INFRASTAR
Training school®

Innovation and Networking for Fatigue and Reliability Analysis of Structures – Training for Assessment of Risk

Design and assessment criteria for safety and cost efficiency

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Coordinated by Université Gustave Eiffel

Overview

- General performance criteria for the build environment
- Self-contained approach to assess performance
- Simplification = Generalisation
- How safe is safe enough? => A calibration problem!

The build environment

- As the main contributor to our societal development,
- And, as a major consumer of natural resources,
- Needs proper strategies for decision support for further development and maintenance !!
- Objective: sustainable development.

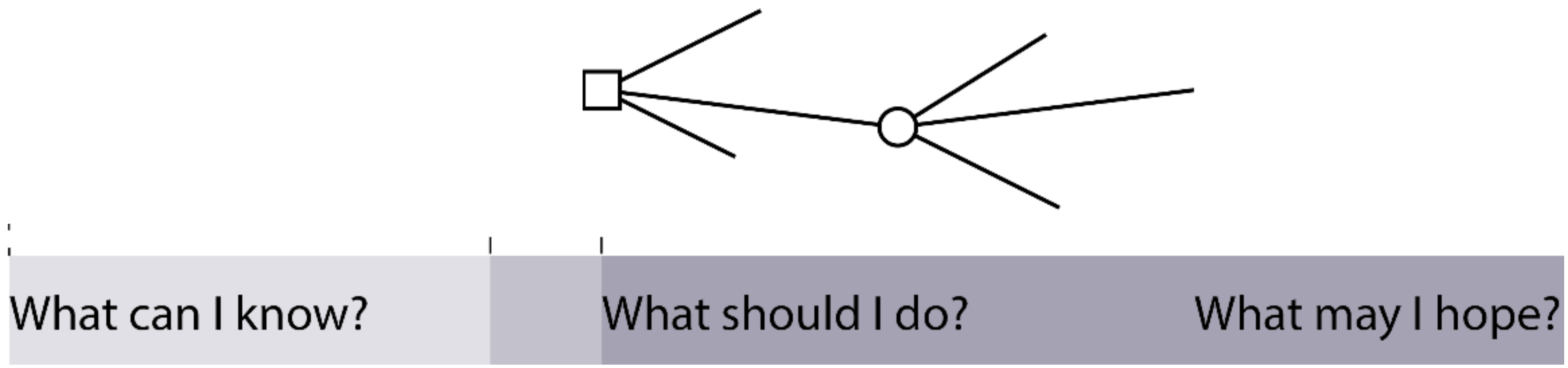
The build environment

Strategy

- Decisions are made
- It is not how we can identify the right decision, but how we identify the “best” decision
- Reasonable to assess the effect of different decision alternatives on “our” utility

Formal Decision Theory

Actions	State	Utility
$\boldsymbol{a} \in \boldsymbol{A}$	$\boldsymbol{\theta} \in \boldsymbol{\Theta}$	$u(.)$

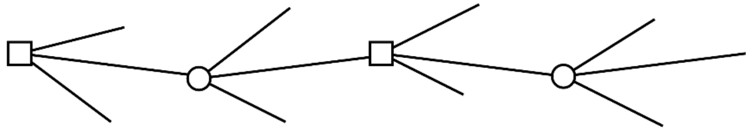


- ➢ Reasonable strategy
- ➢ Challenging to apply
- ➢ Simplifications necessary

System definition

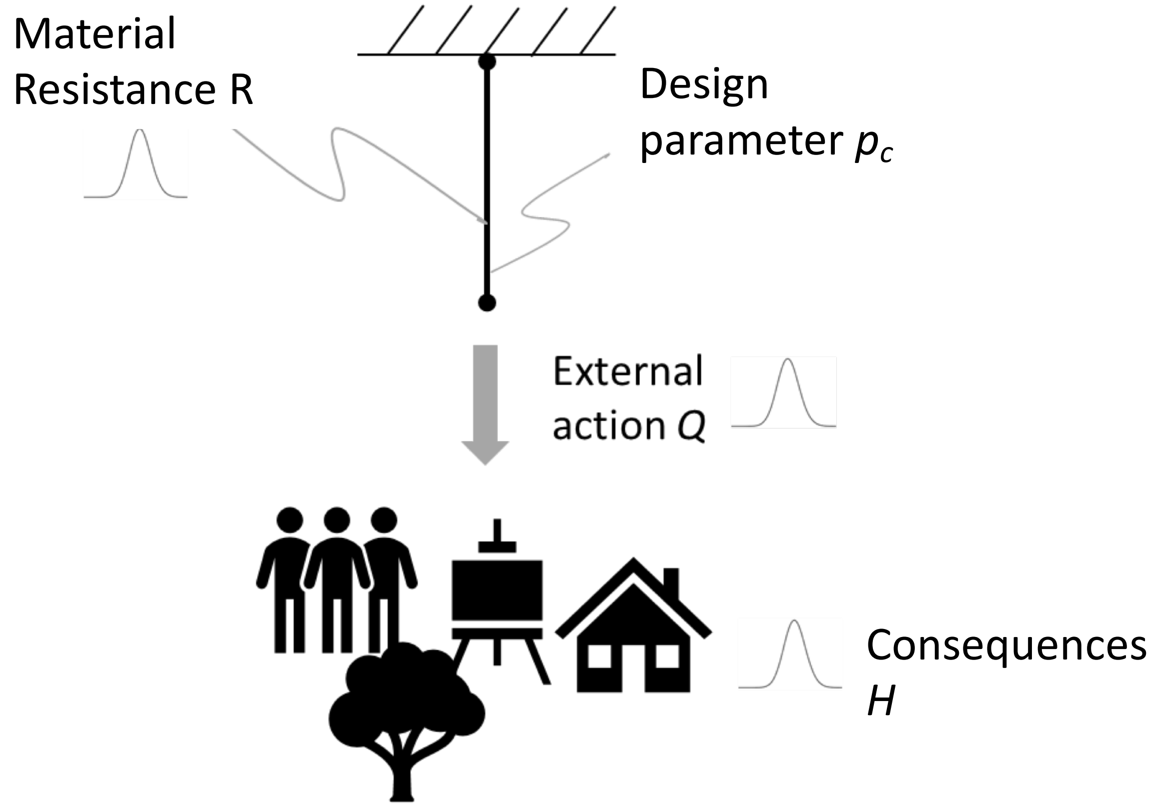
- Reduction and simplification
- Decision alternatives ←→ utility

Experiment	Sample	Actions	State	Utility
$\boldsymbol{e} \in \boldsymbol{E}$	$\boldsymbol{z} \in \boldsymbol{Z}$	$\boldsymbol{a} \in \boldsymbol{A}$	$\boldsymbol{\theta} \in \boldsymbol{\Theta}$	$u(.)$

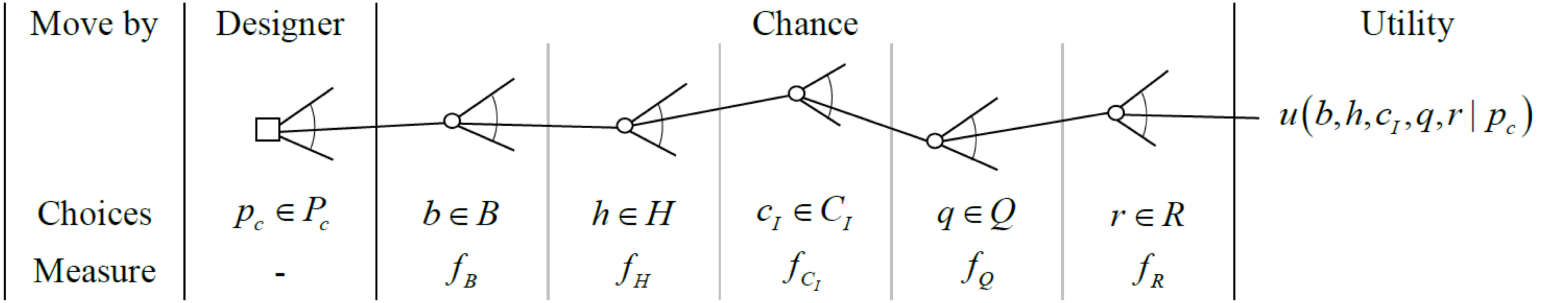


Structural design decision problem

➢ Objective: minimum use of resources over time



Structural design decision



$$\boldsymbol{p}_{\boldsymbol{c},\boldsymbol{opt}} = \underset{\boldsymbol{p}_{\boldsymbol{c}}}{\operatorname{argmax}}\{E_{\boldsymbol{\Theta}}[u(\boldsymbol{\theta},\boldsymbol{p}_{\boldsymbol{c}})]\} = \underset{\boldsymbol{p}_{\boldsymbol{c}}}{\operatorname{argmin}}\{E_{\boldsymbol{\Theta}}[C_{tot}(\boldsymbol{\theta},\boldsymbol{p}_{\boldsymbol{c}})]\}$$

