Georgia Institute of Technology

Systems Realization Laboratory

Set-Based Design: A Decision-Theoretic Perspective

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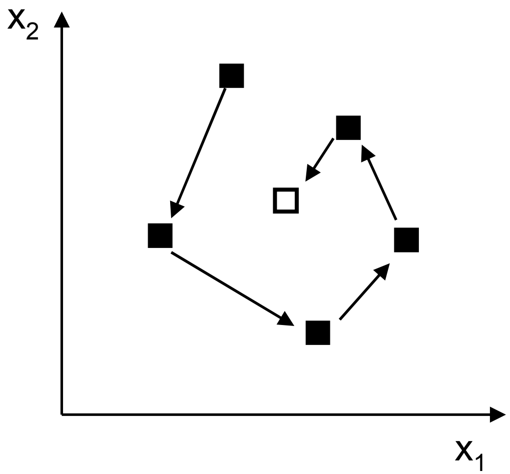
Objectives

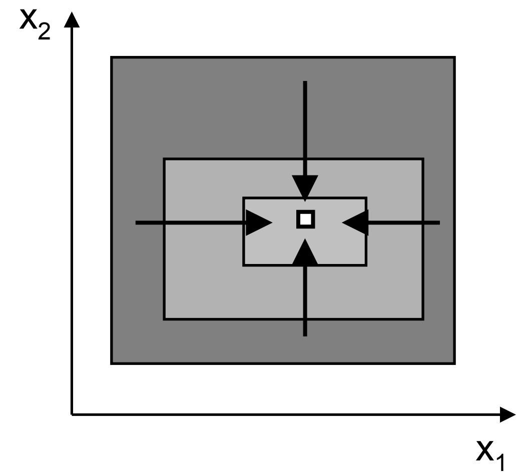
- Make you familiar with the concepts of Set-Based Design
- Help you think about the characteristics of set-based design in terms of *Decision Theory*

What is Set-Based Design?

