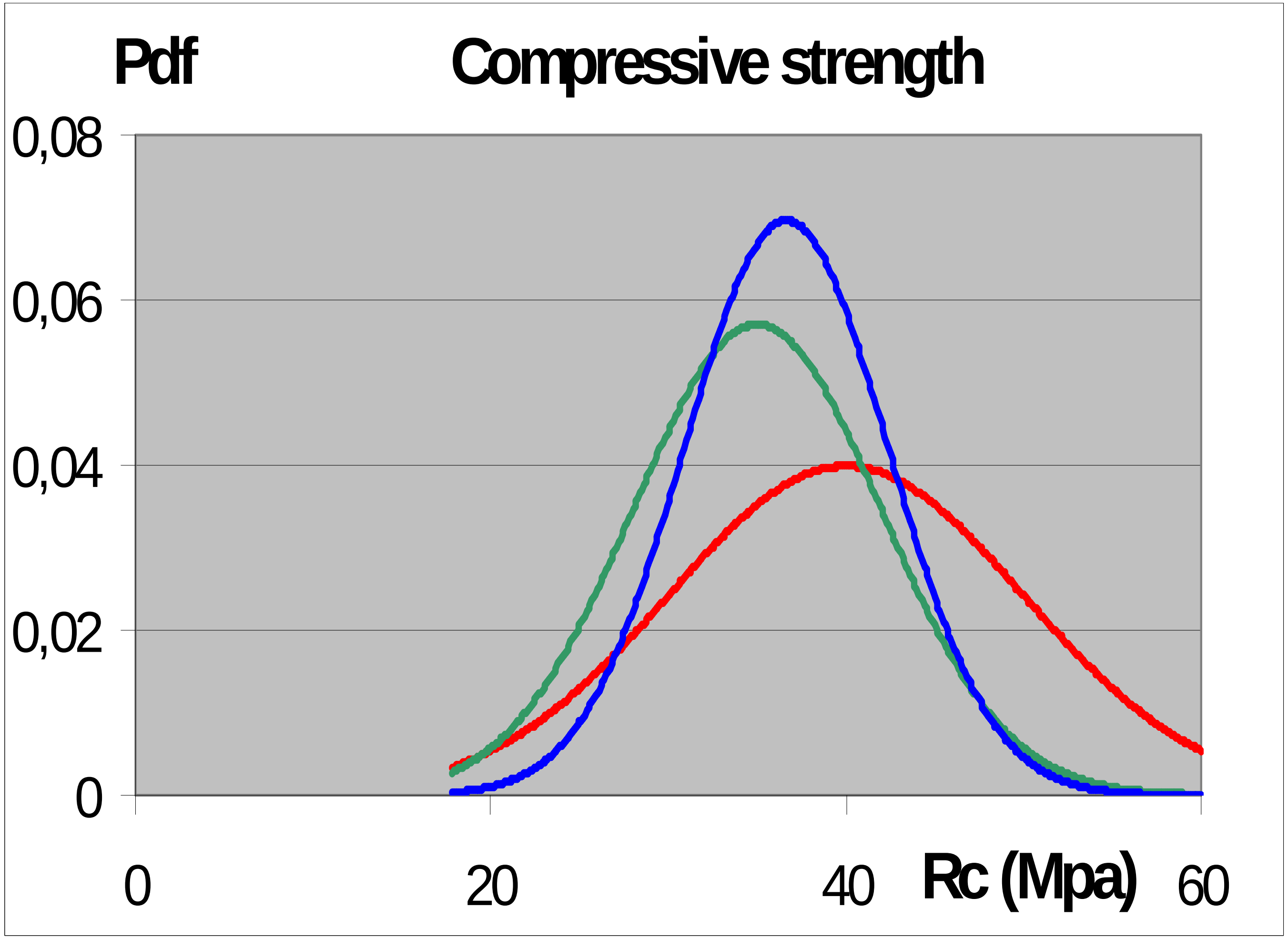
Obs.

