Performance based design of concrete structures

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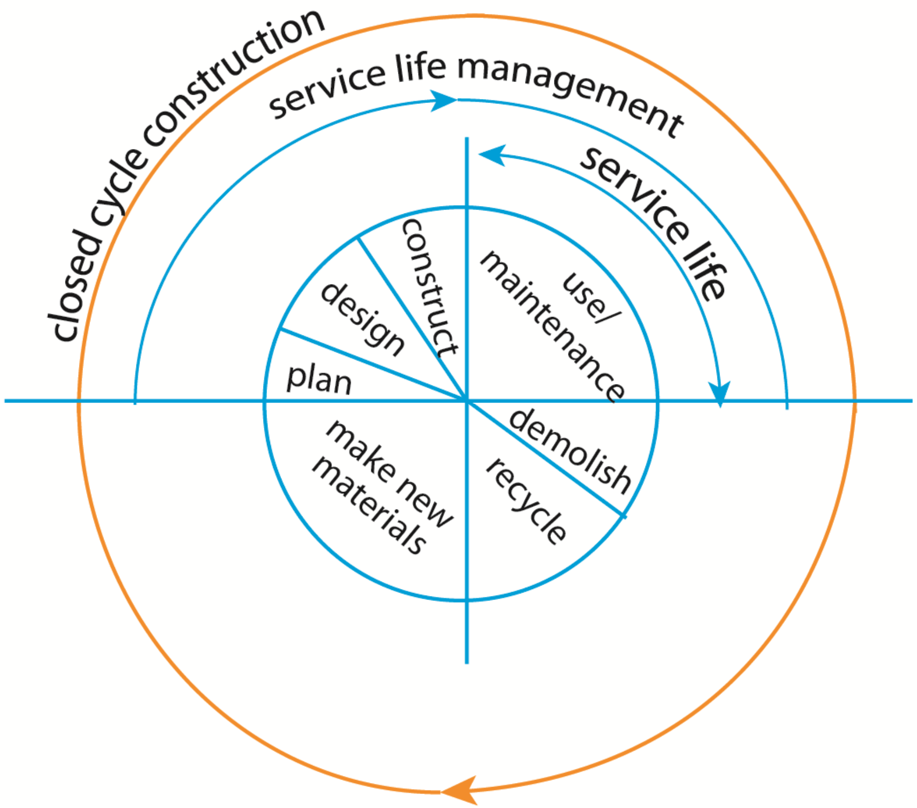
Performance based service life design of concrete structures

Contents:

1. Introduction: what is service life and what is performance?
2. Example: performance in a structural design
3. Which performances have to be taken into account?
4. Example: design on durability – corrosion of the reinforcement
5. Optimization of the design
6. Performance based design
7. Conclusions

1. Introduction: what is service life?

Service life is that stage of a life of a structure when it is in use



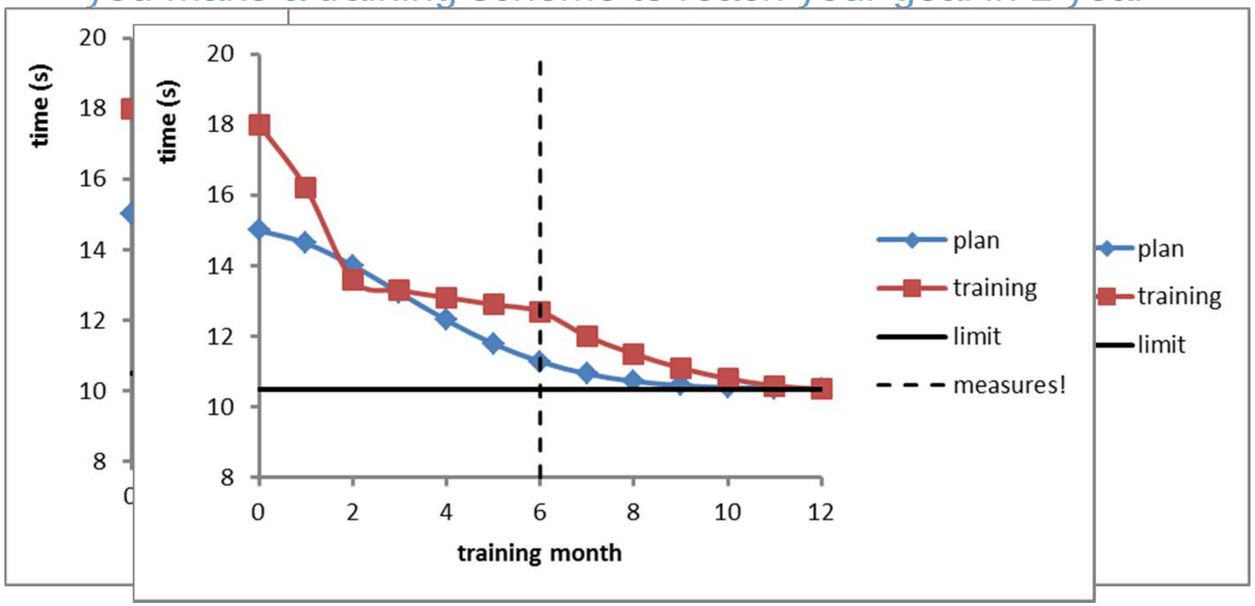
end of service life

1. Introduction: what is performance

A **performance** is a **task** that is executed with a certain **quantified** result (limit)

Example: you want to run the 100 m in 10.5 seconds

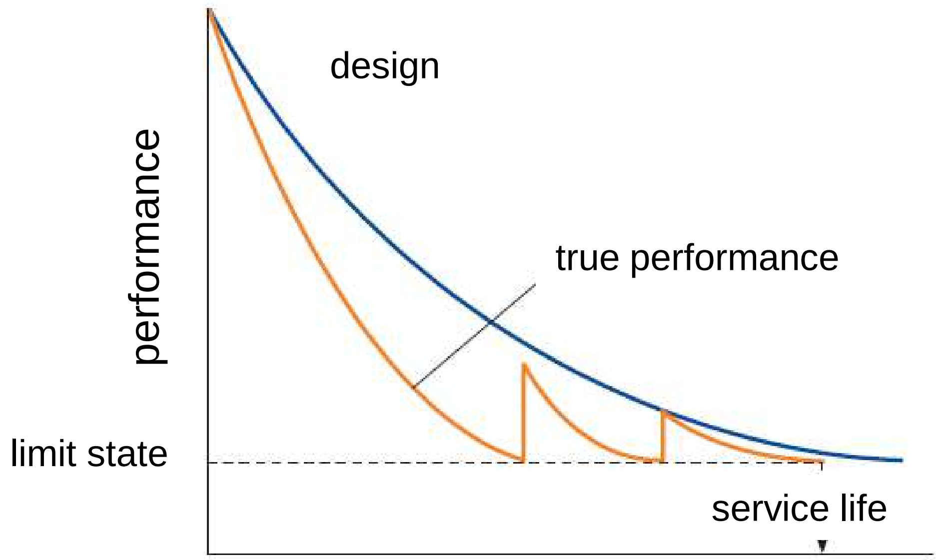
you make a training scheme to reach your goal in 1 year



1. Introduction: what is performance

A **performance** is a **task** that is executed with a certain **quantified** result (limit state)

Performances for structures are similar to that of a sportsman/woman:



1. Introduction: what is performance

Why should you care
about the performance?

1. Introduction: what is performance

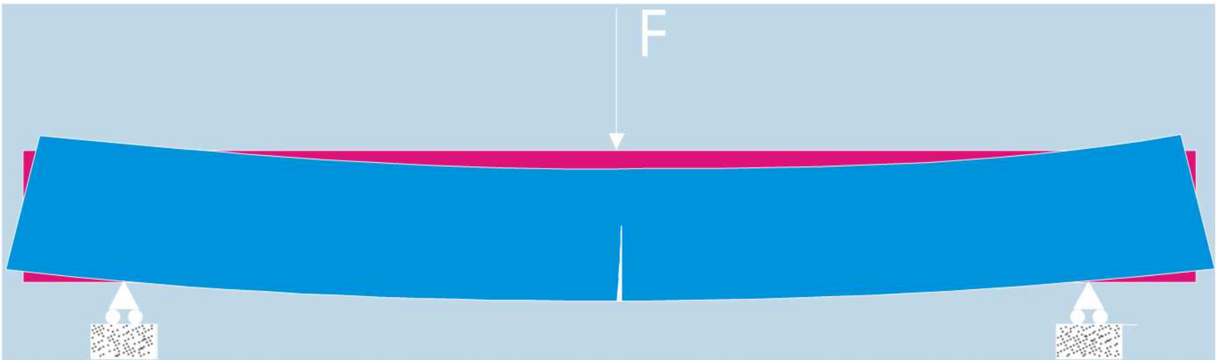
Now we know why it is important, but WHICH, HOW, and HOW LONG?


Performance based service life design of concrete structures

Contents:

2. Performance in a structural design

Example: beam on two supports



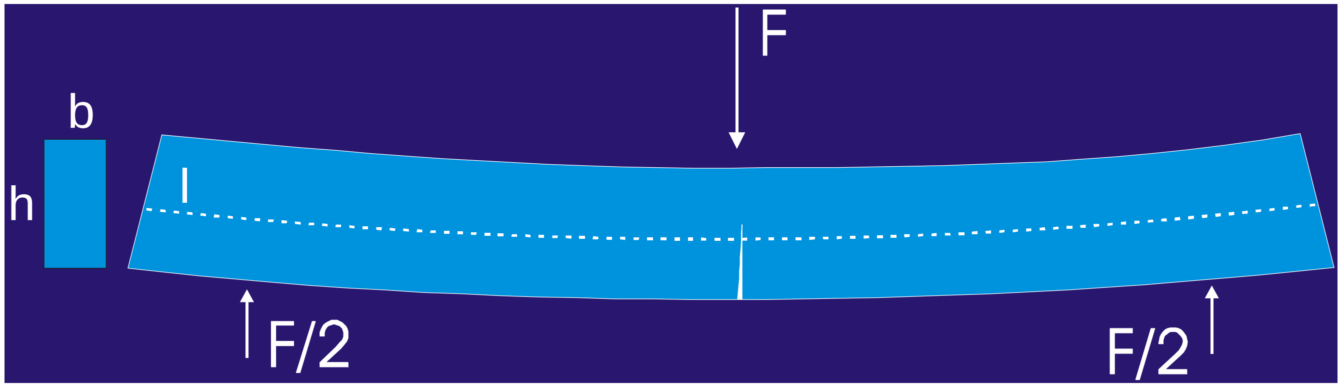
Question: can this bar withstand the load?

- What is the influence of the load F, or rather:
  the reaction S of the structural element on the load?
- What is the resistance R against the load?
- Is the rest capacity Z=R-S>0 to that the beam does not fail?