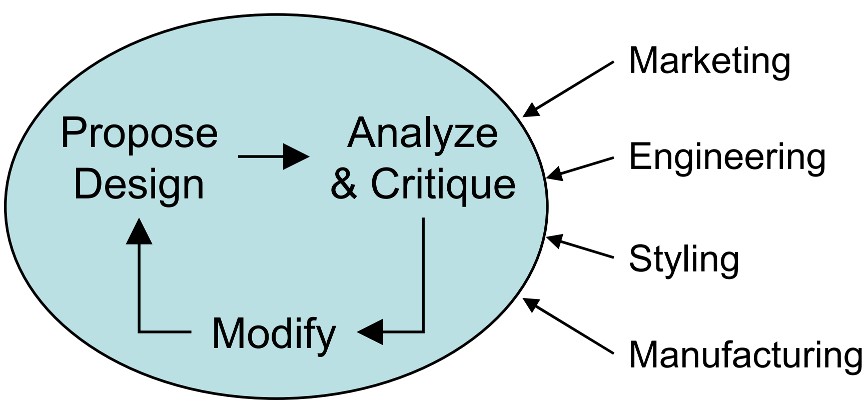
“Point-based” Design

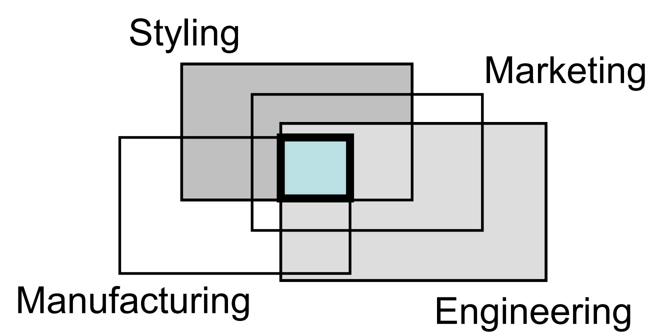


Set-based Design



Eliminate Dominated Alternatives



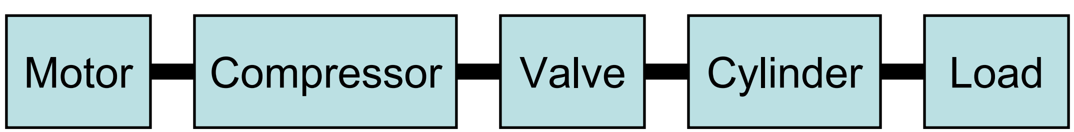


Foundations by Ward, Sobek & Liker

- Ward (1989):
  - *Mechanical Design Compiler*
  - Compile high-level description into set of possible solutions
  - Eliminate through labeled interval propagation
  - Eliminate only alternatives that can be proven not to work
- Sobek, Ward & Liker (1999):
  - Case study: Toyota Production system
  - Engineers communicate in terms of sets
  - Multiple design alternatives are developed in parallel
  - Paradox: value despite apparent "inefficiencies"

Simple Example: Design of Pneumatic System
(adapted from Ward, 1989)

- Catalog of Components:
  - 50 motors
  - 30 compressors, …
- Interval-Based Characterization of Components
  - Motor: RPM (nom load) = [1740,1800]
  - Cylinder: Force = [0,100] N
- Design Requirements
  - Load: Velocity = every [0,2] m/s
  - Power-supply: 110V AC
- Propagation of set-based requirements
  - Yields relatively small set of feasible solutions

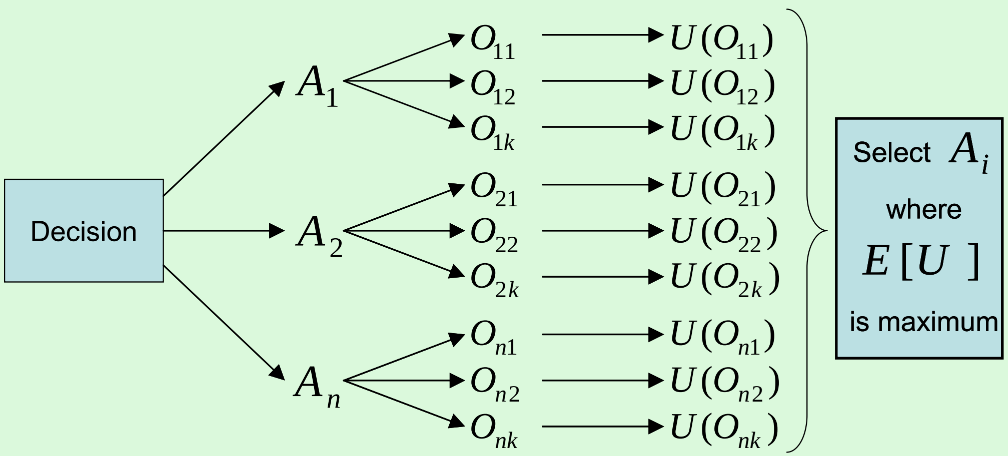


Some Short-Comings in Current State of the Art

- Only *algebraic equations*
  - No differential or partial differential equations
  - No black boxes – equations need to be expressed symbolically
- Only for *catalog design* – configuration of discrete options
  - Significant extensions are needed to support continuous variables
- Only *pure intervals* – no probabilities
  - Ignoring probability information often leads to overly conservative designs
- Weak on *optimization* beyond constraint satisfaction
  - What if satisfying all the constraints still leaves many alternatives?

