Using CVaR for Adequacy Assessments and in Resource Expansion Models

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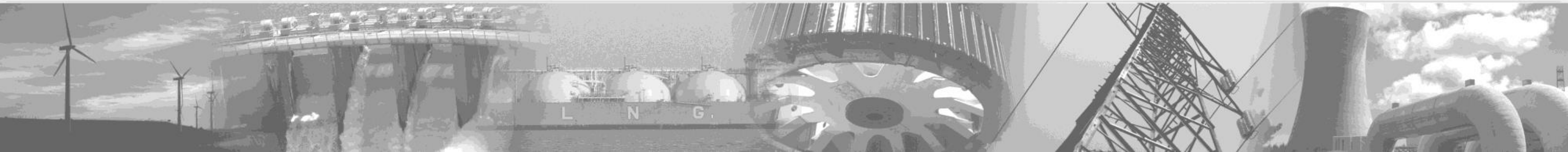


Outline

- Introduction
- Problem description
- Reliability analysis
- Hierarchical approach
- Integrated approach
- Conclusions

Introduction

- The ***expansion planning problem*** (EPP) of power systems is originated from the necessary changes in the system due to energy load growth during the passing of time
- Decision: when and in which projects to invest?
- Typical trade-off:

Cost x Reliability

Minimize Investment + Operation Cost

Guarantee Minimum Quality of Supply

Problem description

- General model

$$\text{Min } I(x) + O(x, w)$$

$$\text{s.t. } R(x, \xi) \leq \overline{R}$$

where:

x	vector of investment decisions
$I(x)$	investment cost function
$O(x, w)$	operation cost function
w	hydro inflow uncertainty
$R(x, \xi)$	reliability measure
ξ	operating state uncertainty

Problem description

- Investment problem
  - Objective: selection of the best set of generators, similar to the portfolio selection problem

- Operation problem
  - Also known as optimal hydrothermal scheduling problem
  - Objective: given an fixed investment decision, determine the least cost dispatch to supply the energy demand in a specified horizon
  - Hydro inflows uncertainty: multi-stage stochastic optimization problem

Problem description

- Reliability problem
  - Objective : evaluate system's adequacy in probabilistic terms
  - For generating systems, "failure" is commonly measured by the system's lack of generation capacity:

$$R = \max(D - G, 0)$$

where

R load shedding

D system's demand

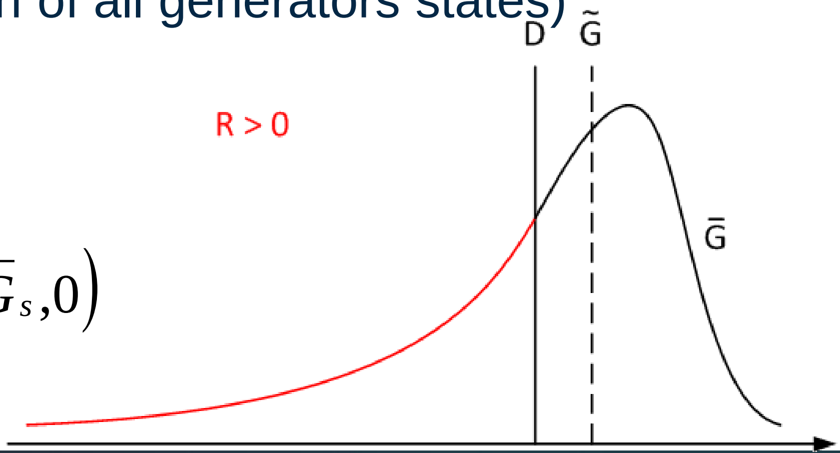
G system's total capacity

Reliability analysis

- Generator operating state can be either:

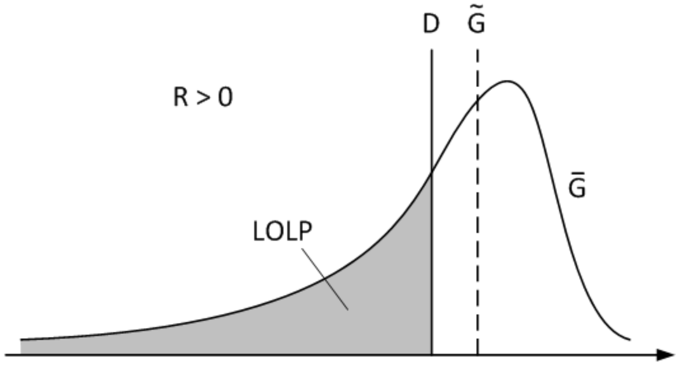
$$\xi_j \begin{cases} 0 = \text{failure, with probability } p_j \\ 1 = \text{operative, with probability } (1 - p_j) \end{cases}$$

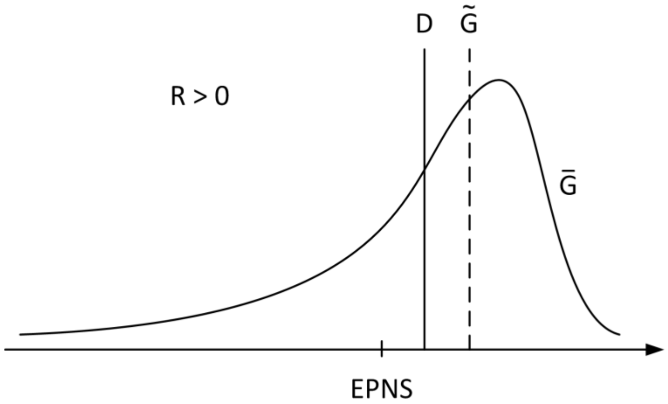
- System state is represented by vector $\xi = [\xi_1 \quad \xi_2 \quad \cdots \quad \xi_J]$
- Total system capacity is defined as $\overline{G} = \sum_{j=1}^{J} \xi_j \overline{g}_j$
- Finite supported distribution
  - Space of states: S (combination of all generators states)
  - Probability : $p_s = P(\xi_s)$
  - System capacity: $\overline{G}_s$
  - Load shedding: $R_s = \max(D - \overline{G}_s, 0)$



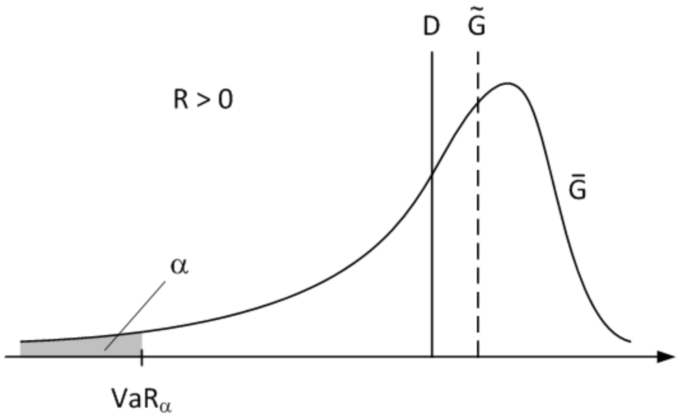
Risk measures

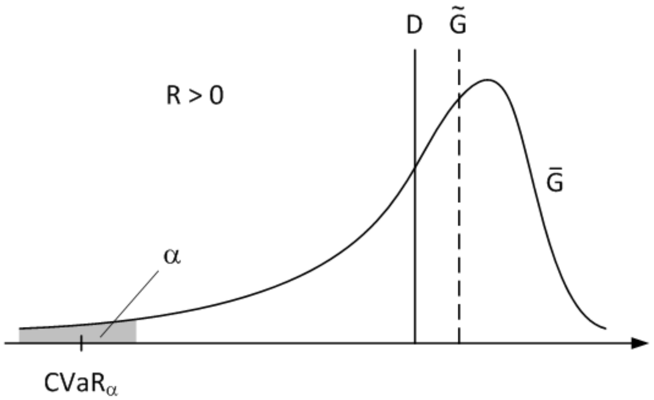
- Based on the distribution function of load shedding R
- Typical measures: LOLP & EPNS





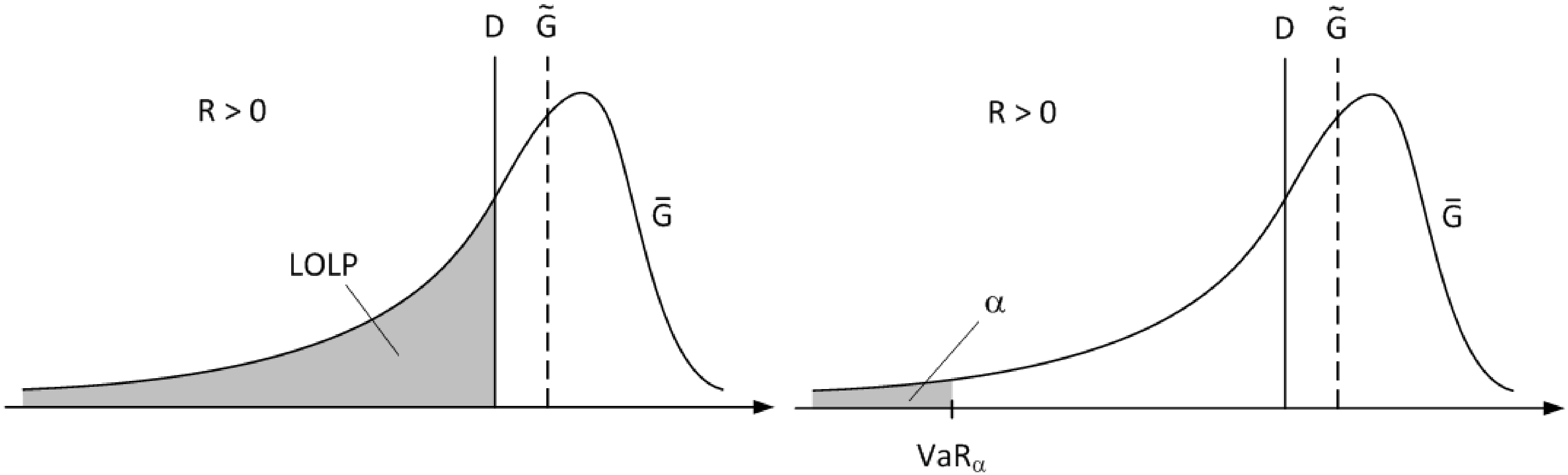
- Risk measures: VaR_{α} & $CVaR_{\alpha}$





Risk measures

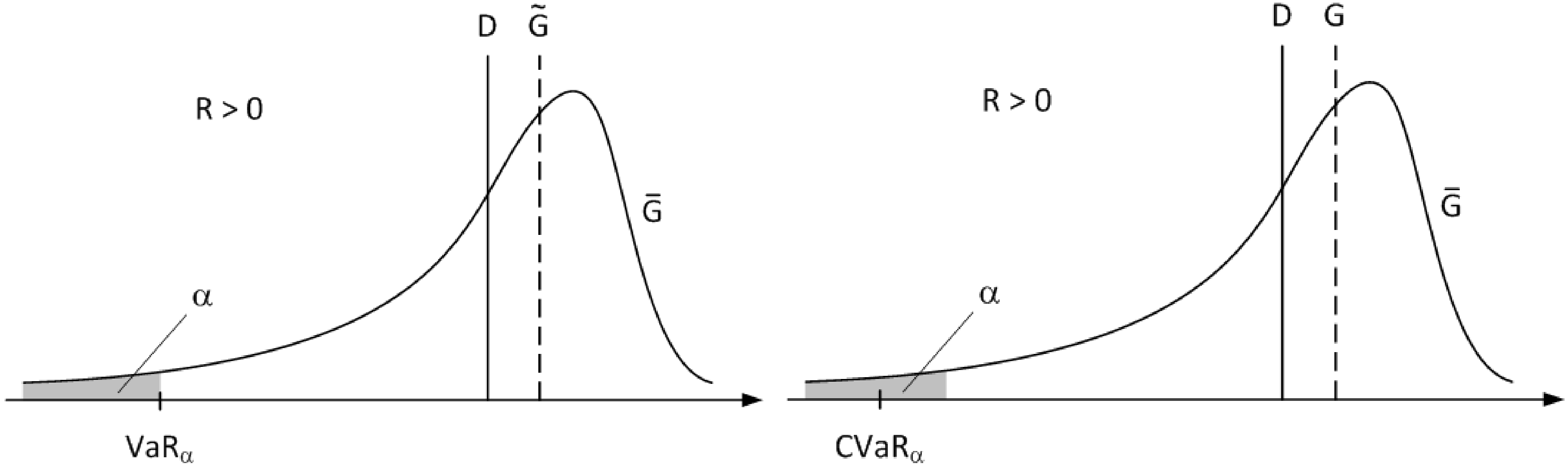
- LOLP X VaR_{α}



- VaR_{α} allows us to capture more critical events for the system
- $VaR_{5\%}$ answers the question “what is the maximum possible load shedding considering the 95% best states”?
- Inducing a more balanced expansion
  Very used in finances for this purpose