2. Performance in a structural design

- $S = l/2 * F/2$
- $R = 1/6 * b * h^2 * f_c$

- $Z = R - S = bh^2 f_c/6 - lF/4$



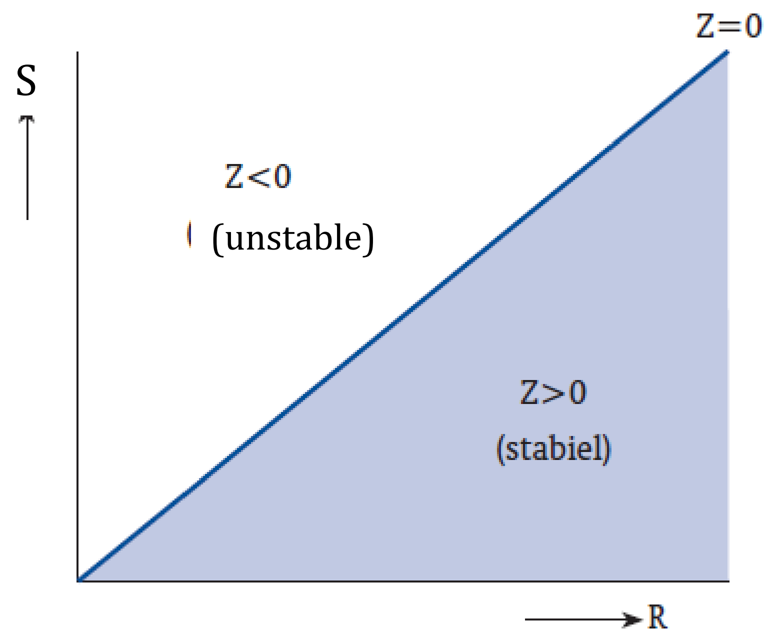
Performance demand:

- Z>a with a an acceptable limit

- **But what is acceptable?**

2. Performance in a structural design

- $Z = R\text{-}S = bh^2 f_c/6 - lF/4$

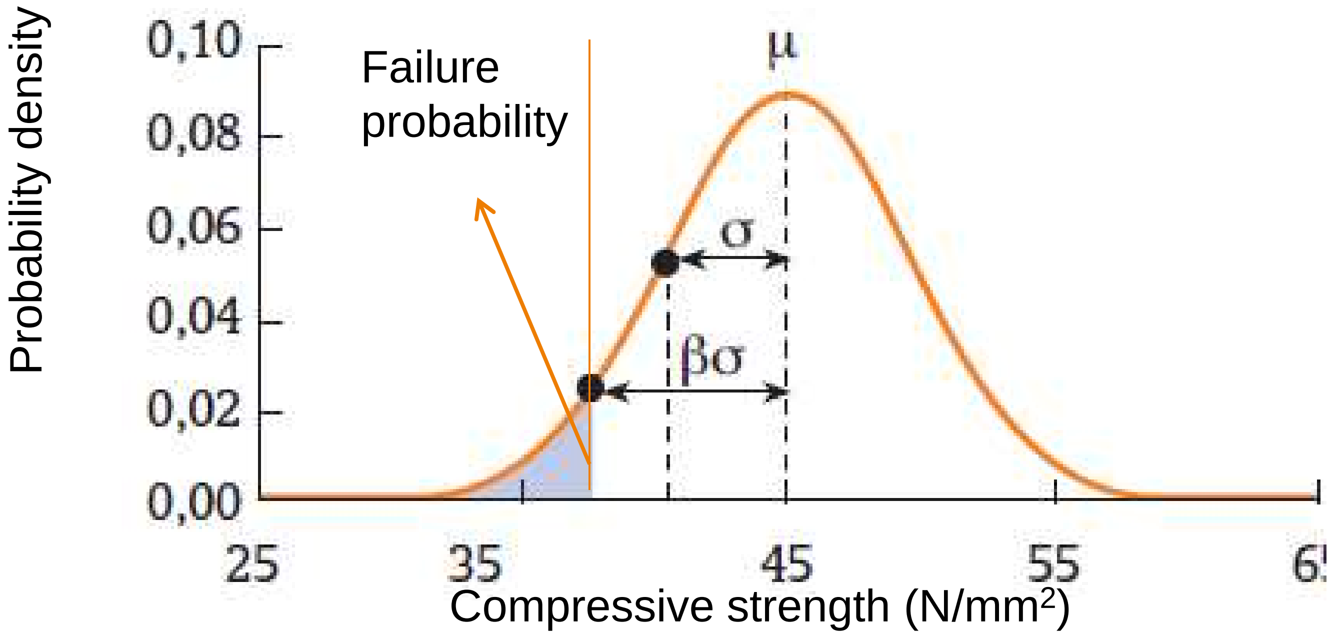


Performance demand:

- Z>a is thus the limit state
- **But what is acceptable limit?**

2. Performance in a structural design

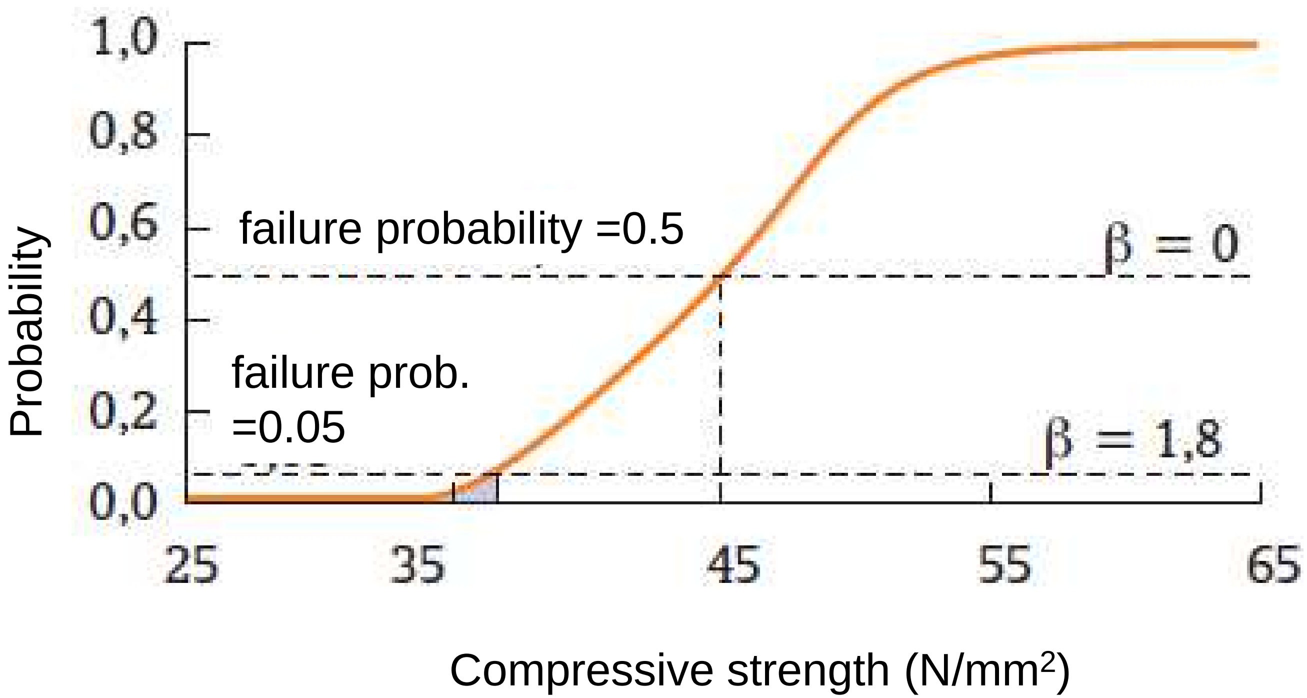
- Limit states cannot be calculated on the basis of average variables because the probability that the compressive strength is actually lower is too high (= 50 %)



E.g.: the characteristic compressive strength = the strength with a 5 % (single sided) failure probability

2. Performance in a structural design

- Z = R-S >a => calculate!, but …. the variables are stochastic functions, viz. they vary!!

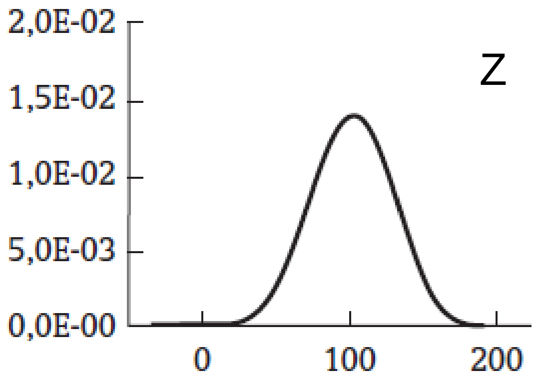


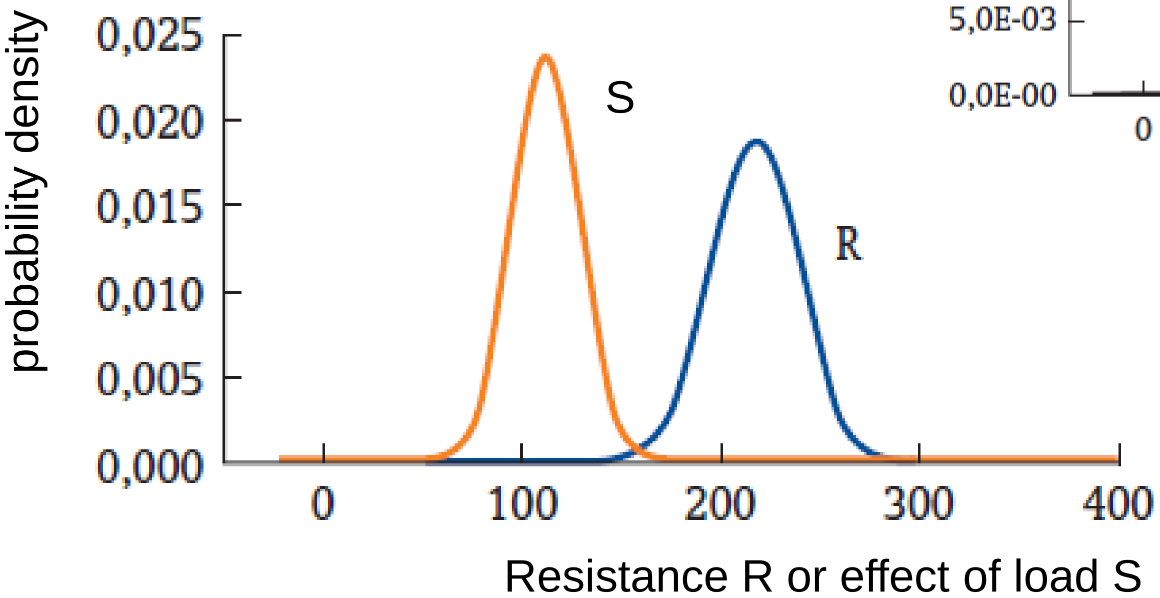
E.g.: the characteristic compressive strength = the strength with a 10 % (single sided) failure probability

2. Performance in a structural design

- The chance that Z takes on an unacceptable value must be smaller than a on forehand agreed upon value:

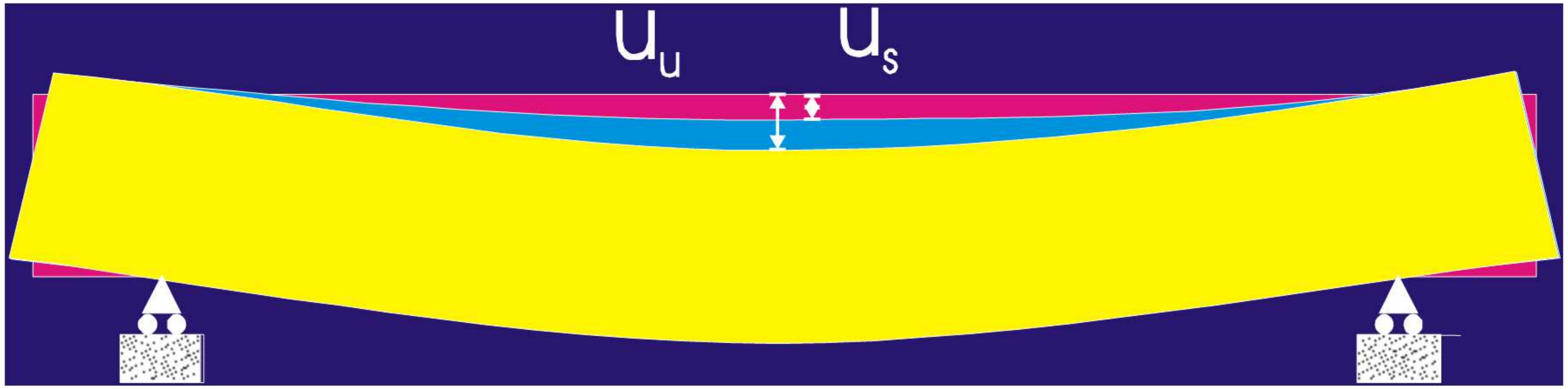
  $\{ Z = R-S<a\} < P_{acc}=\Phi(-\beta)$





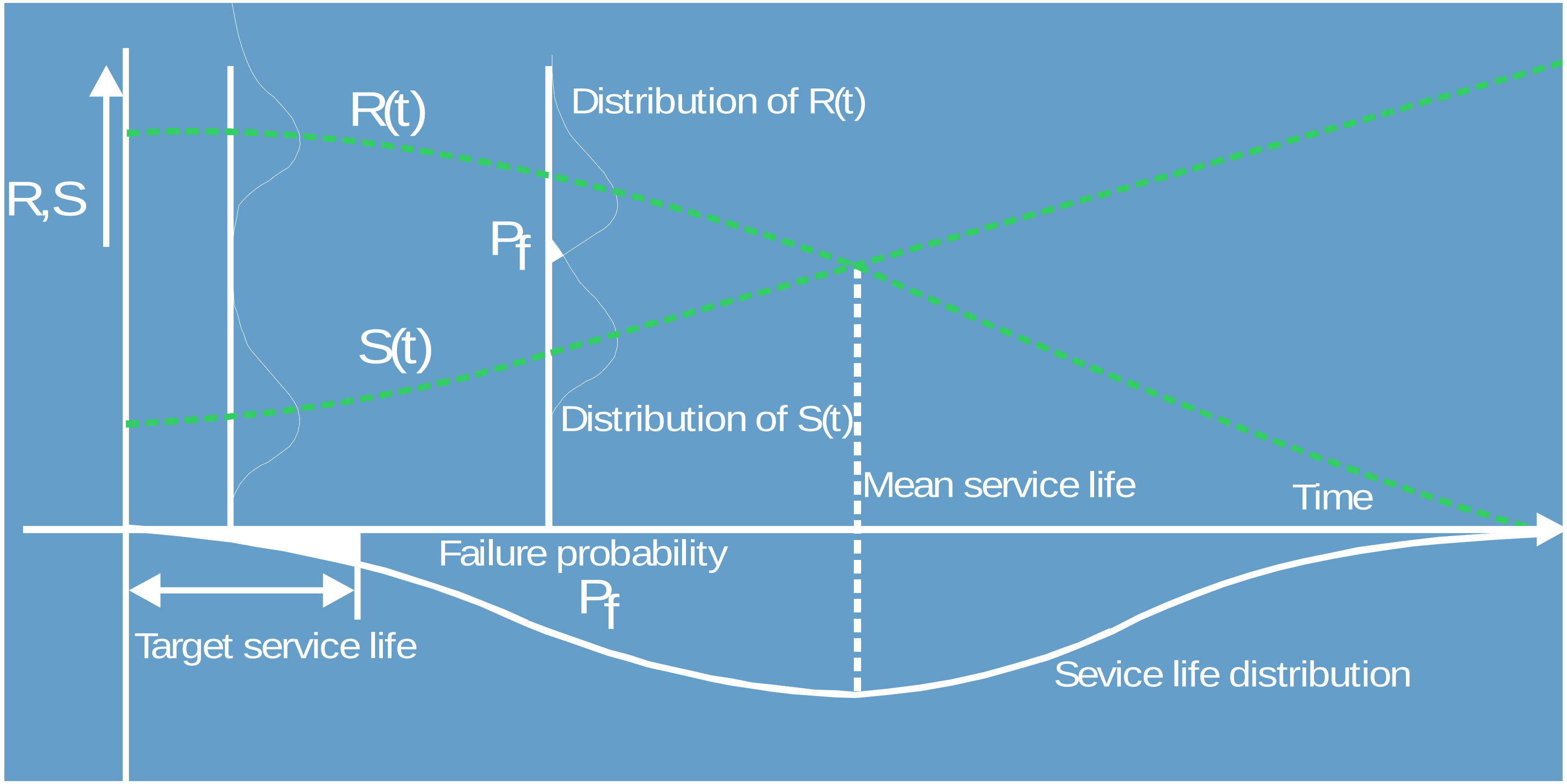
2. Performance in a structural design

- β is called reliability index is need to be upon
- Its value usually depend on the type of limit states:
  - ultimate limit state: β=3.8
  - service limit state: β=1.5



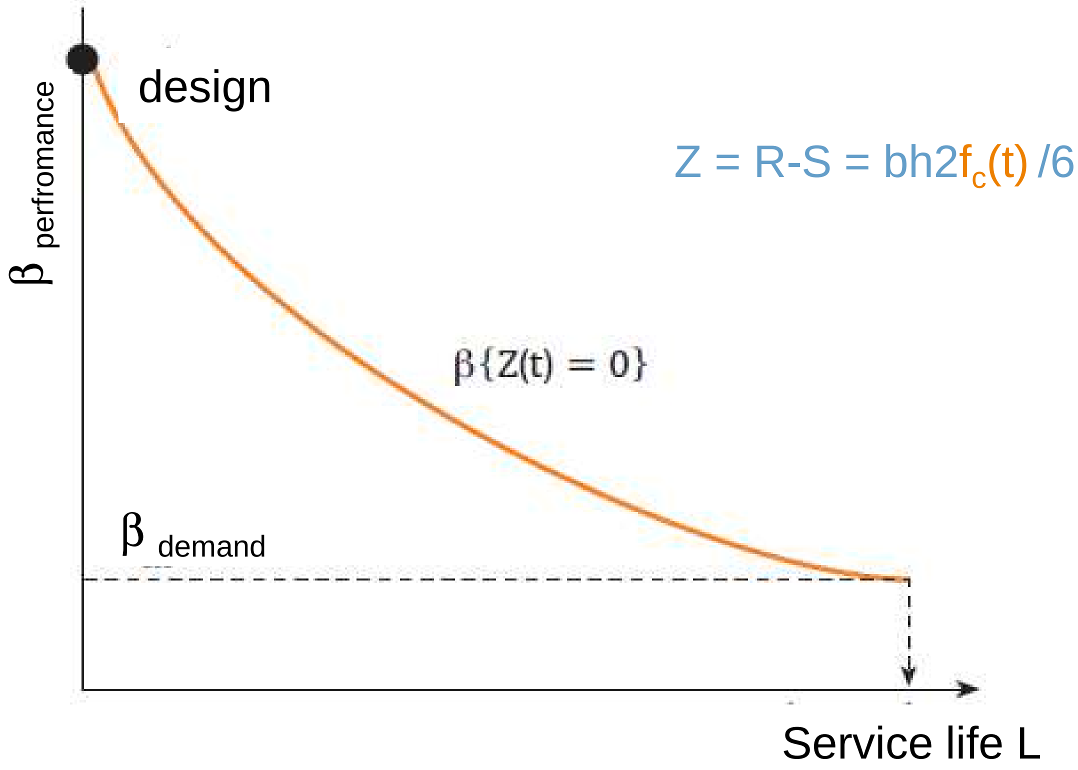

2. Performance in a structural design

- R and S may be time-dependent (and so is thus Z)
- on the basis of the time dependency the service life can be determined



2. Performance in a structural design: summary

- A performance consists of:
  1. A behaviour model Z(t) of which Z(t) = 0 the limit state describes
  2. A pre-defined, agreed upon, reliability index β
  3. A pre-defined, agreed upon service life L



$Z = R\text{-}S = bh2f_c(t)/6 - lF(t)/4$


2. Performance in a structural design

- The probabilistic calculation of Z is usually not so easy as R and S are functions of many different variables

- that is why in structural design partial safety factors are used:

$$Z = R_k/\gamma_R - S_k\gamma_S$$

2. Performance in a structural design

So why bother?

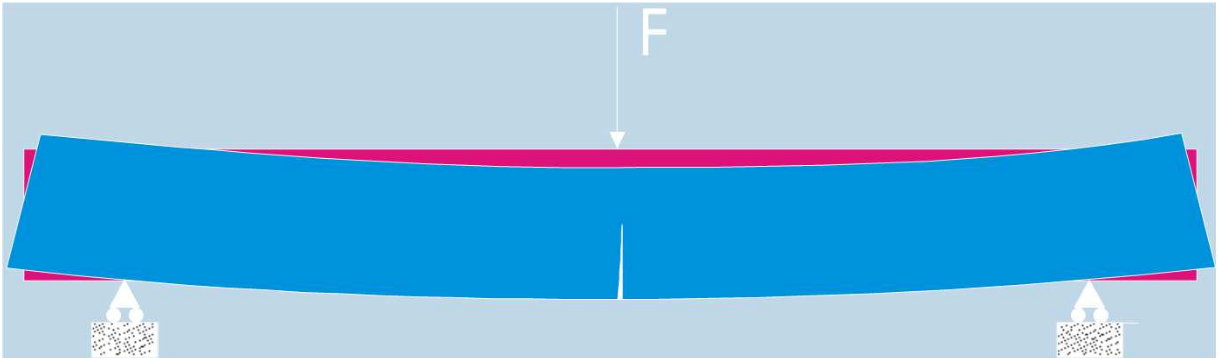
- what to do if longer or shorter service lives are required than implicitly included in the standards?
- are the current demands optimal?
- what to do with new contract forms like DCM?
- what kind (and amount) of maintenance can be expected?
- how to judge new materials?

