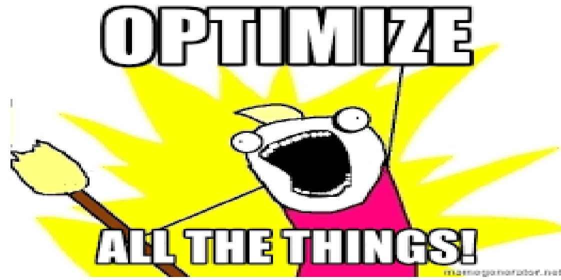

Introduction and Some Advances in Optimization of Engineering Systems

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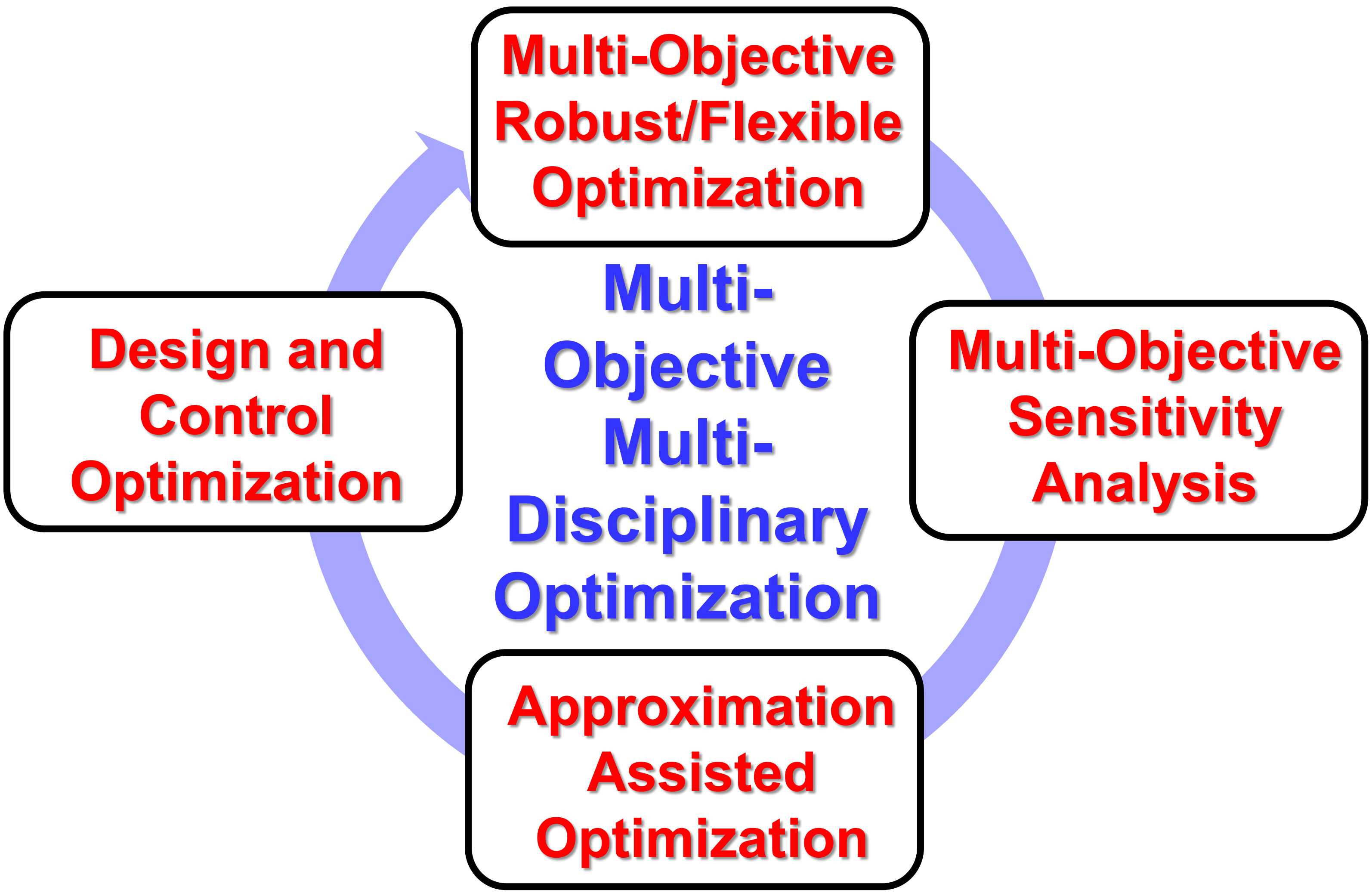
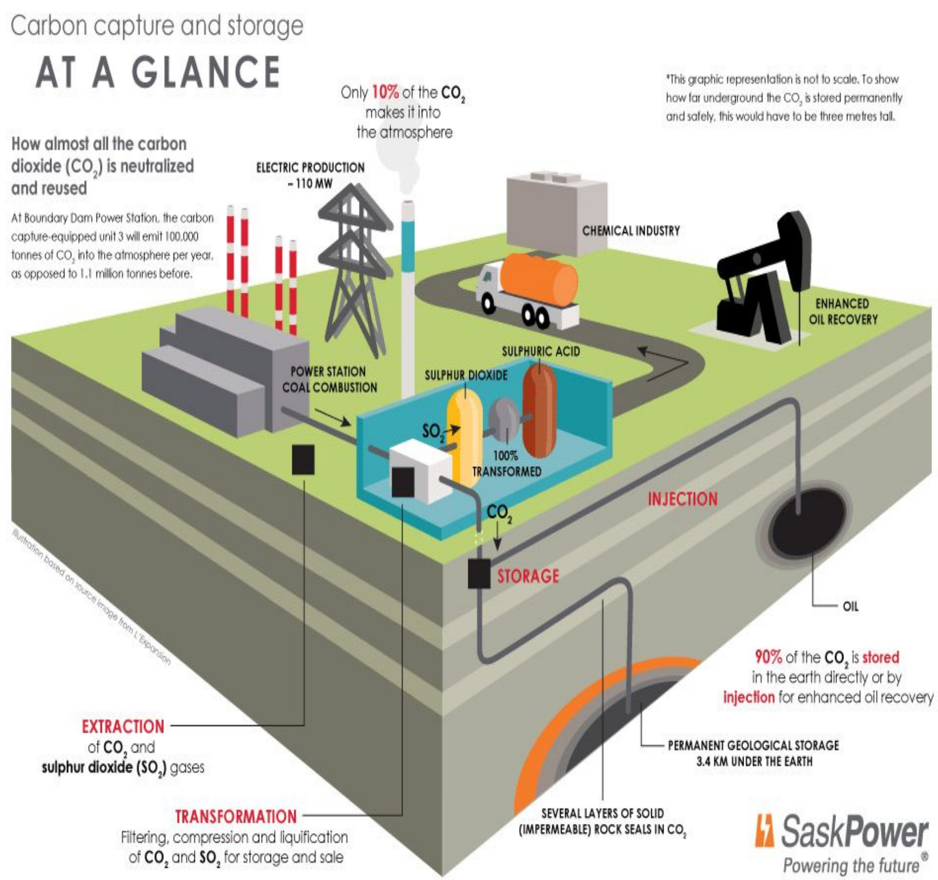
Flexible Carbon Capture Technologies for a Renewable-Heavy Grid
ARPA-E Workshop; Dr. Scott Litzelman
Crystal City Marriott, Arlington, VA
July 31, 2019

Outline


Multi-Objective Robust/Flexible Optimization
Design and Control Optimization
Multi-Objective Multi-Disciplinary Optimization
Multi-Objective Sensitivity Analysis
Approximation Assisted Optimization

Big Picture

- Optimizing design, operation and control of engineering systems, e.g. CCS, may require considerations of:
  - multiple subsystems (disciplines)
  - multiple objectives and constraints
  - uncertainty
  - computationally expensive simulations



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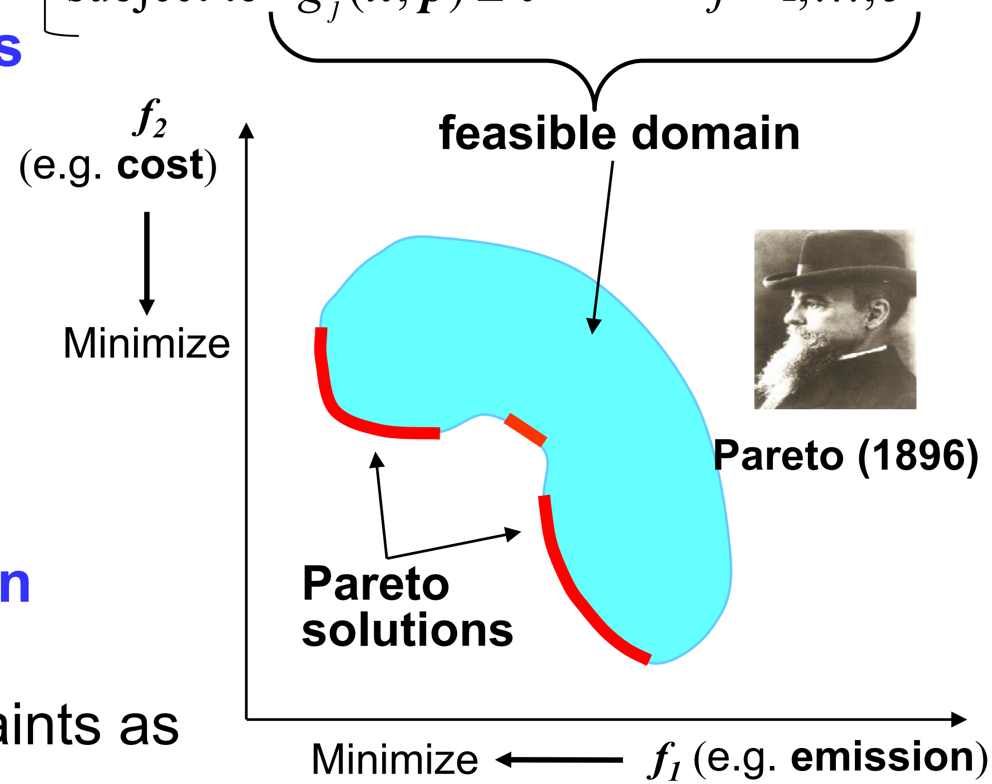
Terminology: Multi-Objective Optimization