Updating process

Posterior

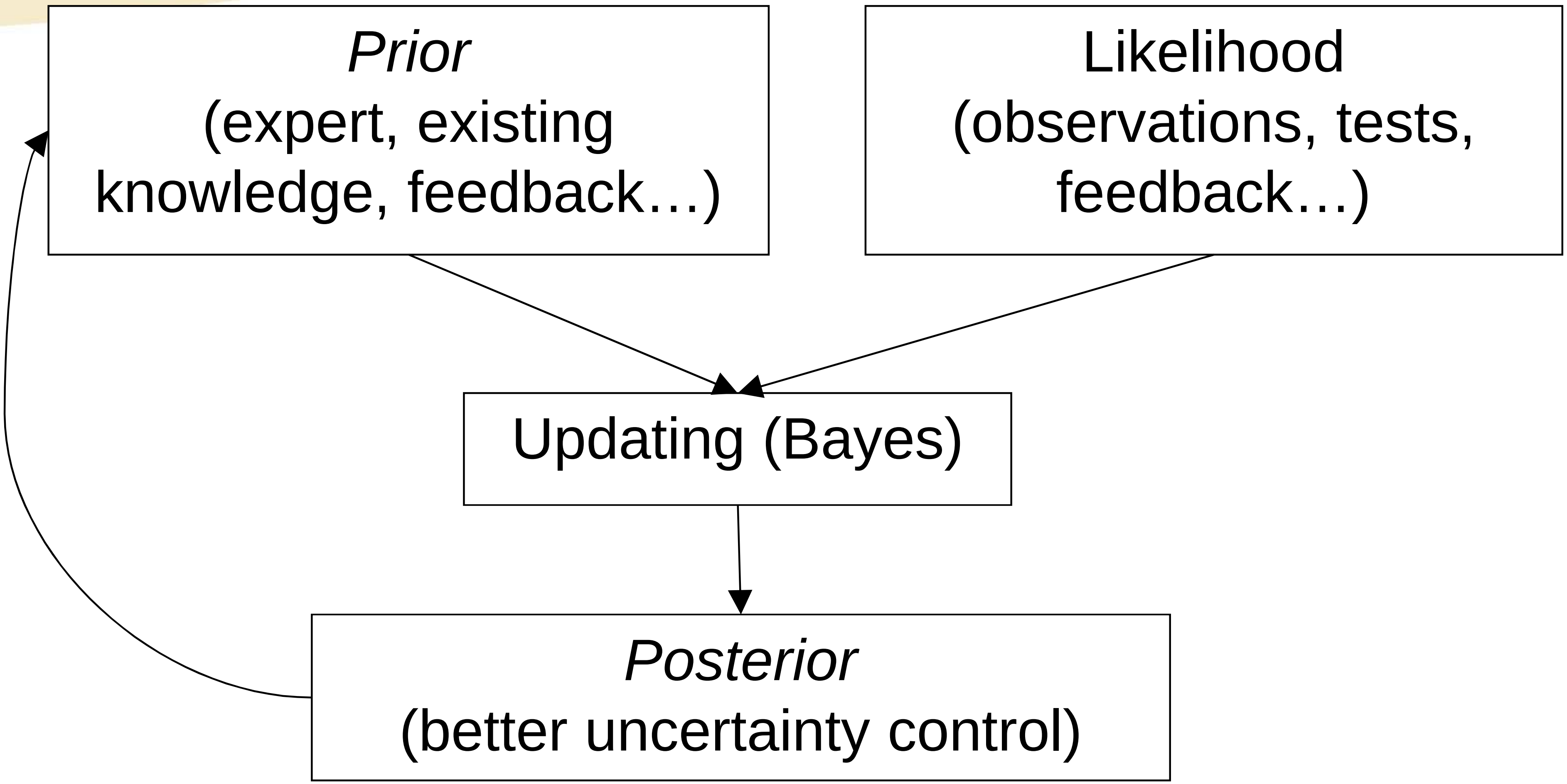
Updating of a continuous parameter

Example with Normal distributions



1. *A priori law: N(40, 10)*
2. Observation: N(35, 7)
3. *A posteriori: N(36.6, 5.7)*

Bayesian approach



Bayesian networks

- **Simple updating :**
  evolution of one single parameter

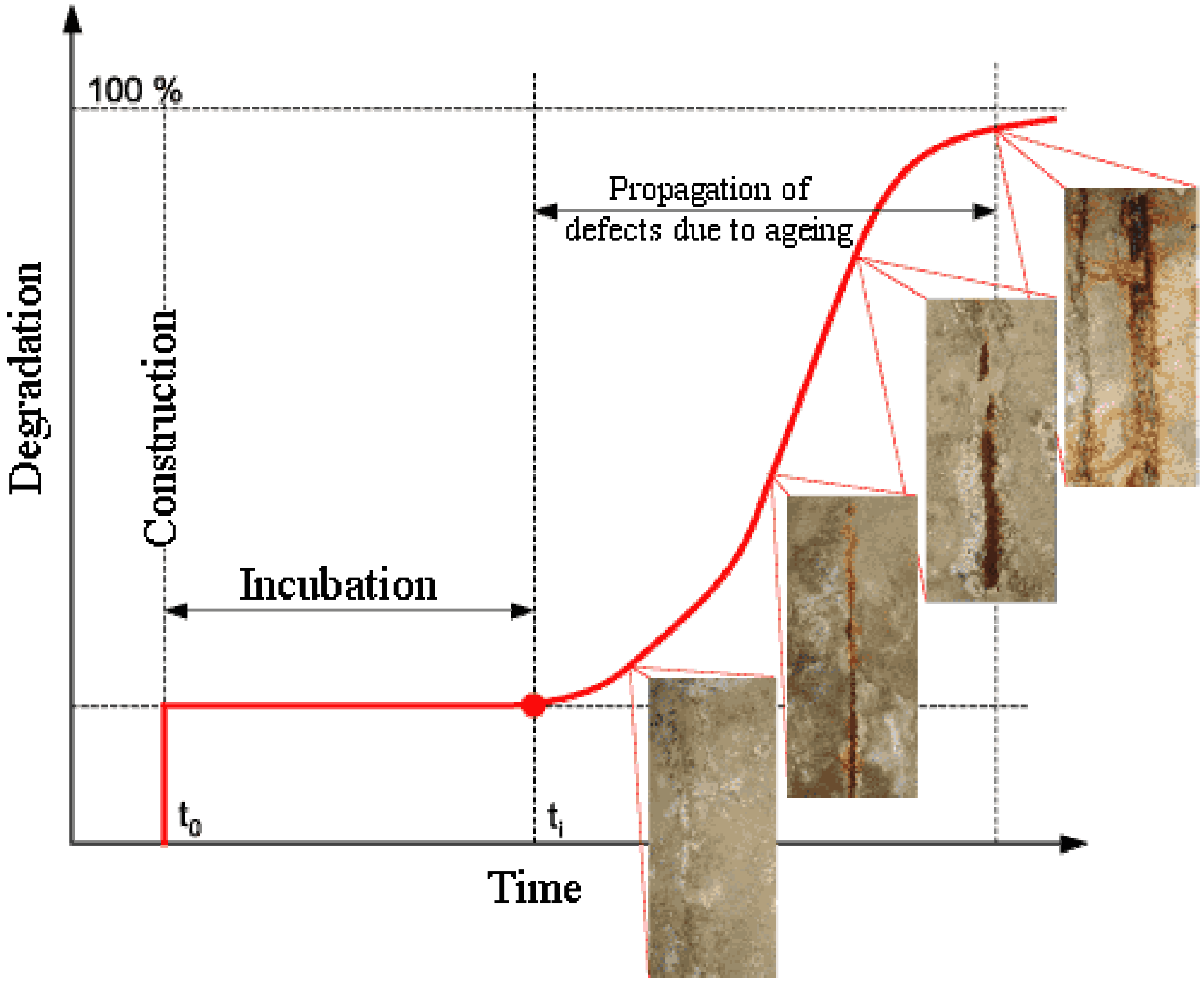
  => Bayes' theorem
  (analytical solution for some cases)

- **Degradation modeling function of numerous uncertain parameters**
  => Bayesian networks
  (numerical simulation)