$$E_{\boldsymbol{\Theta}}[C_{tot}(\boldsymbol{\theta},\boldsymbol{p}_{\boldsymbol{c}})] = (E[C_0] + E[C_1]p_C) - E[H]P_f(\boldsymbol{p}_{\boldsymbol{c}})$$

$$P_f(\boldsymbol{p}_{\boldsymbol{c}}) = \int_{p_C r<q} f_{R,Q}(r,q)\,dr\,dq$$

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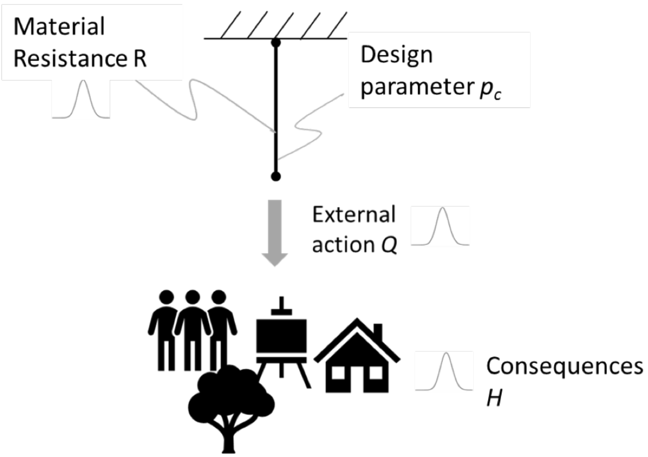
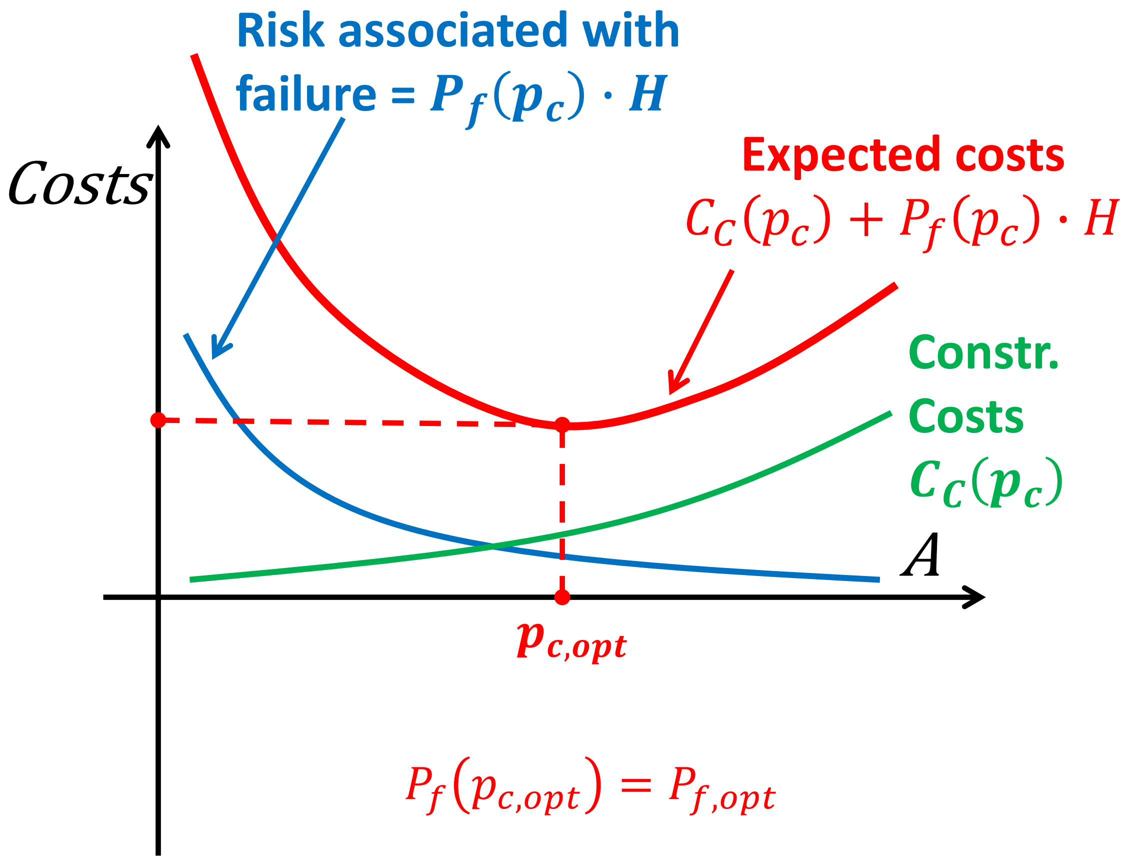
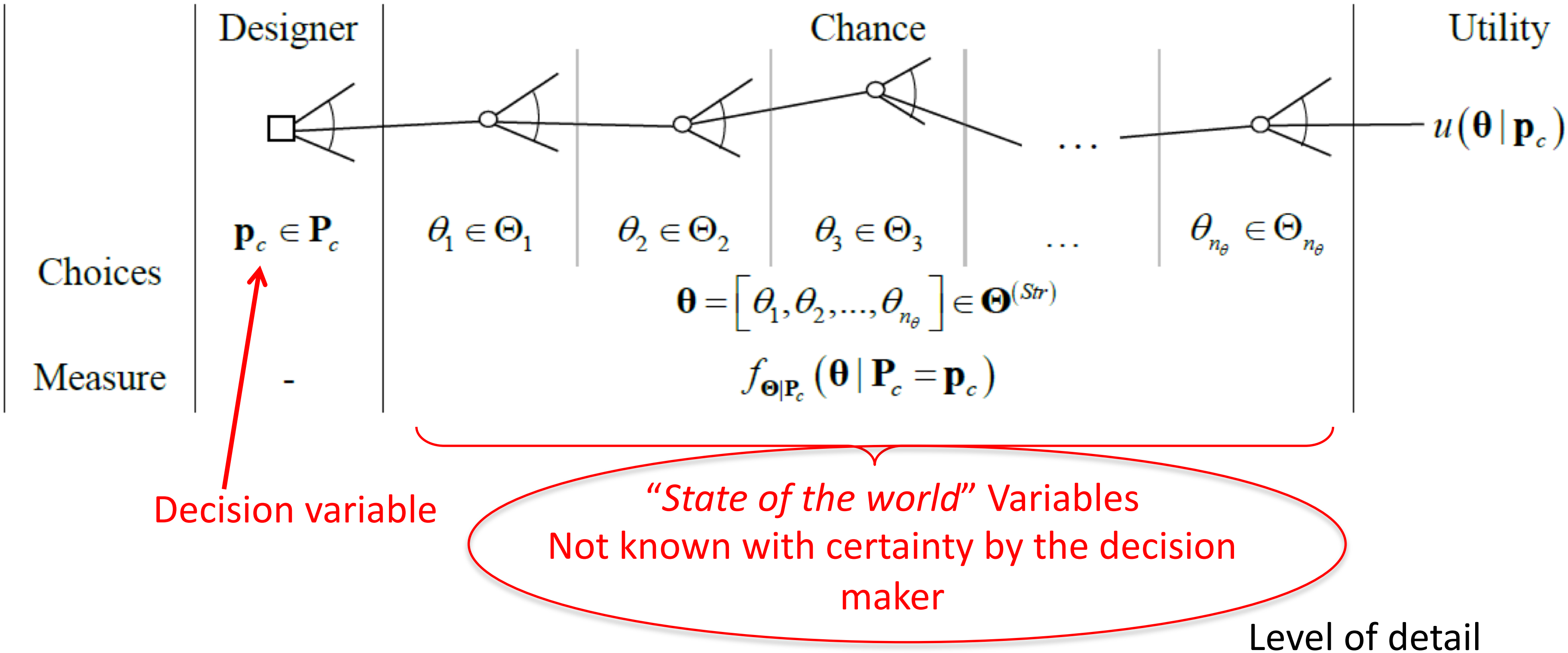
Risk informed decision