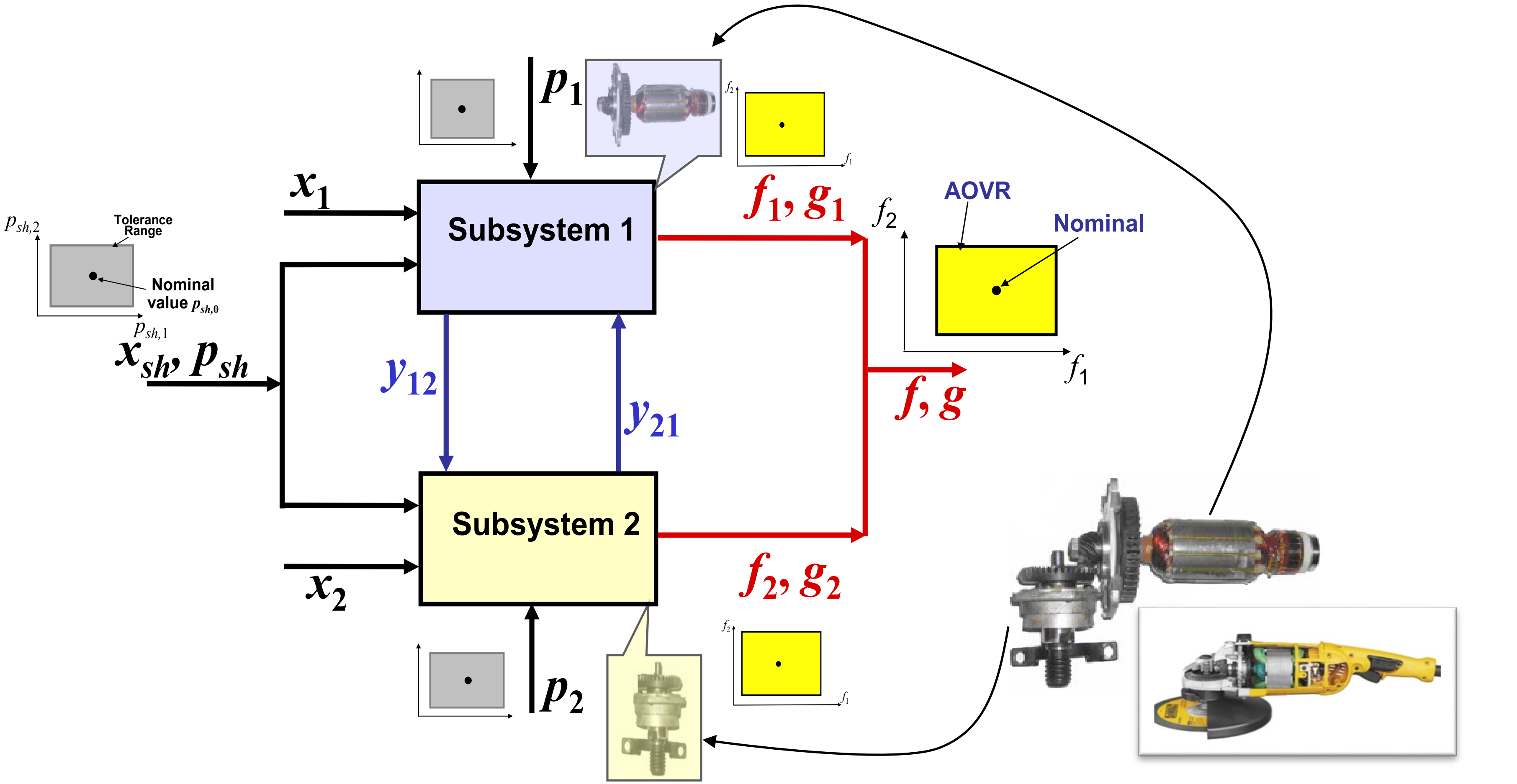
- $f_1,\ldots,f_M$: ***objectives*** **such as cost, emission intensity, NPV**
- $\boldsymbol{x}$: ***decision variables*** **such as size, pressure, flow rate; *changed* during optimization**
- $\boldsymbol{p}$: ***parameters*** **such as material, temperature, *fixed* during optimization**
- g_j: ***constraint*** **such as limit on emission, stress, budget**

[There might be equality constraints as well!]

$$\begin{cases} \underset{\boldsymbol{x}}{\text{minimize/maximize}} & f_m(\boldsymbol{x},\boldsymbol{p}) \quad m=1,\ldots,M \\ \text{subject to} & g_j(\boldsymbol{x},\boldsymbol{p}) \le 0 \quad j=1,\ldots,J \end{cases}$$



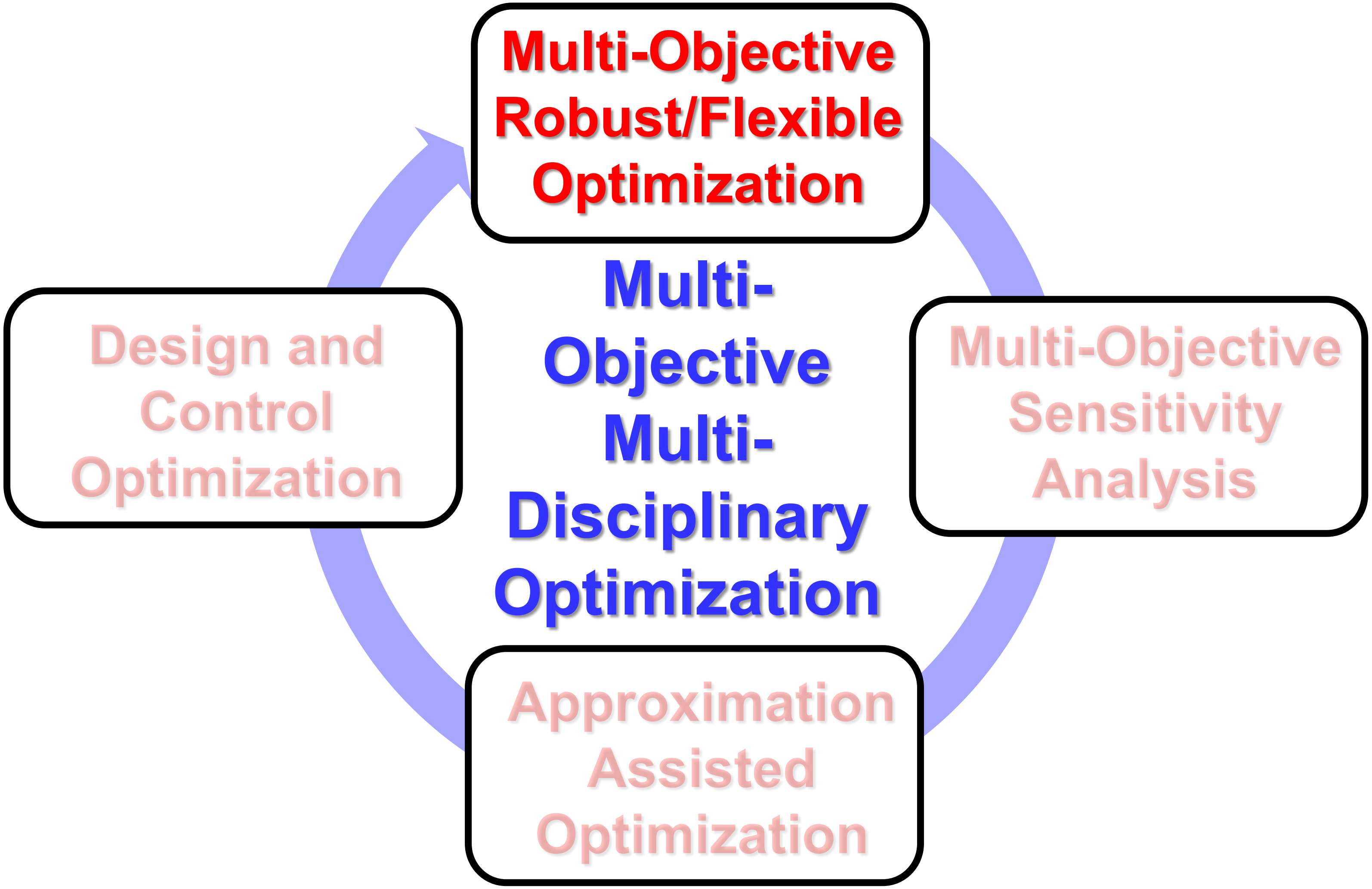
Terminology: Multi-Disciplinary Optimization (MDO)



Li and Azarm 2008, "Multiobjective collaborative Robust Optimization (McRO) with Interval Uncertainty and Interdisciplinary Uncertainty Propagation," *Journal of Mechanical Design* (ASME Trans), 130(8)

Hu et al. 2013, "New Approximation Assisted Multi-objective collaborative Robust Optimization Under Interval Uncertainty," *Structural and Multidisciplinary Optimization*, 47(1)