Life time of concrete structure

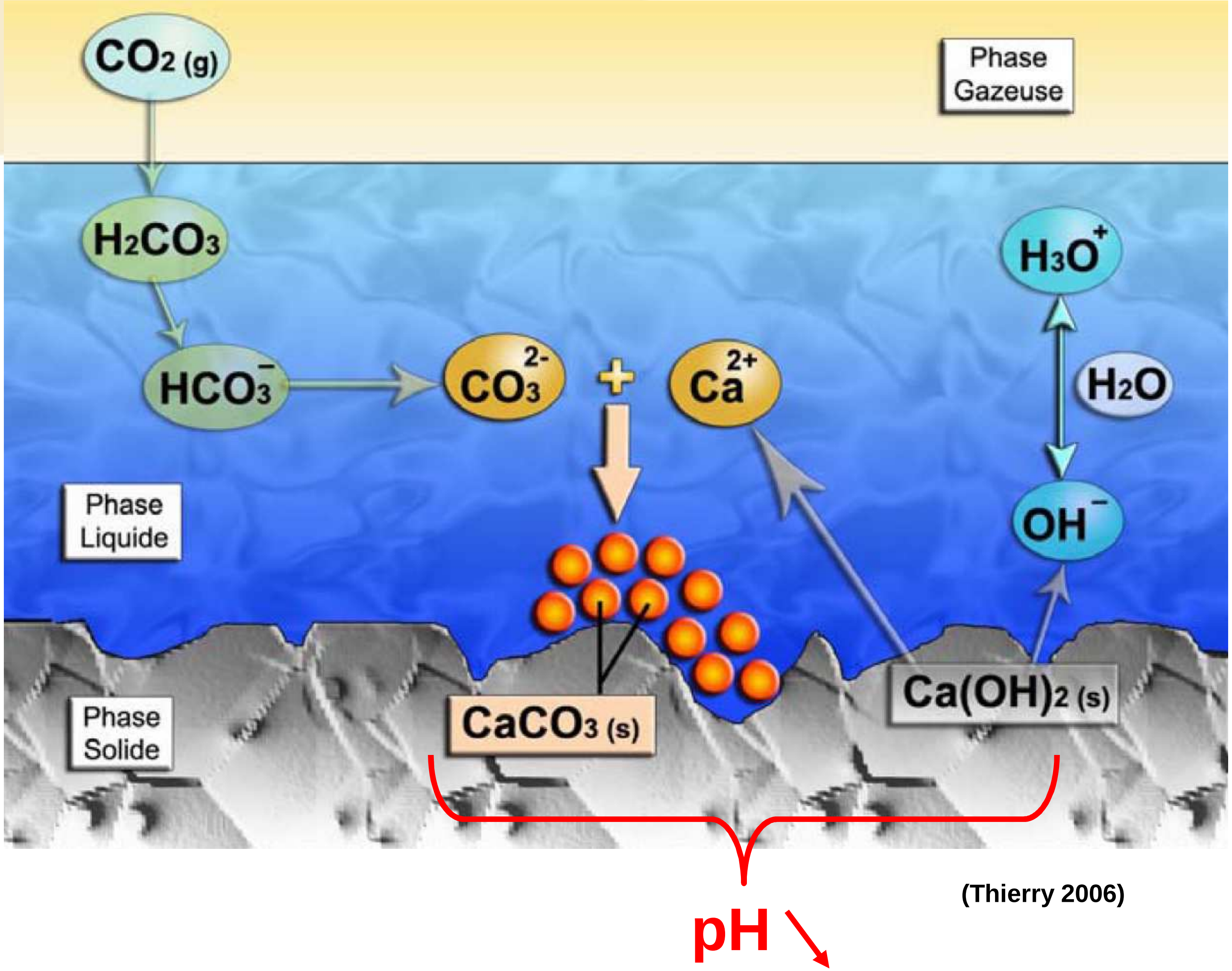
Concrete structure

Concrete degradation vs time



➡ **Life time assessment: important stake for structure owner**

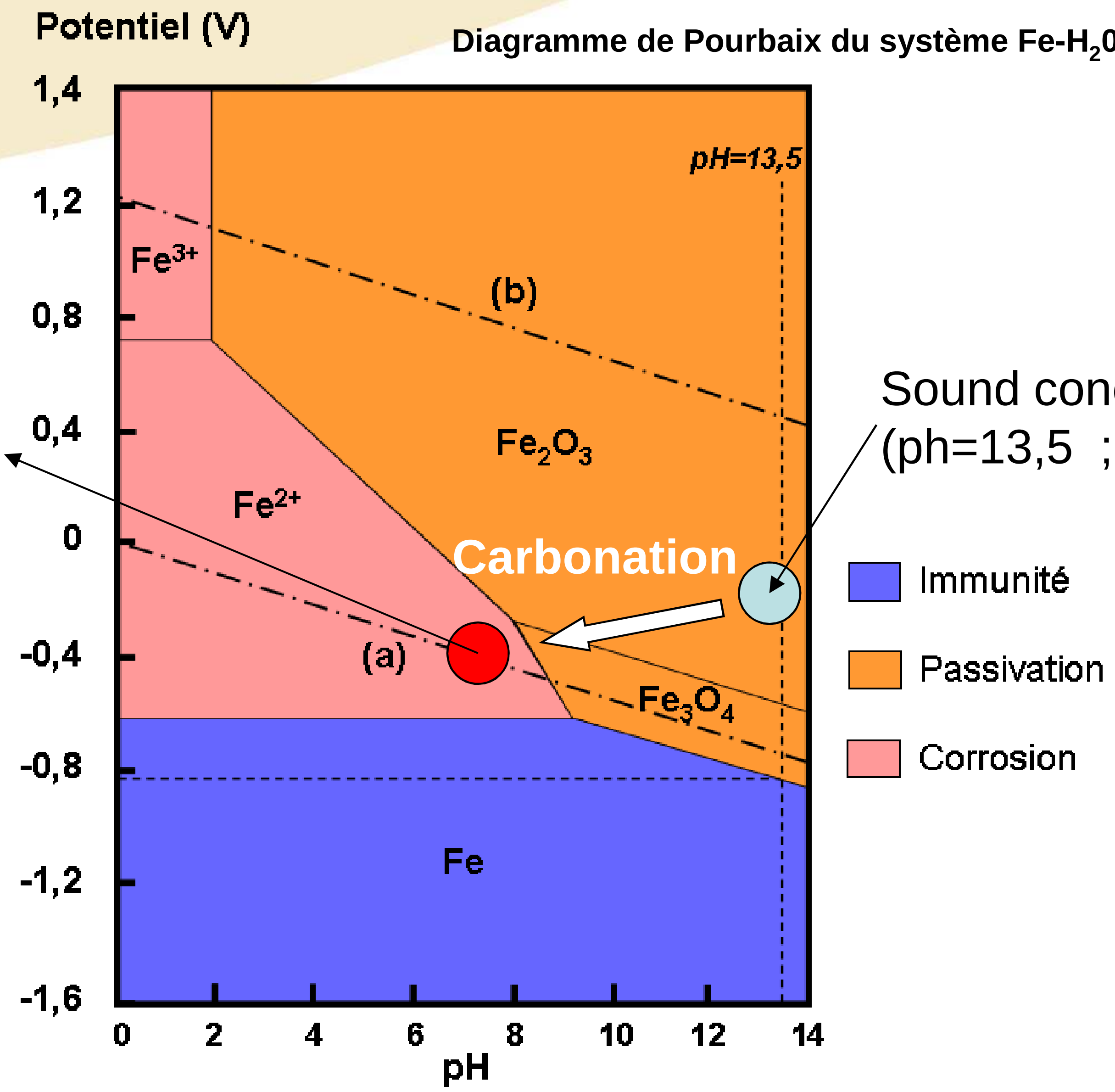
Carbonation of concrete



(Thierry 2006)