Performance based service life design of concrete structures

Contents:

3. Determining the performances to take into account

Going back to the beam example:



Questions to ask are:

(1) Which loads are working on the structure?

(2) Does it matter?

3. Determining the performances to take into account

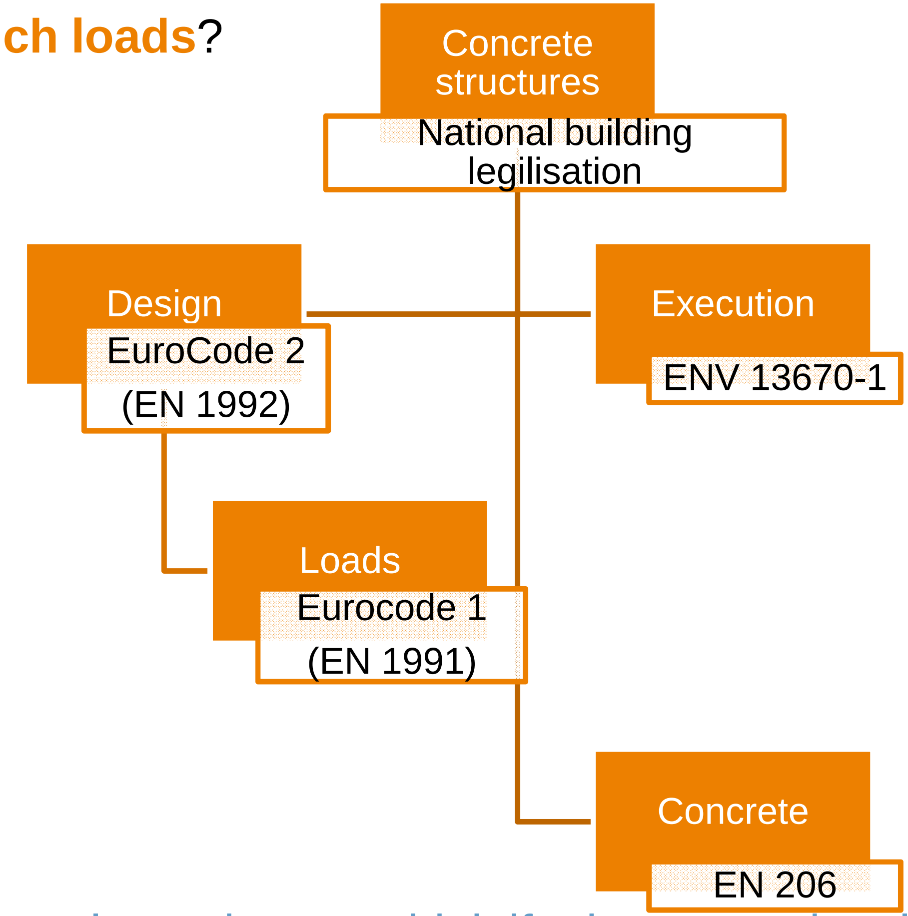
(1) Question 1: **which loads**?

- all loads that have to be taken into account are prescribed in the standards. In Europe this are the EuroCodes
- Load include:
  - Mechanical loads (self weight; wind, earthquakes, traffic loads,…)
  - Environmental loads (CO_2, Cl, sulphates, moisture, …..)
  - Fire

- Nevertheless, you always have to think if other exceptional loads may play a role

3. Determining the performances to take into account

(1) Question 1: **which loads**?

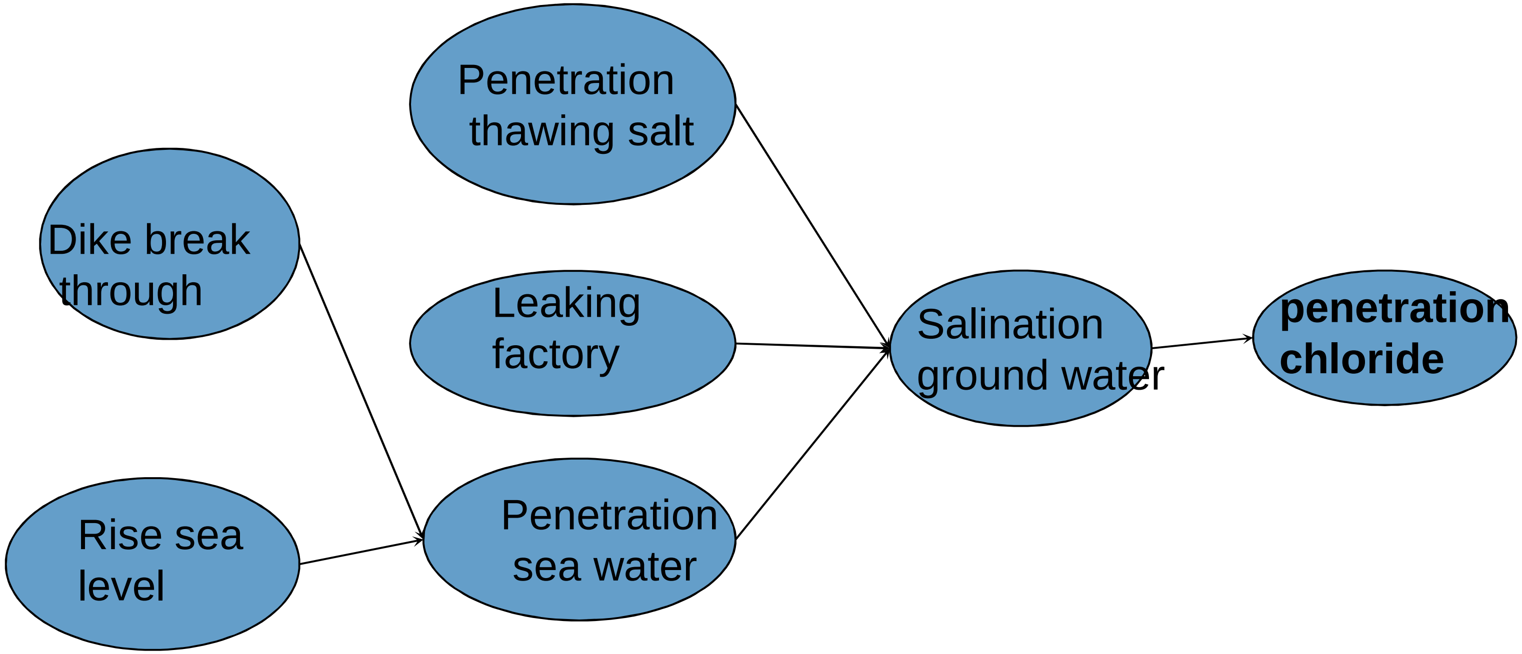


- Nevertheless, you always have to think if other exceptional loads may play a role

3. Determining the performances to take into account

(1) Question 1: **which loads**?

- First: try to assess which of the loads are of importance, now, or **DURING SERVICE LIFE** (e.g. make an event tree)

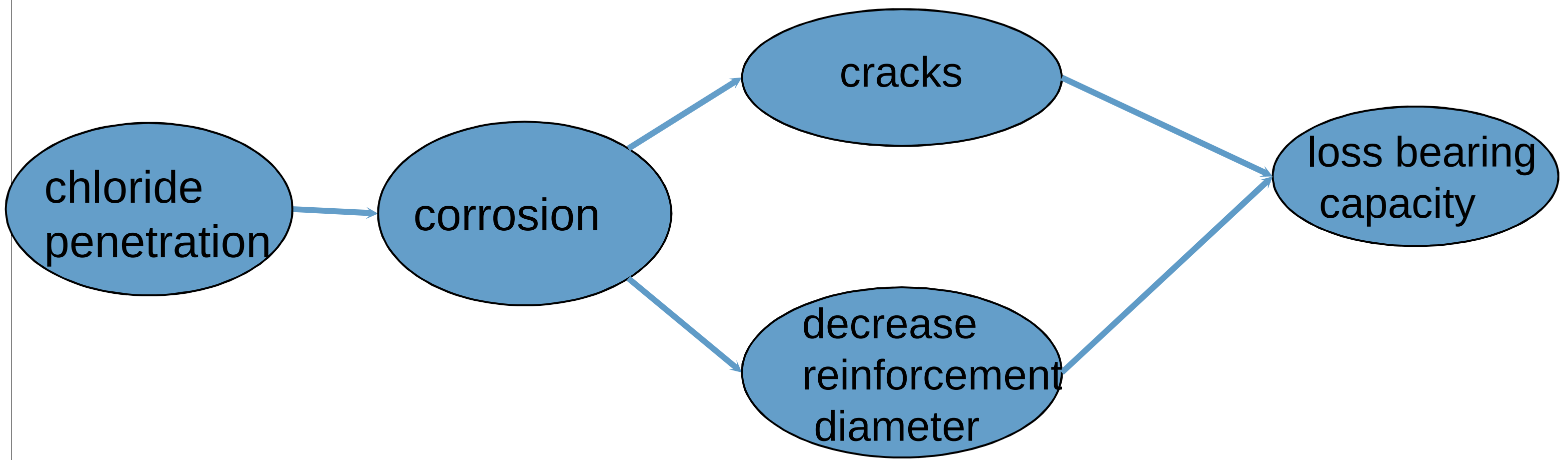


Reminder: structures fail more often due to forgotten treats rather than identified treats!

3. Determining the performances to take into account

(1) Question 2: **does it matter**?

- Second: check the effect of the load (e.g. use a failure mode and effect analysis (FMEA)




3. Determining the performances to take into account

(1) Question 2: **does it matter**?

- Third, and last step (much later on in the process) will be to consider the consequence of the effects of failure (e.g. make a risk analysis):
  - loss of lives / health issues
  - Economical loss
  - Ecological loss etc.

