Massachusetts Institute of Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Fundamentals of Systems Engineering

Prof. Olivier L. de Weck

Session 5

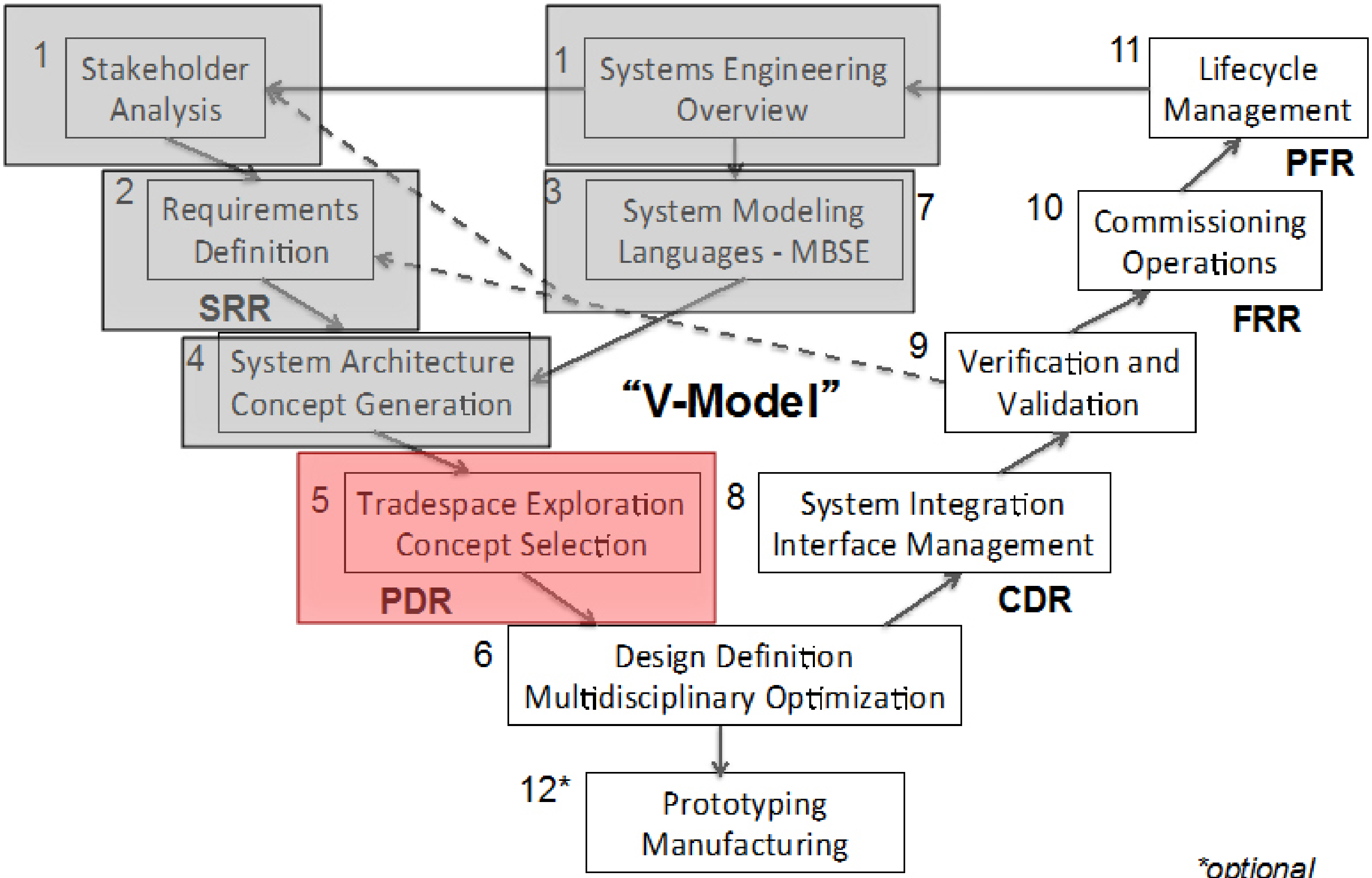
Concept Selection and Tradespace Exploration

A3 is due next week ! A4 out today.

Assignment	*Topic*	*Weight*
A1 (group)	Team Formation, Definitions, Stakeholders, Concept of Operations (CONOPS)	12.5%
A2 (group)	Requirements Definition and Analysis Margins Allocation	12.5%
A3 (group)	System Architecture, Concept Generation	12.5%
A4 (group)	Tradespace Exploration, Concept Selection	12.5%
A5 (group)	Preliminary Design Review (PDR) Package and Presentation	20%
Quiz (individual)	Written online quiz	10%
Oral Exam (individual)	20' Oral Exam with Instructor 2-page reflective memorandum	10%