Need for a Strong Foundation

- Our approach: Build on the foundation of Decision Theory



Normative Decision Theory

\+

Reality of Design Context

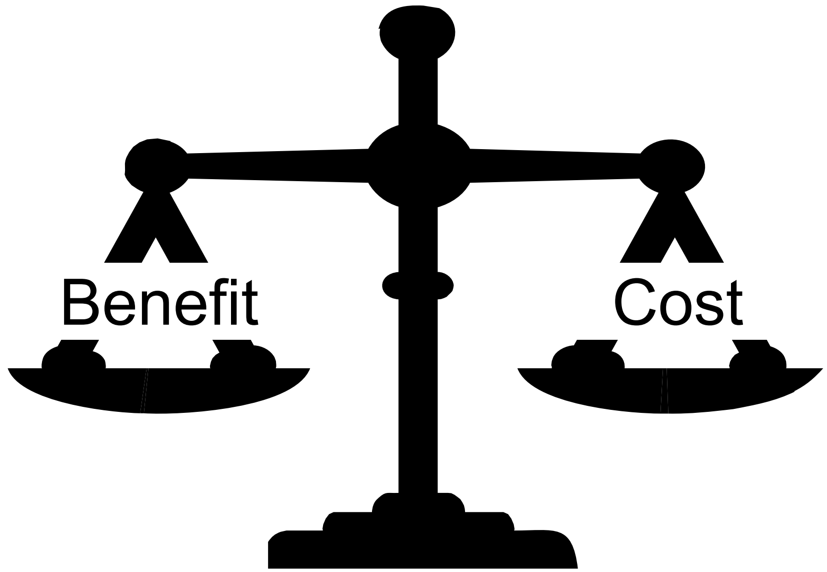
- Bounded rationality
- Limited resources
- Incomplete knowledge
- Diverse information and knowledge needs
- Collaboration among geographically distributed stakeholders
- …