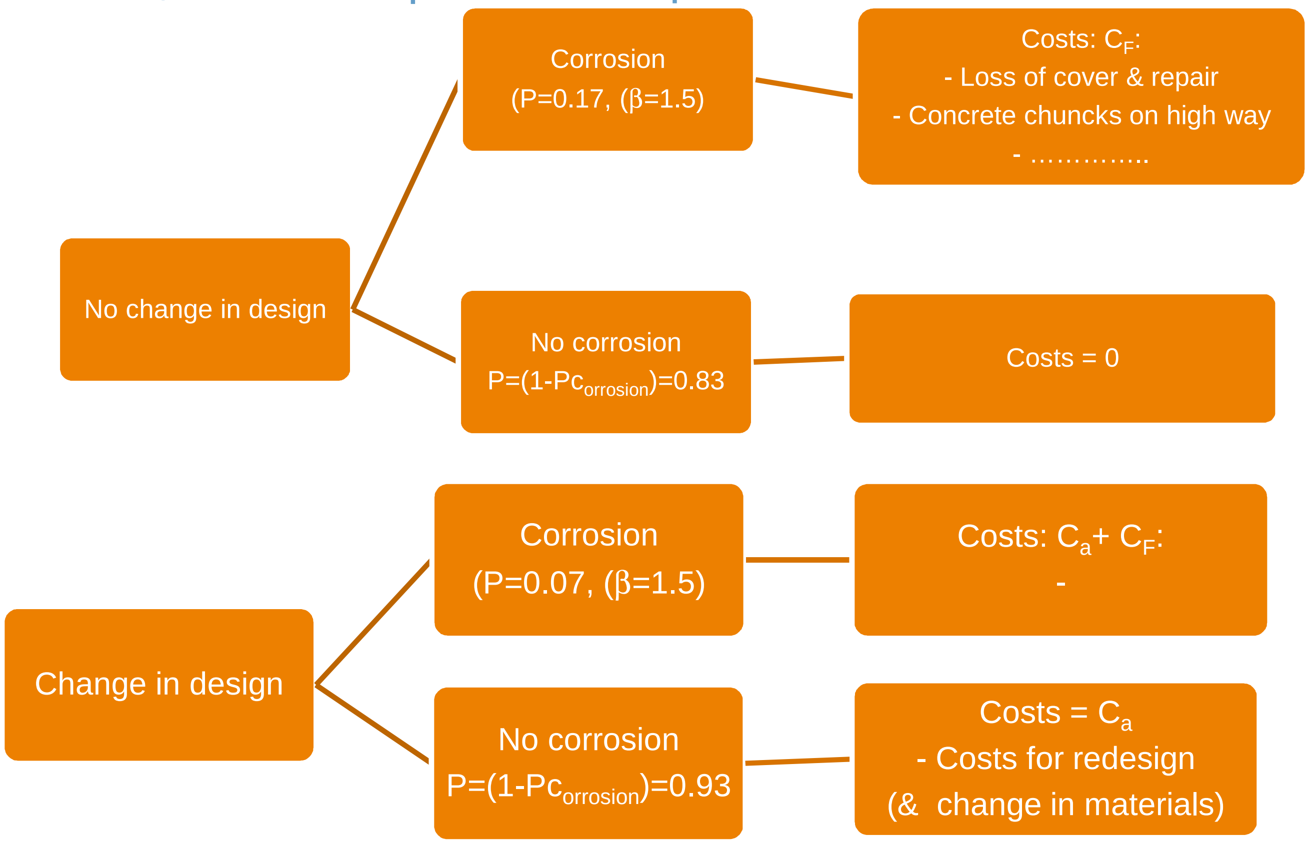
- **Risk = probability of an event x the consequences**

- Most often, the risks are expressed as costs.

3. Determining the performances to take into account

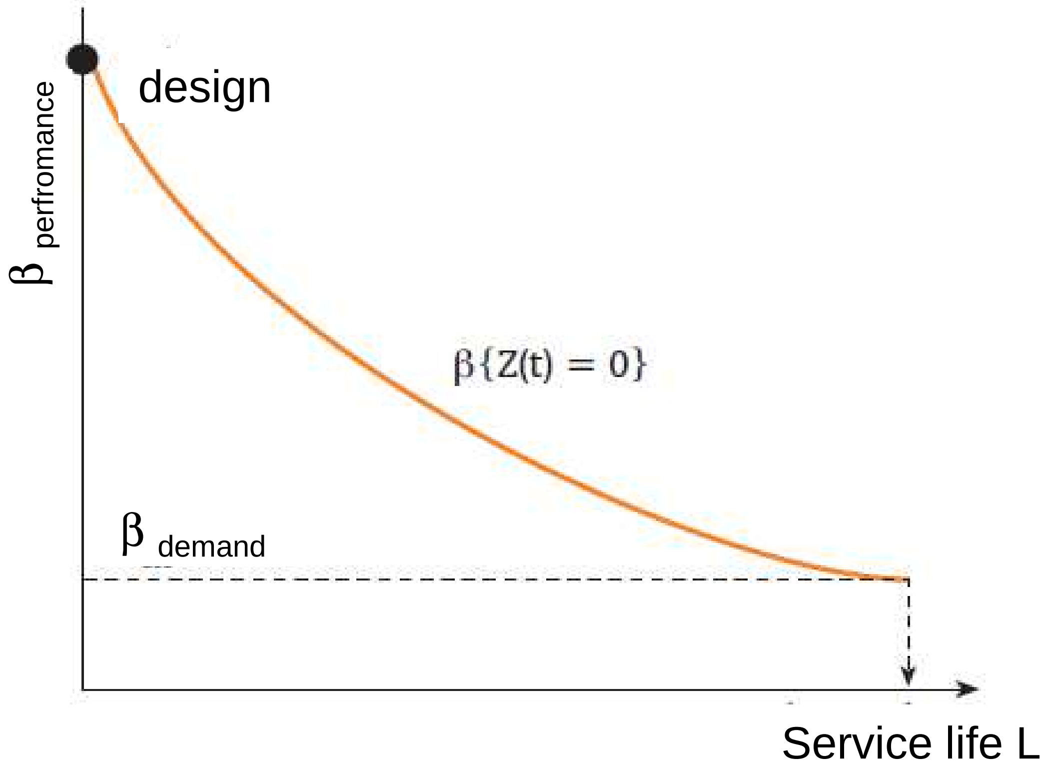
(1) Question 2: **does it matter**?

- Often, the consequences are presented as a decision tree:



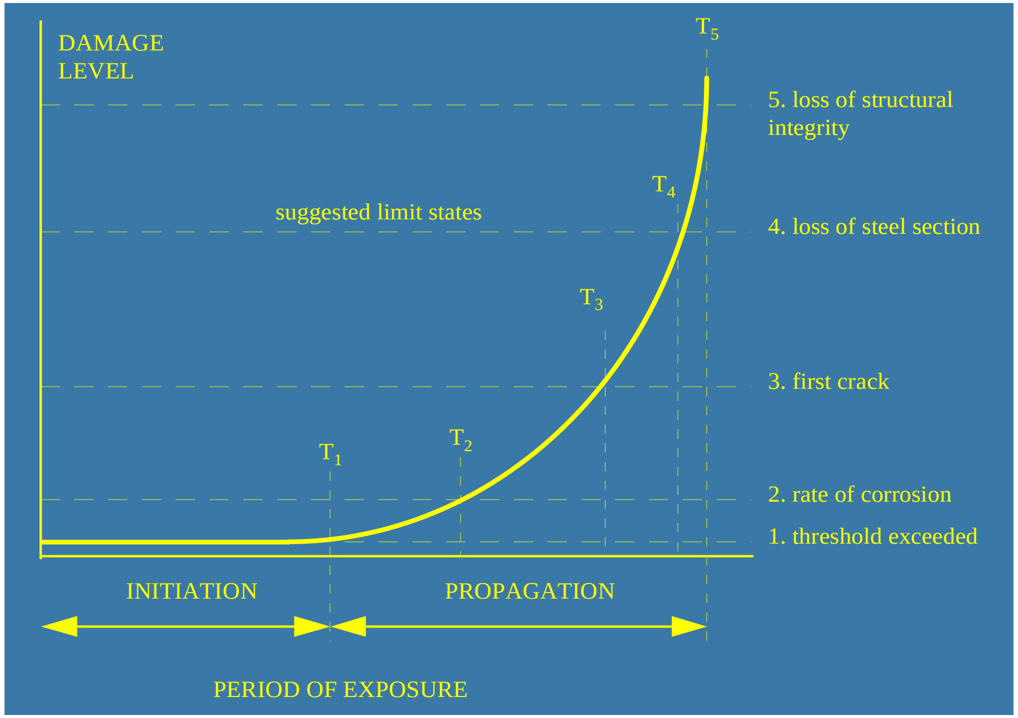
3. Determining the performances to take into account

- Recap section 2: performance consists of:
  1. A behaviour model Z(t) of which Z(t) = a the limit state describes
  2. A pre-defined, agreed upon, reliability index β
  3. A pre-defined, agreed upon service life L



3. Determining the performances to take into account

- Recap which performances and which demands:
  - Step 1: analyse all loads, their effects (and a first order consequence), i.e. Z=R-S
  - Step 2: define the limit state (Z=R-S<a?) especially important with respect to service limit states



3. Determining the performances to take into account

- Recap which performances and which demands:
  - Step 3: define the reliability (failure probability)

reliability class	consequences of failure		reliability index β ultimate limit state	
	probability loss of lives	Probability economic damage	Reference period = 1 year	Reference period = 50 years
1	small	negligeable	5.2	4.3
2	Medium	small	4.7	3.8
3	large	large	4.2	3.2

3. Determining the performances to take into account

- Recap which performances and which demands:
  - Step 4: define the time (service life) for which the performance is valid

Category (without large repairs)	Indicative service life (year)	example
1	10	Temporary structures
2	10-25	Replaceable structural elements agricultural buildings
3	15-30	agricultural buildings
4	50	Bridges, sluices & water locks
5	100	Monumental buildings and structures (tunnels, bridges and water defence structures)

3. Determining the performances to take into account

- Result: an overview of all possible failure mechanisms, and their limits

Durability aspect)	Limit state	β
ASR	eliminate	-
Freeze-thawing With de-icing salt	eliminate	-
Initiation corrosion - chlorides	Critical chloride content at reinforcement	SLS =1.5
Initiation corrosion - carbonation	Carbonation front at reinforcement	SLS=1.5
corrosion	Failure of the beam	ULS=3.8

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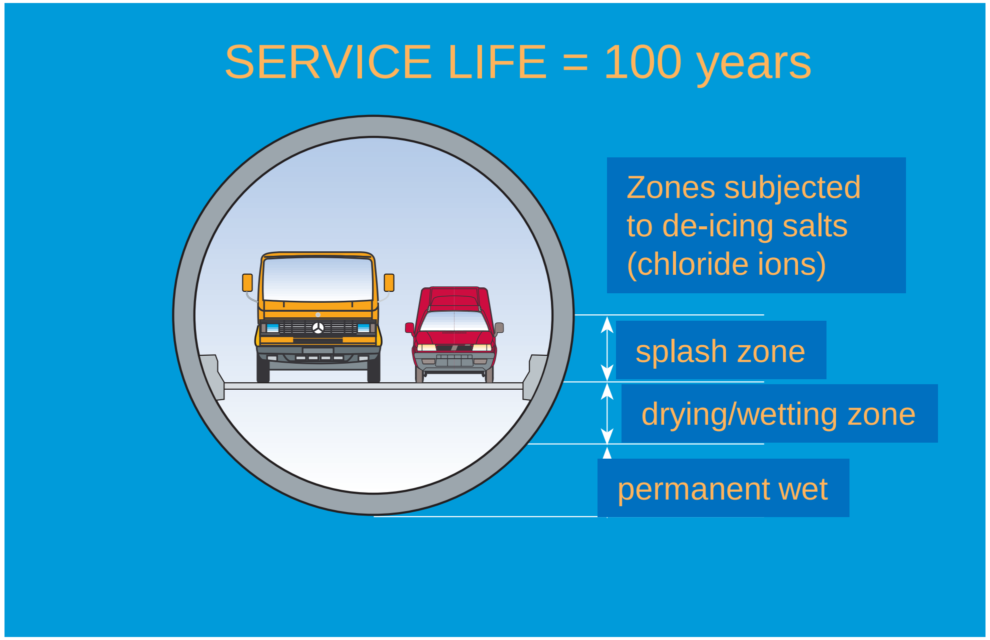
4. Example: design on durability

- STEP 1: check environmental loads and determine which degradation mechanisms are possible
- STEP 2/3: define limit states and reliability
- STEP 4: define a service life



Degradation mechanism		Limit state	reliability
Corrosion due to	chloride	Onset of corrosion	$\beta=1.5$
	carbonation	Onset of corrosion	$\beta=1.5$
………..			