The "V-Model" of Systems Engineering

16.842/ENG-421 Fundamentals of Systems Engineering

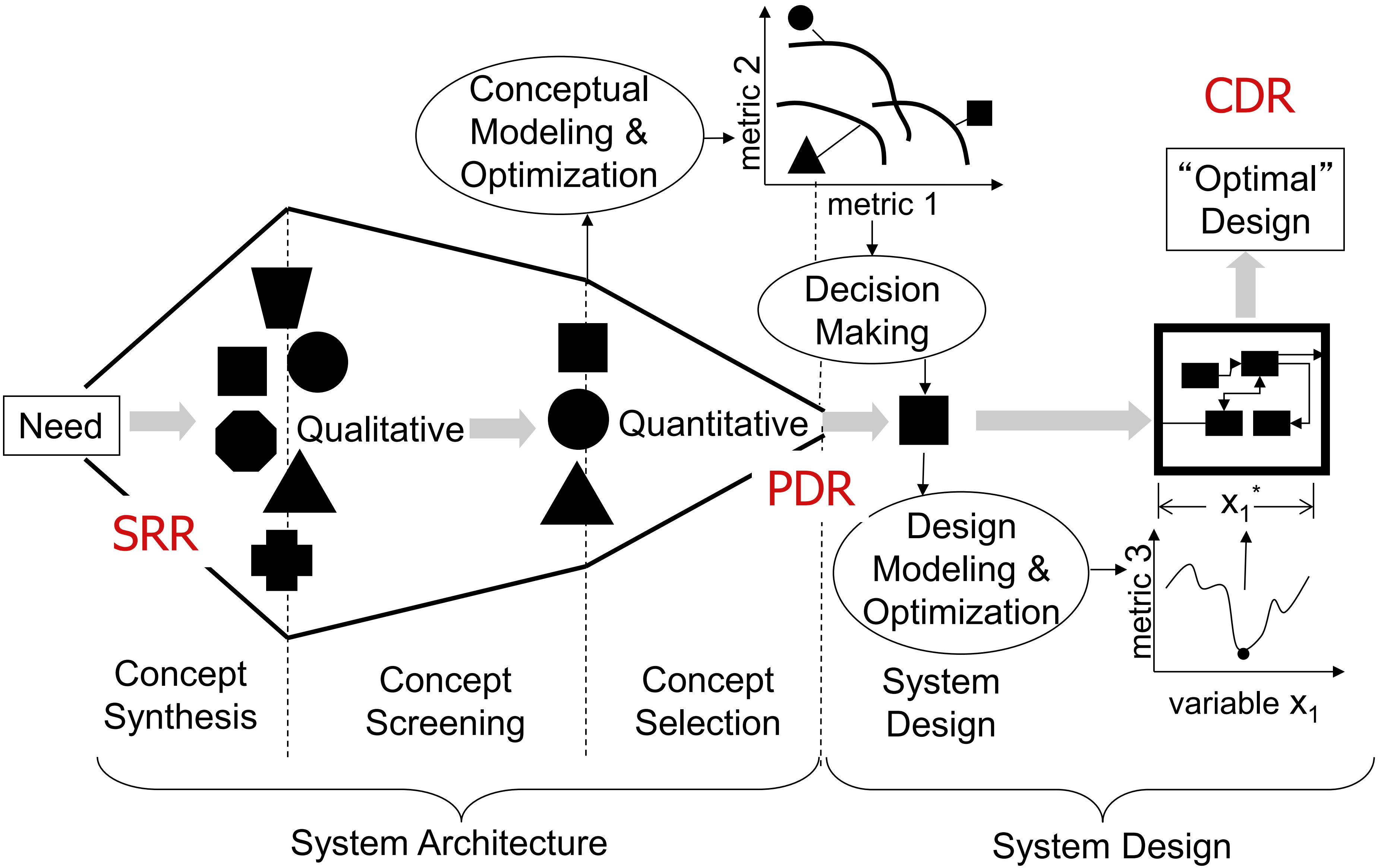


Numbers indicate the session # in this class

Session Outline

- Decision Analysis
- Issues in Concept Selection
- Simple Methods of Concept Selection
  - Pugh Matrix
  - Multi-Attribute Utility
- Non-Dominance
  - Pareto Frontiers, Multiobjective Optimization
- Preliminary Design Review (PDR)