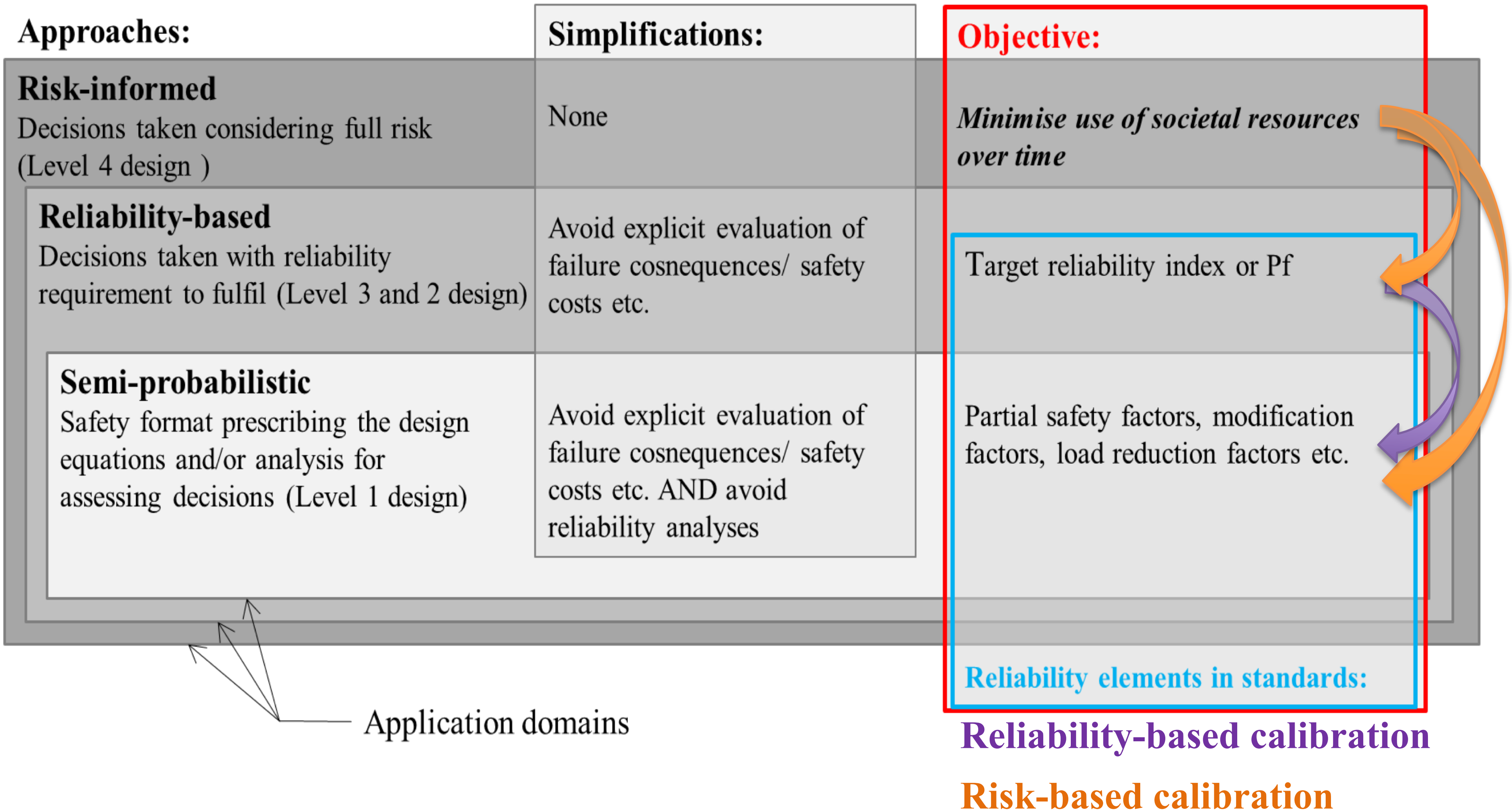
Generalization of the risk informed design problem



Level of detail sensibly chosen!

$$\boldsymbol{p}_{c,opt} = \underset{\boldsymbol{p}_c}{\operatorname{argmax}} \{E_{\boldsymbol{\Theta}}[u(\boldsymbol{\theta}|\boldsymbol{p}_c)]\}$$

Simplified design methods



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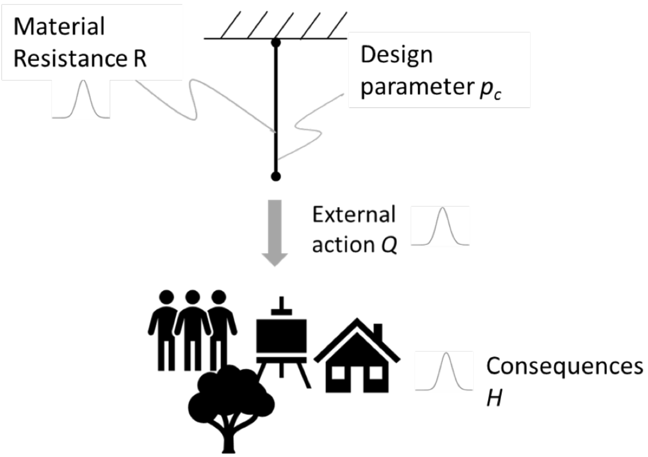
Simplified design and assessment of decision approaches [ISO 2394]

- **Level 4: Risk-informed**

Simplification

  - **Levels 3 (and 2): Reliability-based**

Reliability based design (Level 3 and 2)



Design:

$$p_c\colon\ P_f(p_c) = P_{f,target}$$

Level 3 ≡ Level 4 ⇔ $P_{f,target} \equiv P_{f,opt}$

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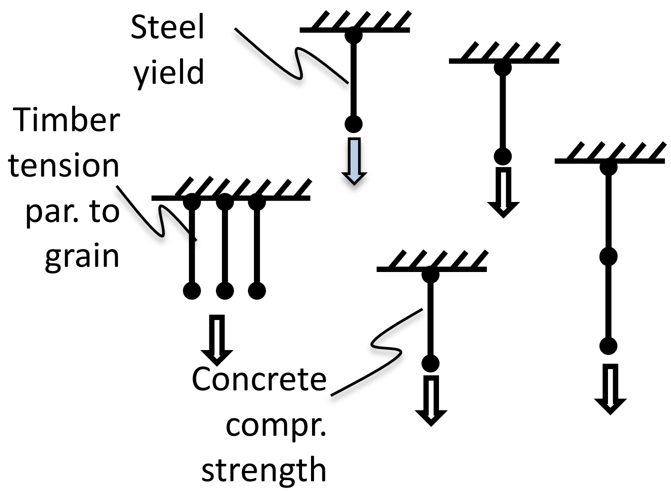
Code calibration, why?