4. Example: design on durability

- STEP 5: validate the first design (example for one demand)

	variables
Performance demand: $\{c(x = x_c, t = L) \leq c_{crit}\} \leq P\{\beta = 1.5\}$	x = depth from concrete surface x_c = concrete cover t = time since exposure L = service life c = chloride concentration c_{crit} = critical chloride content
Behavioral model for chloride penetration (diffusion): $c(x,t) = c_s\,(1 - \mathrm{erf}\,(\frac{x}{\sqrt{4k_e k_c \int D(t)dt}}))$	c_s = surface chloride concentration erf = error function k_e = environmental factor k_c = curing factor D = diffusion coefficient
Time dependent diffusion coefficient (material resistance): $D(t) = D_{inf} + (D_0 - D_{inf})(t_0/t)^n$	D_{inf} = diffusion coefficient at inf.time D_0 = diffusion coefficient at ref.time t_0 n = ageing coefficient

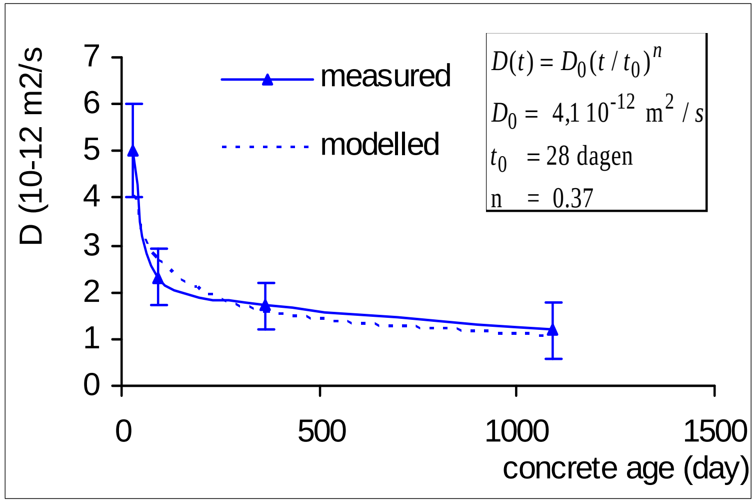
4. Example: design on durability

STEP 5a: Determine ALL variables in the model (e.g. by field or lab measurements)

. Determination of the material resistance:

- in compliance test (standard tests under standard conditions, e.g. temperature, concentrations and rh)
- measured at different ages ('age-factor')

Model: $D(t) = D(t_0)f(t)$



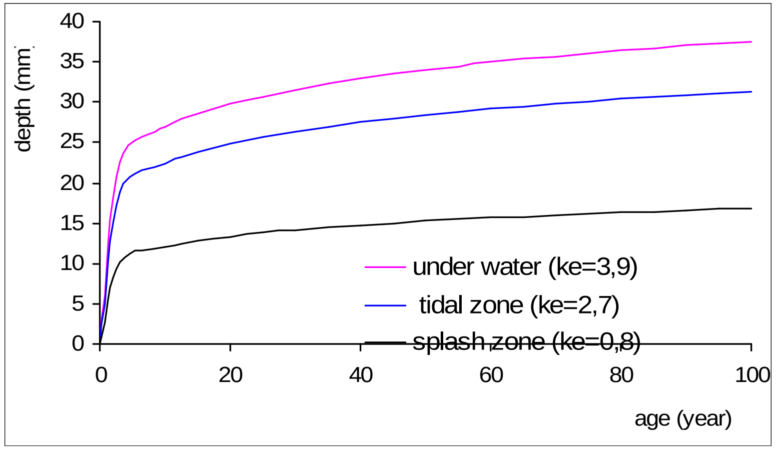
4. Example: design on durability

STEP 5a: Determine ALL variables in the model

Influence factor:

- execution: k_c
  - curing (rh/moisture)
  - hardening conditions (under higher / lower temperature)

- environment: k_e
  e.g. marien:
  - permanently under water
  - tidal zone
  - splash zone
  - atmosferic zone



Complete model:

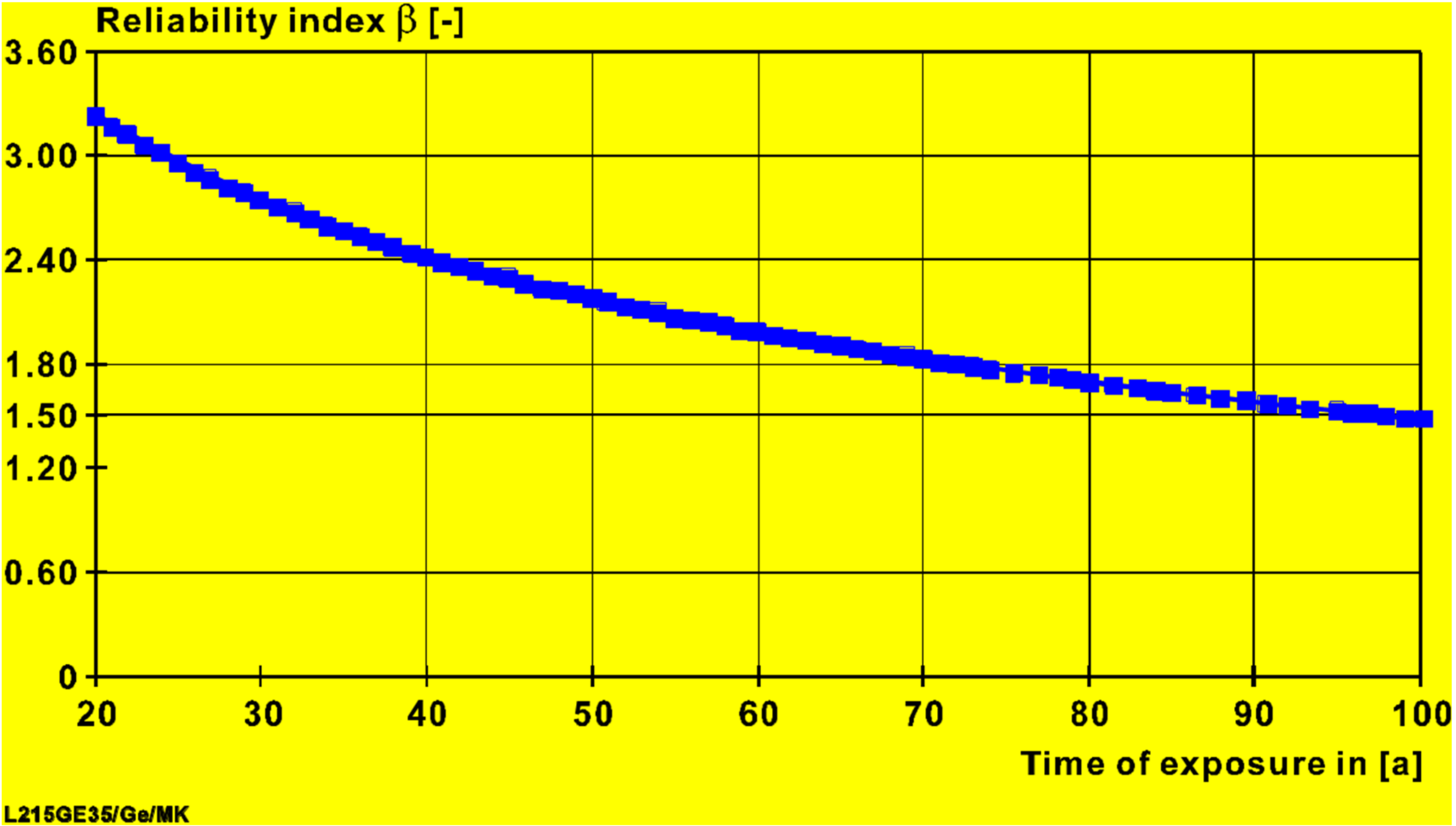
$$D(t)=k_c k_e D(t_0) f(t)$$


4 . Example: design on durability

Variable No	Parameter	Dimension	μ	σ	Distr. Type
1	x_c – Concrete Cover	[mm]	37	2	Expon. Distr.
2	$D_{RCM,0}$ - Cl^--Migration Coef.	$[10^{-12} m^2/s]$	4.75	0.71	Normal Distr.
3	C_{Crit} – Critical Chloride Content	[wt.-%/binder]	0.70	0.10	Normal Distr.
4	n - Age Exponent	[-]	0.60	0.07	Normal Distr.
5	k_t - Factor Test	[-]	1		Deterministic
6	k_{en}- Factor Environment	[-]	1.00	0.10	Normal Distr.
7	k_{ex}- Factor Execution	[-]	1.00	0.10	Normal Distr.
8	C_S - $c(Cl^-)$ - Concrete Surface	[wt.-%/binder]	4.00	0.50	Normal Distr.
9	t_0 – Reference Time	[year]	0.0767	-	Deterministic

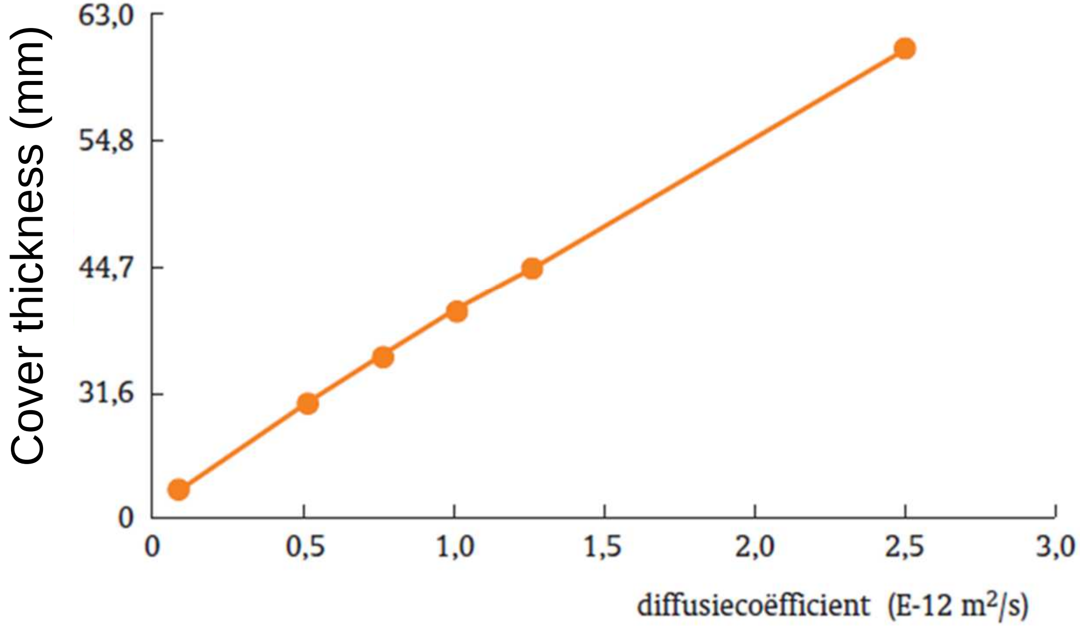
4. Example: design on durability

- STEP 5b: calculate if the design is durable enough



4. Example: design on durability

- If the design is durable enough, you are finished. If not:
- STEP 5c adapt the design.
- Often, a trade off can be made, e.g. cover thickness versus cover resistance (= change of concrete composition)