⇒ **Strongly depends on transport properties of concrete (diffusivity, porosity)**

Corrosion of steel in concrete

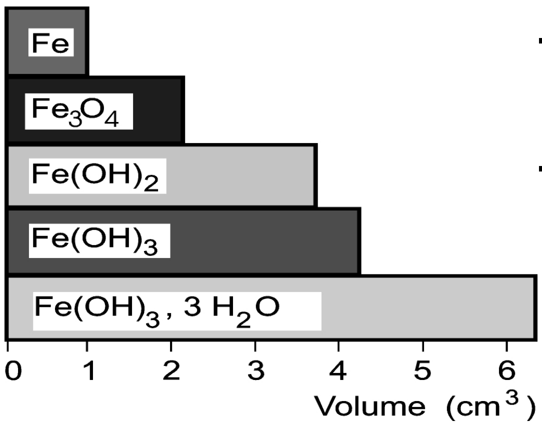


Carbonated concrete
(ph=7 ; E=-400 mV)

CORROSION

Sound concrete
(ph=13,5 ; E=-200 mV)

Volume increase of steel oxydation products



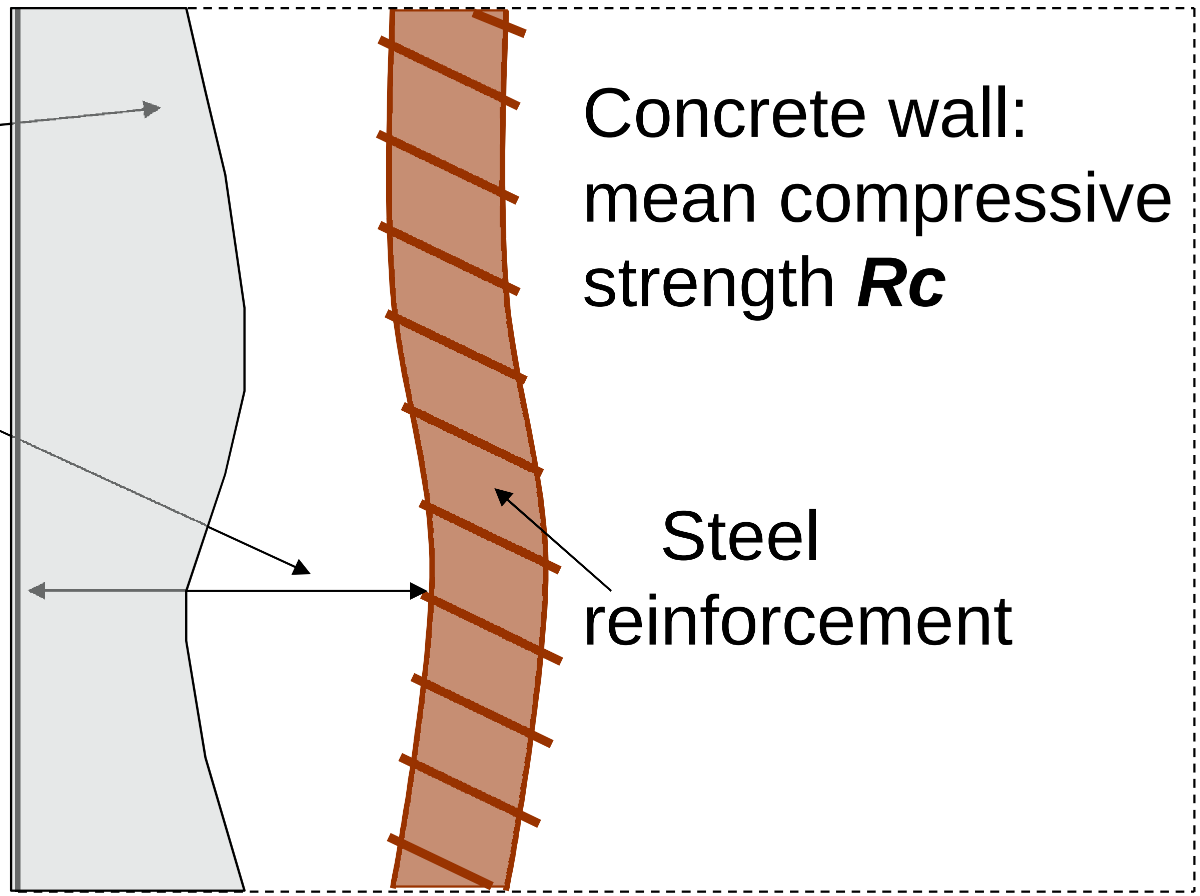
Mechanical stresses leading to concrete cracking

Corrosion risk for concrete structures

Carbonation depth
X = f(Rc, RH, t,…)

d: concrete cover

Environment:
relative humidity
RH



Limit state: failure when x ≥ d (corrosion starts)

Carbonatation models for concrete

- **Engineering models:**

$$x = \gamma f(RH) k(Rc) \sqrt{t}$$

(Petre Lazar 2001)

with:
- RH: relative humidity
- Rc: compressive strength of concrete
- γ: exposition coefficient to CO_2
- t: time

and:

$$\begin{cases} f(RH) = -3.5833RH^2 + 3.4833RH + 0.2 \\ k(Rc) = \sqrt{365}\left(\dfrac{1}{2.1\sqrt{Rc}} - 0.06\right) \end{cases}$$

Carbonation rate mainly depends on Rc: influence of cement type ?