Outline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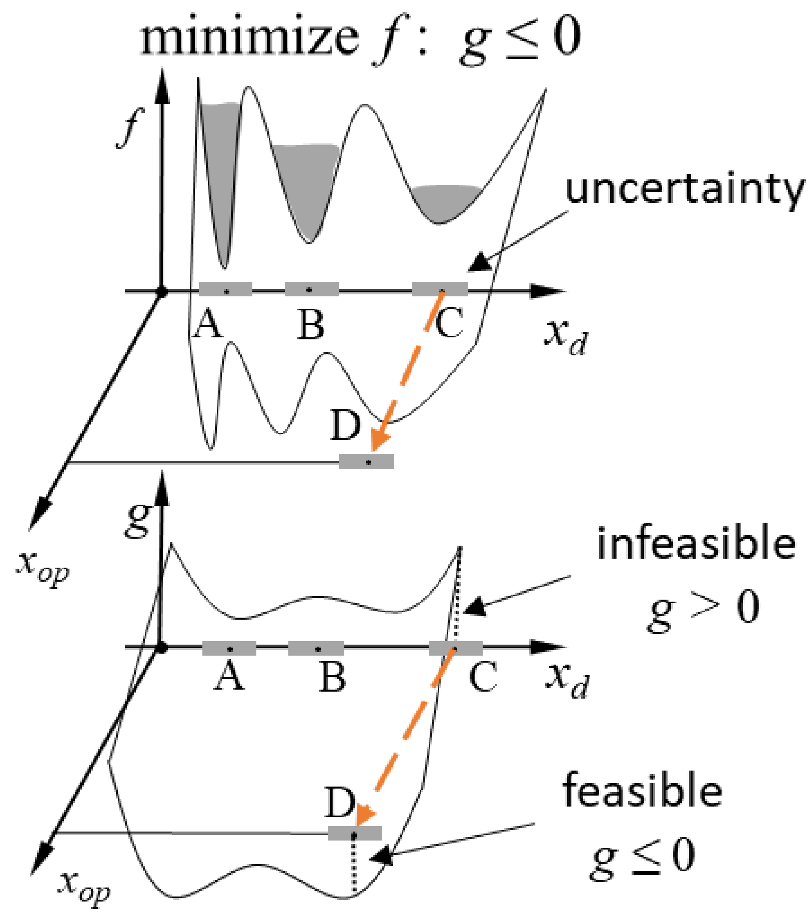
Multi-Objective Robust/Flexible Optimization (MORO/MOFO):

What is the Problem?

- **Robust Optimization:**
  Optimize design x_d and operational variables x_{op} for all realizations of uncertainty

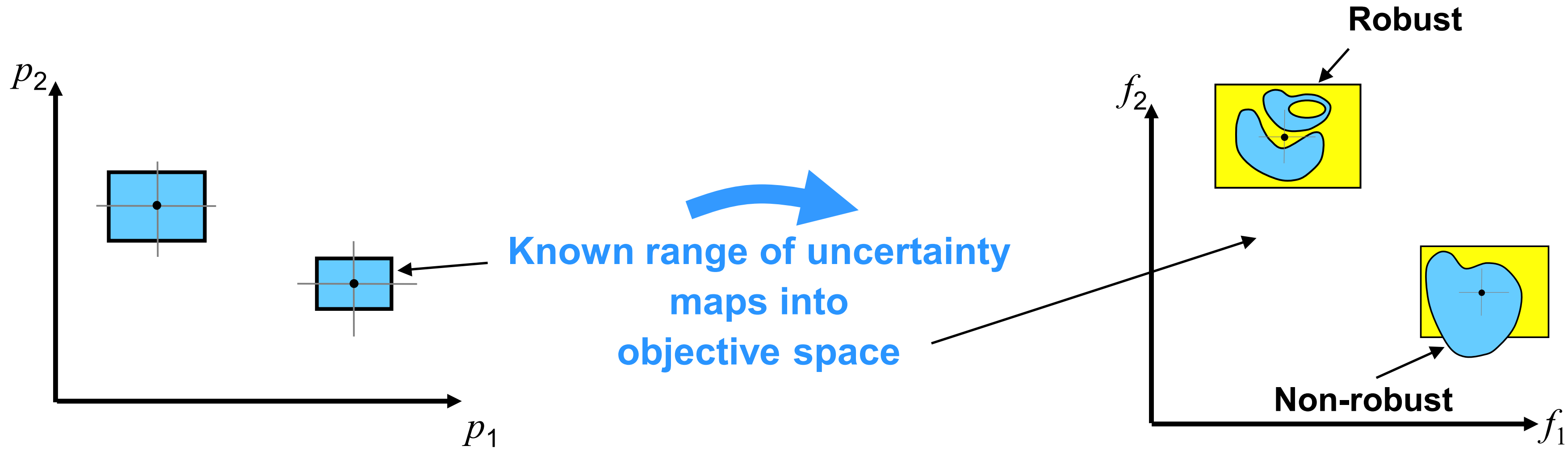
- **Flexible Optimization:**
  Optimize design x_d for all realizations of uncertainty while using operational variables x_{op} to mitigate or eliminate effects of uncertainty

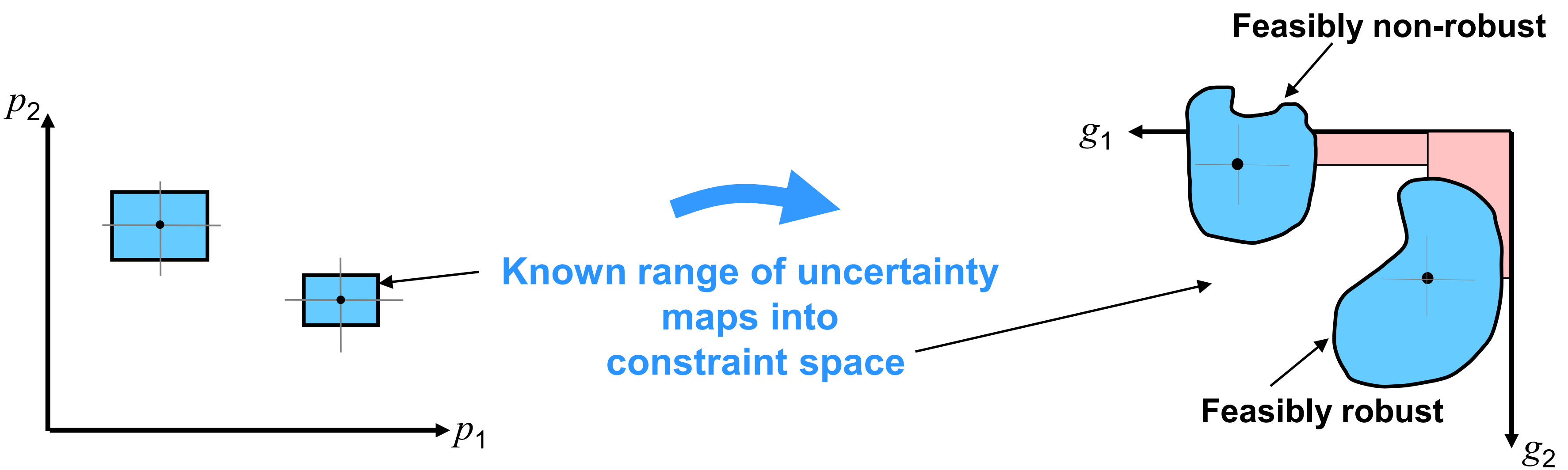


Li et al. 2006, "A New Deterministic Approach using Sensitivity Region Measures for Multi-Objective and Feasibility Robust Design Optimization," *Journal of Mechanical Design* (ASME Trans), 128(4)

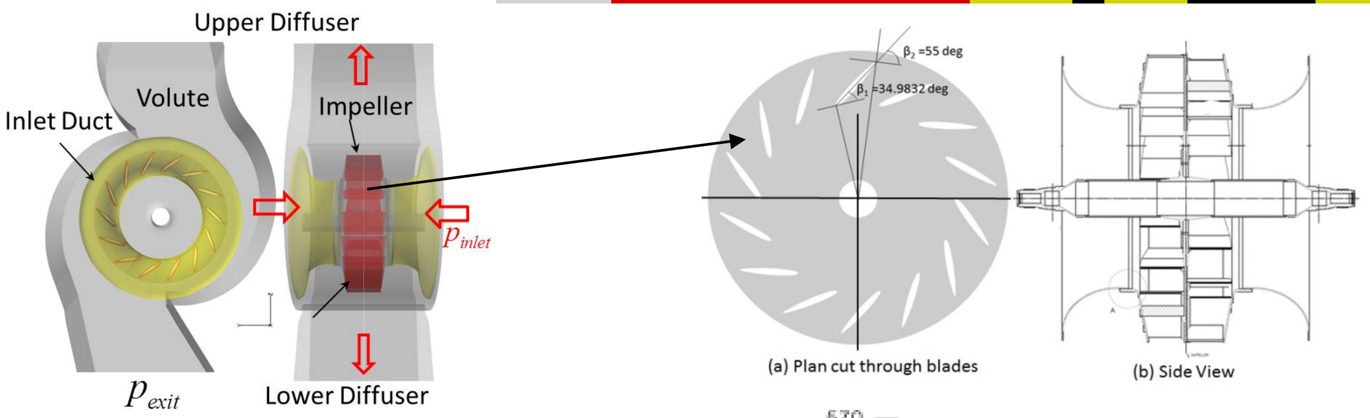
Azarm and Lee, 2016, "Multi-objective Robust Design Optimization with Operational Flexibility under Interval Uncertainty," *ASME IDETC*

MORO/MOFO:
Approach (Basic Idea)