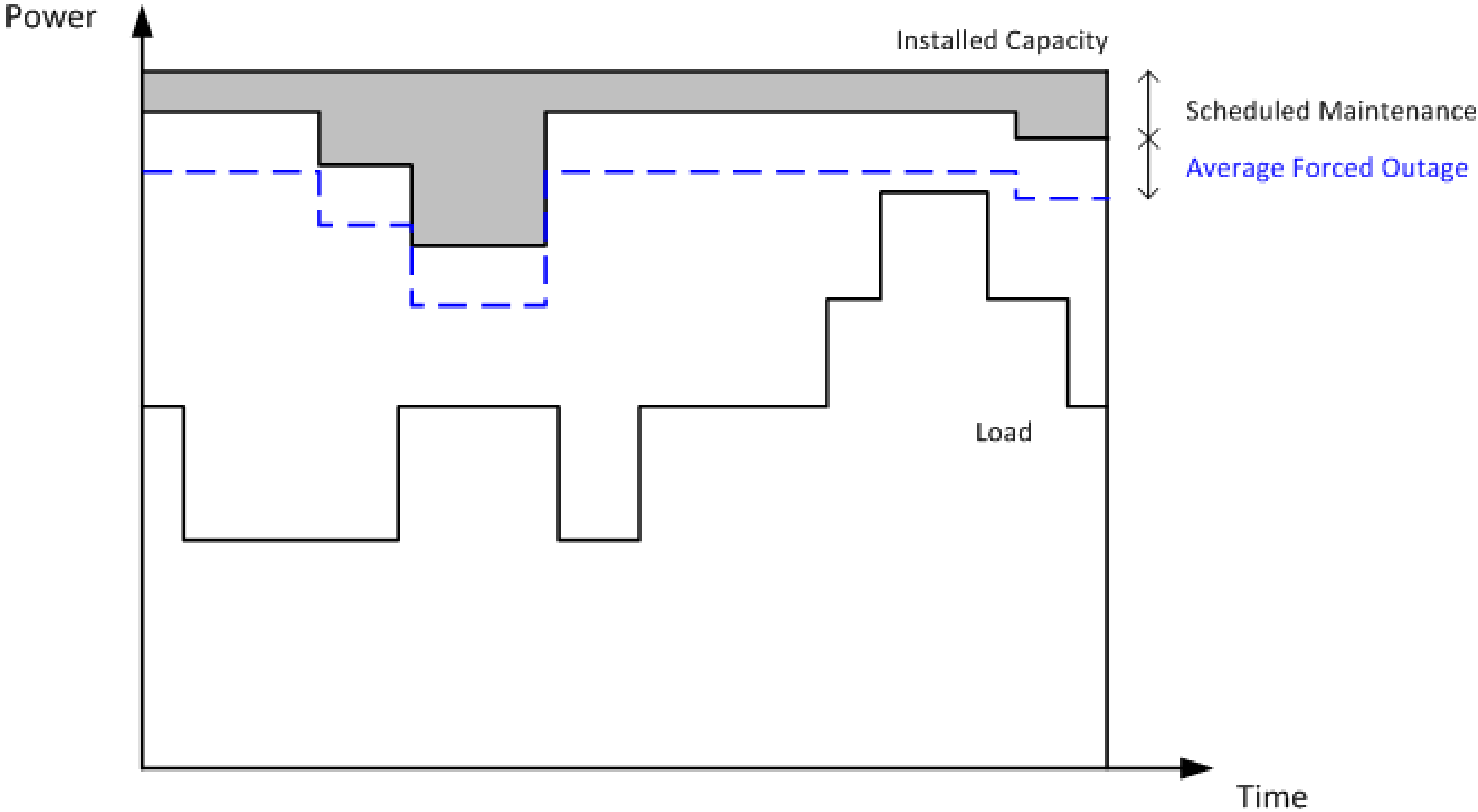
Risk measures

- VaR_α X $CVaR_\alpha$

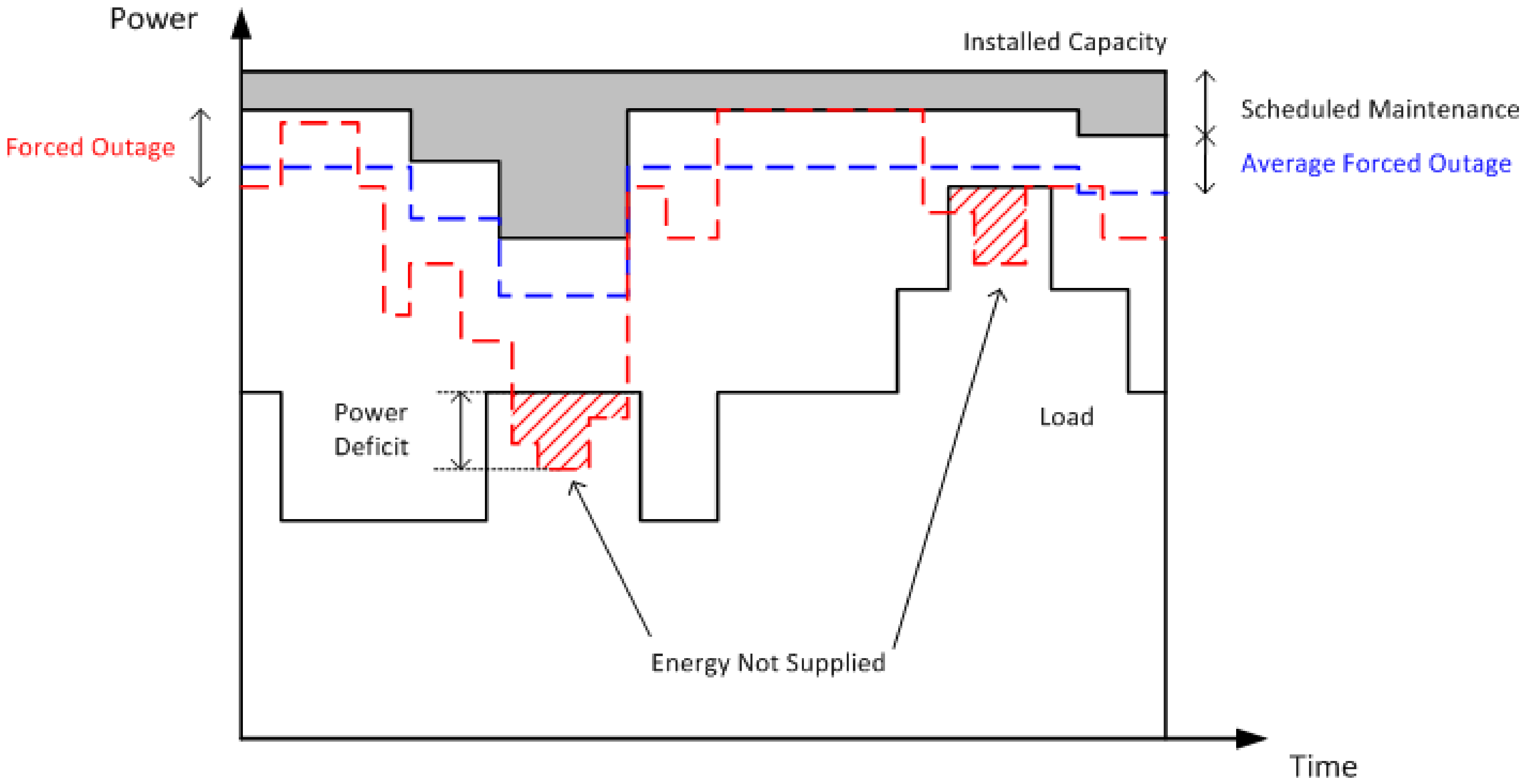


- VaR is "blind" to the severity of the events that lead to load shedding, that is, a 1% load curtailment has the same weight in the reliability evaluation as a 10% load curtailment.
- In order to capture both the probability and severity of the events we use CVaR

Risk measures – critical events CVaR X EPNS



Risk measures – critical events CVaR X EPNS



Evaluation of risk measures

- The analytical evaluation of the risk measure needs the evaluation of system states, but…

- Number of system states:
  - 1 generator $|S| = 2^1 = 2$ states
  - 2 generators $|S| = 2^2 = 4$ states
  - 30 generators $|S| = 2^{30} \approx 10^9$ states (1 billion)

- Huge problem!

Hierarchical approach

- Step 1: Solve economic planning problem (i.e., forget the reliability requirements) and find a investment plan "x"

$$\begin{aligned} \text{Minimize} \quad & I(x) + O(x) \\ \text{subject to} \quad & \sout{R(x) \leq \bar{R}} \\ & x \in X \end{aligned}$$

  - If "x" meets the reliability criterion → solution found!
  - If not, go to step 2
- Step 2: complement the plan "x" with new reinforcements until reliability criterion is met

Integrated approach

- How to consider reliability constraints in EPP?
  - The representation of the risk measure the in expansion planning problem would need the representation of at least one constraint/variable for each system state
    → computationally infeasible