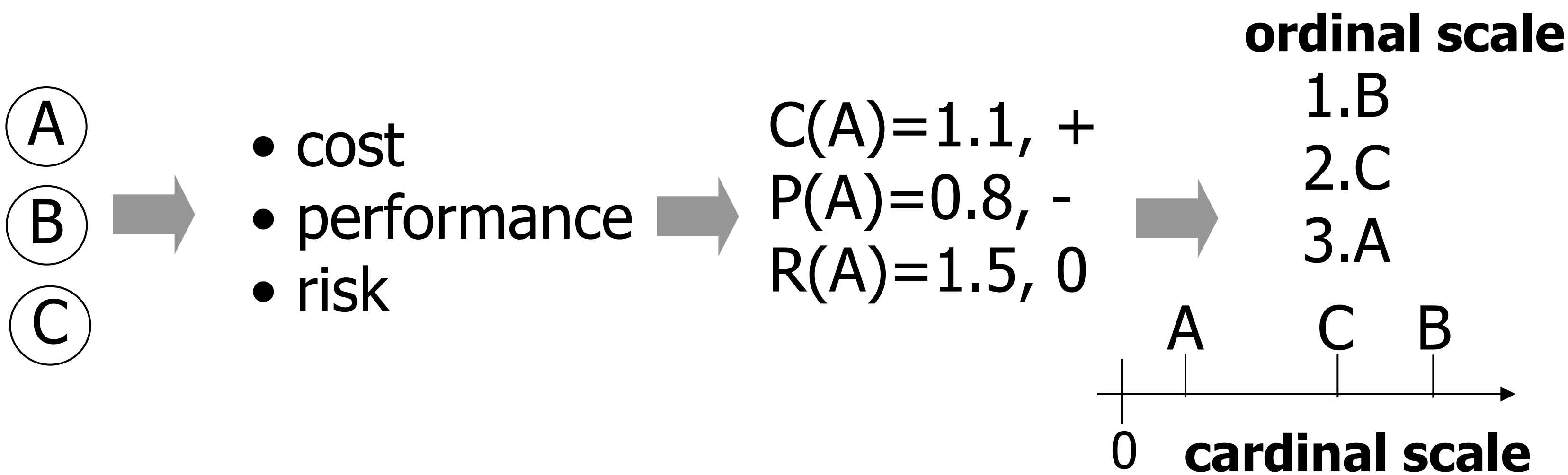
System Architecture → Design



Decision Analysis

- Methods and Tools for ranking (and choosing) among competing alternatives (courses of action)

- Components of a decision
  - alternatives
  - criteria
  - value judgments
  - decision maker (individual or group) preferences



Issues in Concept Selection

- multiple criteria – how to deal with them ?
- what if there are ties between alternatives?
- group decision making versus individual decision making?
  - relates to stakeholder analysis
- uncertainty
  - right criteria?
  - right valuation?
  - are the best alternatives represented?

‘Simple’ Methods of Concept Selection

- Pugh Matrix
  - Uses +, 0, - to score alternatives relative to a datum
  - Named after Stuart Pugh
- Utility Analysis
  - Maps criteria to dimensionless Utility (0→1)
  - Rooted in Utility Theory (von Neumann-Morgenstern 1944)

Pugh Matrix Steps

1. Choose or develop the criteria for comparison.
   - Based on a set of system requirements and goals.

2. Select the Alternatives to be compared.
   - The alternatives are developed during concept generation.
   - All concepts should be compared at the same level of abstraction and in similar language.

3. Generate Scores.
   - Use a concept as **datum**, with all the other being compared to it
   - Evaluate each alternative as being better (+), the same (S, o), or worse (-) relative to the datum.

4. Compute the total score
   - Three scores will be generated, the number of (+), (-), (o)
   - The overall total is the number of (+) minus the number of (-)
   - The totals should not be treated as absolute in the decision making process but as guidance only.

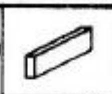
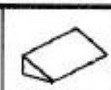
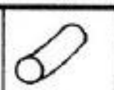
5. Variations on scoring
   - A number of variations on scoring Pugh's method exist.
   - For example a seven level scale could be used for a finer scoring system where:

     +3 meets criterion extremely better than datum
     +2, +1, 0, -1, -2, -3

Adapted from
Source: http://www.enge.vt.edu/terpenny

Pugh Example (Simple)