Formal, Systematic but Practical Methods for Engineering Design

Formalisms	Representations	Methods	Tools

Trade-off Between Information Cost and Value

Information Economics



Information is only valuable
to the extent that it leads to better decisions

No change in the decision → benefit of information is zero

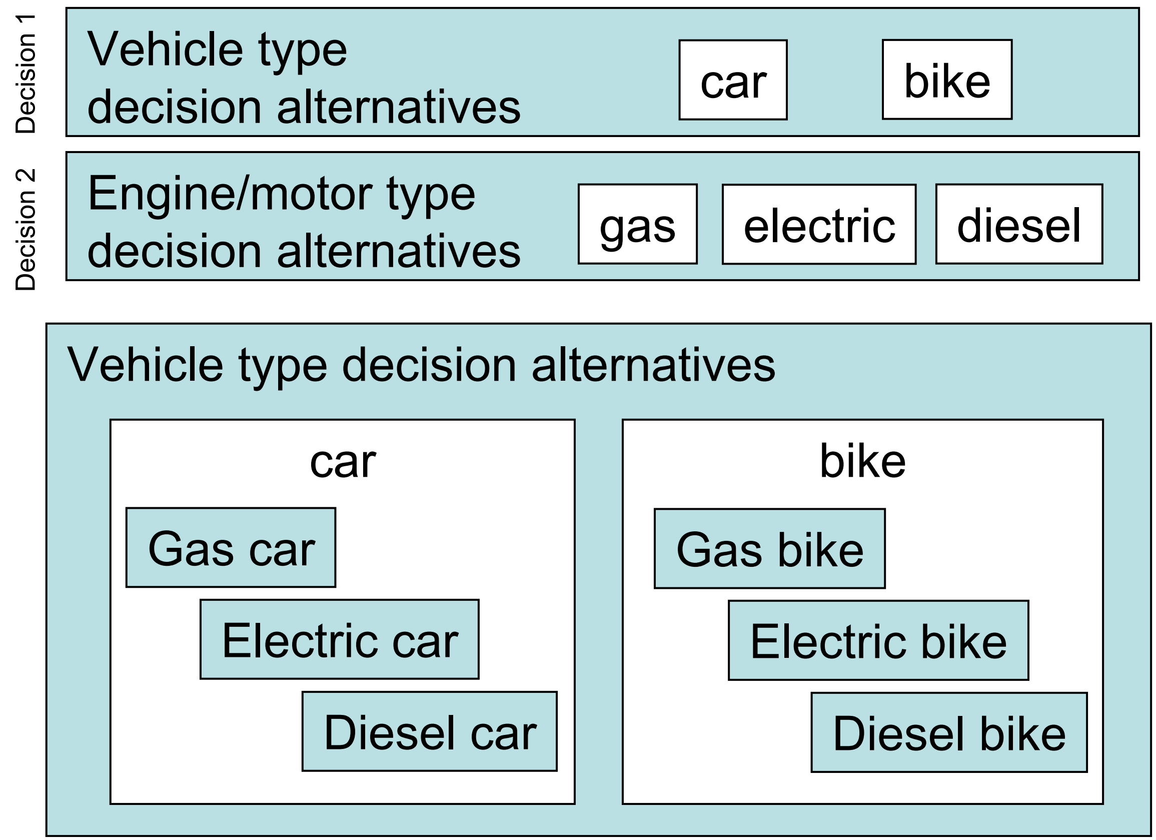
Overview of Presentation

- What is Set-Based Design?
- Current Limitations of Set-Based Design
- Set-Based Design from a Decision-Theoretic Perspective
  - Set-based design and sequential decision making
  - Expressing the utility of decision alternatives as intervals
  - Decision policy: eliminate non-dominated design alternatives