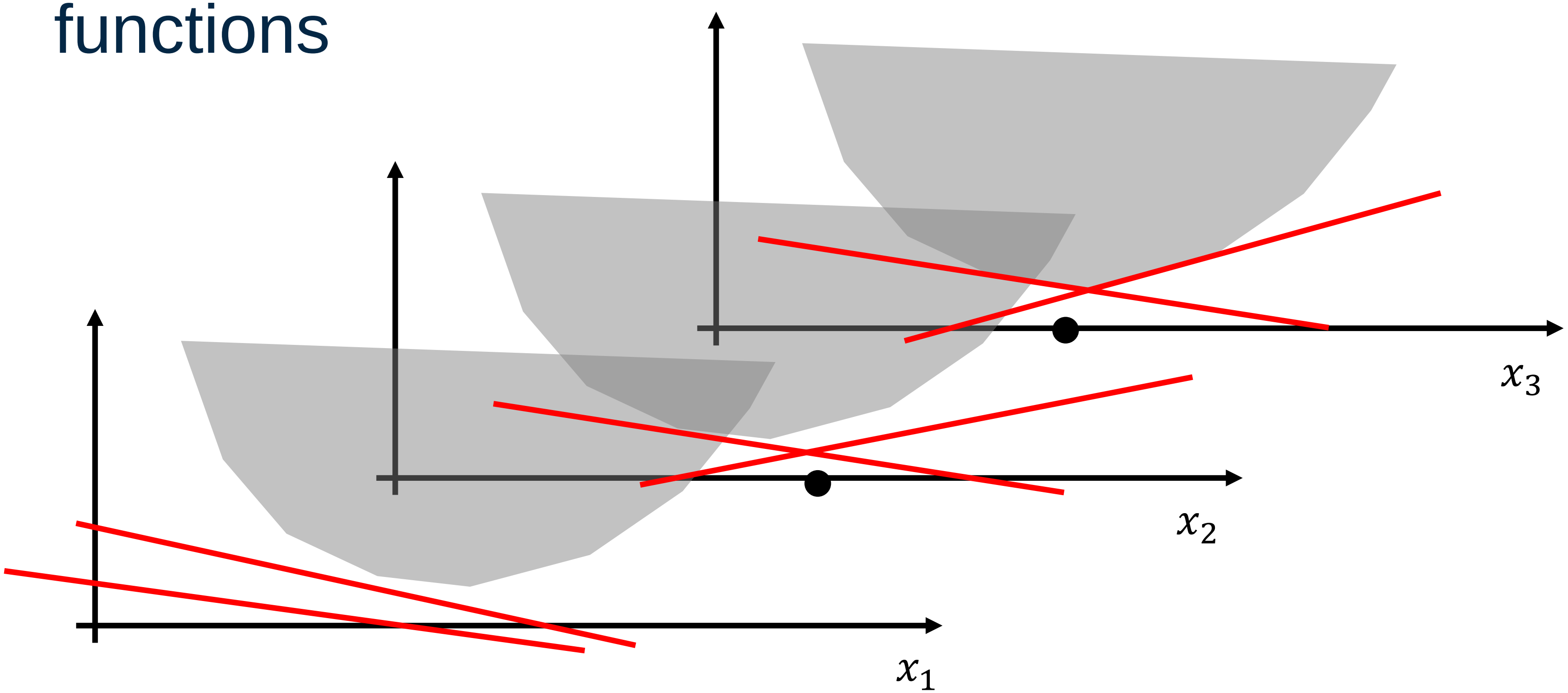
- Benders' decomposition

Decomposition scheme

- Investment problem approximation
  - Solved by MIP techniques (B&B + Heuristics from commercial solver)
- Operation subproblem
  - Solved using SDDP (*Stochastic Dual Dynamic Programming)*
- Reliability subproblem
  - Solved by *Monte Carlo sampling*

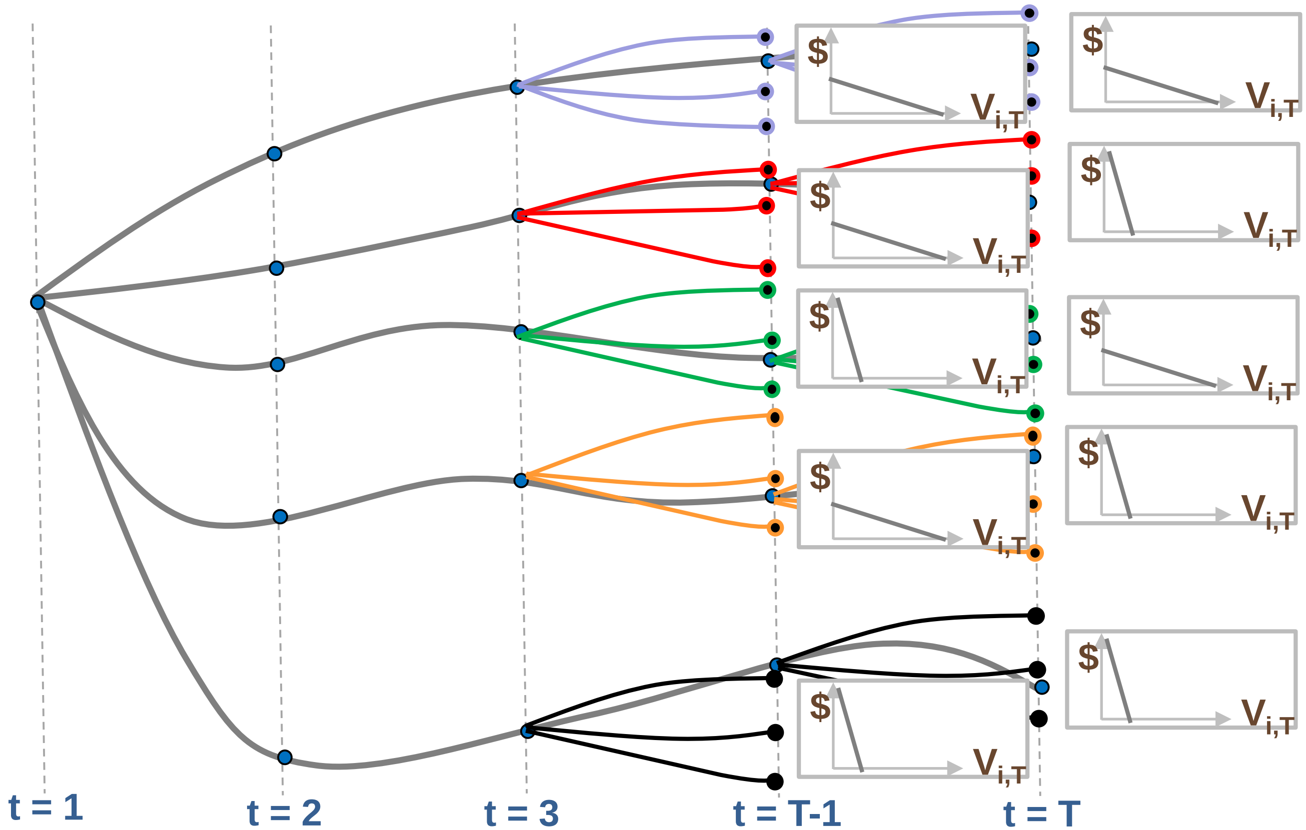
Decomposition scheme - SDDP

- Operation subproblem
  - Solved using SDDP: iterative construct value functions



Decomposition scheme - SDDP

- Operation subproblem
  - Solved using SDDP: parallelizable!



Decomposition scheme

- Reliability subproblem
  - "Analytical" single area model:

    Fast Fourier Tranforms for capacity PDF

    Kernel Densisty estimation for load and renewables PDF
  - Multi area model:

    Monte Carlo sampling + MaxFlow Theorem
  - *Complete DC model:*

    Monte Carlo sampling + LP solver (DCOPF)

Decomposition scheme

- Reliability subproblem: recent advances

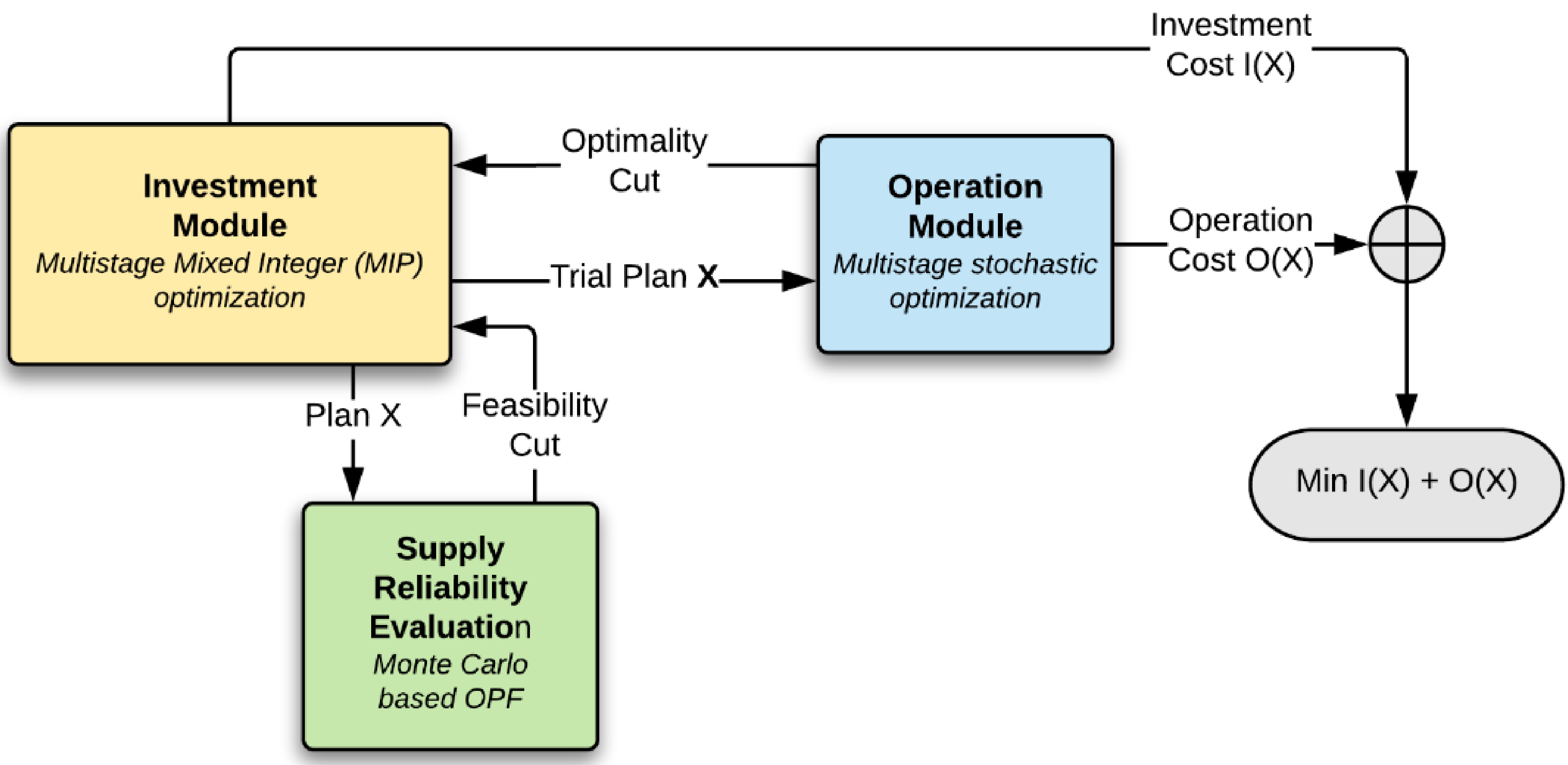
- Hybrid Monte Carlo Markov Chain (MCMC) and Cross Entropy (CE) scheme for variance reduction in the reliability evaluation module

- Co-optimization of probabilistic dynamic reserves (important for renewable penetration)

Decomposition scheme - CVaR

- Reliability subproblem
  - Remark 1:
    - EPNS e $CVaR_{\alpha}$ can be incorporated in the decomposition scheme
    - LOLP and VaR_{α} are not convex risk measures [3] and, therefore, cannot be used in decomposition schemes
  - Remark 2:
    - Sensitivity analysis can be carried out with EPNS e $CVaR\alpha$ but not with LOLP and $VaR\alpha$ due to their nonconvex characteristics