MORO/MOFO: Centrifugal Impeller Example



$$\min_{x_{d1}=\beta_1, x_{d2}=\beta_2; x_{op}=p_{exit}} \{f_1 = -\eta(\beta_1,\beta_2,p_{exit},\Omega),$$

$$f_2 = -PW_{out}(\beta_1,\beta_2,p_{exit},\Omega)\}$$

$s.t.:$

$$g_1 = 1-\Delta p_{exit}(\beta_1,\beta_2,p_{exit},\Omega)/\Delta p_{exit,nominal} \le 0$$

$$g_2 = 1-\eta(\beta_1,\beta_2,p_{exit},\Omega)/\eta_{nominal} \le 0$$

$$g_3 = \eta(\beta_1,\beta_2,p_{exit},\Omega)-1 \le 0$$

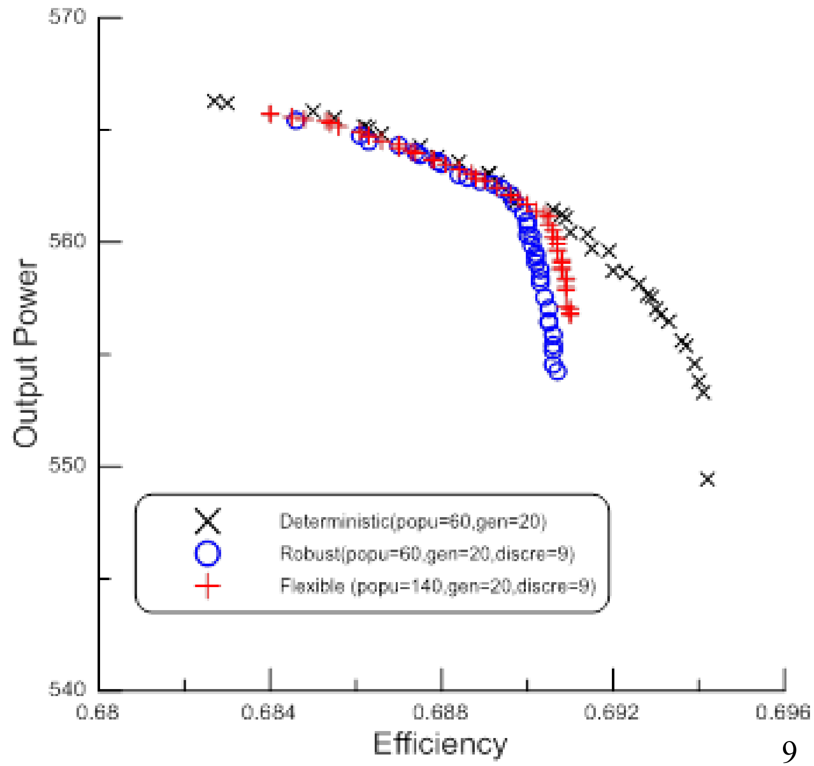
$$g_4 = \mu_{PS}(\beta_1,\beta_2,p_{exit},\Omega)-0.6 \le 0$$

$$g_5 = \mu_{SS}(\beta_1,\beta_2,p_{exit},\Omega)-0.6 \le 0$$

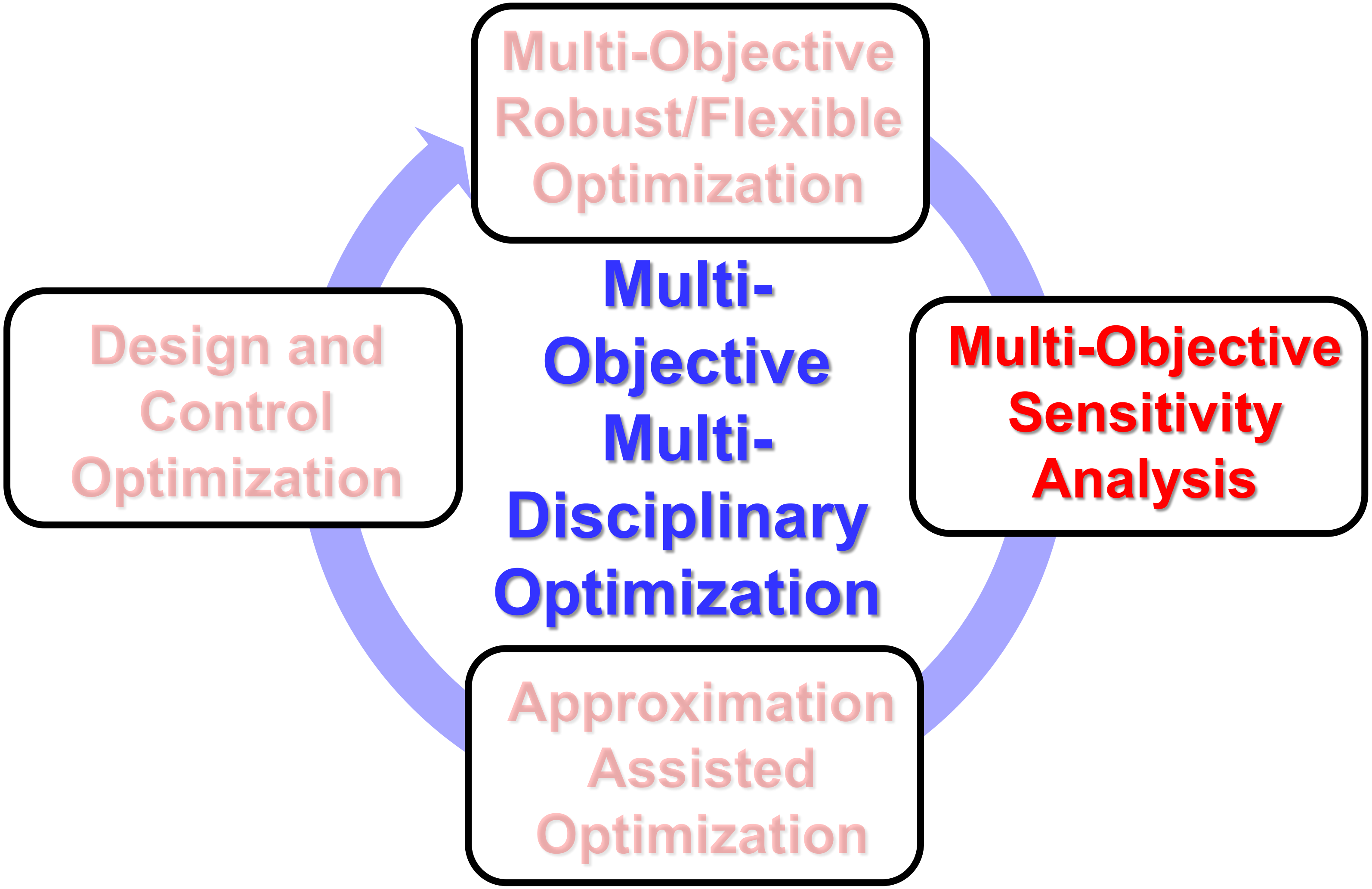
$$25 \le \beta_1 \le 40;\ 40 \le \beta_2 \le 60$$

$$\Delta p_{exit,nominal} \le \Delta p_{exit} \le \Delta p_{exit,nominal}+10$$

$$\forall\Omega:\ \Omega_{nominal}\text{-}10 \le \Omega \le \Omega_{nominal}+10$$



Outline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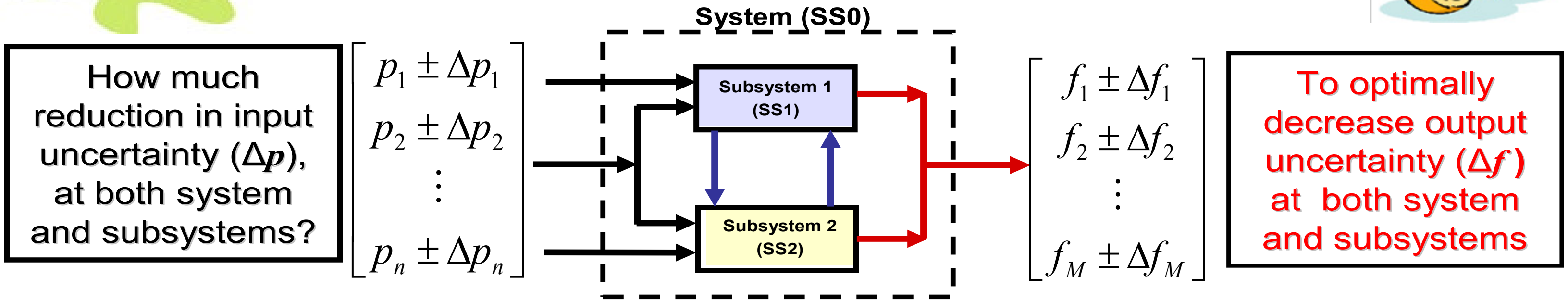
Multi-Objective Sensitivity Analysis (MOSA)

What is the Problem?

- **Determine key parameters for uncertainty reduction!**

Multi-Disciplinary, Multi-Objective Sensitivity Analysis (MiMOSA)



Objective: Optimally determine, with minimum investment (cost), the amount of uncertainty reduction needed in input parameters that results in minimum transmitted uncertainty in system outputs (or performance)

Li et al. 2009, "Interval Uncertainty Reduction and Sensitivity Analysis with Multi-Objective Design Optimization," *Journal of Mechanical Design* (ASME Trans), 131

Li et al. 2010, "Optimal Uncertainty Reduction for Multi-Disciplinary Multi-Output Systems Using Sensitivity Analysis," *Structural and Multidisciplinary Optimization*, 40