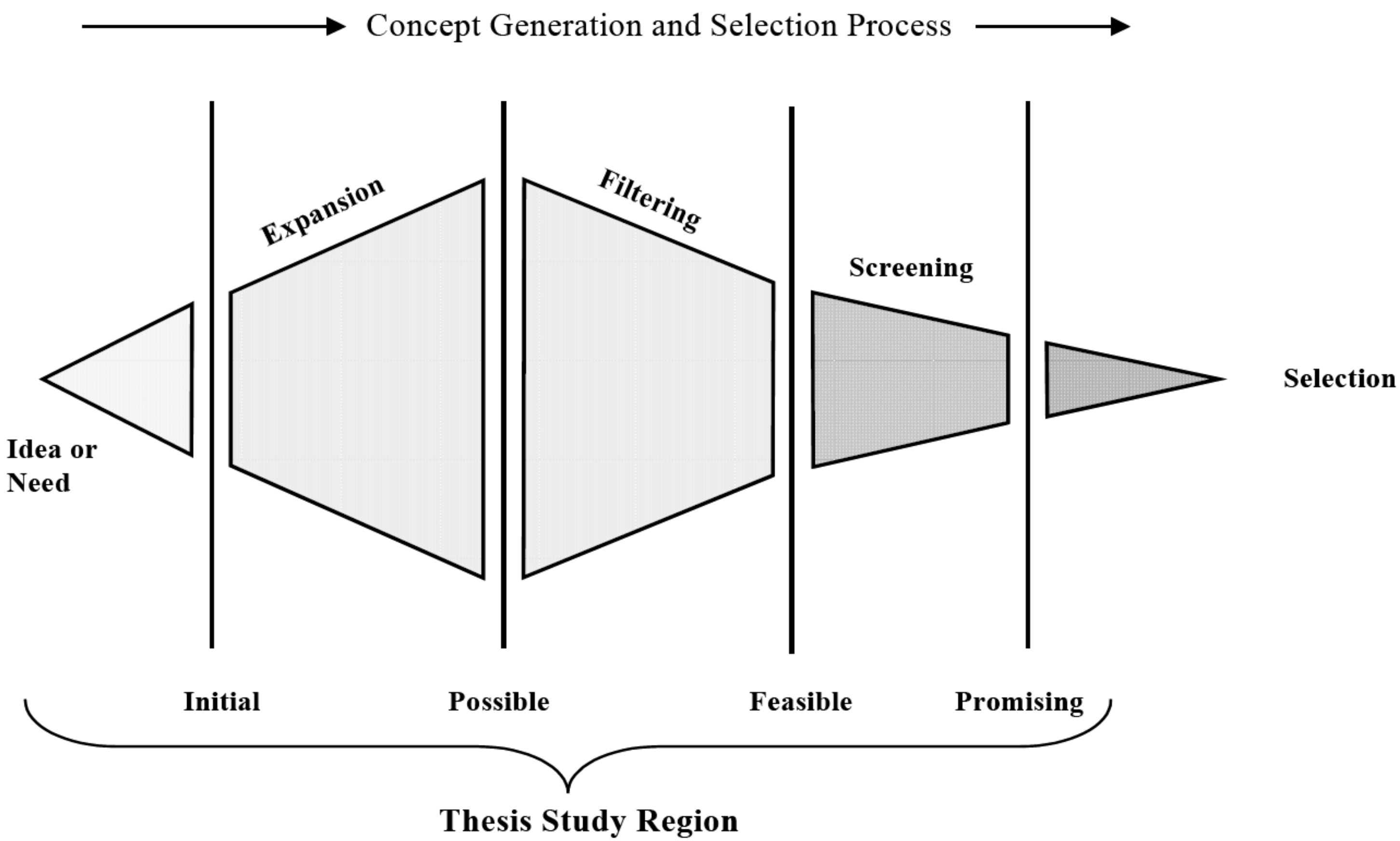
Evaluation Matrix

Concept / Criteria											
	1	2	3	4	5	6	7	8	9	10	11
A	+	−	+	−	+	−	D	−	+	+	+
B	+	S	+	S	−	−		+	−	+	−
C	−	+	−	−	S	S	A	+	S	−	−
D	−	+	+	−	S	+		S	−	−	S
E	+	−	+	−	S	+	T	S	+	+	+
F	−	−	S	+	+	−		+	−	+	S
Σ+	3	2	4	1	2	2	U	3	2	4	2
Σ−	3	3	1	4	1	3		1	3	2	2
ΣS	0	1	1	1	3	1	M		1	0	2

Partner Exercise (5 min)

- What do you see as the main advantages and potential disadvantages or pitfalls of the Pugh Matrix method?
  - Turn to your partner
  - Discuss for 5 minutes
  - Share

Pugh Example (Complex)



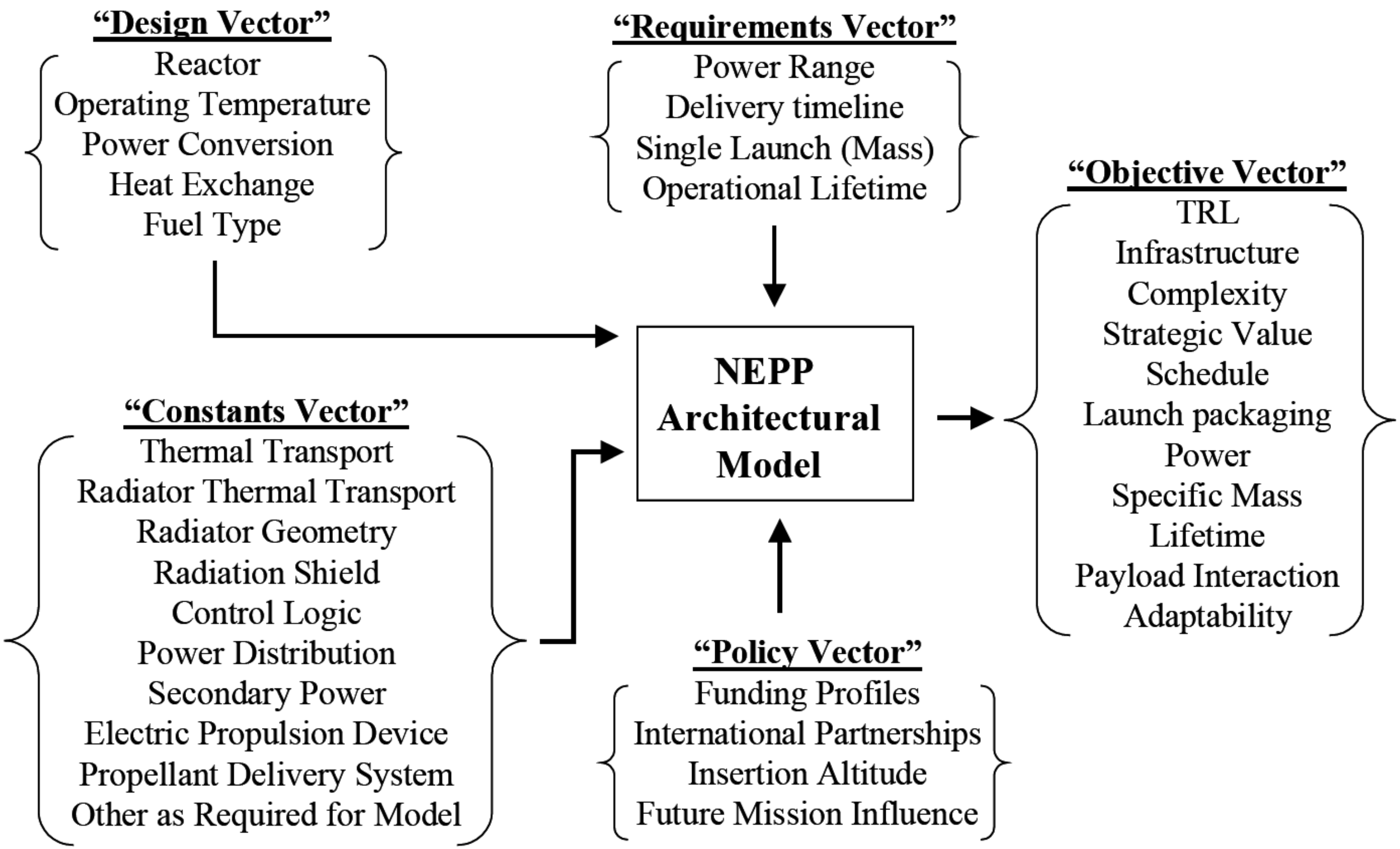
Definition, Expansion and Screening of Architectures for Planetary Exploration Class Nuclear Electric Propulsion and Power Systems