Decomposition scheme

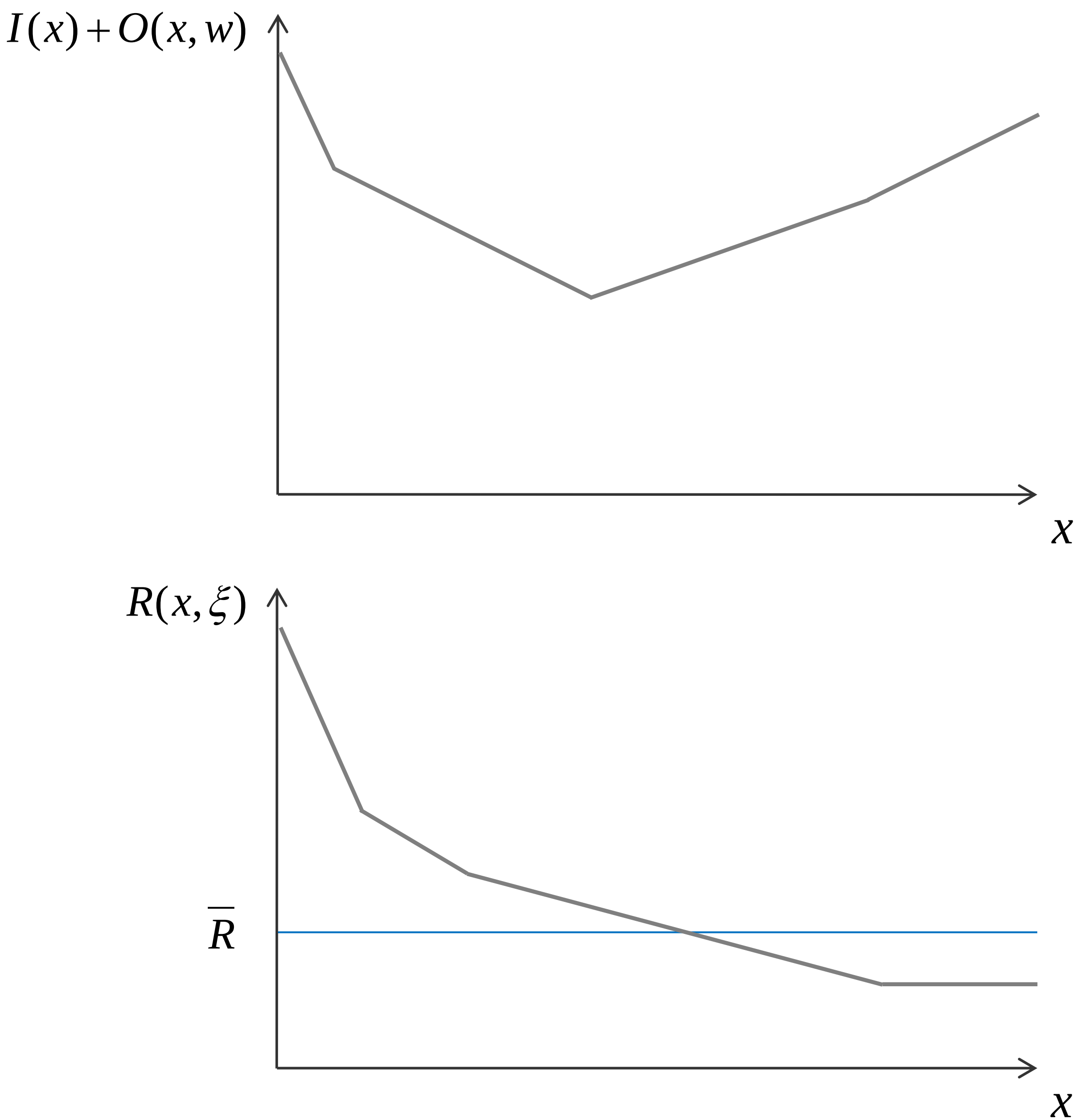


Decomposition scheme

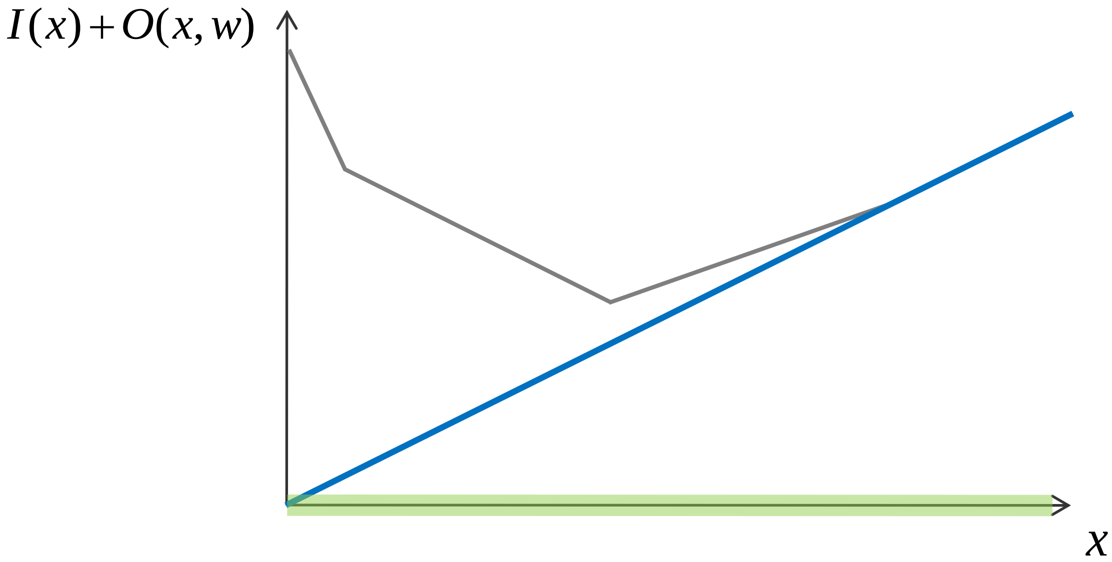
- Master problem (Investment problem approximation)

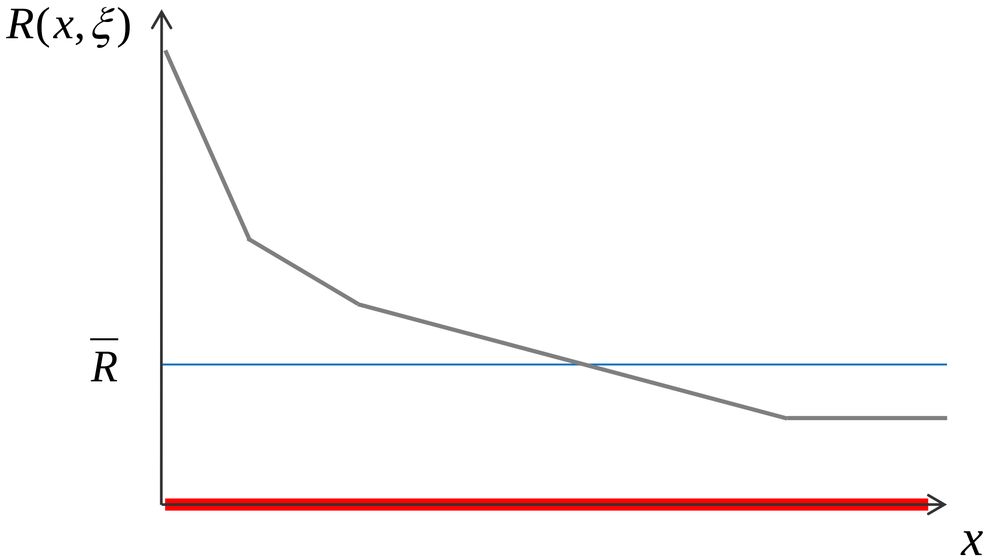
$$
\begin{aligned}
\text{Minimize} \quad & \sum_{j \in \mathcal{G}^C} c_j x_j + \alpha \\
\text{subject to} \quad & \alpha \geq O(x^i) + \sum_{j \in \mathcal{G}^C} \frac{\partial O(x^i)}{\partial x_j^i}(x_j - x_j^i) && i \in \mathcal{A} \\
& R(x^i) + \sum_{j \in \mathcal{G}^C} \frac{\partial R(x^i)}{\partial x_j^i}(x_j - x_j^i) \leq \bar{R} && i \in \mathcal{R} \\
& x \in X
\end{aligned}
$$