  - Searching through a set of non-dominated alternatives: Branch & Bound
- Implication for Modeling and Simulation in Design
- Implications for PLM
- Conclusion

Set-Based Design and Sequential Decisions

Sequential decisions:

In the first decisions, the designer chooses *from a set*



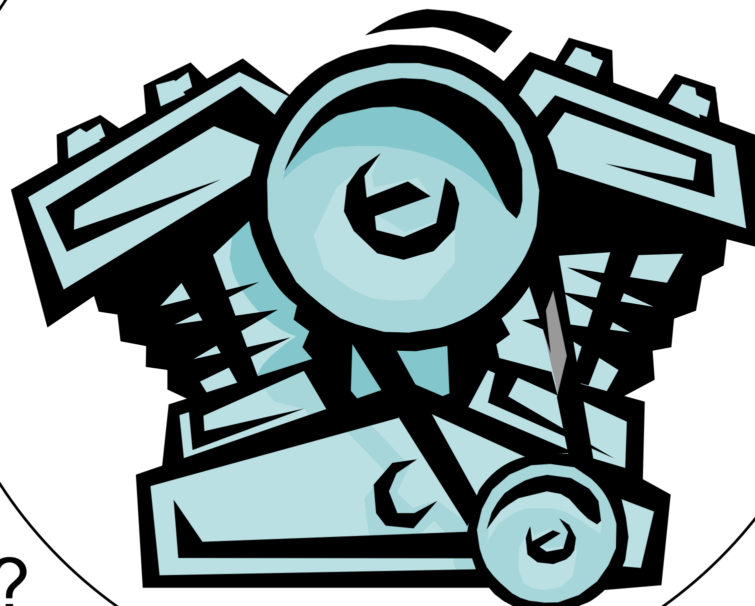
Each *decision alternative* is a set of *design alternatives*
→ Decision alternatives are *imprecisely* defined

Set-Based Decision Alternatives

Cost = ?
$ [400,1000]

SET OF

150 hp Gas Engines



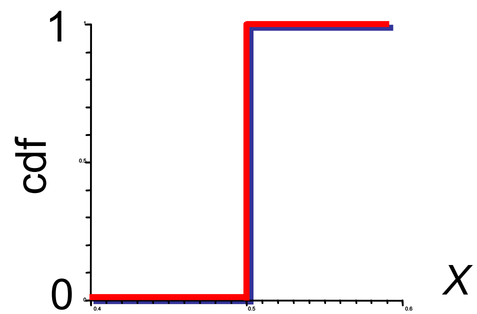
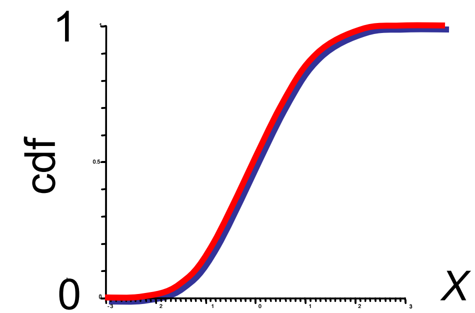
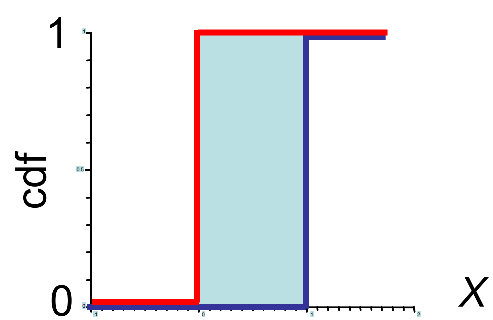
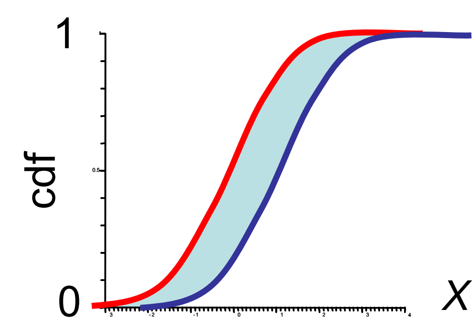
Mass = ?
[100,300] kg