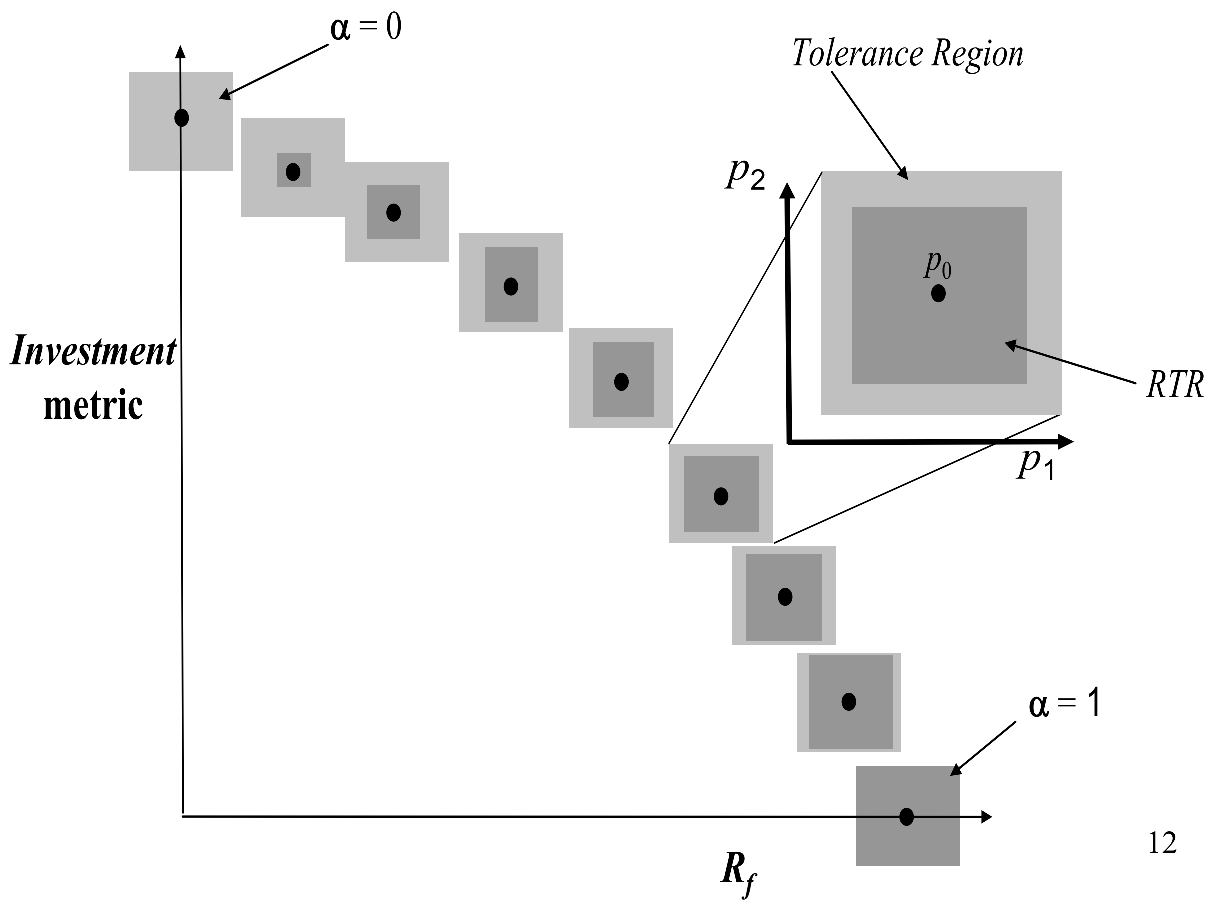
MOSA/MiMOSA
Approach (Basic Idea)

- minimize investment in uncertainty reduction of inputs, while also
- minimize uncertainty in outputs

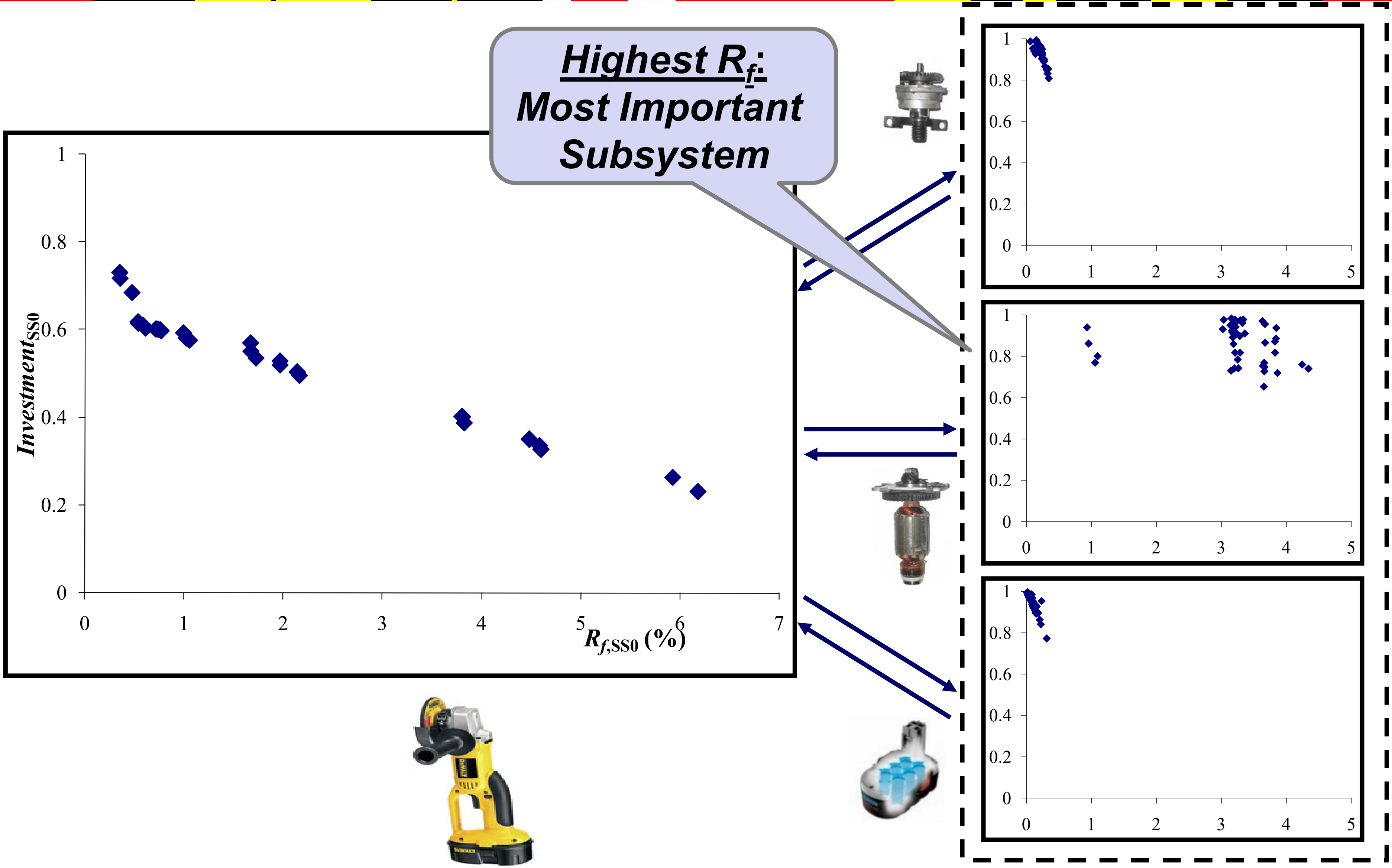
$$\begin{cases} \min\limits_{\alpha} \; R_f(\alpha) \\ \min\limits_{\alpha} \; I(\alpha) \end{cases}$$

Objective Variation

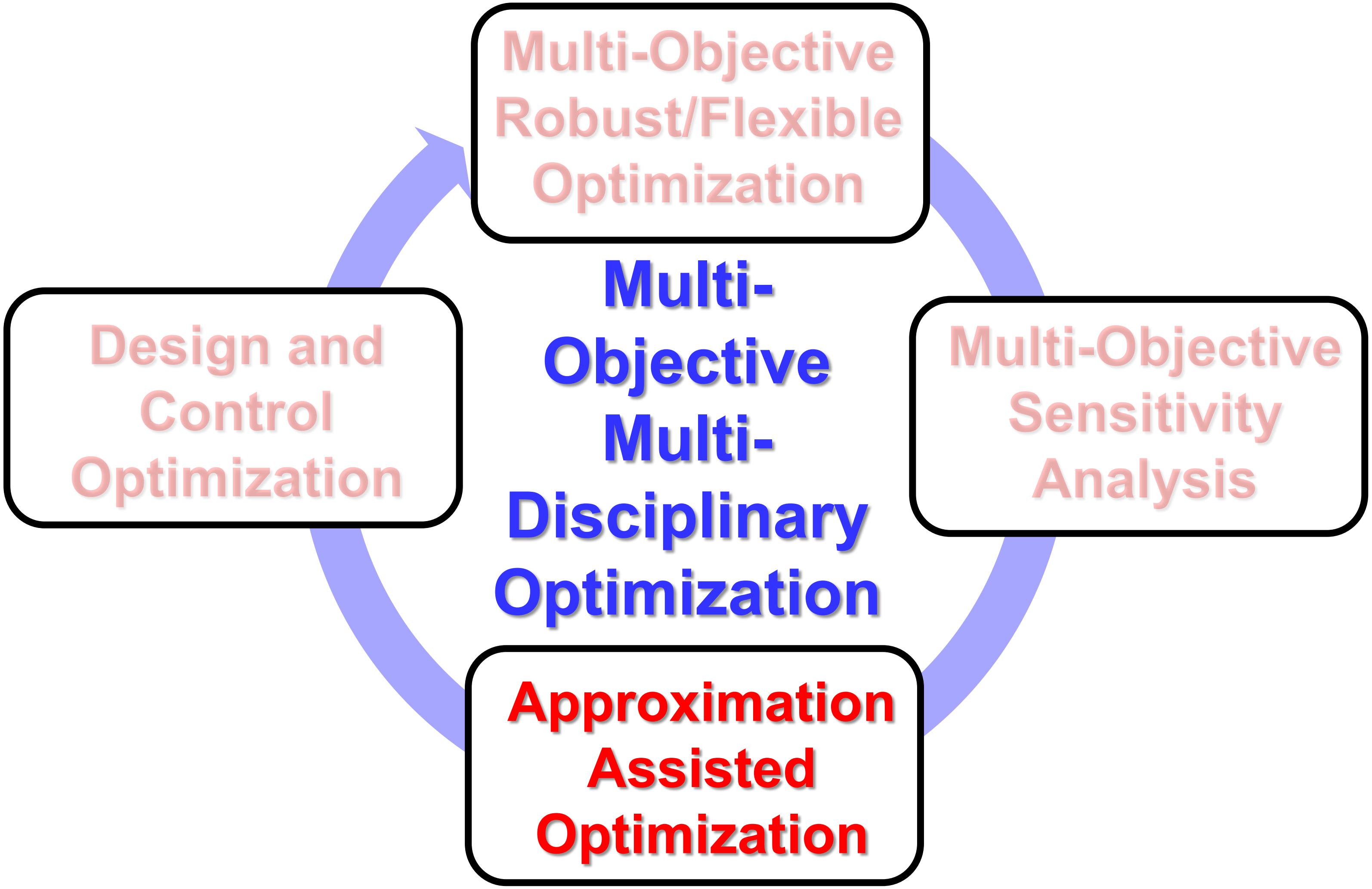
Uncertainty Reduction Cost: *Investment* (*I*)