Decomposition scheme - example

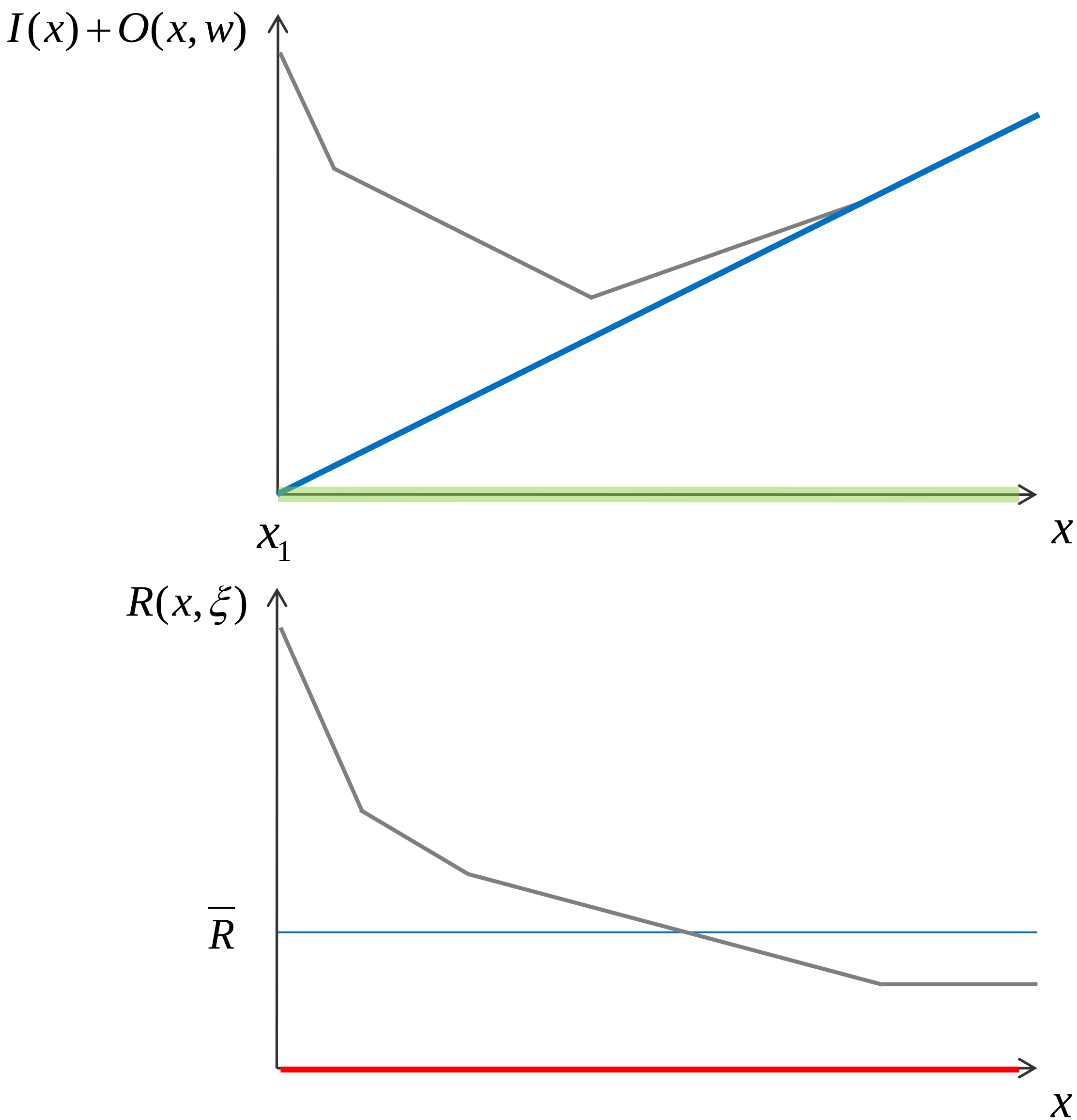


Decomposition scheme - example





Decomposition scheme - example

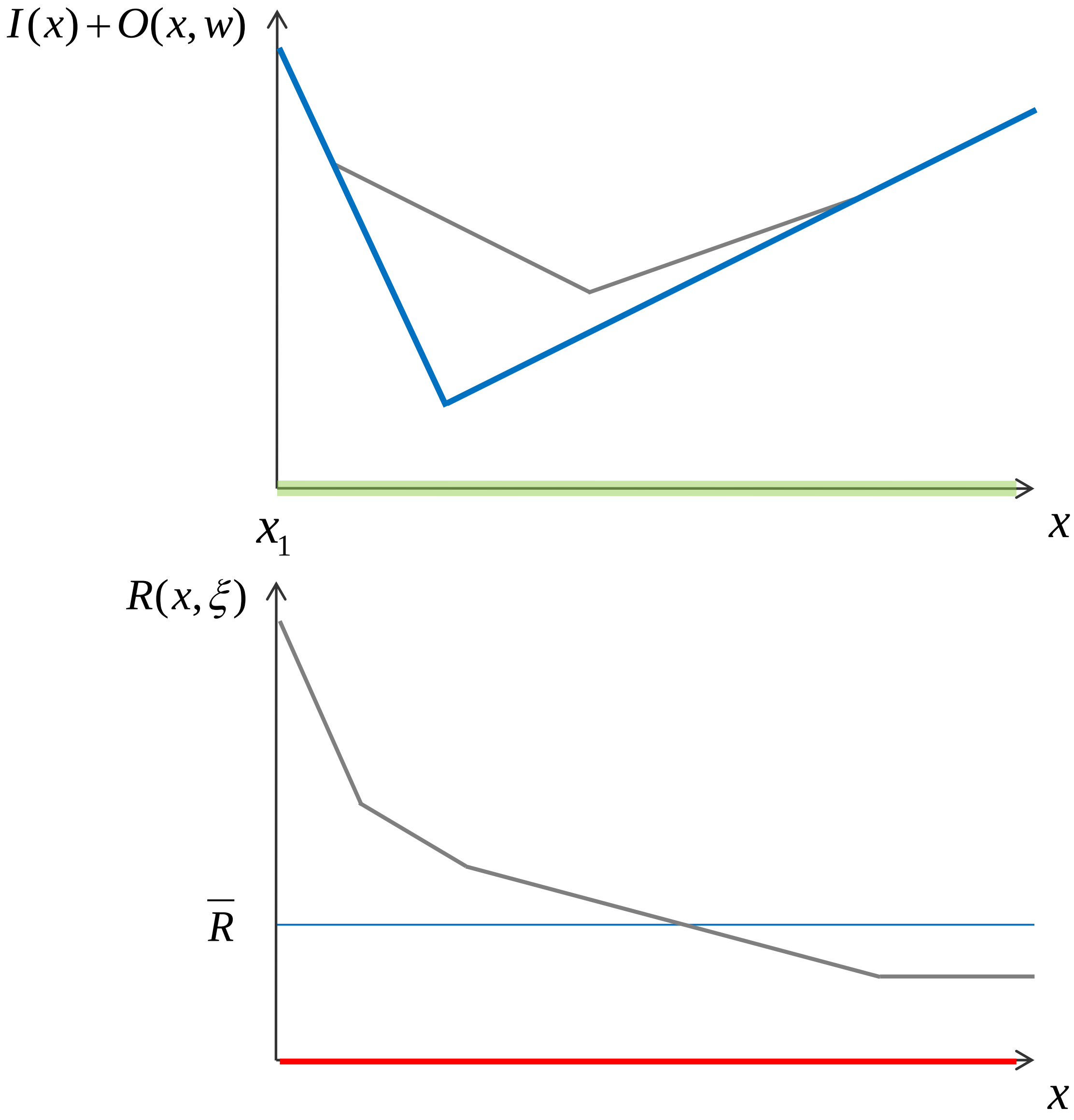


Investment

Operation

Reliability

Decomposition scheme - example

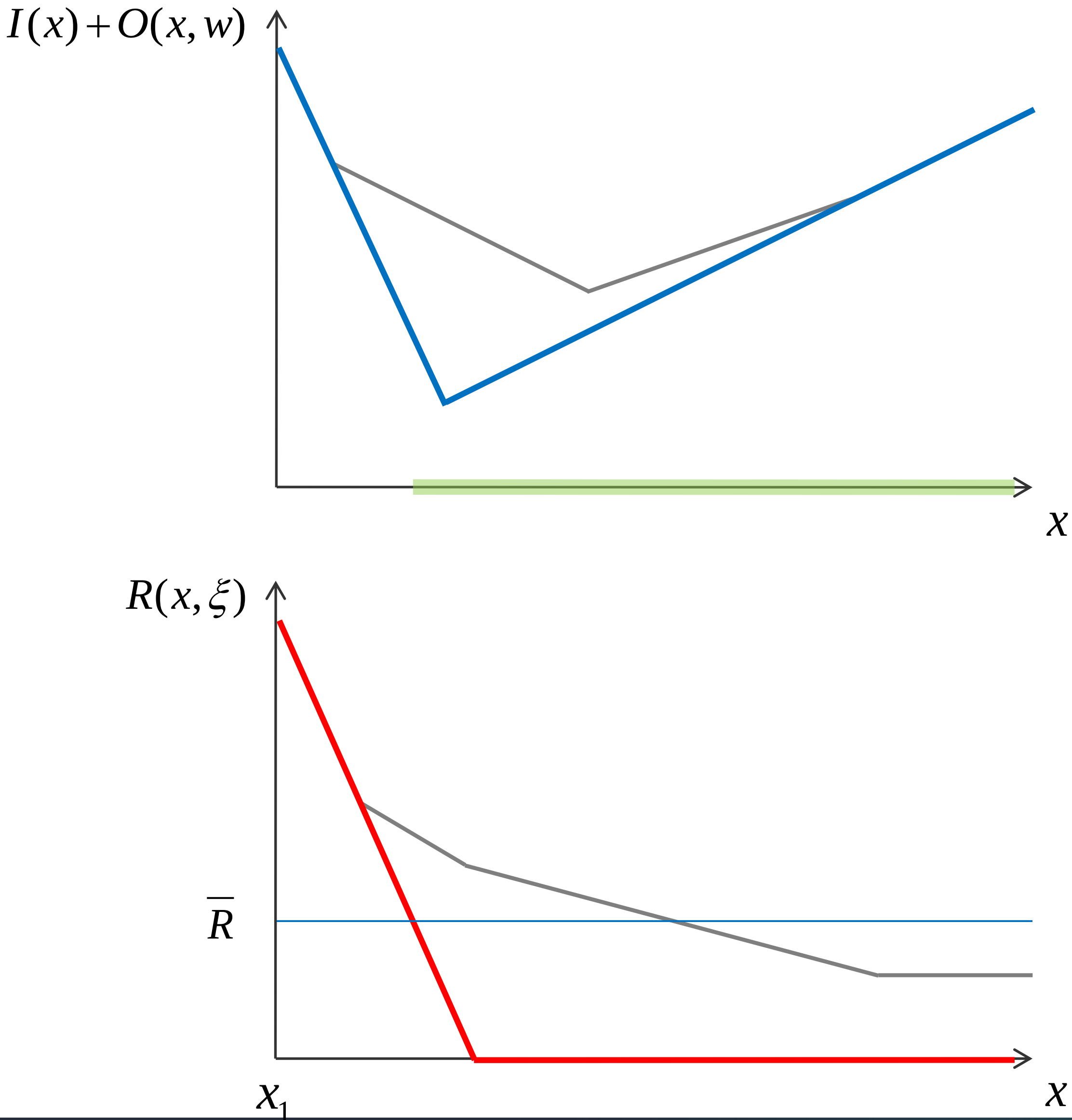


Investment

Operation

Reliability

Decomposition scheme - example



Investment

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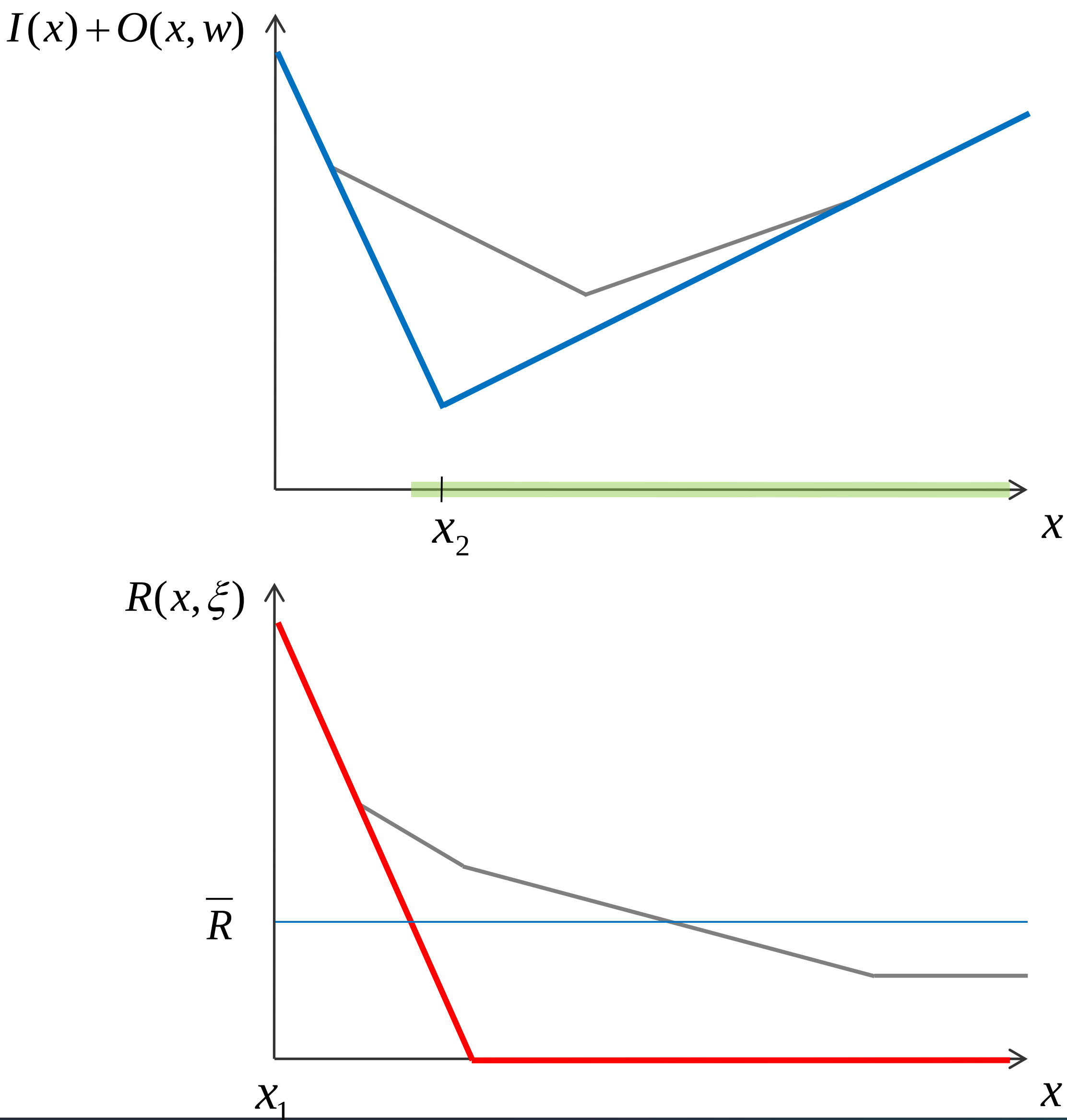
Decomposition scheme - example