Carbonatation models for concrete

- **Engineering models related to physical parameters:**

Carbonation rate related to the amount of cement hydrates likely to be carbonated (C-S-H but also Portlandite, Ettringite and Aluminates) and CO_2 pressure

$$x_c(t) = \sqrt{\frac{2.err1\left(\frac{D^0_{CO_2}}{Q_1}\right)_{ref} Q_1 P_0 t}{RT\left(1+\beta C_2\left(\frac{P_0}{P_{atm}}\right)^n\right).\left(\frac{\varphi_p C_2}{1+n}\left(\frac{P_0}{P_{atm}}\right)^n + Q_1\right)}}$$

(Hyvert et al 2010, Mai-Nhu et al 2012)

Where:

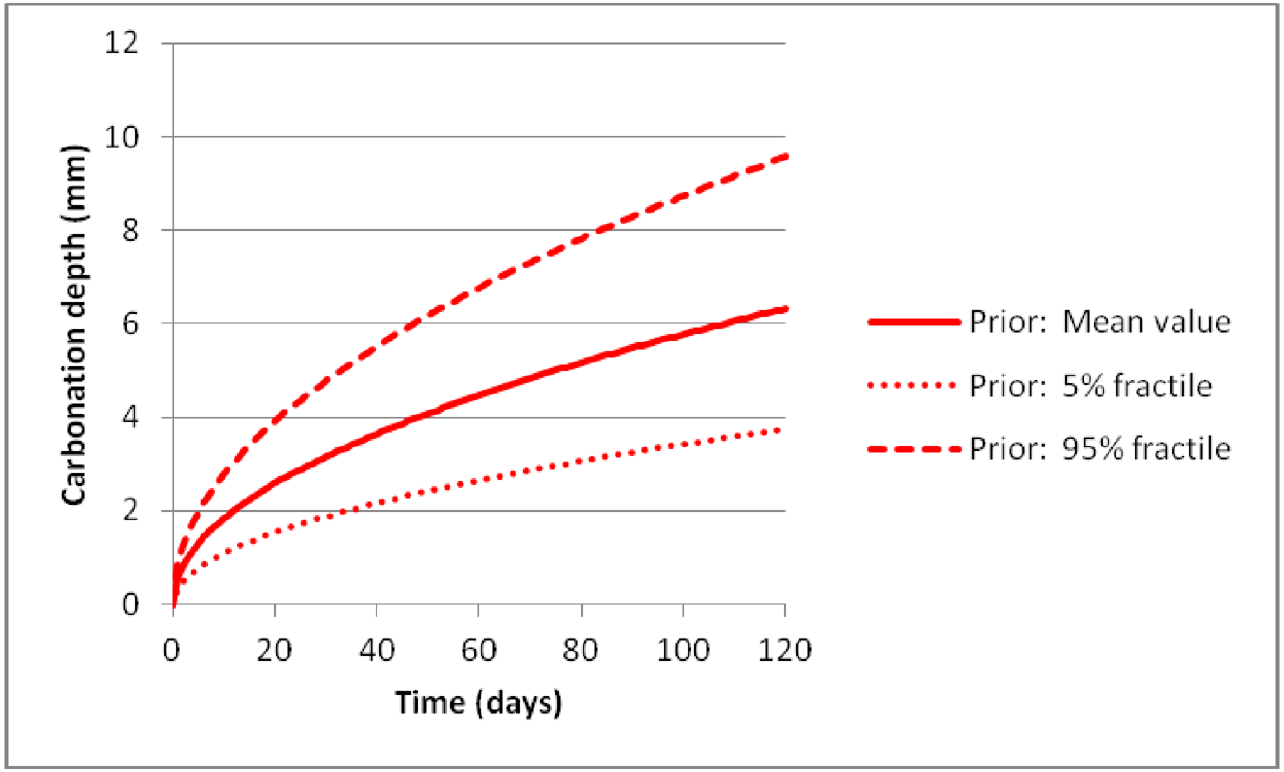
$$err1 = \frac{\left(\frac{D^0_{CO_2}}{Q_1}\right)_{\text{mod èle}}}{\left(\frac{D^0_{CO_2}}{Q_1}\right)_{ref}} = \frac{\frac{\left(x_c^{\exp}\right)^2 RT}{2P_{Khan}t_{Khan}}}{6{,}44.10^{-13}\left(27{,}2e^{-0{,}032 f_{cm,28}}\right)^2}$$

Prior estimation of carbonation depth

• APPLET's French national project:

- Life time of structures, variabilities and uncertainties related to concrete characteristics

- Compressive strength (CEM I + silica fume): mean value at 28 days : 58.3 MPa
  standard dev : 4.3 MPa (CV=7.3 %)
- Accelerated carbonation test (CO_2 pp = 50%)



Uncertainties:

Concrete compres. strength:
LogN (58,3 MPa; 4,3 MPa)

Model error:
LogN (1,11 MPa; 0,52 MPa)

Experimental data

• **APPLET's French national project:**

Carbonation tests at different times (CO_2 pp = 50%)

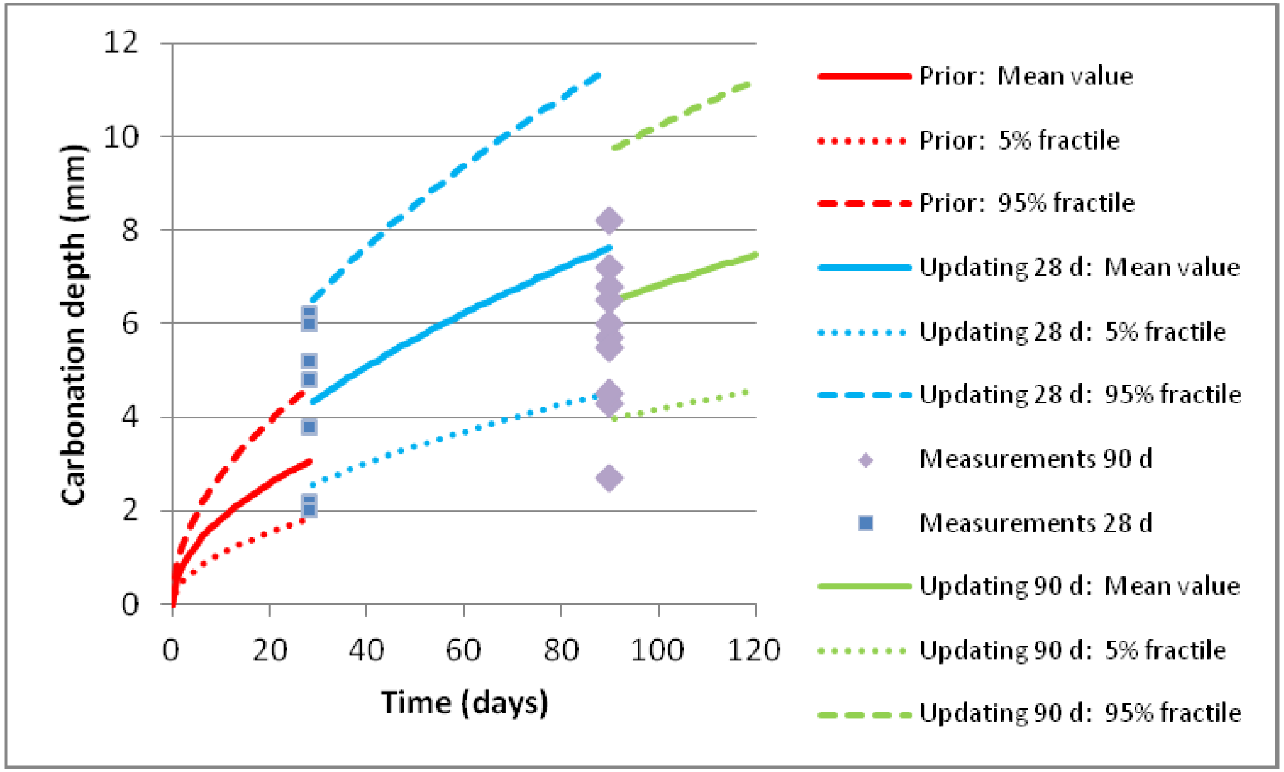
Age	Carbonation depth (mm)										Mean value (mm)	Standard deviation (mm)	Coefficient of variation
28 j	5,2	6	5,2	2	3,8	4,8	6,2	6	2,2	2	4,34	1,72	39,5 %
90 j	6,5	8,2	5,7	2,7	6	5,5	7,2	6,8	4,3	4,5	5,74	1,59	27,8 %