- Notice: more performance demands play a role that may limit possibilities

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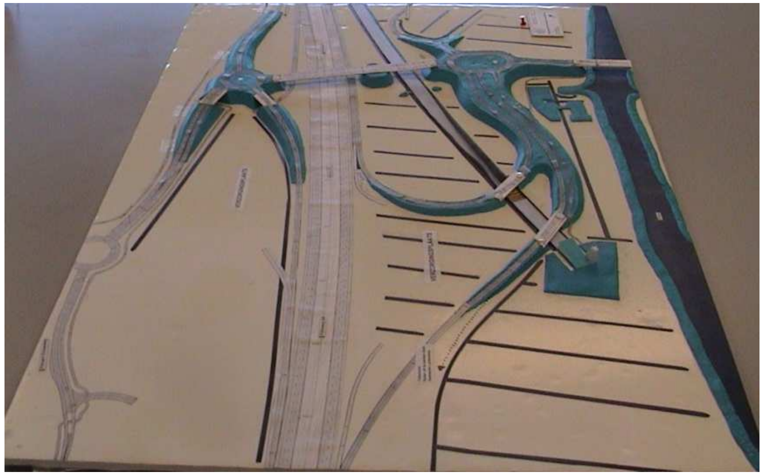
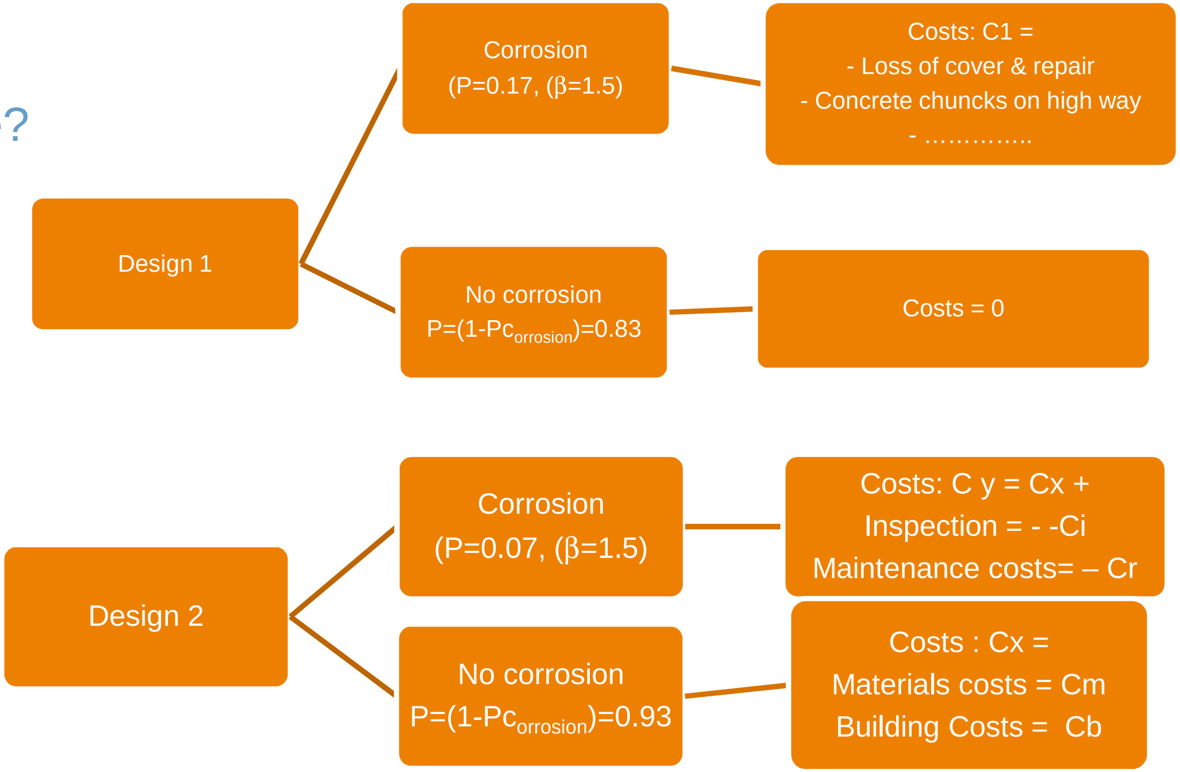


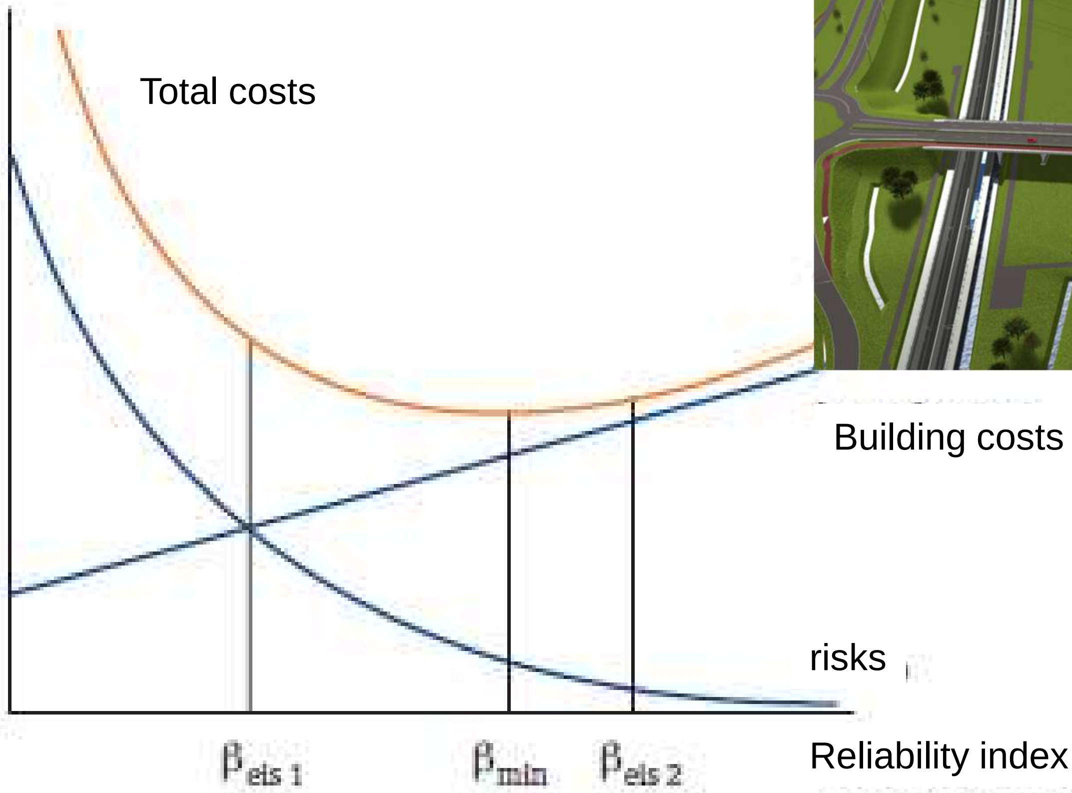
5. Optimization of the design

- Design process =
  - development of 1 (or more) design alternatives
  - with a series of performance demands
  - AND a series of measured both for the design, execution and use (maintenance)
- Which one to choose?




5. Optimization of the design

- Which one to choose?



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6. Performance based design – further advantages & developments

- Performance based design of structures is an integrated approach which does not only apply to mechanical loads but also to durability and other demands

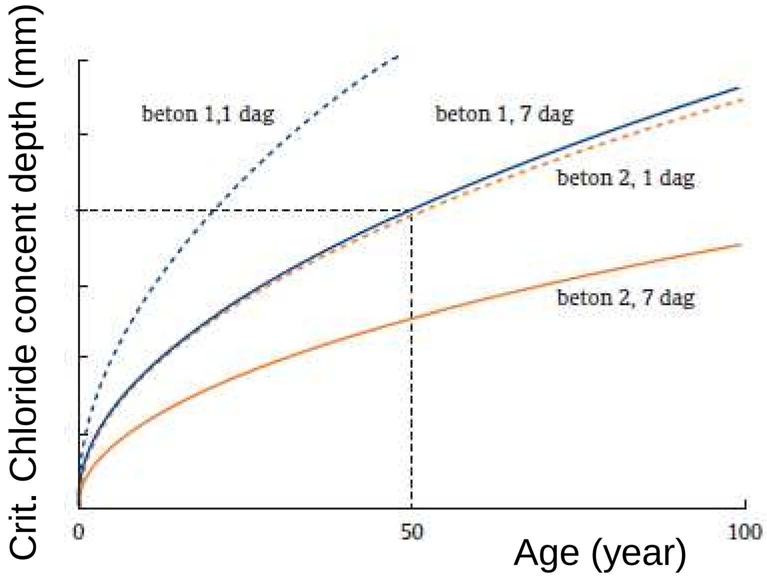
- It moreover in an integral part of the full framework / contracts for

  Design – Construct - Maintain

- In which performances are:
  - defined in the design stage
  - realised in the construction stage
  - monitored during the use stage
  - and if required improved or changed during the maintenance

6. Performance based design – further advantages & developments

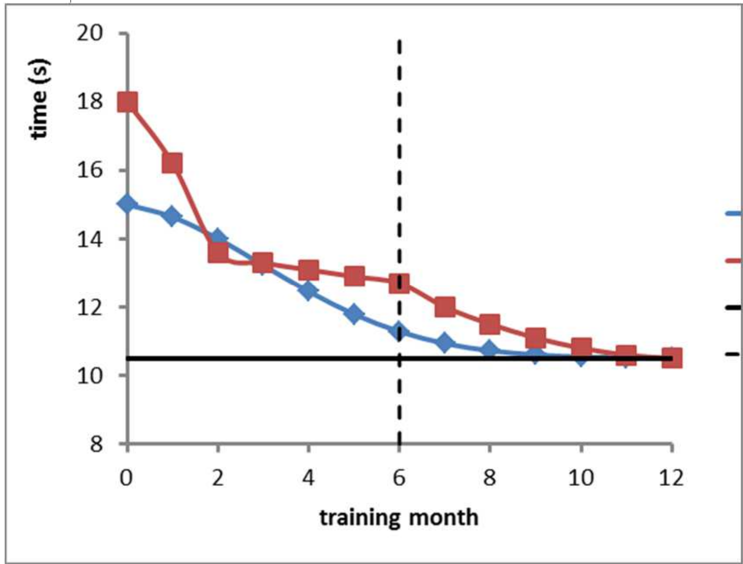
- Construct:
  - New performance criteria due to construct methods
  - Execution methods as part of design (e.g. Curing)