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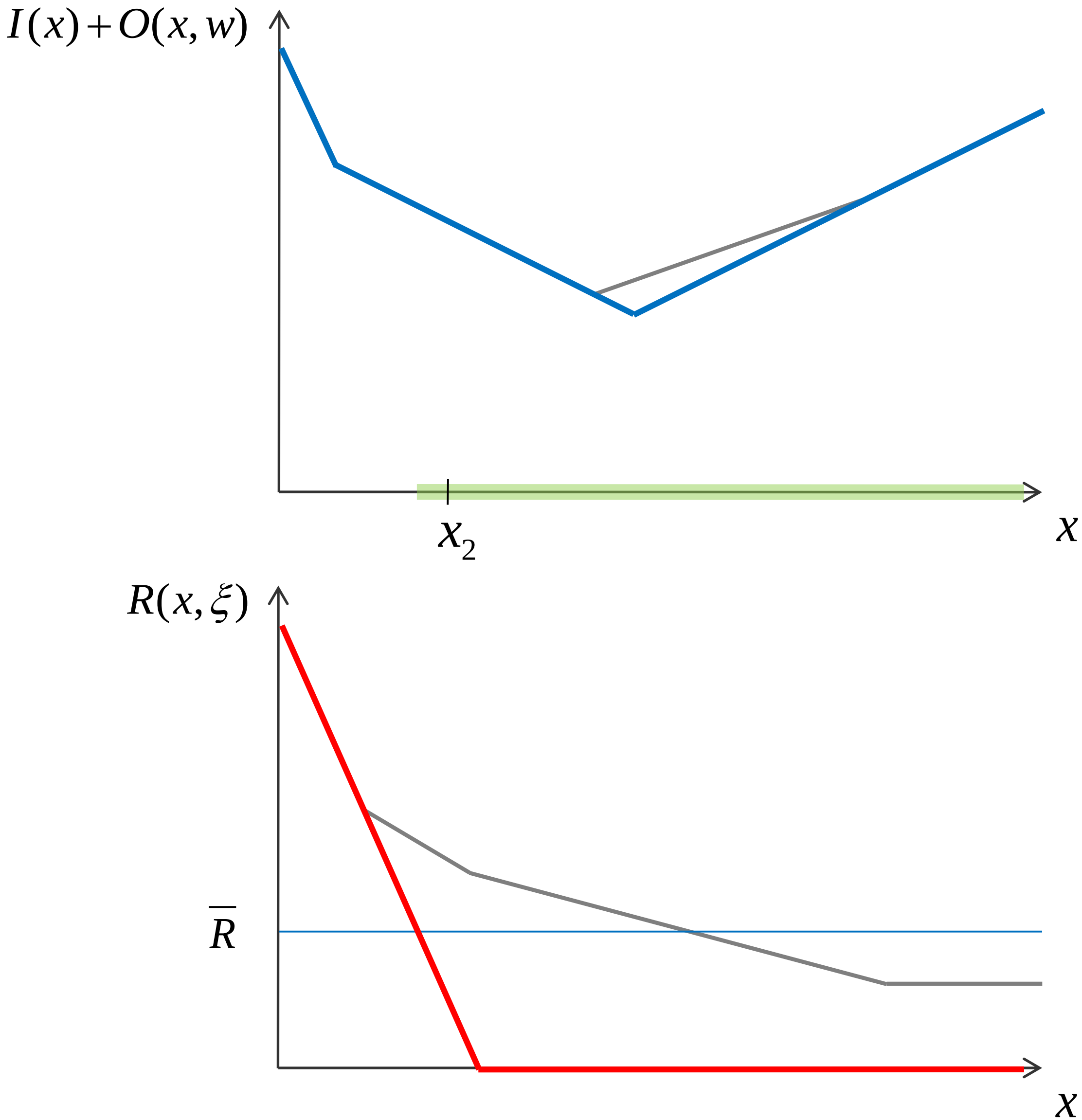
Decomposition scheme - example



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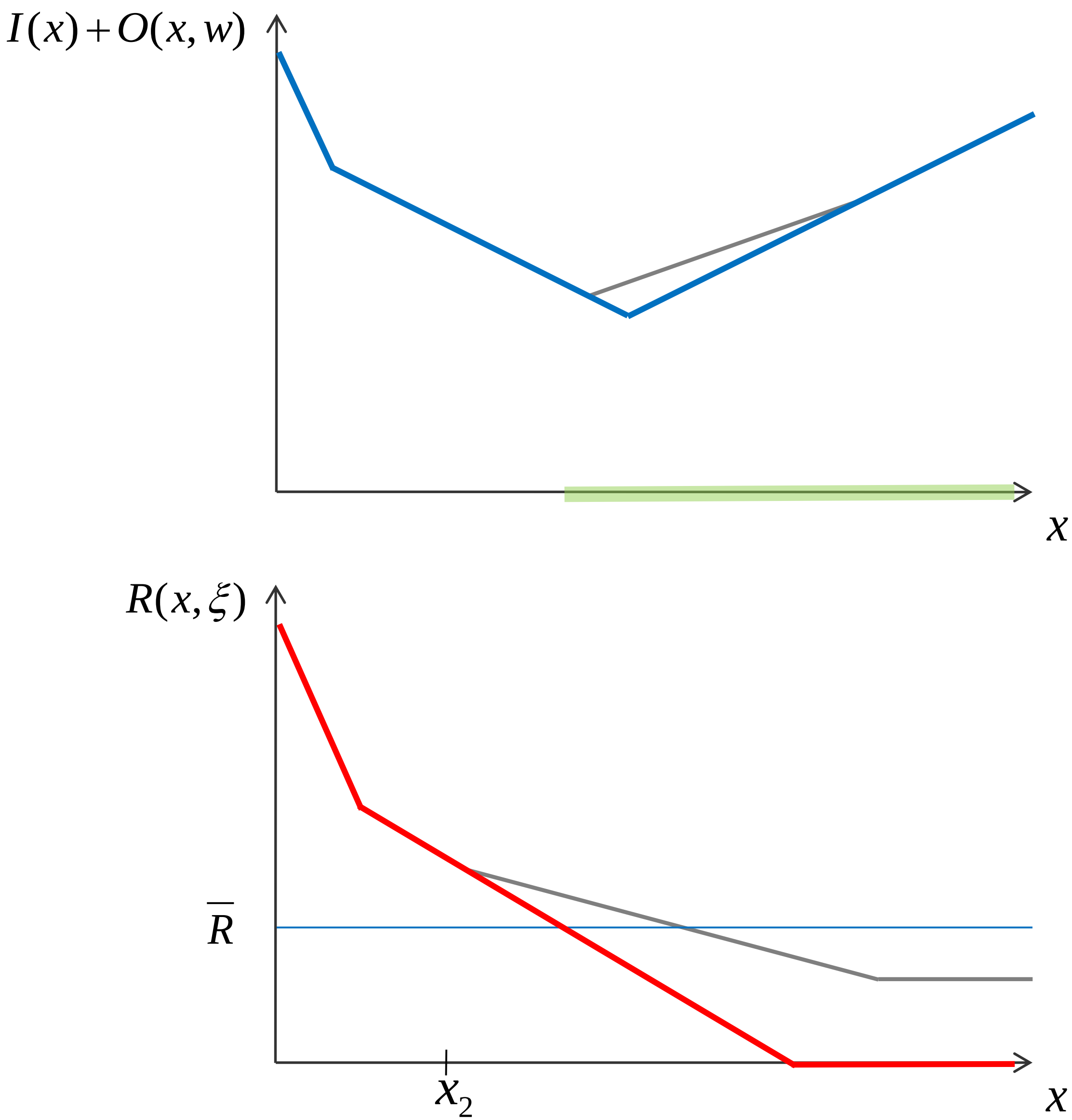
Decomposition scheme - example



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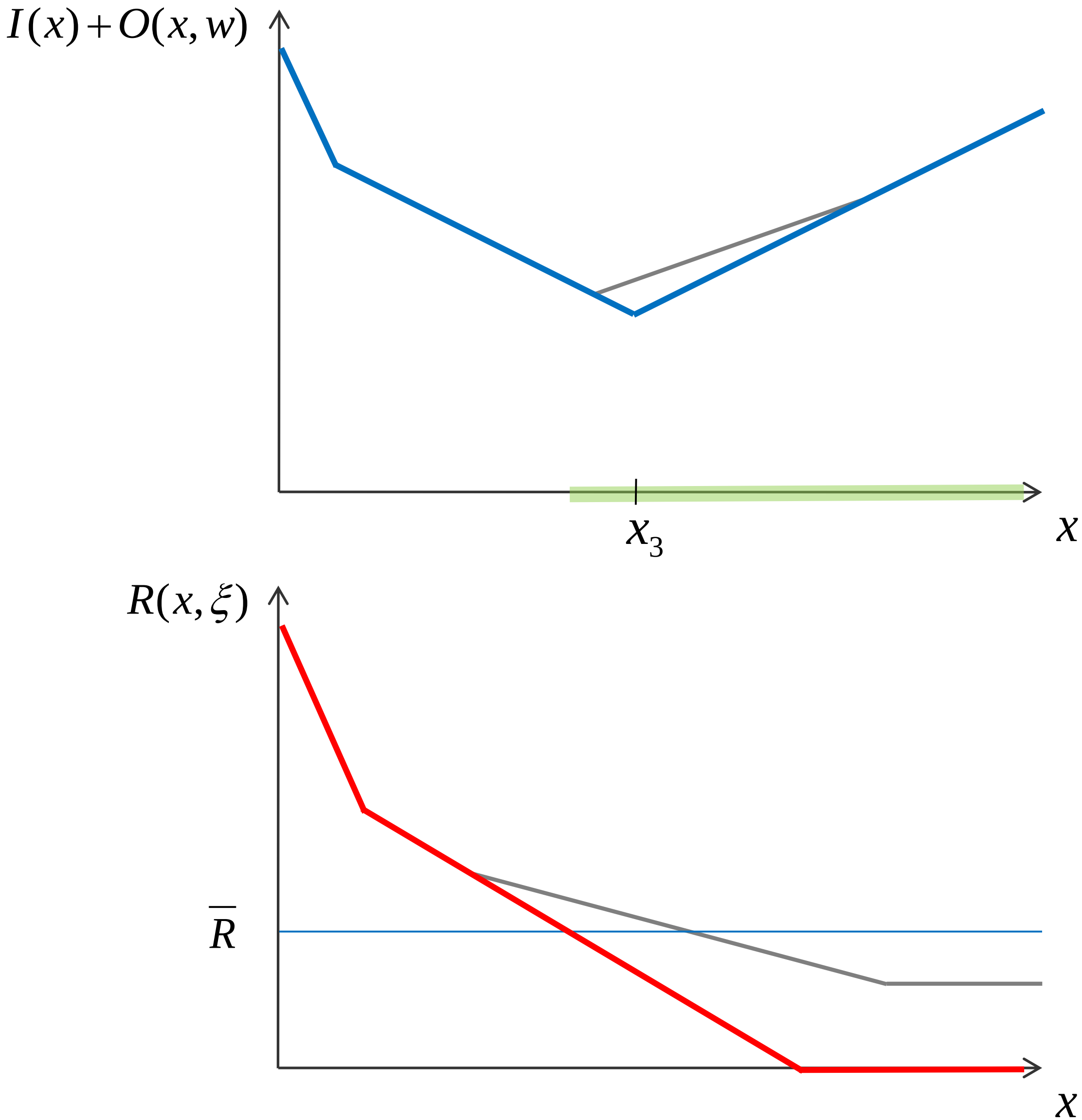
Decomposition scheme - example