Efficiency = ?
[25,30] %

Reliability = ?
[95,99] %

Imprecise Alternative → Imprecise Performance

Imprecision and Variability → P-Box

	Deterministic	**Probabilistic**
Precise	 Precise Scalar	 Precise Distribution
Imprecise	 P-box of interval	 Probability-box

Other Sources of Imprecision in Design

- Some other sources of uncertainty best represented by intervals
  - Simulations and analysis models – abstractions of reality
  - Statistical data – finite samples of environmental factors
  - Bounded rationality – imprecise subjective probabilities
  - Expert opinion – lack or conflict of information
  - Preferences – incomplete or non-stationary
  - Numerical implementation – limited machine precision

- Consequence:

The performance (expected utility) of a decision alternative is best expressed in terms of intervals

e.g. mass = [100,300] kg, cost = $ [400,1000] → utility = […,…]

Decision Making Under Interval Uncertainty

- In normative decision theory:

  Decision Policy = Maximize Expected Utility

- In set-based design:

  Uncertainty expressed as intervals or probability boxes

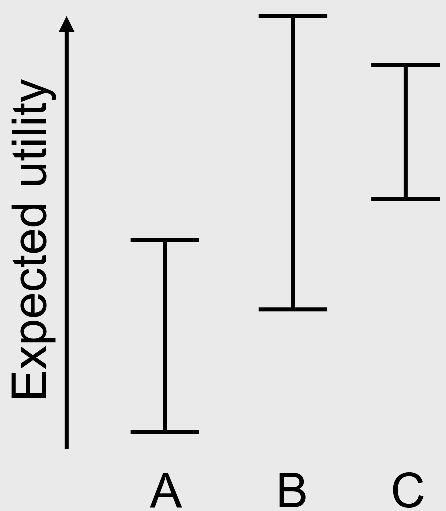
  Expected Utility → Interval of Expected Utility

How to make a decision when expected utilities are intervals?

Decision Making for Intervals of Expected Utility

How can a decision be reached?

Consider 3 design alternatives {A, B, C} with expected utility intervals as shown:



Which alternative is the most preferred?

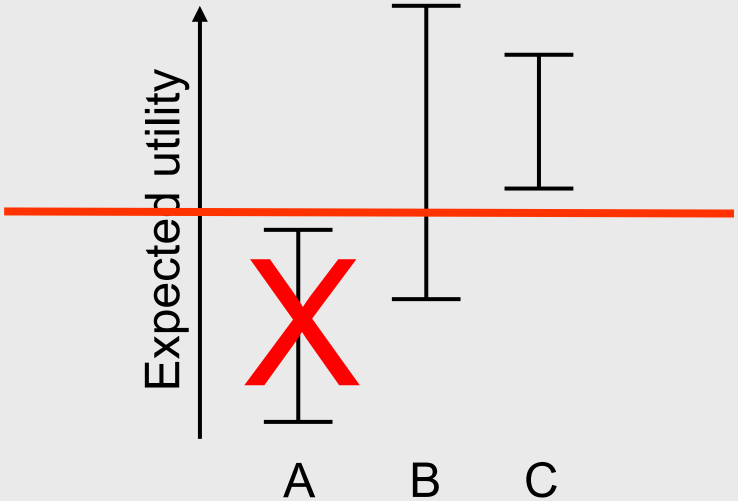
Possible policies include:

- Interval Dominance
- Maximality
- Γ-maximin
- Γ-maximax
- Hurwicz criterion η
- E-admissibility