- Simplification:
  1. No explicit evaluation of costs, consequences, etc → **simplify calculations**



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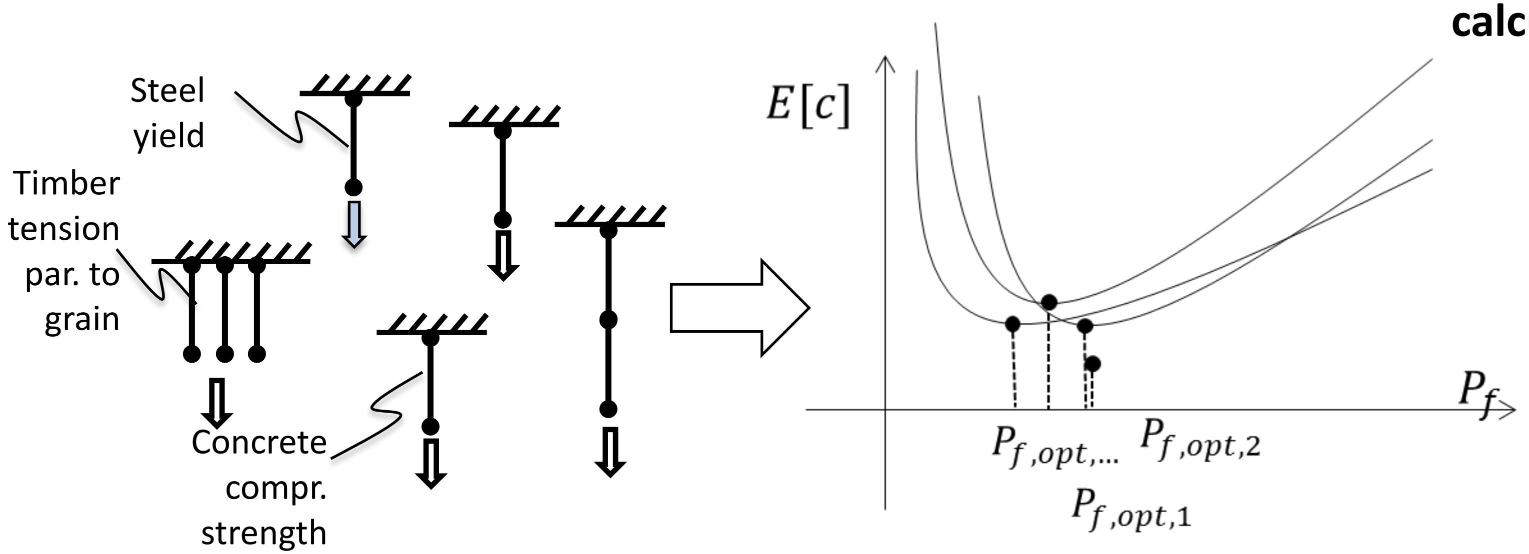

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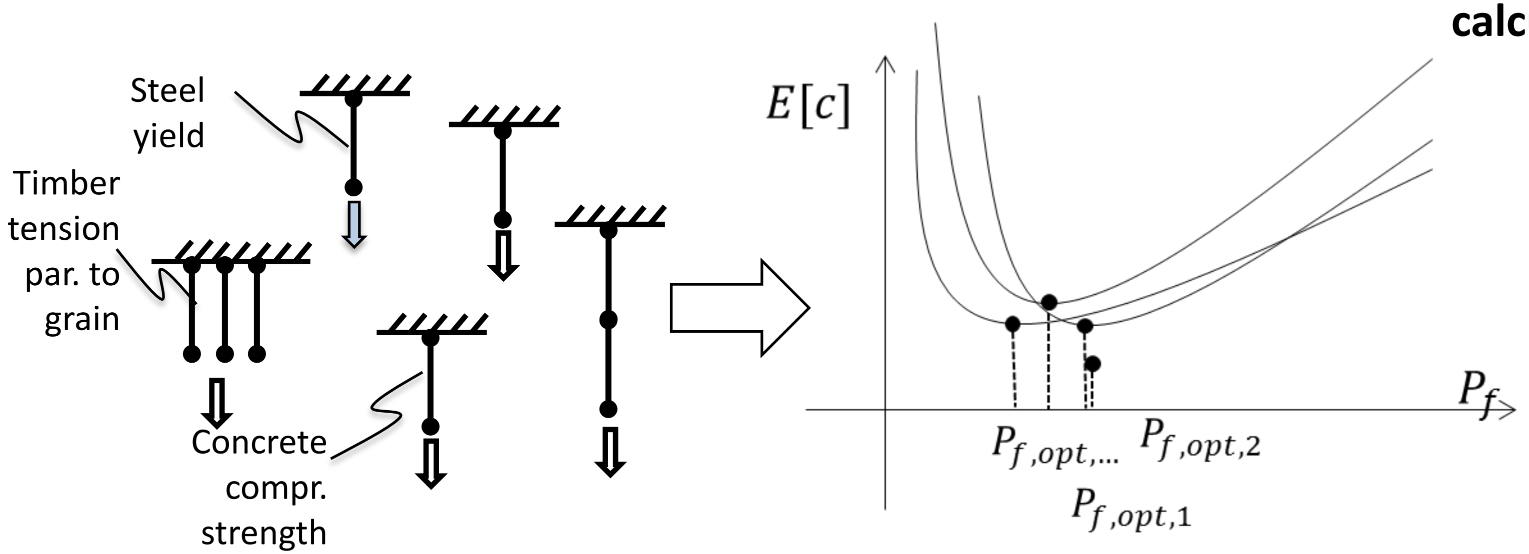
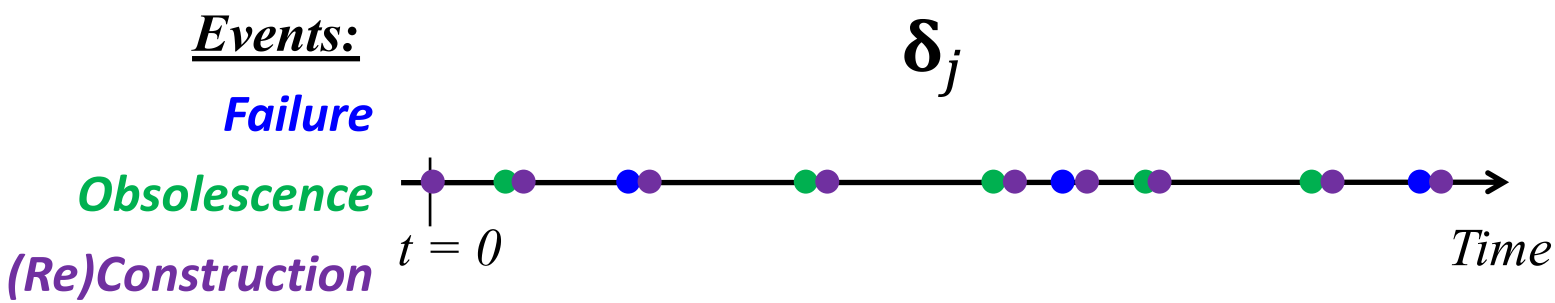


  2. One $P_{f,target}$ for a class of structures → **simplify standards and calculations**

CALIBRATION: what $P_{f,target}$ **is optimal for the class?**

Code calibration as a decision problem under risk

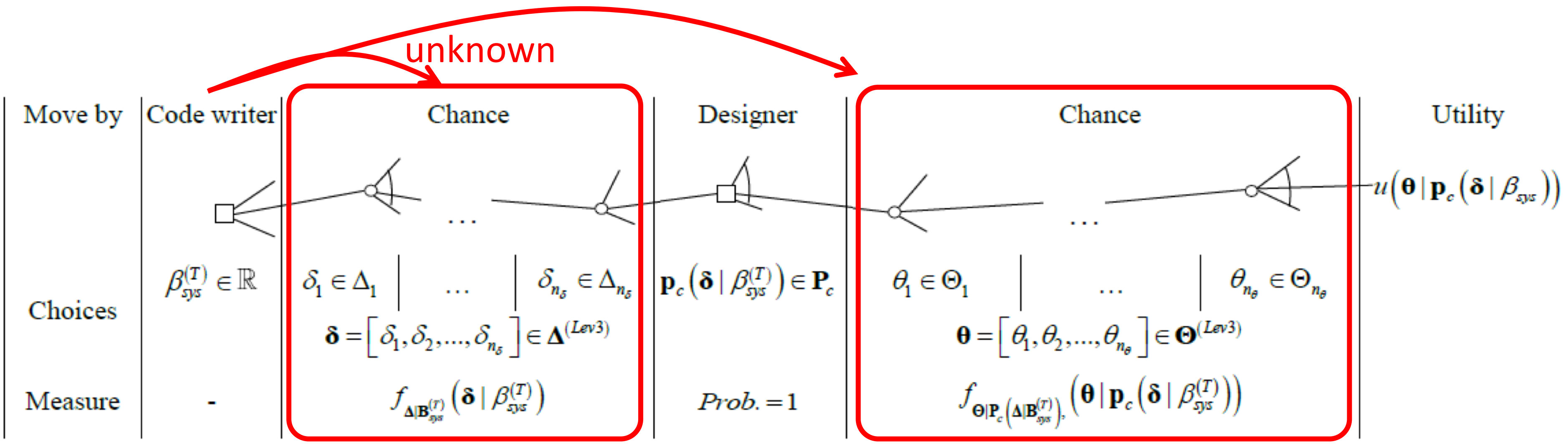
- Decision variable: $\boldsymbol{\beta_{target}}$ for Level 3 and 2 design
  - each structure in the class defined by $\boldsymbol{\delta}$
  - present and future structures