Strong variability: 30 to 40% !

Posterior estimation of carbonation depth

• APPLET's French national project:

•Experimental data are used to update the prior estimation of carbonation depth



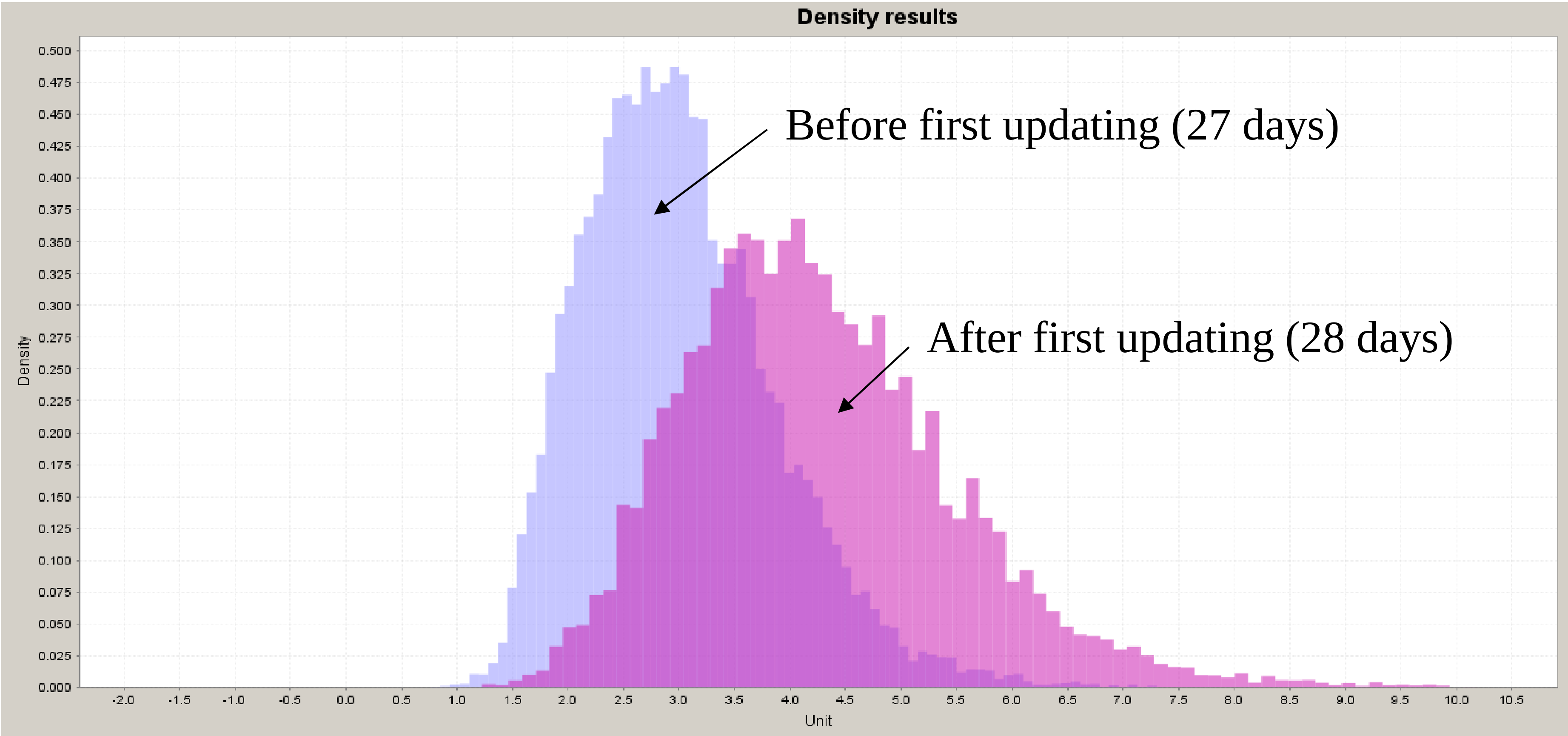
Model/experimental data:

- 28 days: underestimation of carbonation depth
- 90 days: overestimation of carbonation depth
- uncertainty ↗ then ↘ (CV from 30 to 40 %)