Investment

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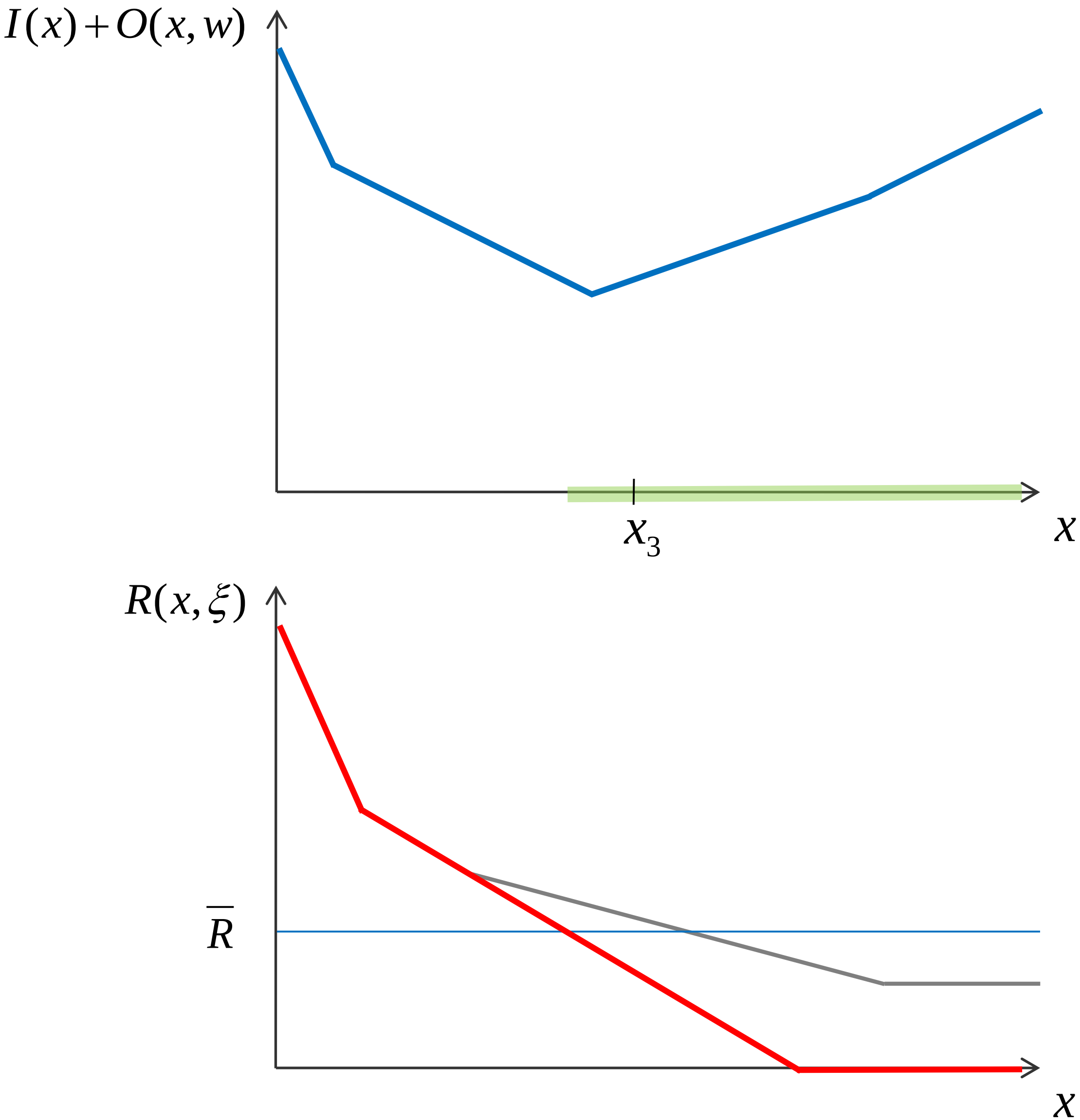
Decomposition scheme - example



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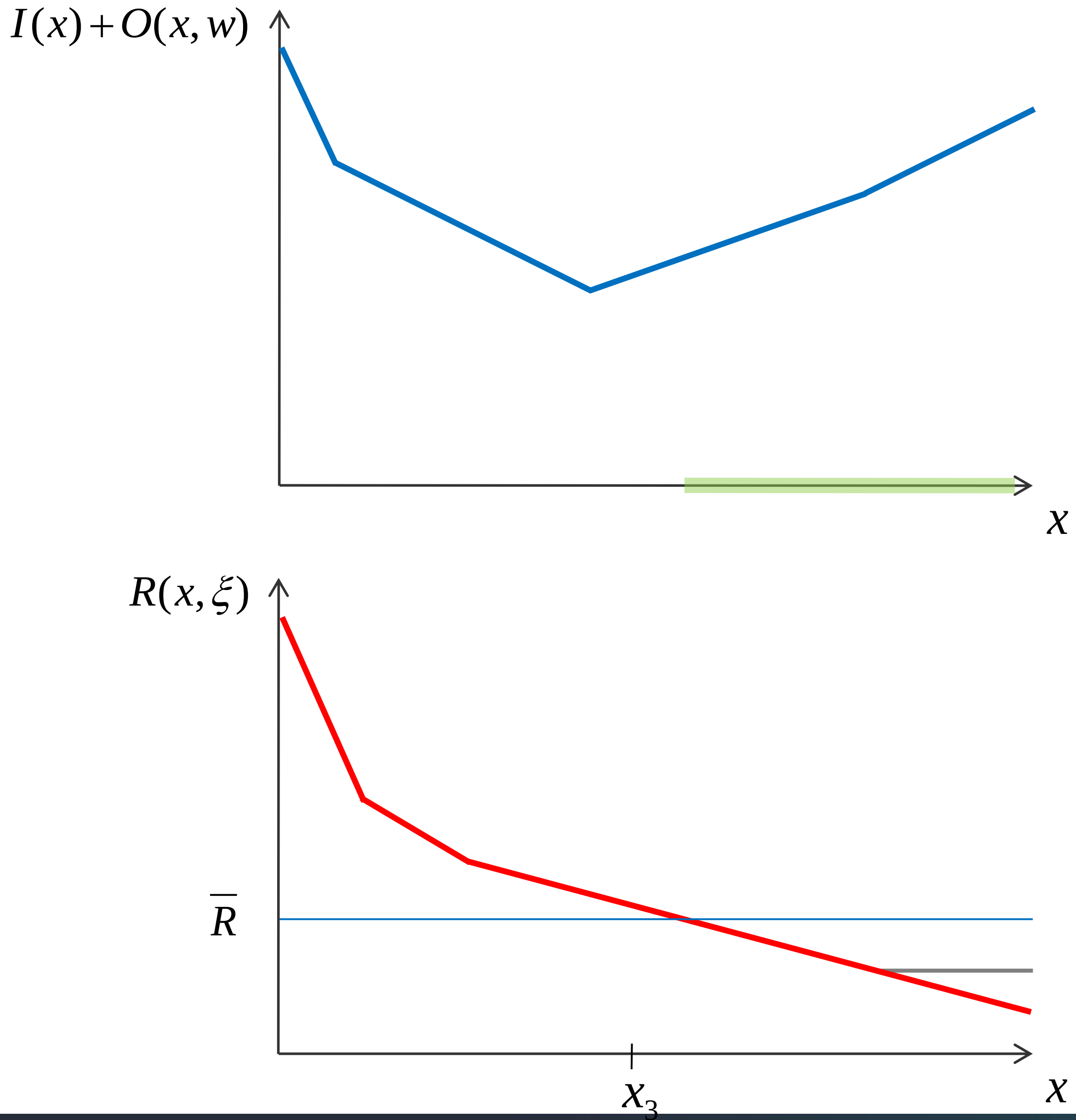
Decomposition scheme - example



Investment

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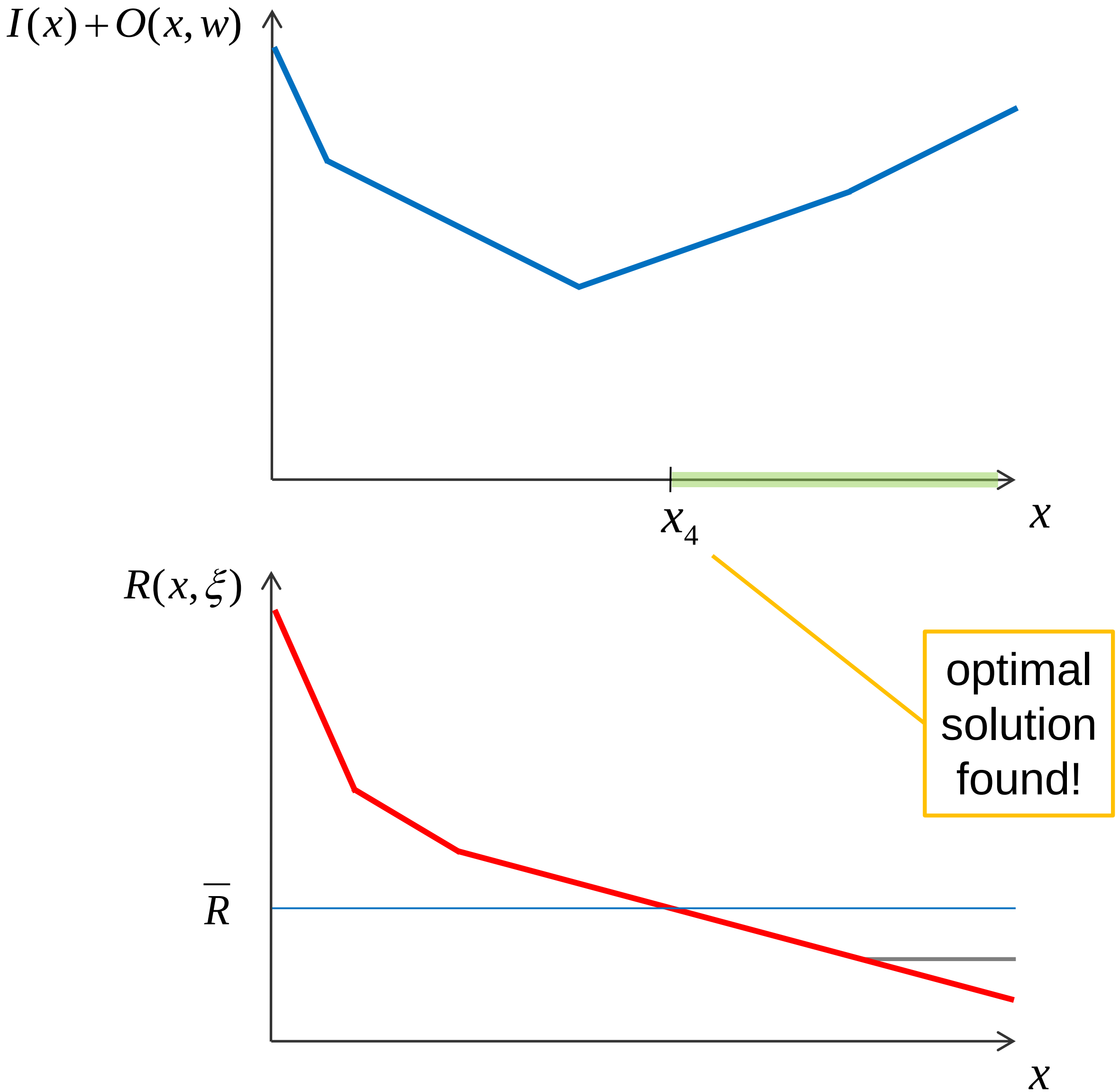
Decomposition scheme - example



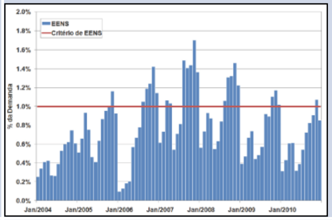
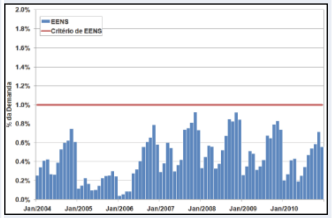
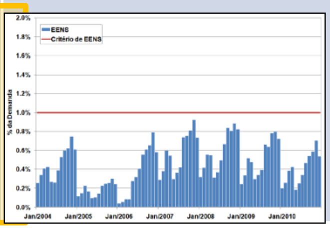
Investment