- Decision maker: **society** (codes guard the interest of society)
- Level of detail in system representation consistent with the generalisation over classes

Optimisation of β_t for Level 3 codes

- Game between *Code writer* and *Chance*
  1. *Code writer* selects a β_t
  2. *Chance* chooses a possible structure to be designed $\boldsymbol{\delta} \in \boldsymbol{\Delta}^{(Lev3)}$
  3. Designer finds dimensions $\mathbf{p}_c$ giving $\beta \equiv \beta_t$
  4. *Chance* chooses a state of the nature $\boldsymbol{\theta} \in \boldsymbol{\Theta}^{(Lev3)}$



e.g. limit state, variables

e.g. realisation of variables

Optimisation of $\beta_{sys,t}$ for Level 3 codes

- Game between *Code writer* and *Chance*
  1. *Code writer* selects a β_t
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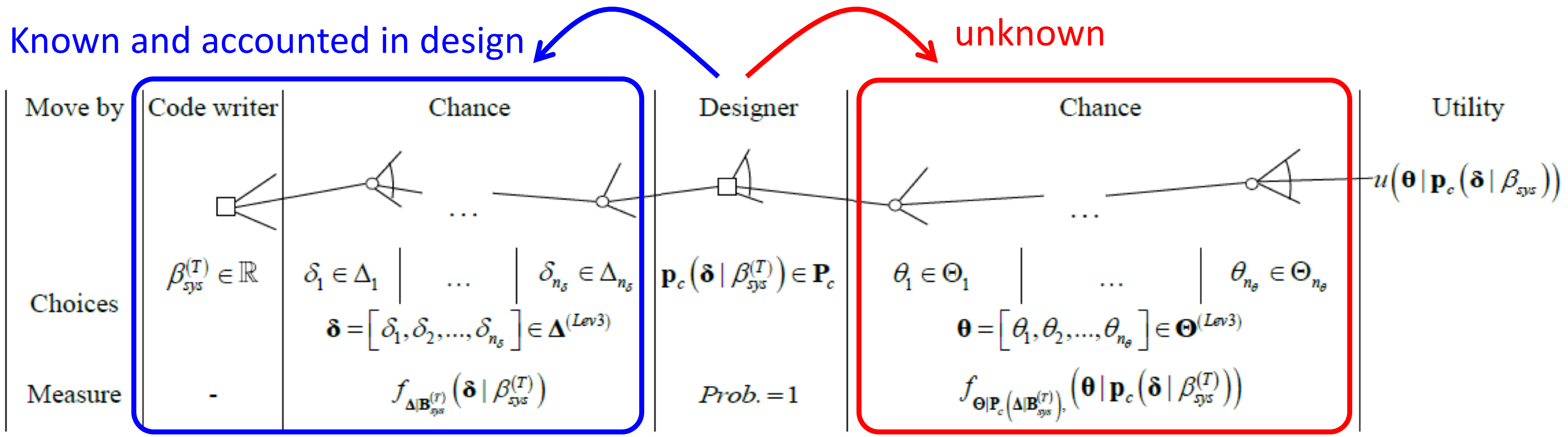


e.g. limit state, variables

e.g. realisation of variables

Current target reliability values in JCSS PMC and ISO 2394

- Based on monetary optimization

		Failure consequences		
		Minor	Moderate	Large
Relative cost of safety	Large	$3.1\ (P_f \approx 10^{-3})$	$3.3\ (P_f \approx 5 \cdot 10^{-4})$	$3.7\ (P_f \approx 10^{-4})$
	Normal	$3.7\ (P_f \approx 10^{-4})$	$4.2\ (P_f \approx 10^{-5})$	$4.4\ (P_f \approx 5 \cdot 10^{-6})$
	Small	$4.2\ (P_f \approx 10^{-5})$	$4.4\ (P_f \approx 5 \cdot 10^{-6})$	$4.7\ (P_f \approx 10^{-6})$

- Risk optimisation philosophy included by differentiation of consequences and cost for safety.
- Differentiation is coarse - > consistent with level of information.
- But qualification into classes is difficult.

Background Reliability Target Table

- Objective function

$$E\left[C_{tot}\left(p\right)\right] = C_{constr}\left(p\right) + E\left[C_f\left(p\right)\right]\frac{1}{\gamma} + E\left[C_{obs}\left(p\right)\right]\frac{1}{\gamma}$$

$$= \left[C_0 + C_I p\right] + \left[C_0 + C_I p + H\right]\frac{\lambda P_f^{(1a)}\left(p\right)}{\gamma} + \left[C_0 + C_I p + D\right]\frac{\omega}{\gamma}$$

- Yearly probability of failure based on the simple $R - S$ problem.
- The variability of R and S chosen such that it represents the characteristics of a class of structures.