by

Bryan K. Smith

SDM Thesis, Feb 2003

Architectural Space



Filtered Concepts

Reactor	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UN	UN	UN	UN	UN	UN	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UN	UN	UN	UN	UN	UN
Temp	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H
Conversion	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE
Exchange	D	D	D	D	D	D	D	D	D	D	D	D	I	I	I	I	I	I	I	I	I	I	I	I

Reactor	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UN	UN	UN	UN	UN	UN	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UN	UN	UN	UN	UN	UN
Temp	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H
Conversion	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE
Exchange	D	D	D	D	D	D	D	D	D	D	D	D	I	I	I	I	I	I	I	I	I	I	I	I

Reactor	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UN	UN	UN	UN	UN	UN	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UN	UN	UN	UN	UN	UN
Temp	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H
Conversion	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE
Exchange	D	D	D	D	D	D	D	D	D	D	D	D	I	I	I	I	I	I	I	I	I	I	I	I

X	Direct HP and LM	LM	Liquid Metal	B	Brayton
X	Direct TE and Rankine	GC	Gas Cooled	R	Rankine
X	GC with TE and Rankine	HP	Heat Pipe	TE	Thermoelectric
X	High Temperature UO_2	M	Medium	D	Direct
X	Remaining Concepts	H	High	I	Indirect

Concept Screening Matrix (Pugh)

Concept Combinations																								
Reactor	LM	LM	LM	LM	LM	LM	LM	LM	LM	HP	HP	HP	HP	HP	HP	HP	HP	HP	GC	GC	GC	GC	GC	GC
Conversion Device	B	B	B	R	R	R	TE	TE	TE	B	B	B	R	R	R	TE	TE	TE	B	B	B	B	B	B
Heat Exchange	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	D	D	D
Fuel	UO_2	UN	UN	UO_2	UN	UN	UO_2	UN	UN	UO_2	UN	UN	UO_2	UN	UN	UO_2	UN	UN	UO_2	UN	UN	UO_2	UN	UN
Operating Temp.	M	M	H	M	M	H	M	M	H	M	M	H	M	M	H	M	M	H	M	M	H	M	M	H
Criteria																								
TRL	0	0	-	-	-	-	+	0	0	-	-	-	-	-	-	-	-	-	0	0	-	-	-	-
Infrastructure	+	0	0	-	-	-	+	0	0	+	0	0	-	-	-	+	0	0	0	0	0	0	0	0
Complexity	0	0	-	-	-	-	+	+	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-
Strategic Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schedule	+	0	-	-	-	-	+	+	0	+	0	-	-	-	-	+	0	0	+	0	-	0	0	-
Launch Packaging	-	-	0	0	0	0	0	0	0	-	-	-	0	0	0	0	0	0	-	-	0	-	-	0
Power	+	+	+	+	+	+	-	-	0	+	+	+	+	+	+	-	-	0	+	+	+	+	+	+
Specific Power	0	+	+	+	+	+	-	-	0	0	+	+	+	+	+	-	-	-	+	+	+	+	+	+
Lifetime	+	+	0	0	0	0	0	0	0	+	+	0	0	0	0	0	0	0	+	+	0	0	0	0
Payload Interaction	-	-	-	-	-	-	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Adaptability	0	+	+	0	+	+	-	-	0	-	0	0	0	0	0	-	-	-	-	0	0	-	-	-
Sum "+"	4	4	3	2	3	3	4	2	0	4	3	2	2	2	2	2	0	0	4	3	2	2	2	2
Sum "0"	5	5	4	4	3	3	4	6	11	3	5	4	4	4	4	4	6	7	5	6	5	4	4	4
Sum "-"	2	2	4	5	5	5	3	3	0	4	3	5	5	5	5	5	5	4	3	2	4	5	5	5
Net Score	2	2	-1	-3	-2	-2	1	-1	0	0	0	-3	-3	-3	-3	-3	-5	-4	1	1	-2	-3	-3	-3
Rank	1	1	4	6	5	5	2	4	3	3	3	6	6	6	6	6	8	7	2	2	5	6	6	6

LM = Liquid Metal	B = Brayton	I = Indirect	M = Medium
HP = Heat Pipe	R = Rankine	D = Direct	H = High
GC = Gas Cooled	TE = Thermoelectric		

= SP-100 Reference

= Promising Concepts

What is Pugh Matrix for?