Interval Dominance Decision Policy

Eliminate only alternatives that are provably dominated

Consider 3 design alternatives {A, B, C} with expected utility intervals as shown:



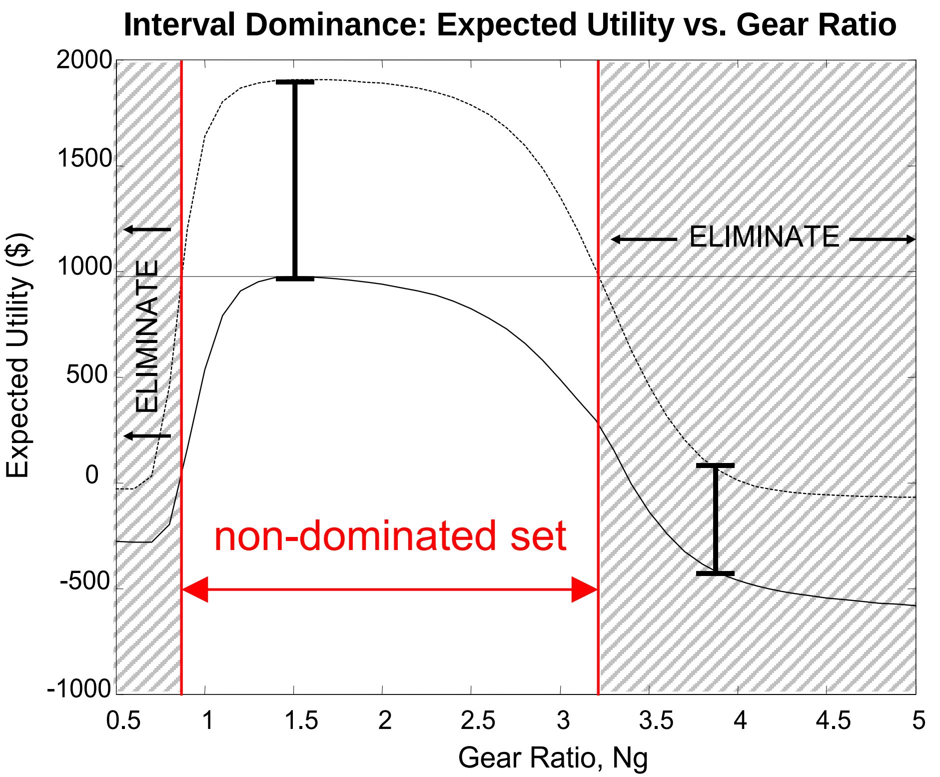
upper bound of A
<
lower bound of C

C dominates A
→ eliminate A

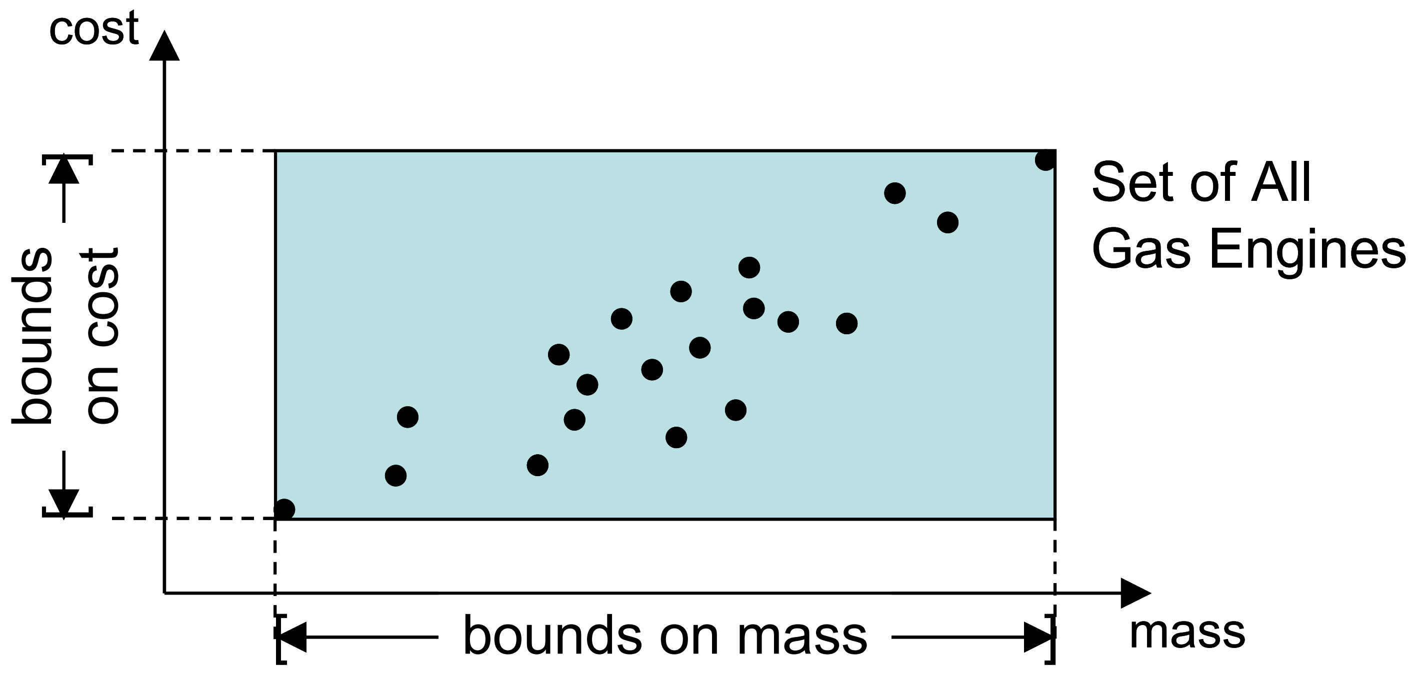
B and C continue to be considered (set-based design)

The Myth of "Optimal Design"

- Due to uncertainty, "optimal design" cannot be determined
- Set of non-dominated solutions
- When uncertainty is large, selecting only the "optimal design" often leads to back-tracking