MiMOSA
Cordless Grinder Example



Outline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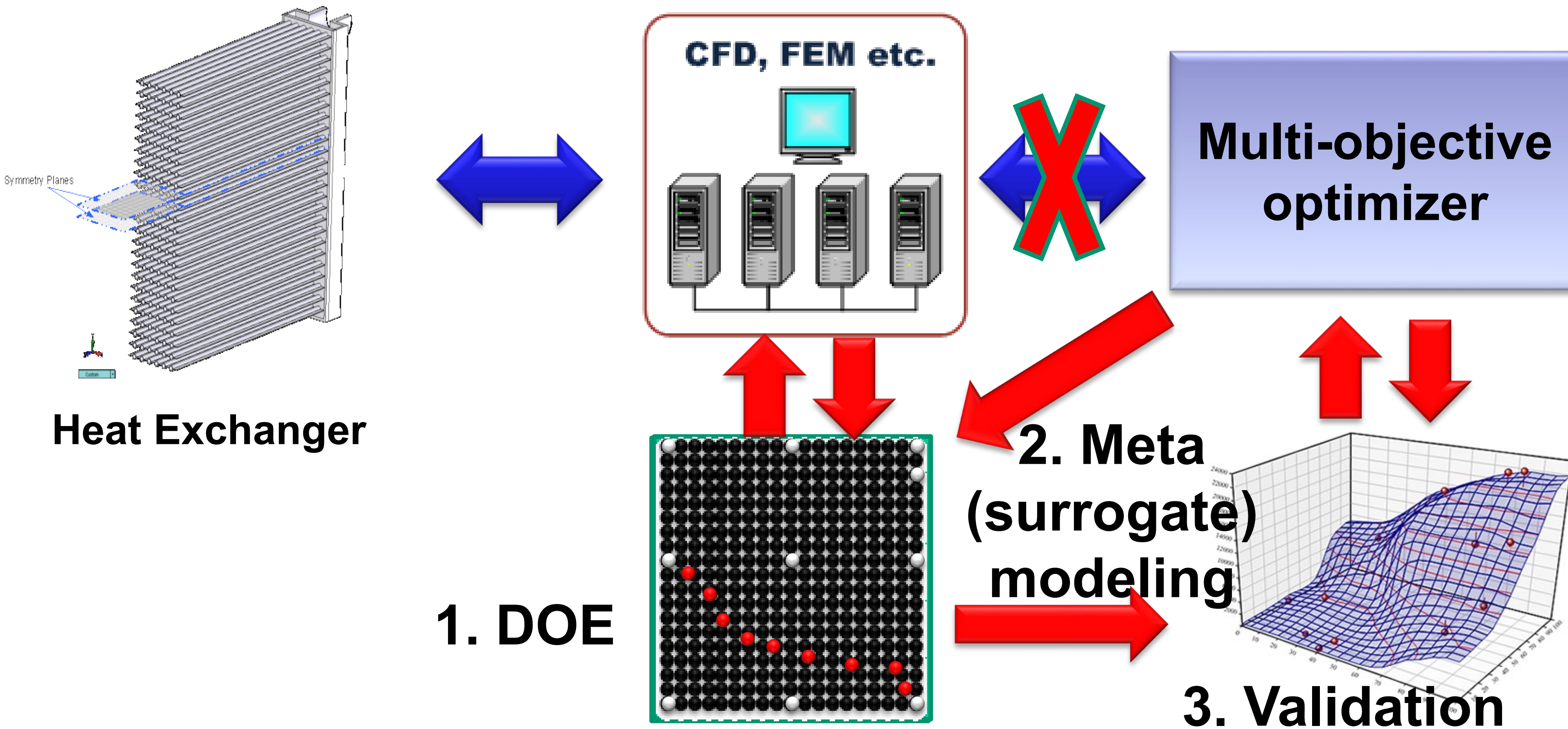
Approximation Assisted Optimization (AAO)

What is the Problem?

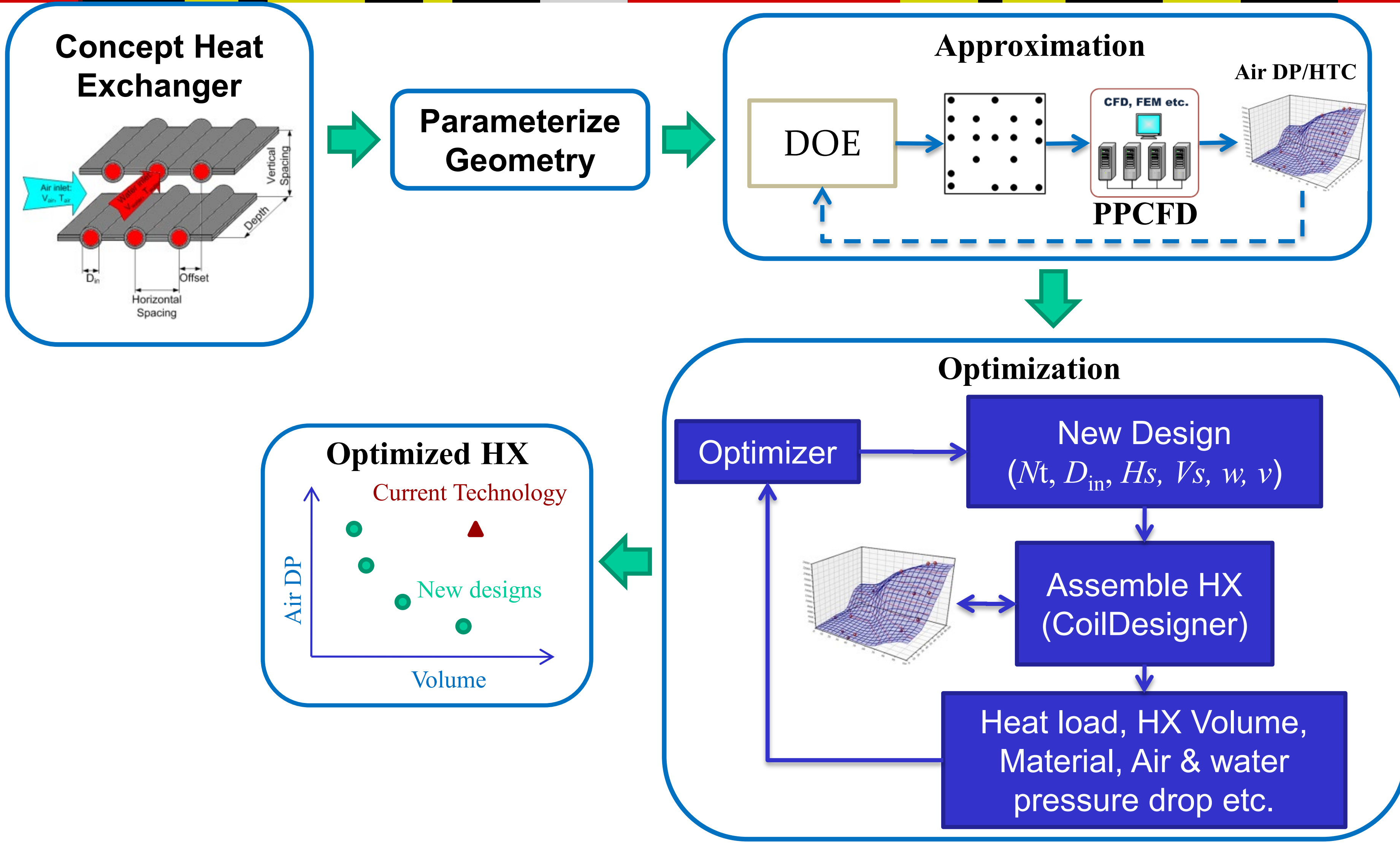


Objective: Optimization of a system that has computationally expensive simulation

Mehr and Azarm, 2005, "Bayesian Meta-Modeling of Engineering Design Simulations: A Sequential Approach with Adaptation to Irregularities in the Response Behavior," *International Journal for Numerical Methods in Engineering*, 62

Abdelaziz et al. 2010, "Approximation Assisted Optimization for Novel Compact Heat Exchanger Designs," *HVAC&R Research*, 16(5)

AAO: Approach



* Parameterized Parallel CFD, Abdelaziz, 2007, Aute et al., 2008

AAO: Heat Exchanger Example

$$\min_{HX} \ ADP, V$$

s.t.