The Pugh matrix <u>is</u> for

- Structuring and representing an evaluation procedure
  - Serves as common visual
  - Provides a discipline
  - Helps break down self-sealing behavior
  - Encourages real teamwork
- Convergence
  - Eliminates weaker ideas
  - Retains a set of strong concepts
- Divergence
  - Helps to identify opportunities for combination

The Pugh matrix <u>is NOT</u> for

- Automatic decision making
  - "the scores or numbers … are for guidance only and must not be summed algebraically."
  - "it avoids the rigidity and false confidence of rating/weighting matrices"
- Completely controlling the process
  - "… stimulates creative unconstrained thinking due to its <u>lack of rigorous structure</u>"
- Trade studies
  - More on this today

Pugh, Stuart, 1991, *Total Design*, Addison-Wesley, New York.

Challenges

- "people who have a lot of experience … exhibit an impatience 'to get on with it' and may consider that the procedure holds them back…"
- "strong willed individuals who have a lot of experience and whose initial concepts have not emerged in the final selection … commence a defense based on emotion, experience, and bluster…"

Role of the Facilitator

- Controls the flow / pace of the session
- Records the results (creates the matrix)
- Maintains a tight discipline on the participants
  - Comparison to the datum concept
  - Preventing tangents
  - Encourages clarification of criteria
  - Encourages clarification of concepts
- Seeks opportunities for divergence (hybrids)

Critique of the Pugh Matrix Method

- Ranking of alternatives can depend on the choice of datum
- Weighting: Some criteria may be more important than others
  - See stakeholder analysis
  - Can implement a "weighted" version of the Pugh method, but need to agree on weightings
- Multi-attribute Utility Analysis and Pugh Method may yield different rank order of alternatives
- The most important criteria may be intangible and missing from the list
- Personal Opinion
  - Pugh Method is useful and simple to use.
  - It stimulates discussion about the important criteria, set of alternatives,…
  - Should <u>not</u> be used as the ONLY means of concept filtering and selection

Utility Theory

- Utility is defined as
  - In economics, utility is a measure of the relative happiness or satisfaction (gratification) gained by consuming different bundles of goods and services. Given this measure, one may speak meaningfully of increasing or decreasing utility, and thereby explain economic behavior in terms of attempts to increase one's utility. The theoretical unit of measurement for utility is the util.

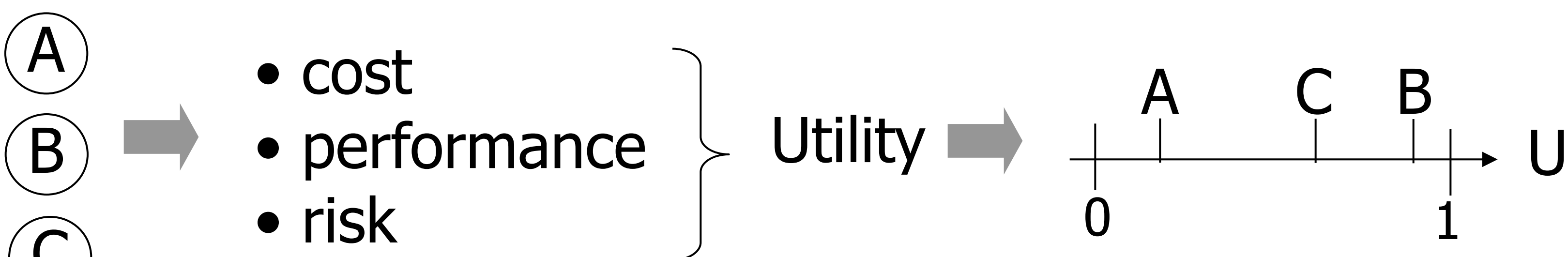
- Generally map criteria onto dimensionless utility [0,1] interval

- Combine Utilities generated by criteria into overall utility

Consumption Set X (mutually exclusive alternatives)