Posterior estimation of carbonation depth

• Evolution of uncertainty

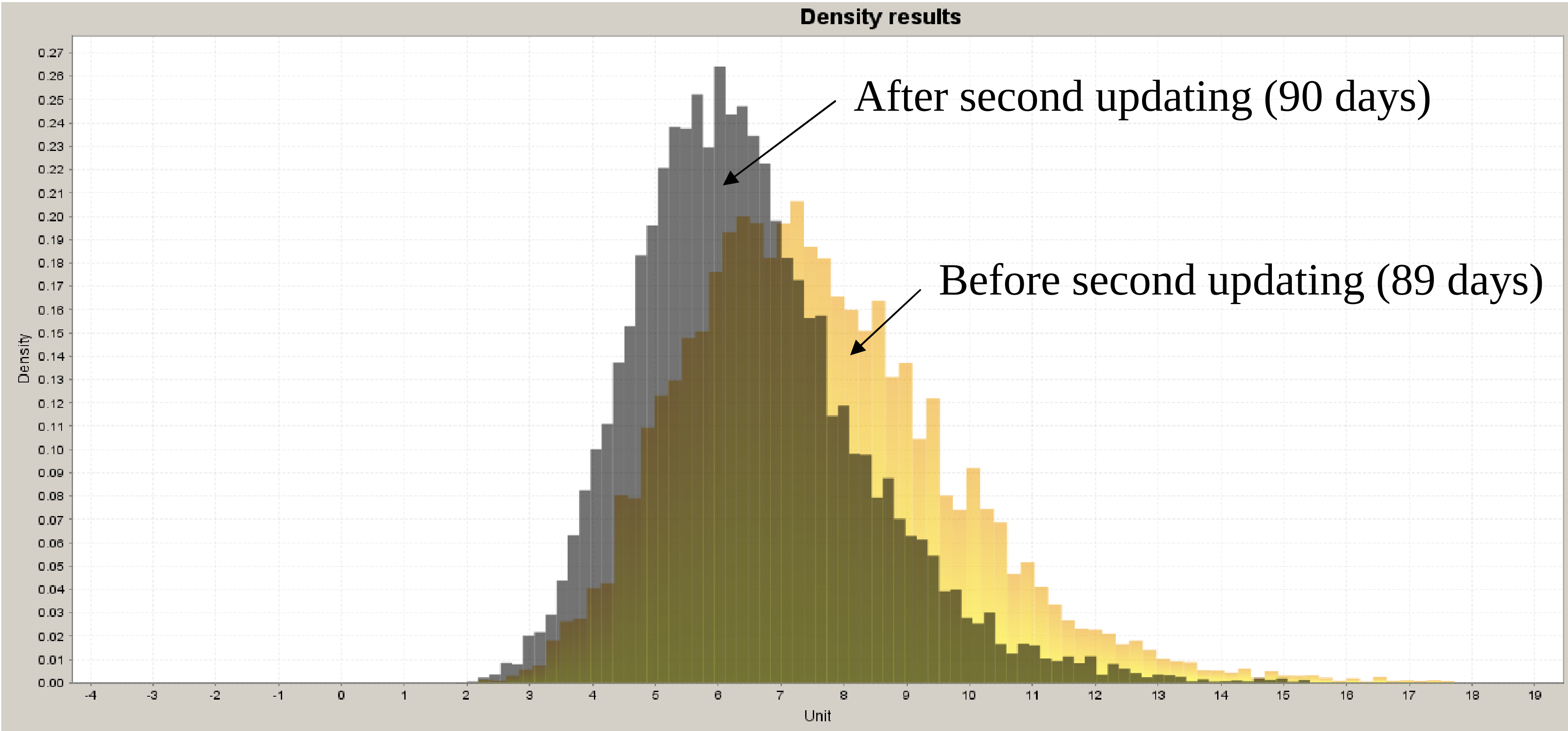
• First updating at 28 days: pdf of carbonation depth