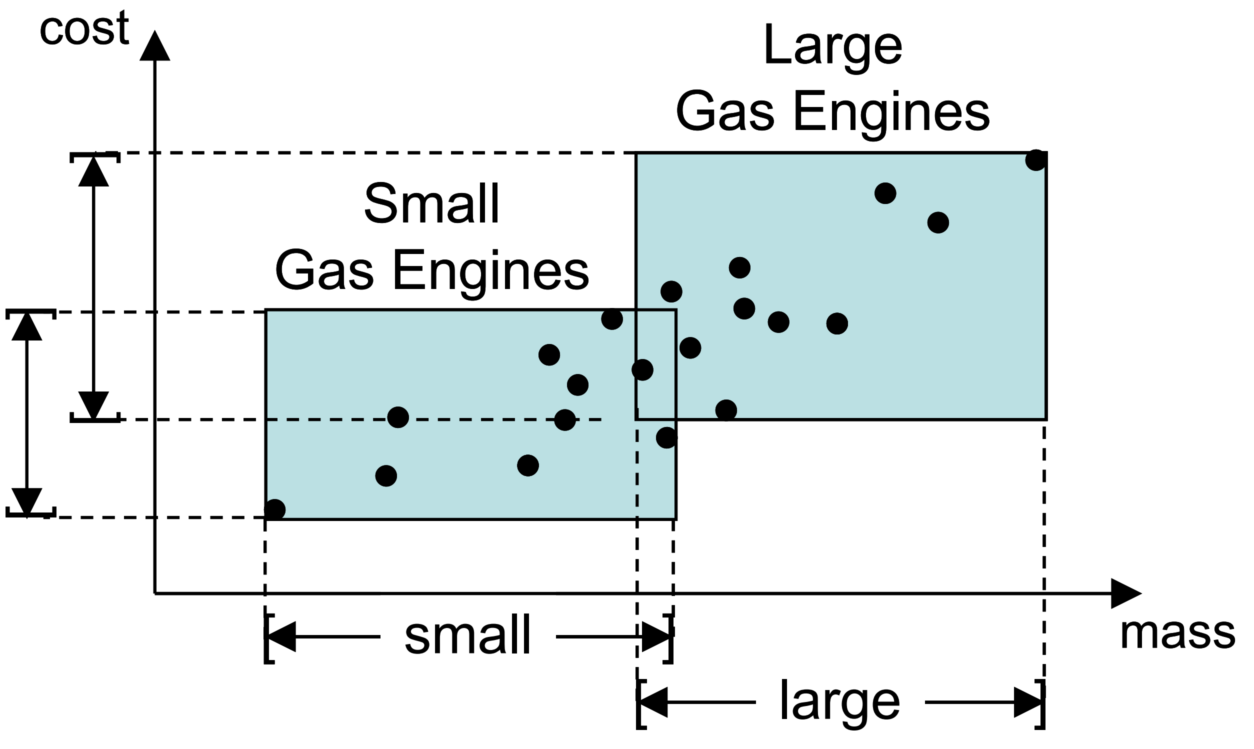


What If Non-Dominated Set is Too Large?



Search non-dominated set using
Branch and Bound approach

What If Non-Dominated Set is Too Large?

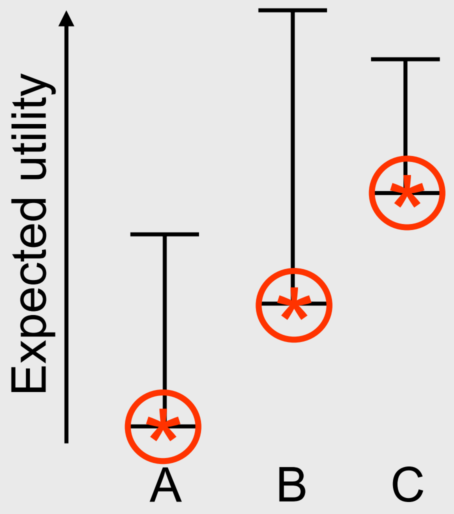


Refine design alternatives
→ Reduces imprecision in performance
→ Allows for additional elimination

Γ-maximin Decision Policy

Avoid a very bad outcome for sure.

Consider 3 design alternatives {A, B, C} with expected utility intervals as shown:



Chose the alternative with the highest lower-bound

→ Robust Solution

Should only be used as a tie-breaker

Consequences for Set-Based Design

Decision Alternatives and their Expected Utilities are Sets

- Unlikely that a single "point solution" will dominate
  - "Point solutions" are often greedy → result in expensive back-tracking
  - "Point solutions" force us to make assumptions that are not supported by current information
- Constraint propagation versus non-domination
  - Intersection of feasible sets for individual disciplines or sub-systems = elimination of dominated solutions
  - Infeasible = overall utility is unacceptably low = dominated
  - But: set of feasible solution is likely to be large → need for efficient search
- Uncertain information should be represented accurately
  - Without overstating what is known
  - But also without omitting much information → need for probabilistic or even hybrid (p-box) representations

Challenges for Modeling and Simulation

- Uncertainty quantification
  - Every model is an abstraction of reality and thus wrong
  - Model accuracy (systematic error) must be stated in terms of intervals
  - Uncertainty quantification of model parameters / inputs / outputs
- Need for abstract models
  - Allow designers to quickly eliminate large portions of the design space
  - Currently not addressed → opportunity: abstraction through data mining
- How to capture abstract models without losing much information?
  - Capturing interval dependence is critical

Challenges for PLM

- Representations of design alternatives in terms of sets
  - Most important at systems engineering level
  - Set-based geometric representations – leverage GD&T support
- Representations for communicating preferences
  - Requirements are too limiting
  - Better communication mechanism than requirements flow-down
- Methods for efficiently propagating constraints
  - Interval arithmetic may yield hyper-conservative results
- Methods for efficiently searching set-based design spaces
  - Branch and bound: How to branch efficiently?

Conclusions

- Set-Based Design
  - Foundation developed by Ward *et al.* starting in late 80's
  - Empirical evidence of superior results: Toyota
  - Many remaining limitations and research issues
- Need for a strong foundation: Decision Theory
  - All sequential design methods are set-based
  - Expected utility of decision alternatives should be expressed as intervals
  - Decision policy: eliminate non-dominated design alternatives
  - Searching through a set of non-dominated alternatives: Branch & Bound

References

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