$$Q = 1\text{kW}$$

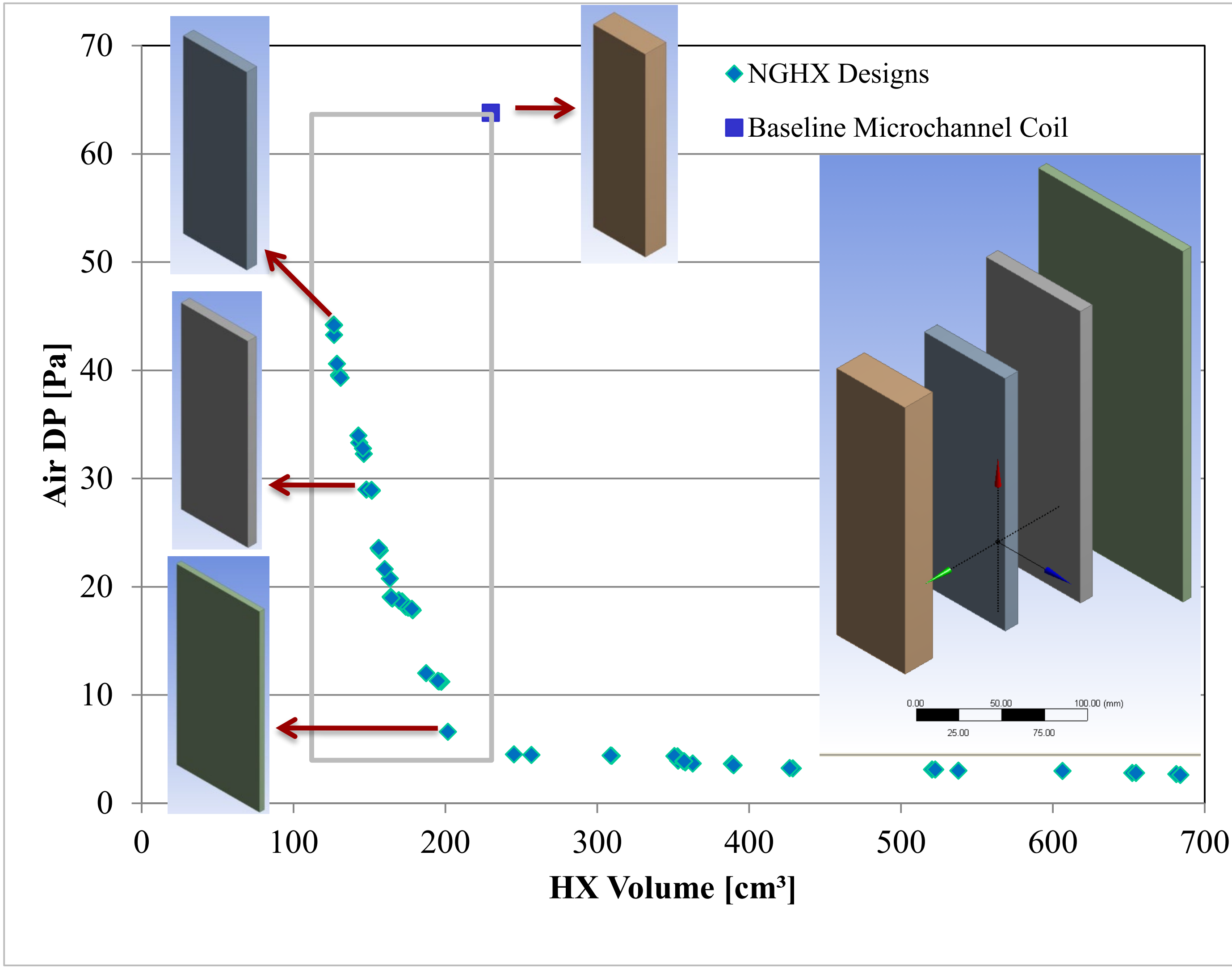
$$ADP \leq ADP_{max}$$

$$RDP \leq RDP_{max}$$

$$HX \equiv [Nt, D_{in}, Hs, Vs, w, v]$$

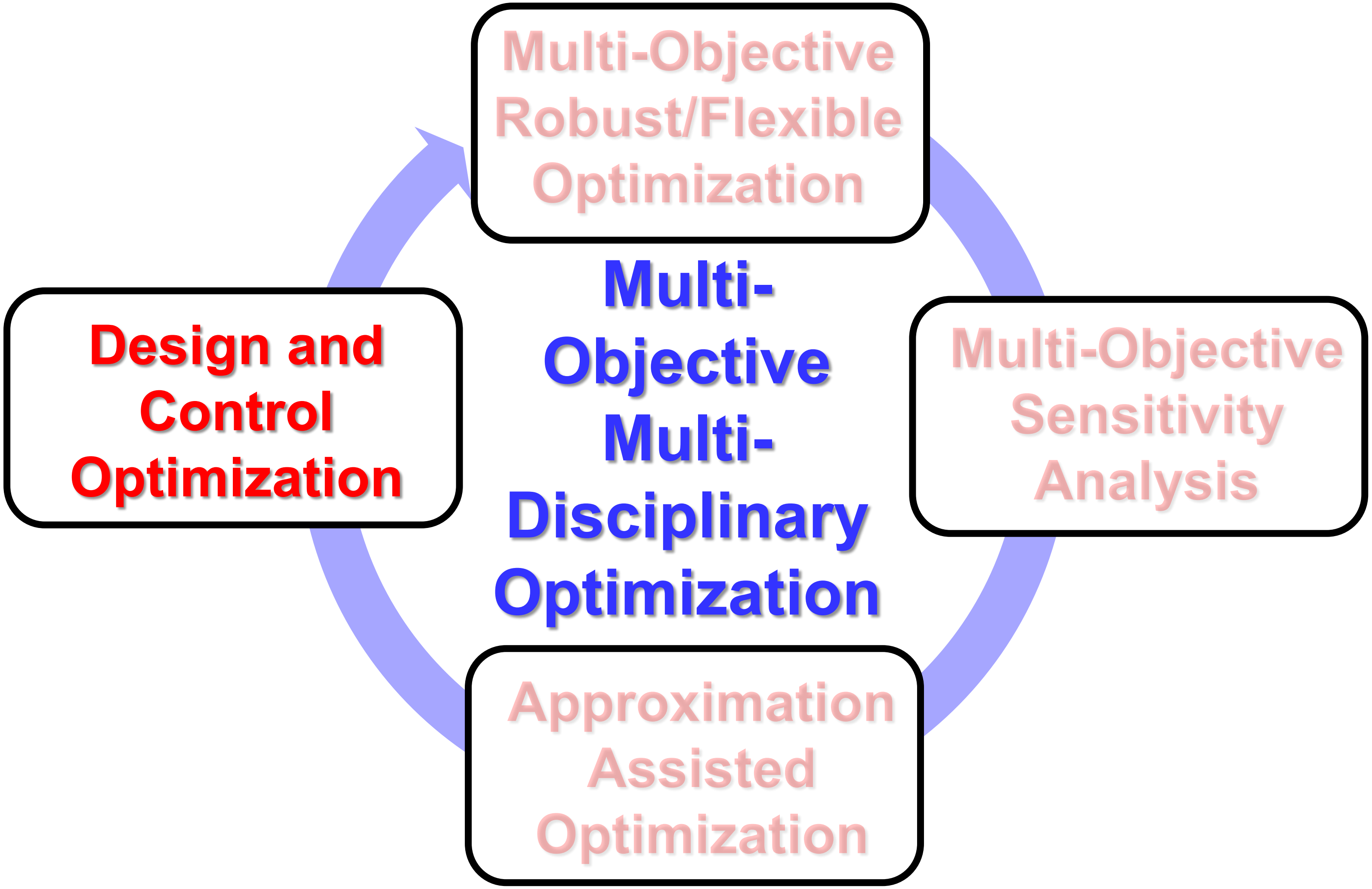
Approximation:

Parameter	Value
Inputs	D_{in}, Hs, Vs, w, v
Responses	Air DP, HTC
DOE	SFCVT, SO
Metamodel	Kriging
Initial	100
New points	100 each
Verification	250
MAS	≥80, 0.1



Aute et al., 2008

Outline



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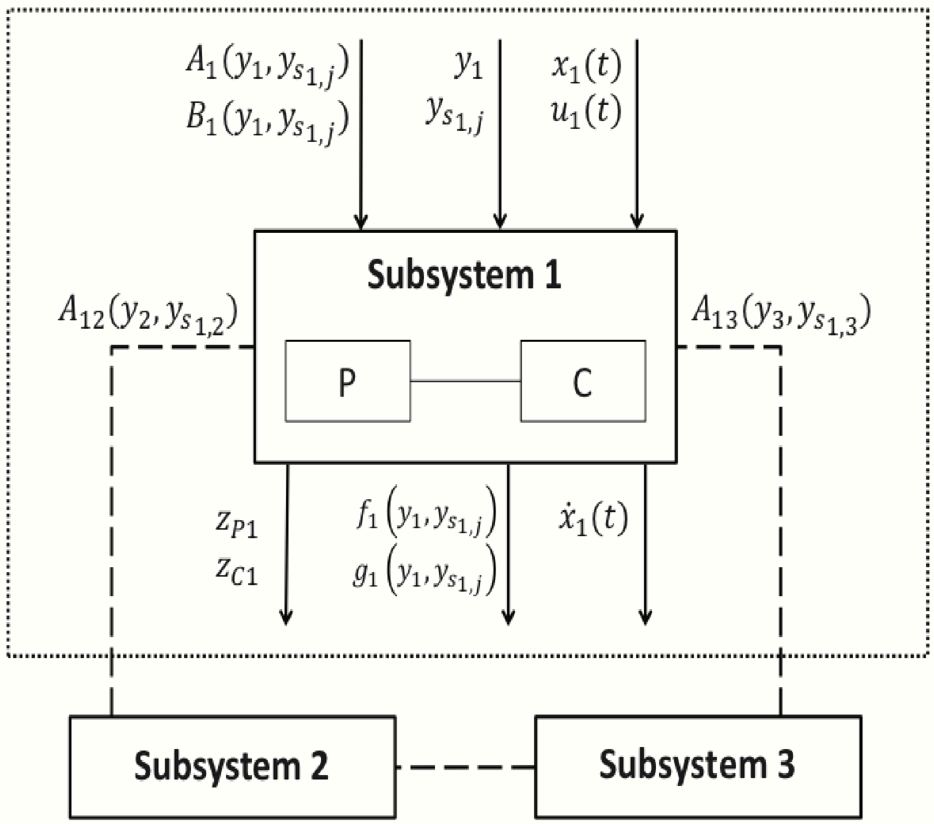
Co-Design: Design and Control Optimization (CoD)

What is the Problem?