Operation

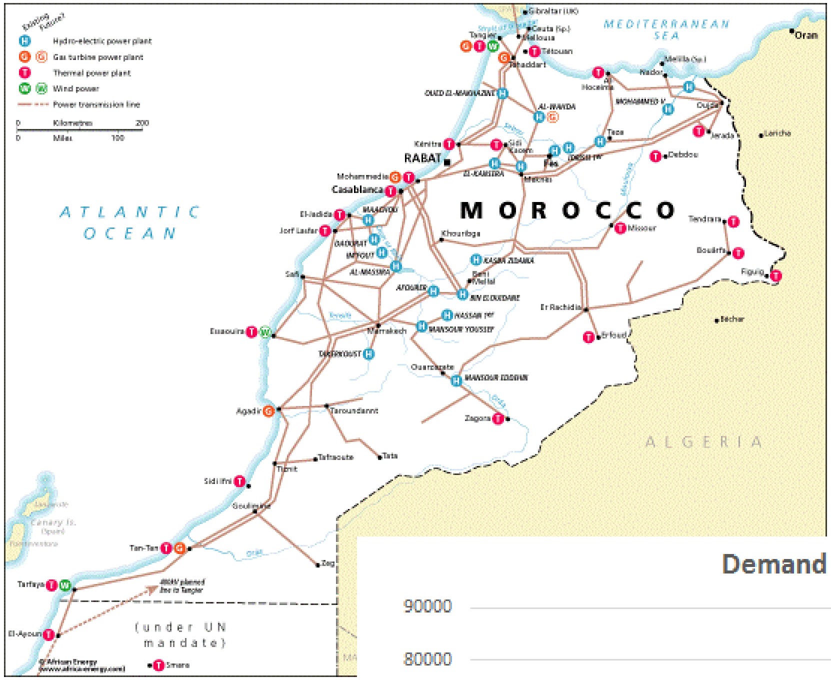
Reliability

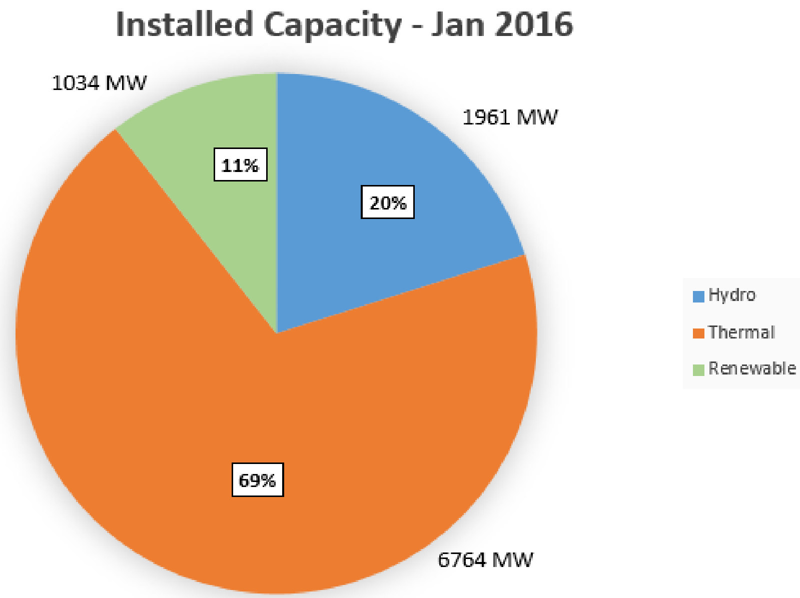
Case study 1: Bolivia

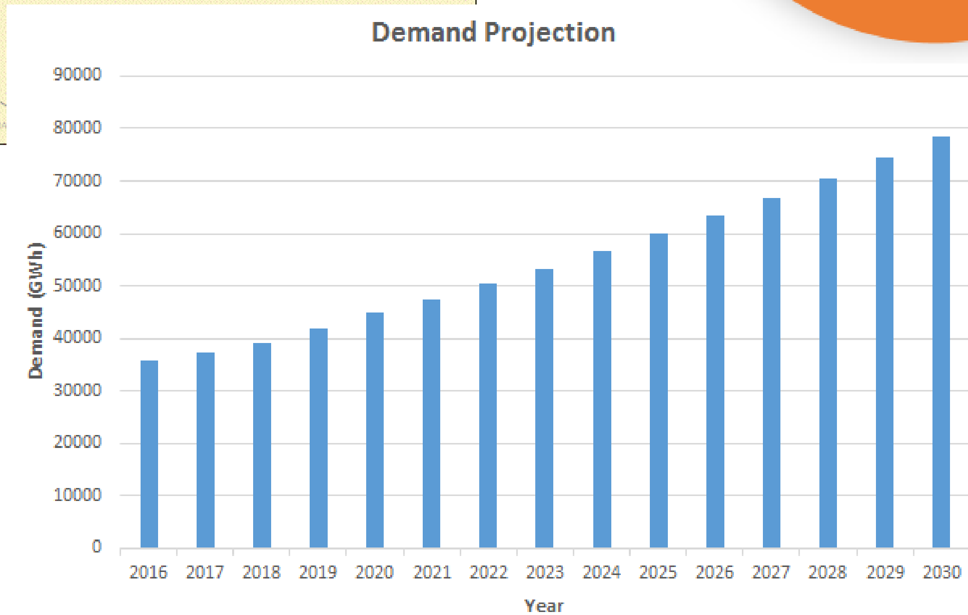
- 7-year horizon (monthly), 83 generators
- Results

App.	Investment cost (M$)	Operation cost (M$)	Total Cost (M$)	#Infeas.	EPNS
No Reliab.	98.42	146.66	245.08	22	
Hier.	117.80	145.02	262.82	0	
Integ.	100.06	152.17	252.23	0	

Case study 2: Morocco-Spain expansion plan

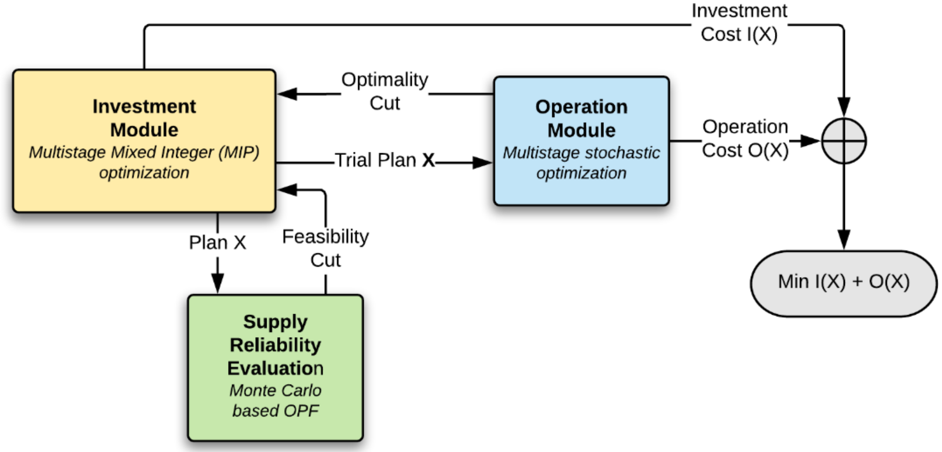


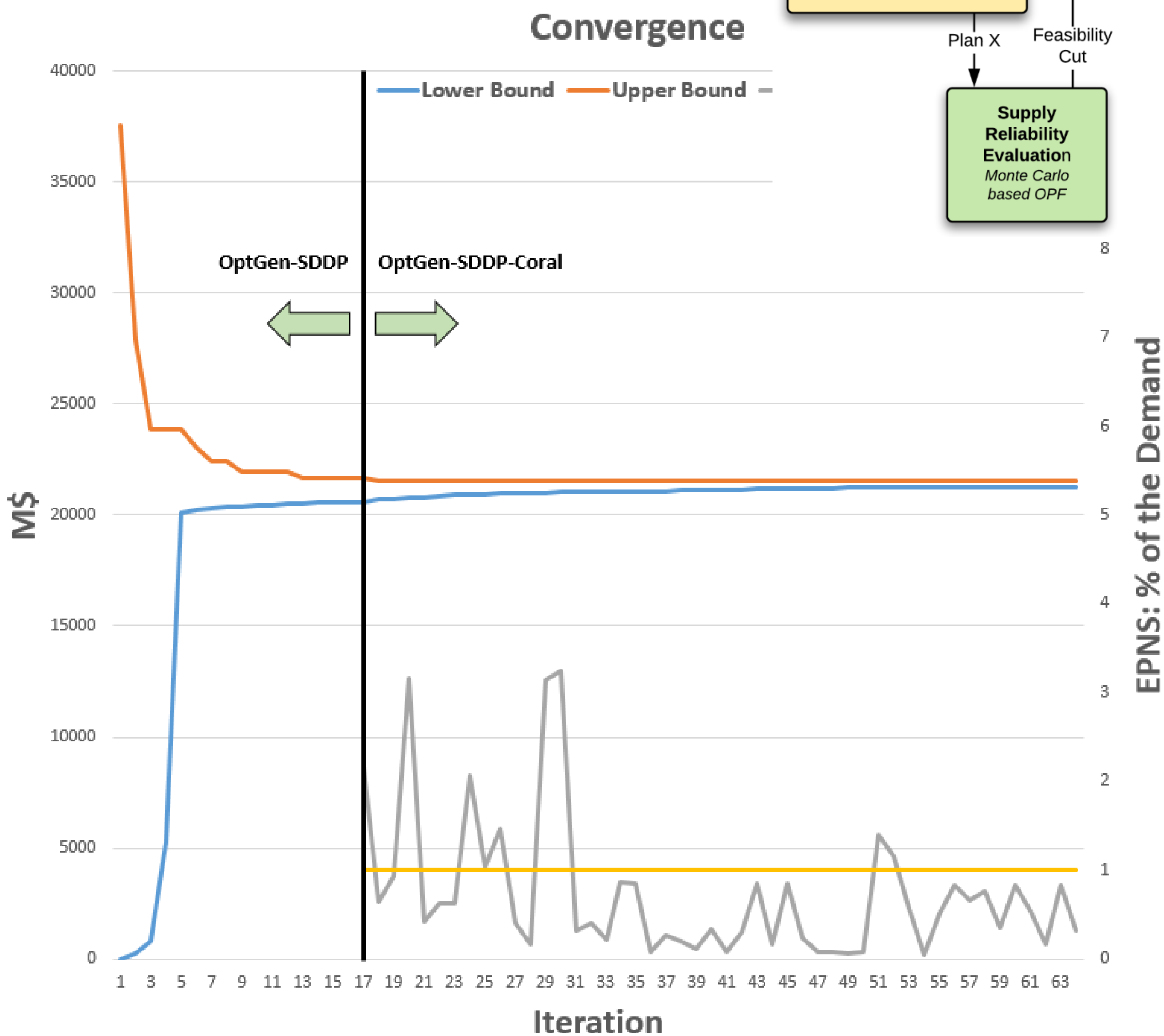




Planning horizon: 15 years
Yearly investment decisions
780 weekly operation stages (21 load blocks in each stage)

Case study 2: results





Conclusions

- Expansion planning trade-off
  - Cost: larger projects, return to scale
  - Reliability: smaller projects, diversification
- The integrated approach revealed to be important
  - The “economic planning” could not be sufficient to guarantee the reliability criterion
  - The hierarchical approach does not lead to the optimum solution
- The application of Benders decomposition allowed the solution of the problem
  - specialized algorithms for each subproblem could be exploited

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THANK YOU!