Background Reliability Target Table

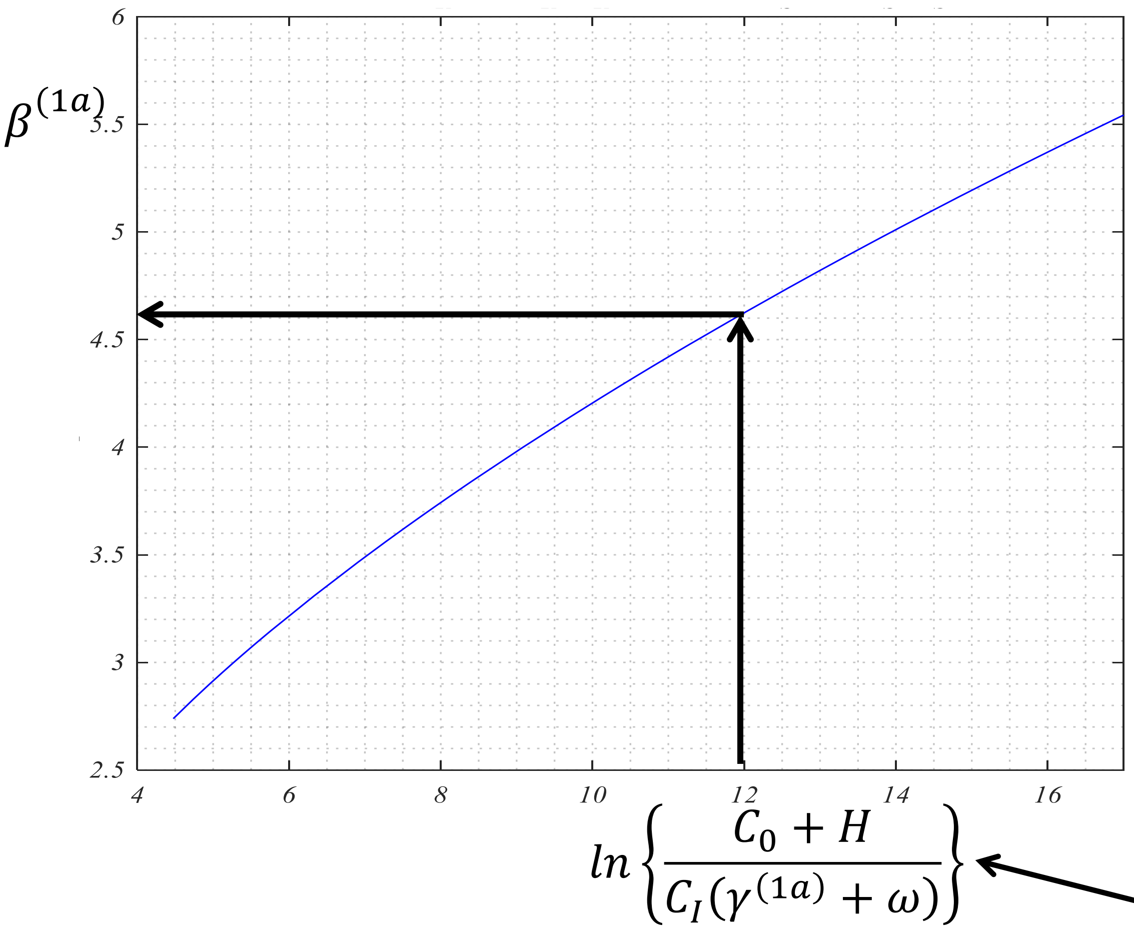
- Optimisation

$$\frac{d}{dp}\left\{C_0 + C_I p + [C_0 + C_I p + H]\,\frac{\lambda P_f^{(1a)}(p)}{\gamma} + [C_0 + C_I p + D]\,\frac{\omega}{\gamma}\right\}\Bigg|_{p=p^*} \equiv 0$$

$$\Rightarrow \frac{C_0 + C_I p^* + H}{C_I} = \frac{1 + P_f^{(1a)}(p^*)\,\frac{1}{\gamma} + \frac{\omega}{\gamma}}{-\left.\frac{dP_f^{(1a)}(p)}{dp}\right|_{p=p^*}\frac{1}{\gamma}}$$

- Reordering and simplification: $\dfrac{C_I \cdot (\gamma + \omega)}{C_0 + H} \approx -\left.\dfrac{dP_f^{(1a)}(p^*)}{dp}\right|_{p=p^*}$

Plot representing target reliabilities



Line satisfying the condition at optimum

$$\frac{C_I \cdot (\gamma + \omega)}{C_0 + H} \approx -\left.\frac{dP_f^{(1a)}(p^*)}{dp}\right|_{p=p^*}$$

for:
$COV_R = 0.15$ and $COV_S = 0.30$

Safety costs;
Failure costs;
Interest rate γ;
Obsolescence rate ω.

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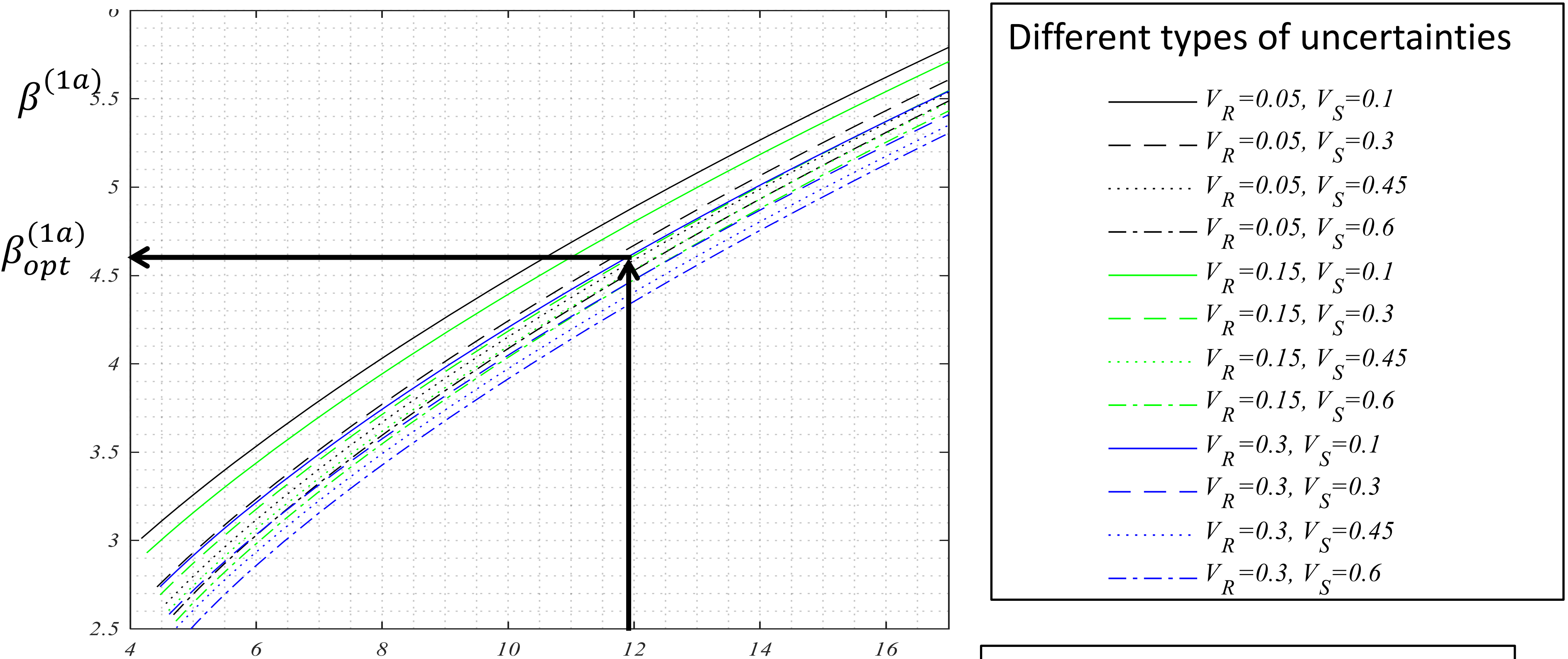
Plot representing target reliabilities



$$ln\left\{\frac{C_0 + H}{C_I(\gamma^{(1a)} + \omega)}\right\}$$

Safety costs;
Failure costs;
Interest rate γ;
Obsolescence rate ω.

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Life Safety

- The reliability requirement, so far, was based on optimisation.
- Our societal preferences for life safety can not be related to potential benefit of a economic endeavour!
- On the other hand, additional reliability is obtained by investing more monetary means.
- Societal willingness to pay (SWTP): How much can a society invest to reduce the fatality rate in structures?

Life Safety – modified objective

$$\frac{d}{dp}\left\{C_0 + C_I p + \quad N_F\, SWTP \quad \frac{\lambda P_f^{(1a)}(p)}{\gamma} + [C_0 + C_I p + D]\,\frac{\omega}{\gamma}\right\}\Bigg|_{p=p^*} \equiv 0$$

- Correspondingly it has to be invested at least:

$$-\frac{dP_f^{(1a)}(p)}{dp} \leq \frac{C_I(\gamma_S + \omega)}{SWTP \cdot N_F} = K_1$$