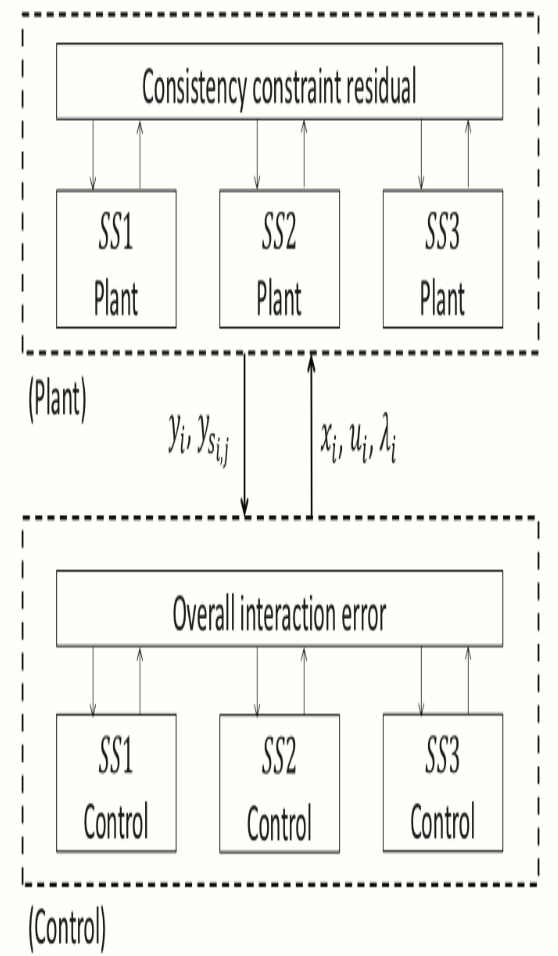
- **Connected systems may require design of both Plant and Control, or Co-Design**
- **Objective: Develop decentralized methods for coordinated design of Plant (P) and Control (C) for connected engineering systems**

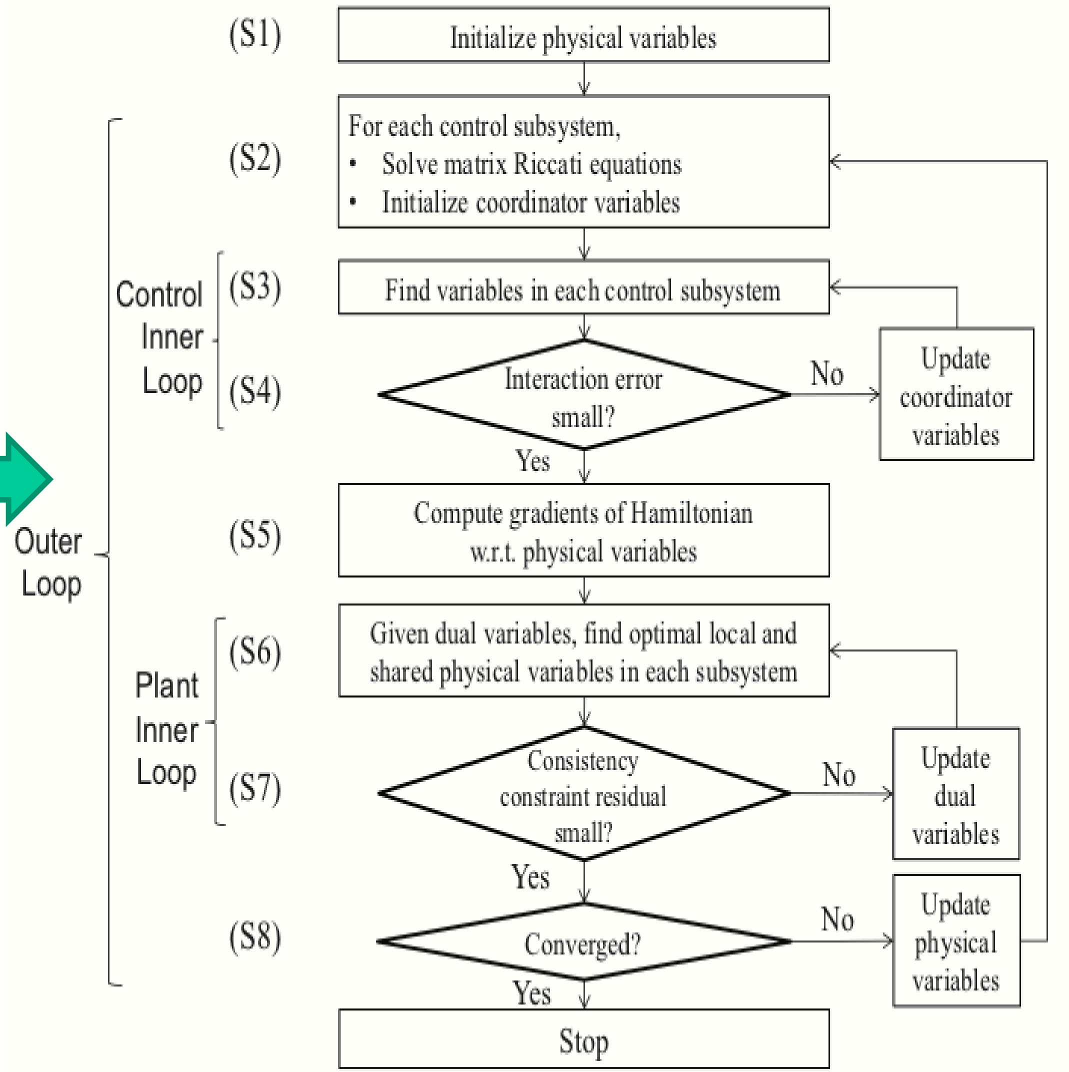


Liu et al. 2017, "On Decentralized Optimization for a Class of Multisubsystem Co-design Problems," *Journal of Mechanical Design* (ASME Trans), 139(12)

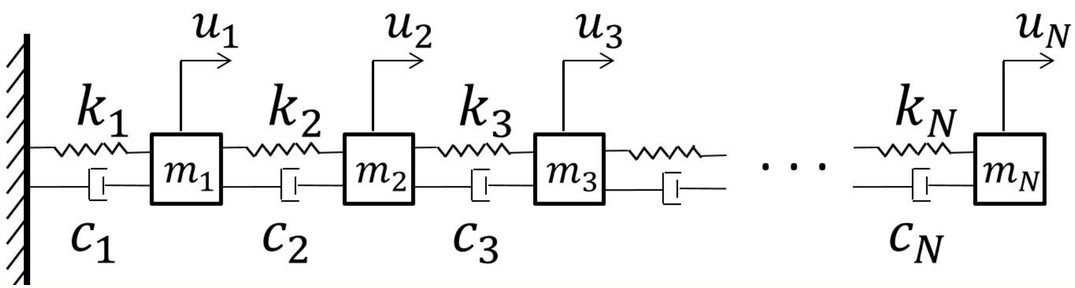
Chanekar et al. 2018, "Co-design of Linear Systems using Generalized Benders Decomposition," *Automatica,* 89

CoD: Approach

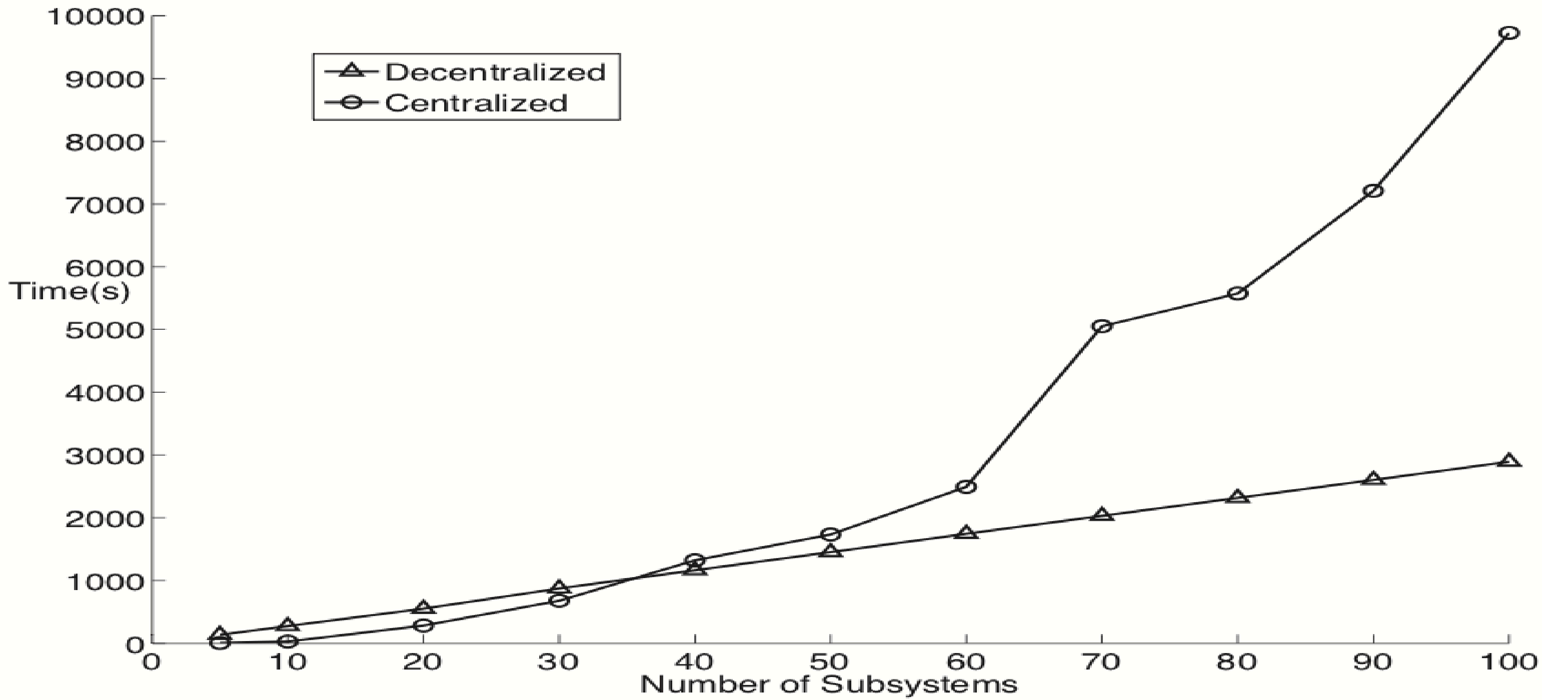




CoD: Example



u_1 u_2 u_3 u_N
k_1 k_2 k_3 k_N
m_1 m_2 m_3 m_N
c_1 c_2 c_3 c_N



Decentralized
Centralized
Time(s)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
90
100
Number of Subsystems

Final Remarks

- Optimization is a necessity for design, operation and control of engineering systems, including CCS systems, when we
  - have multiple objectives, and constraints (with limits on resources, budget, etc.),
  - want optimized solutions which are relatively “insensitive” to uncertainty
  - want to explore tradeoffs between investment in uncertainty reduction of input parameters vs. reduction in system/subsystem output uncertainty
  - have computationally expensive simulations while performing optimization