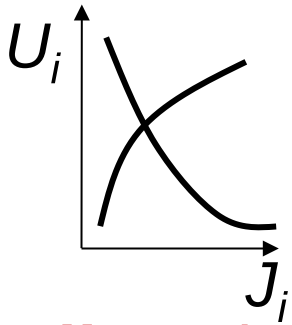
$$U : X \mapsto \Re$$

Ranks each member of the consumption set

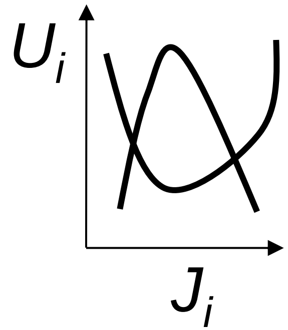


cardinal scale

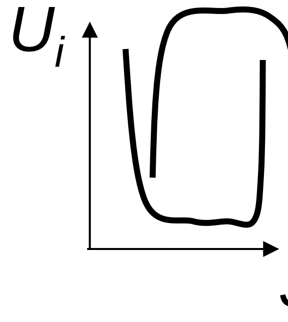
Utility Function Shapes



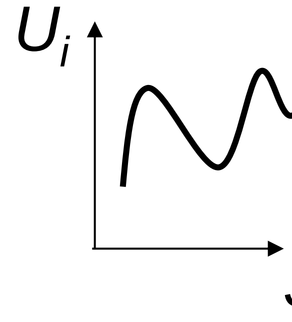
Monotonic increasing decreasing



Strictly Concave Convex



Concave Convex



Non-monotonic

Cook:

Smaller-is-better (SIB)
Larger-is-better (LIB)

Nominal-is -better (NIB)

Range -is-better (RIB)

-

(this is almost never seen In practice)

Messac:

Class 1S
Class 2S

Class 3S

Class 4S

Aggregated Utility

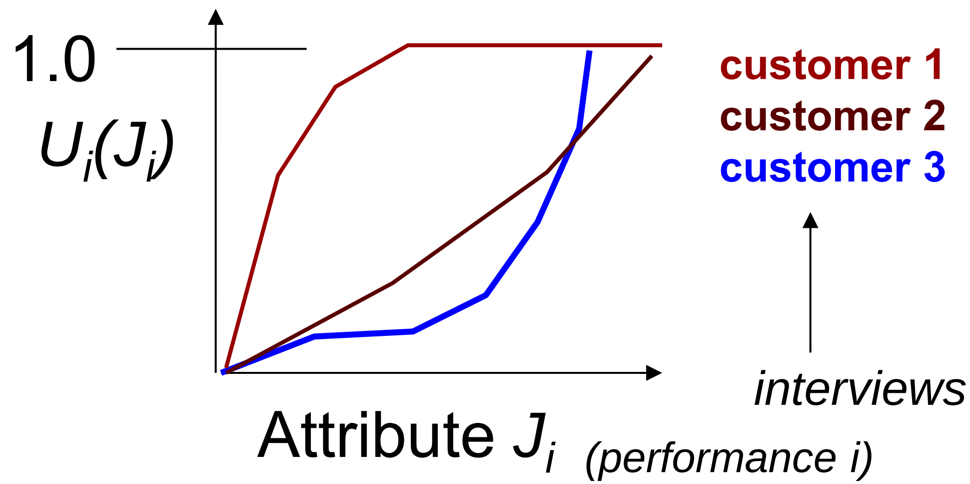
… sometimes called multi-attribute utility analysis (MAUA)
The total utility becomes the weighted sum of partial utilities:

E.g. two utilities combined: $U\left(J_1, J_2\right) = Kk_1k_2U(J_1)U(J_2) + k_1U(J_1) + k_2U(J_2)$

Combine single utilities into overall utility function:

For 2 objectives: $K = (1 - k_1 - k_2)/k_1k_2$

k_i' s determined during interviews
K is dependent scaling factor



Steps: MAUA
1. Identify Critical Objectives/Attrib.
2. Develop Interview Questionnaire
3. Administer Questionnaire
4. Develop Aggregate Utility Function
5. Determine Utility of Alternatives
6. Analyze Results

Caution: "Utility" is a surrogate for "value", but while "value" has units of [$], utility is unitless.

Notes about Utility Maximization

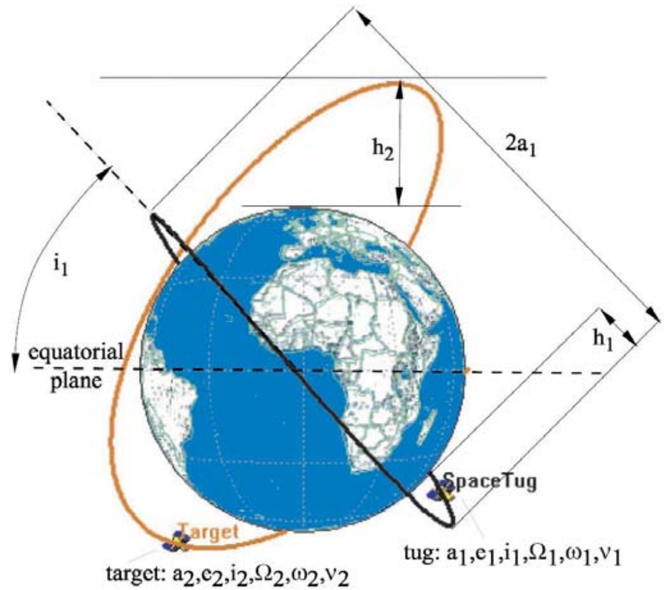
- Utility maximization is very common and well accepted
- Usually **U** is a non-linear combination of criteria *J*
- Physical meaning of aggregate objective is lost (no units)
- Need to obtain a mathematical representation for $U(J_i)$ for all *i* to include all components of utility
- Utility function can vary drastically depending on decision maker …e.g. in U.S. Govt change every 3-4 years
- Requires formulation of preferences <u>apriori</u>

Example: Space Tug Tradespace Exploration

A satellite that has the ability to change the orbital elements ($\alpha, e, i, \Omega, \omega, \nu$) of a target satellite by a predefined amount without degrading its functionality in the process.