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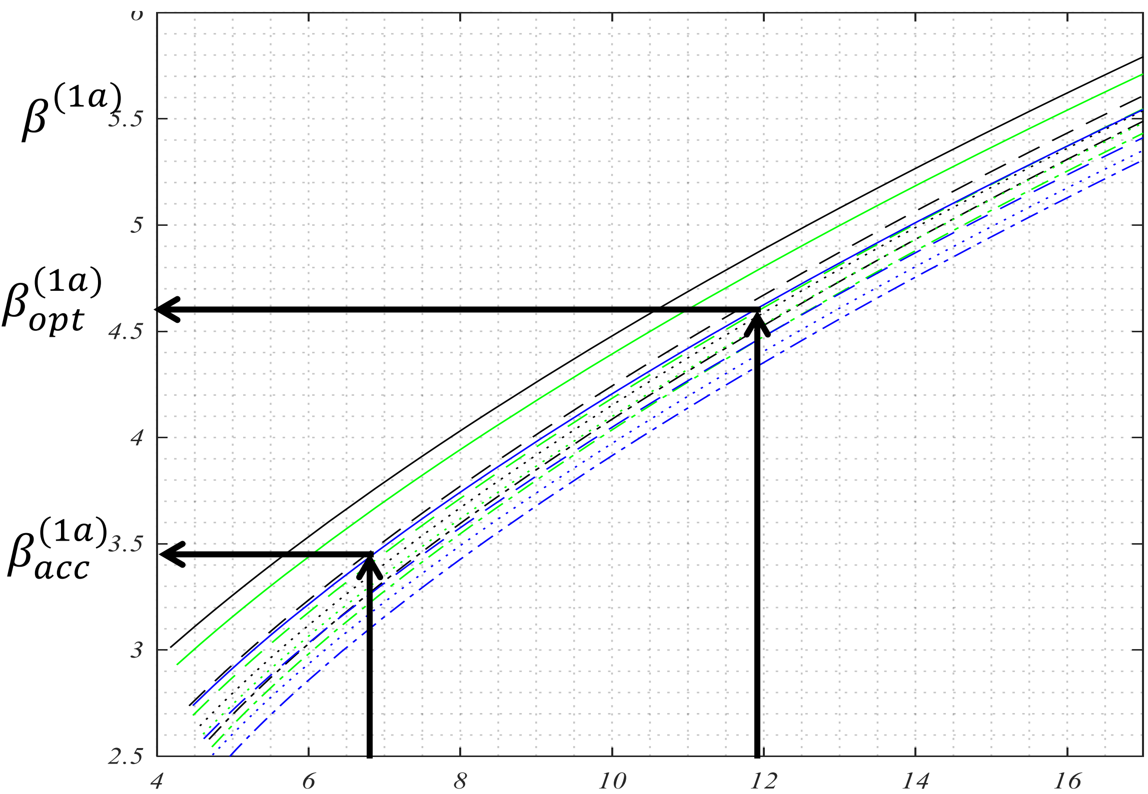
Plot representing target reliabilities



Different types of uncertainties

$$ln\left\{\frac{SWTP \cdot N_F}{C_I\left(\gamma_S^{(1a)}+\omega\right)}\right\} \qquad ln\left\{\frac{C_0 + H}{C_I(\gamma^{(1a)}+\omega)}\right\}$$

Safety costs;
Failure costs;
Interest rate γ;
Obsolescence rate ω.

Marginal Lifesaving Cost Principle with Life Quality Index

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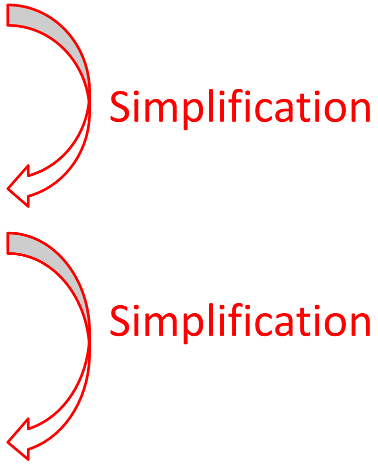
Summary

- Determination of target reliabilities for reliability based design is a calibration problem
- Generalisation and classification requires “low” level of detail of system representation
- Risk criteria can be in-cooperated

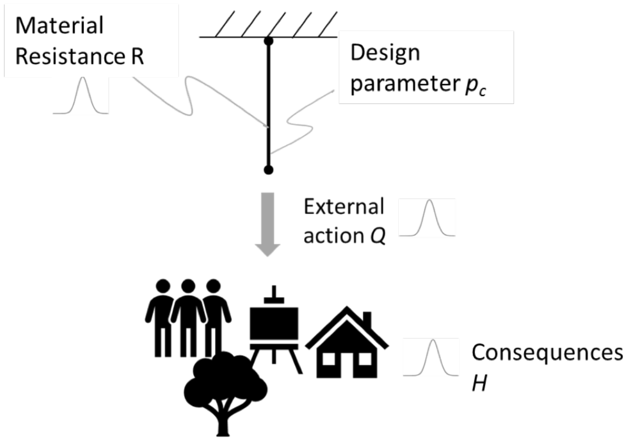
- Risk based design in open to any/(the appropriate) level of detail.

Simplified design and assessment of decision approaches [ISO 2394]

- Level 4: Risk-informed
  - Levels 3 (and 2): Reliability-based
    - Level 1: Semi-probabilistic



Semi-probabilistic approach (Level 1)



Partial Safety Factors
(reliability elements)

Design:

$$p_c: p_c \geq \frac{\gamma_M}{f_k} \cdot \gamma_Q \cdot q_k$$

Level 1 ≡ Level 4 $\Leftrightarrow \gamma_M, \gamma_Q:\ \boldsymbol{P_f}\left(p_c = \frac{\gamma_M}{f_k} \cdot \gamma_Q \cdot q_k\right) \equiv \boldsymbol{P_{f,opt}}$

Code calibration, why?

- Simplification:
  1. No explicit evaluation costs, consequences, etc.
  2. No reliability analyses

→ **simplify calculations**

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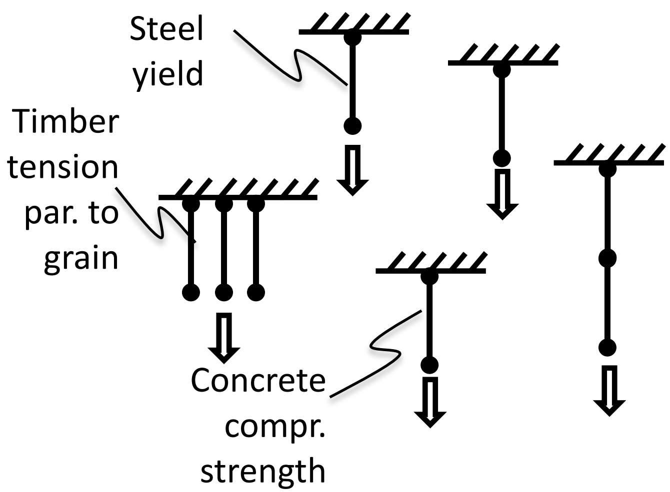