Posterior estimation of carbonation depth

- **Evolution of uncertainty**

- Second updating at 90 days: pdf of carbonation depth

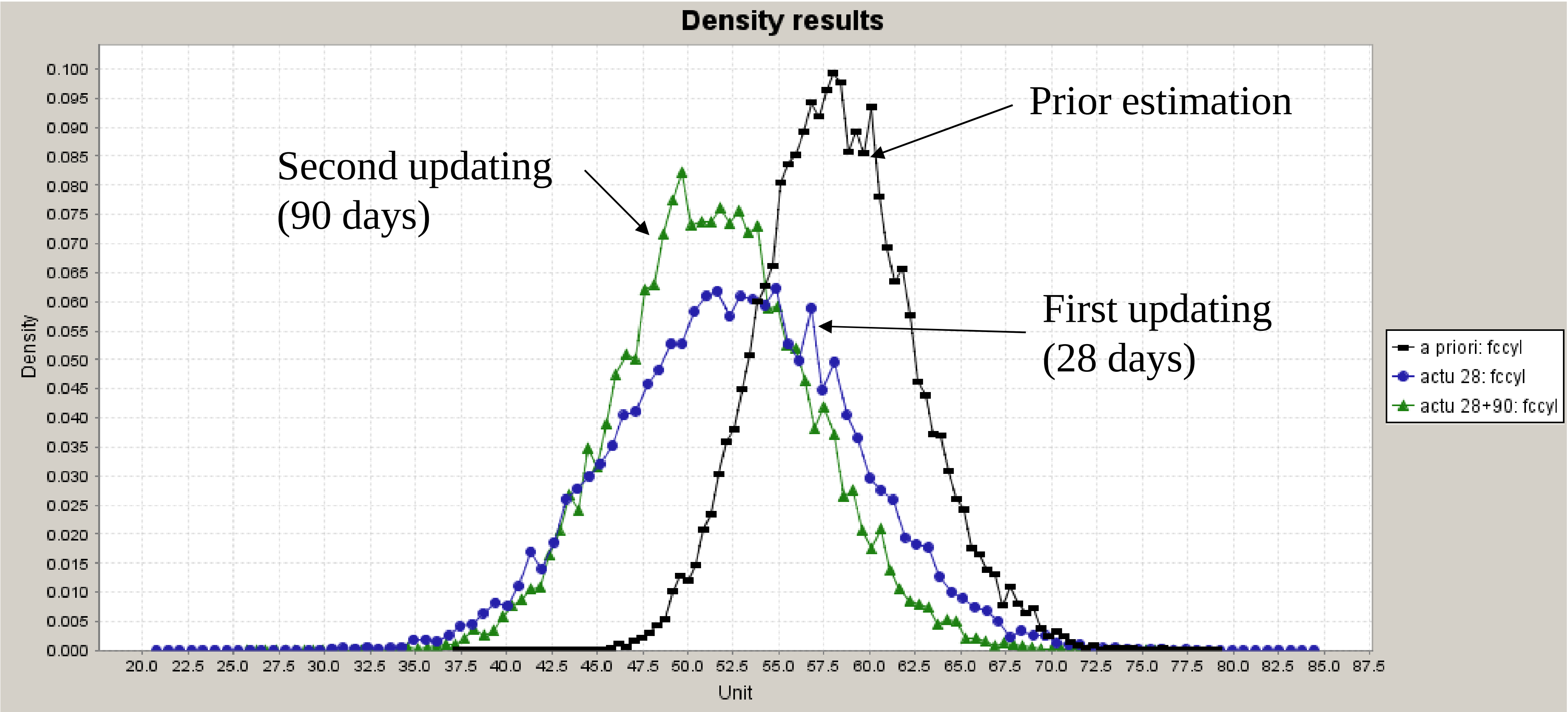


Updating of the random variables

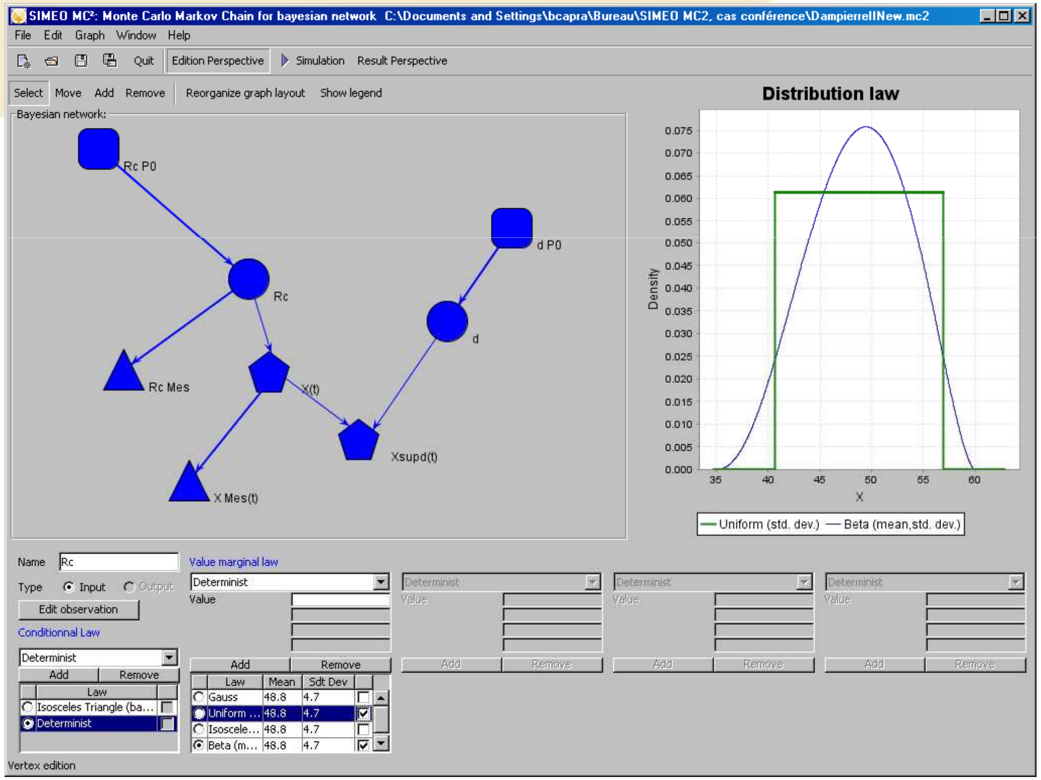
Random variable	Compressive strength (MPa)	Model error
Initial data	Lognormal law: *Mean: 58,3* *Standard deviation: 4,3*	Lognormal law: *Mean : 1,10* *Stand. Dev.: 0,5*
Prior simulated (Monte Carlo) (400 000 drawings)	*Mean: 58,2* *Stand. Dev.: 4,2*	*Mean: 1,10* *Stand. Dev. 0,5*
28 days updating	*Mean: 52,6* *Stand. Dev.: 6,4*	*Mean: 1,35* *Stand. Dev.: 0,7*
90 days updating	*Mean: 51,5* *Stand. Dev.: 5,2*	*Mean: 0,95* *Stand. Dev.: 0,5*

Updating of the random variables

- Updating of compressive strength probability density function



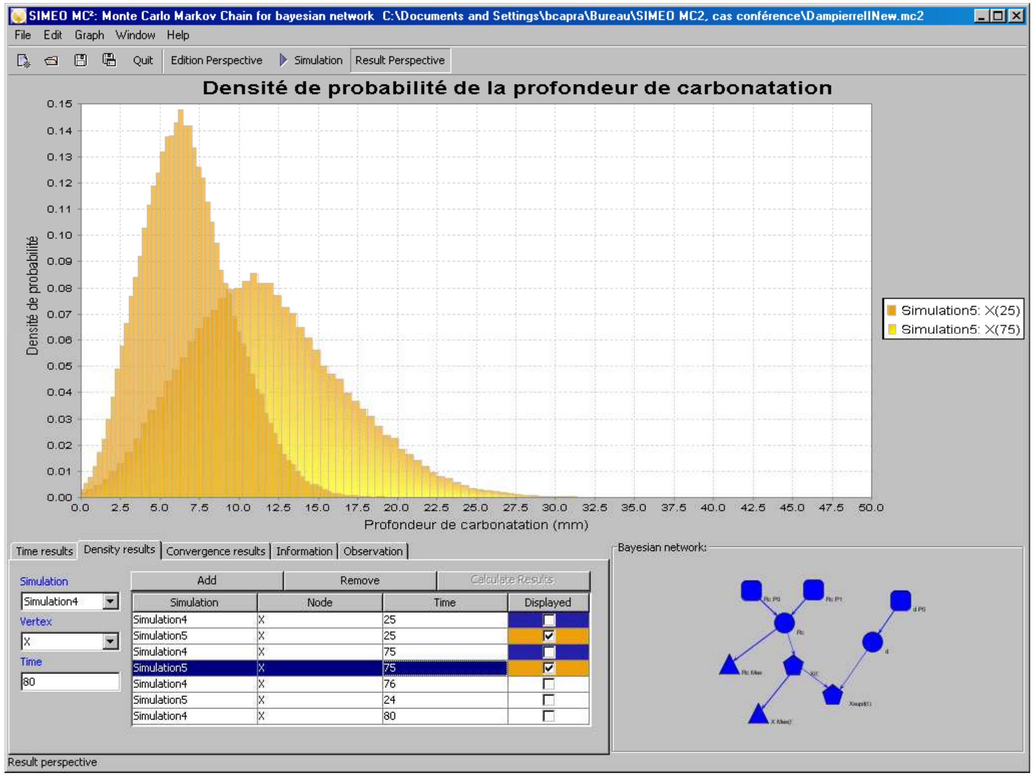
Software: SIMEO MC²



MCMC method

(Markov Chains Monte Carlo)

- Markov Chain
- Métropolis-Hastings algorythm with *Gibbs sampling*



CONCLUSIONS

In the field of infrastructure risk based management, Bayesian networks allow :

- the use of field data for updating
  (especially where few data are available)
- the use of heterogeneous information
  (expert, feedback, tests,…)
- user control of confidence
- a better control of uncertainty for ageing processes

But :

- the method is more complicated than classical reliability approaches (convergence) and must be applied with care
- **does not prevent from non representative models**

Thank you for your attention

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