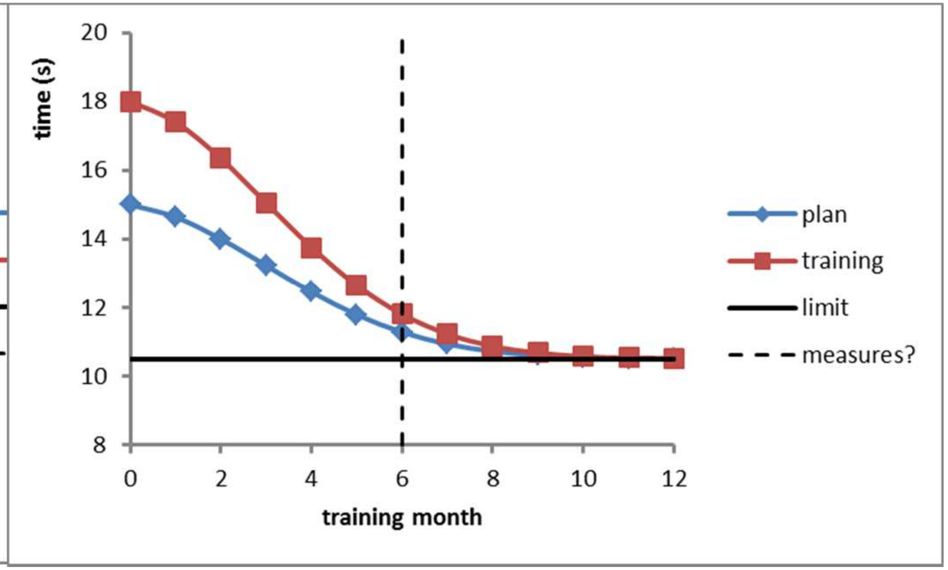


  - Design depends on building process


6. Performance based design – further advantages & developments

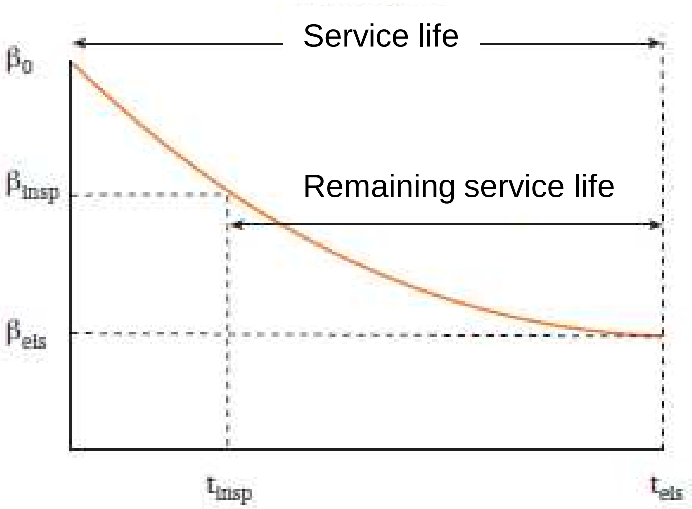
- Birth certificate:
  - Design has to be verified after building
  - If performance are not met, early measures can be taken

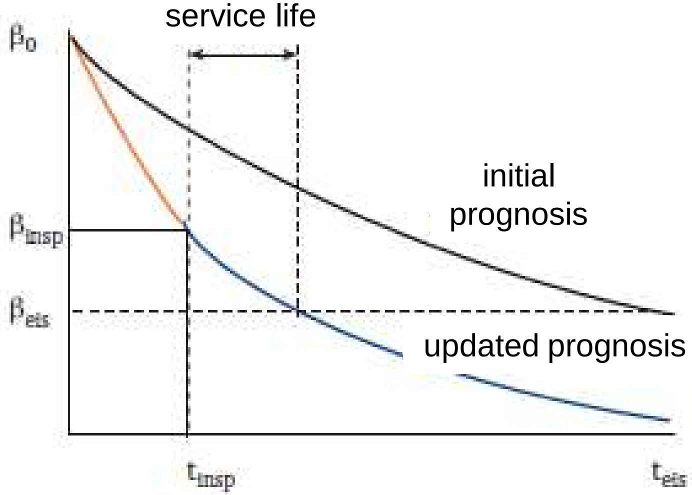




6. Performance based design – further advantages & developments

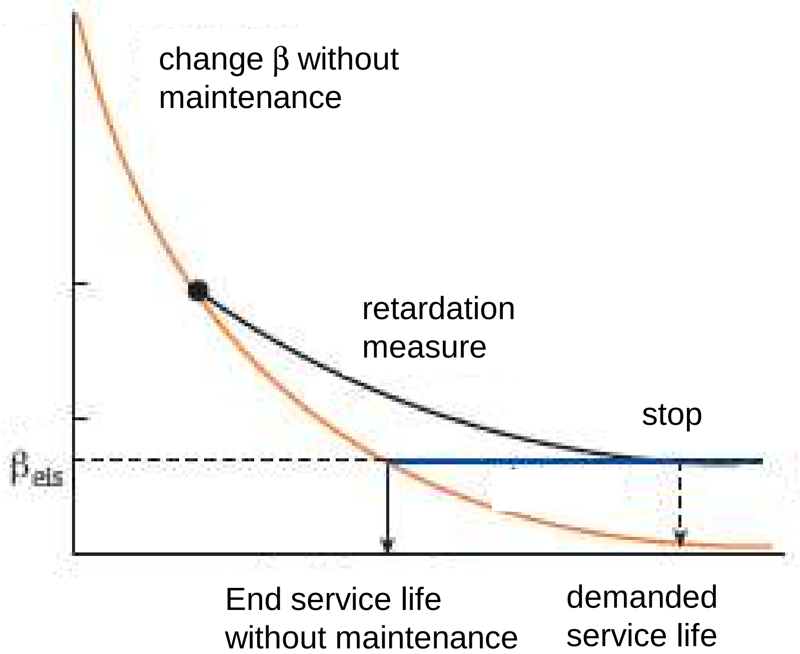
- Management: monitoring & inspection:
  - Easy assessment of the remaining service life

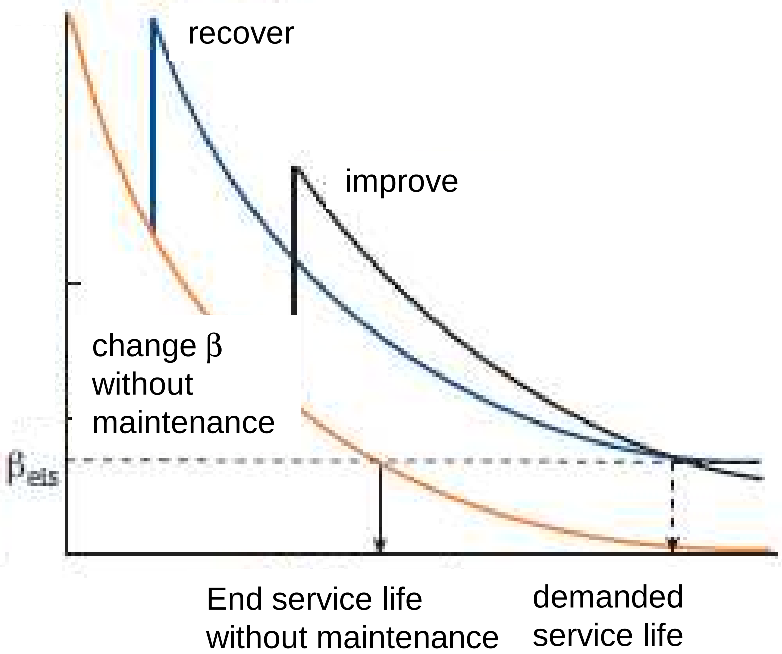




6. Performance based design – further advantages & developments

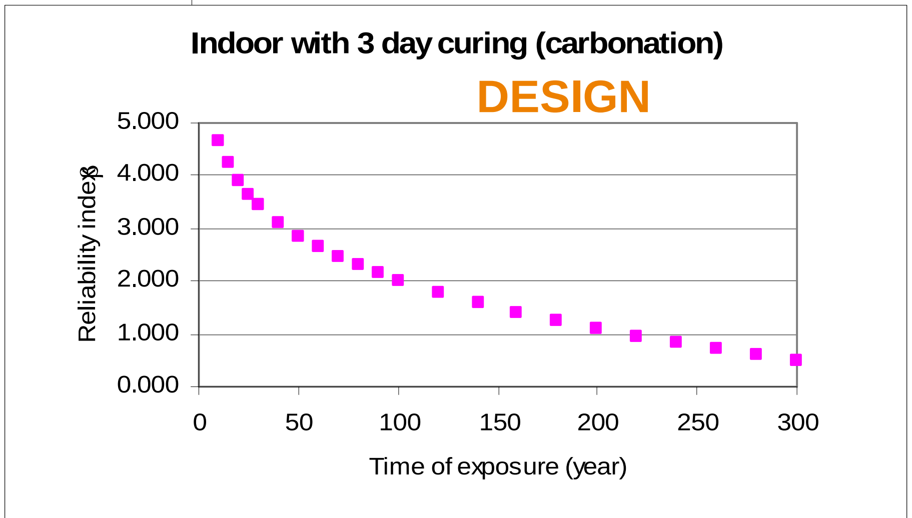
- Management: repair& prevention possibilities much wider
- Also choice easier due to known effect on service life

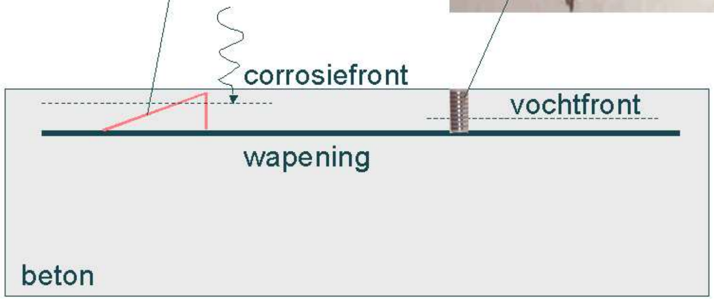




6. Performance based design – further advantages & developments

Example: Green Heart Tunnel






5. Conclusions

- The framework of the performance based DCM(-D) is finished

- The contents are not fully filled out:
  - there are not many time-dependent models available
  - little insights in the effects of repairs on the performance
  - probabilistic calculations are difficult and partial safety factor calculations are not available

- Nevertheless, it is an efficient and objective method that:
  - will save quite some money
  - makes the way free for innovations

Thanks

- I hope you enjoyed the lecture and learned something about the flexibility a performance based design process
- The process will given you a whole range of alternatives, so I hope you will in your future see ample reason to use it!