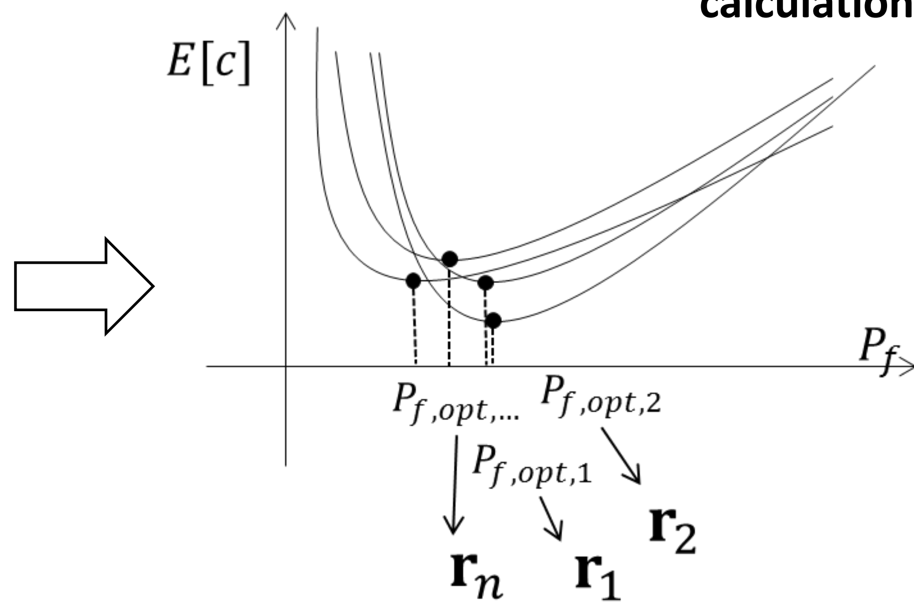

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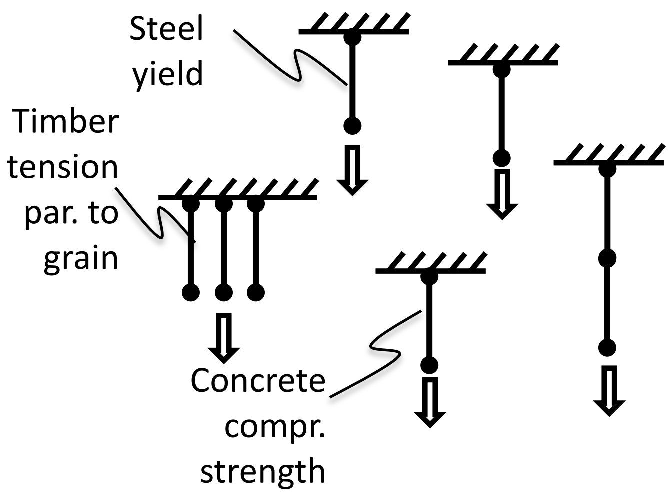
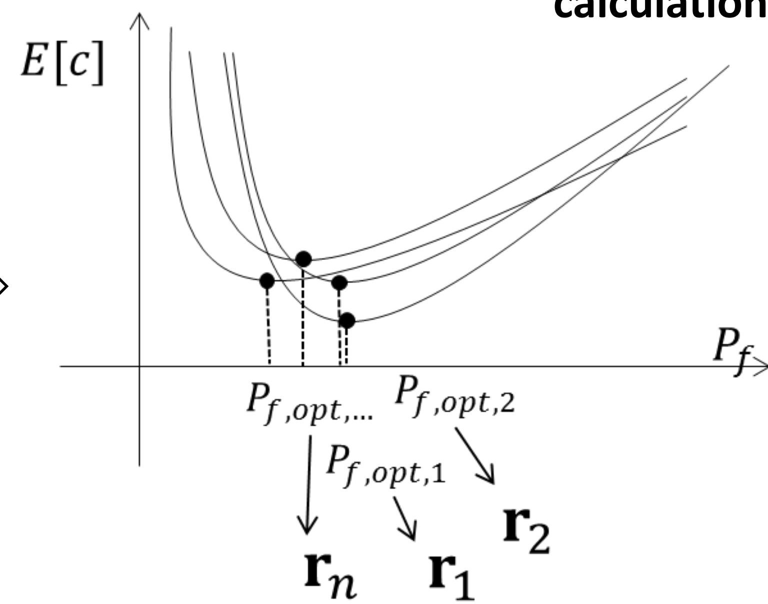


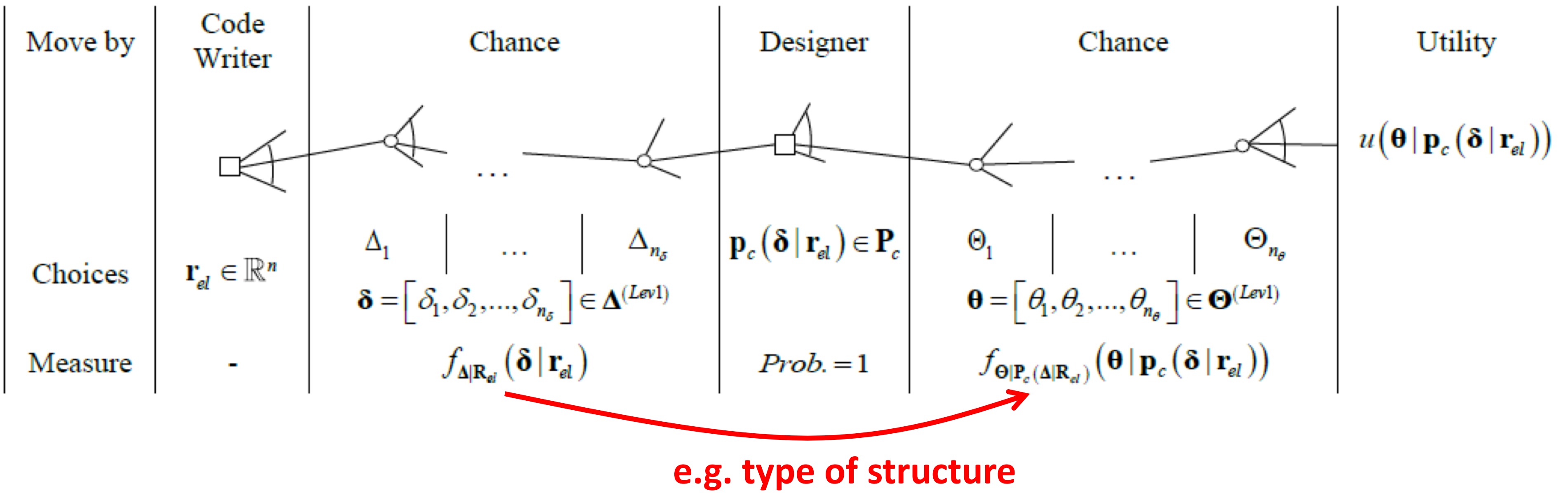


  3. One $\mathbf{r} = [\gamma, \psi_0, k_{mod}]$ for a class of structures → **simplify standards and calculations**

CALIBRATION: what r is optimal for the class?

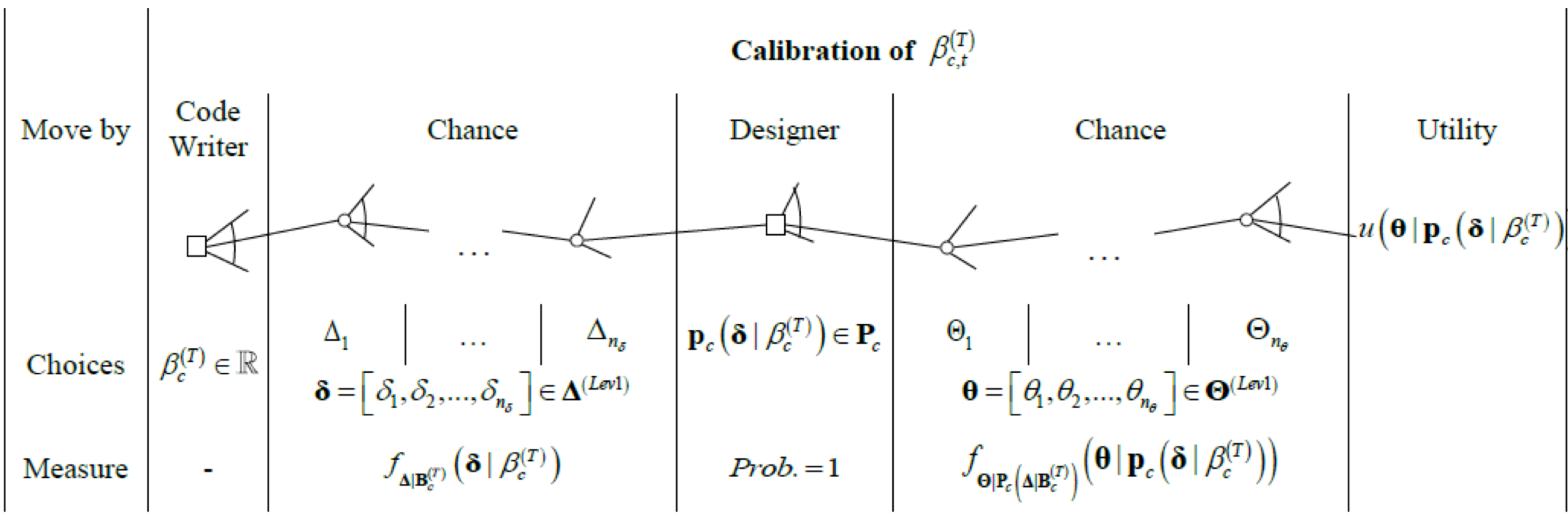
Decision problem

- Decision variable: $\mathbf{r}_{el}$ for Level 1 design for a class of structures
  - Partial safety factors
  - Modification factors
  - Load combination factors



Simplified decision problem

1. **Optimise $\boldsymbol{\beta}_{c,target}$**
   – Decision variables: $\boldsymbol{\beta}_{c,target}$ for Level 1 design for a class of structures



2. **Reliability-based calibration**
   – $\mathbf{r}_{el,opt}$: $\boldsymbol{\beta}_c(\mathbf{r}_{el})$ as close as possible to $\boldsymbol{\beta}_{c,target} = \boldsymbol{\beta}_{c,opt}$

Code Calibration Overview