Typical Mission Scenario

- Waiting in Parking Orbit
- Tasking and Orbital Transfer
- Target Search and Identification
- Rendezvous and Approach
- Docking and Capture
- Orbital Transfer
- Release and Status Verification
- Return to Parking Orbit or Next Targe



System Attributes (Objectives)

- Total ΔV capability - where it can go
  - Calculated from simple model (rocket equation)
- Response time - how fast it can get there
  - Binary - electric is slow - some astrodynamics
- Mass of observation/grappling equipment - what it can do when it gets there
  - Based solely on payload mass

Combine into a Utility [0,1]

- Vehicle wet and dry mass - cost drivers
  - Calculated from simple models - scaling relationships

Keep Cost separate [M$]

McManus, H. L. and Schuman, T. E., "Understanding the Orbital Transfer Vehicle Trade Space," AIAA-2003-6370, Sept. 2003.

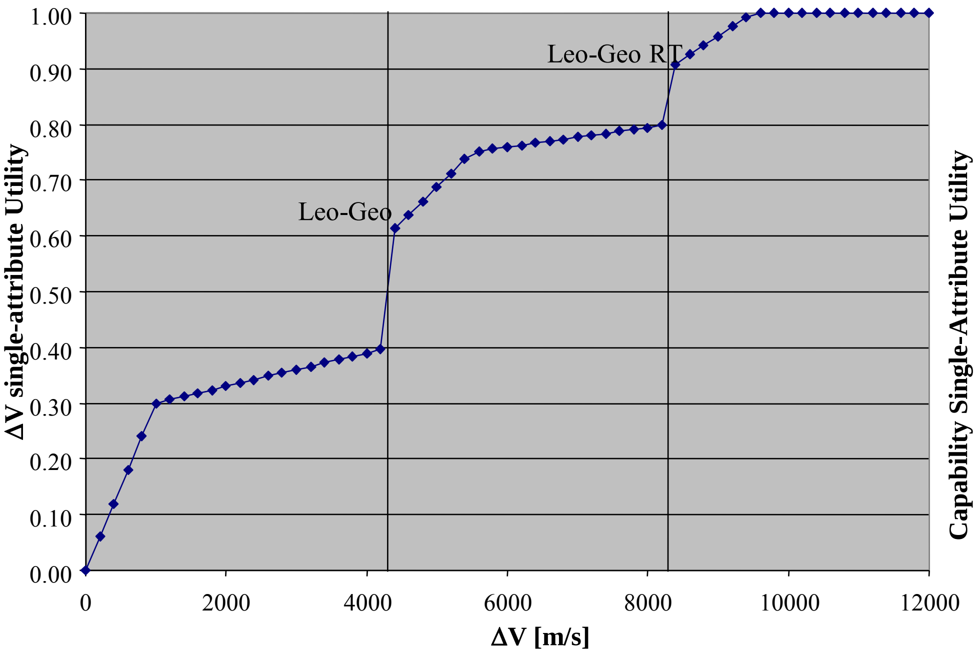
(MATE Method)

What is the utility of a space tug ?

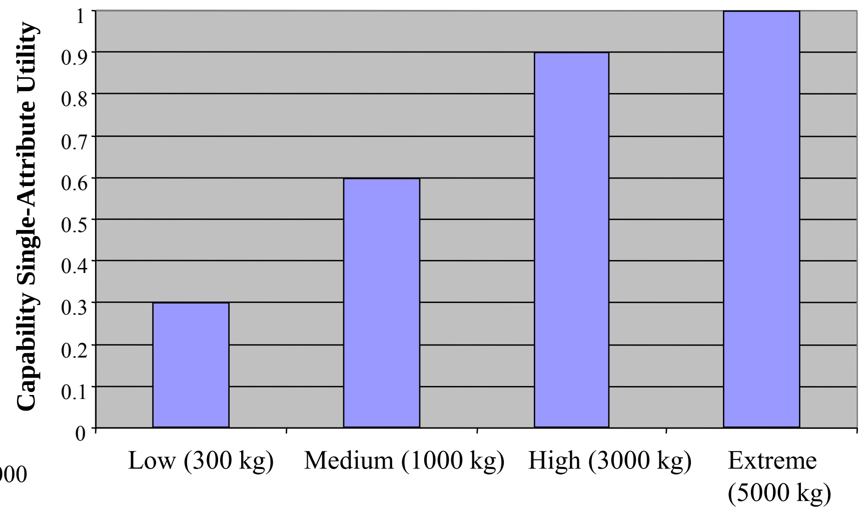
- Response time utility binary (electric bad)
- Total Utility a weighted sum
  - Examples will stress ΔV, then capability
- Cost estimated from wet and dry mass

Weights:
- Capability 0.3
- DV 0.6
-Time 0.1
-Sum: 1.0

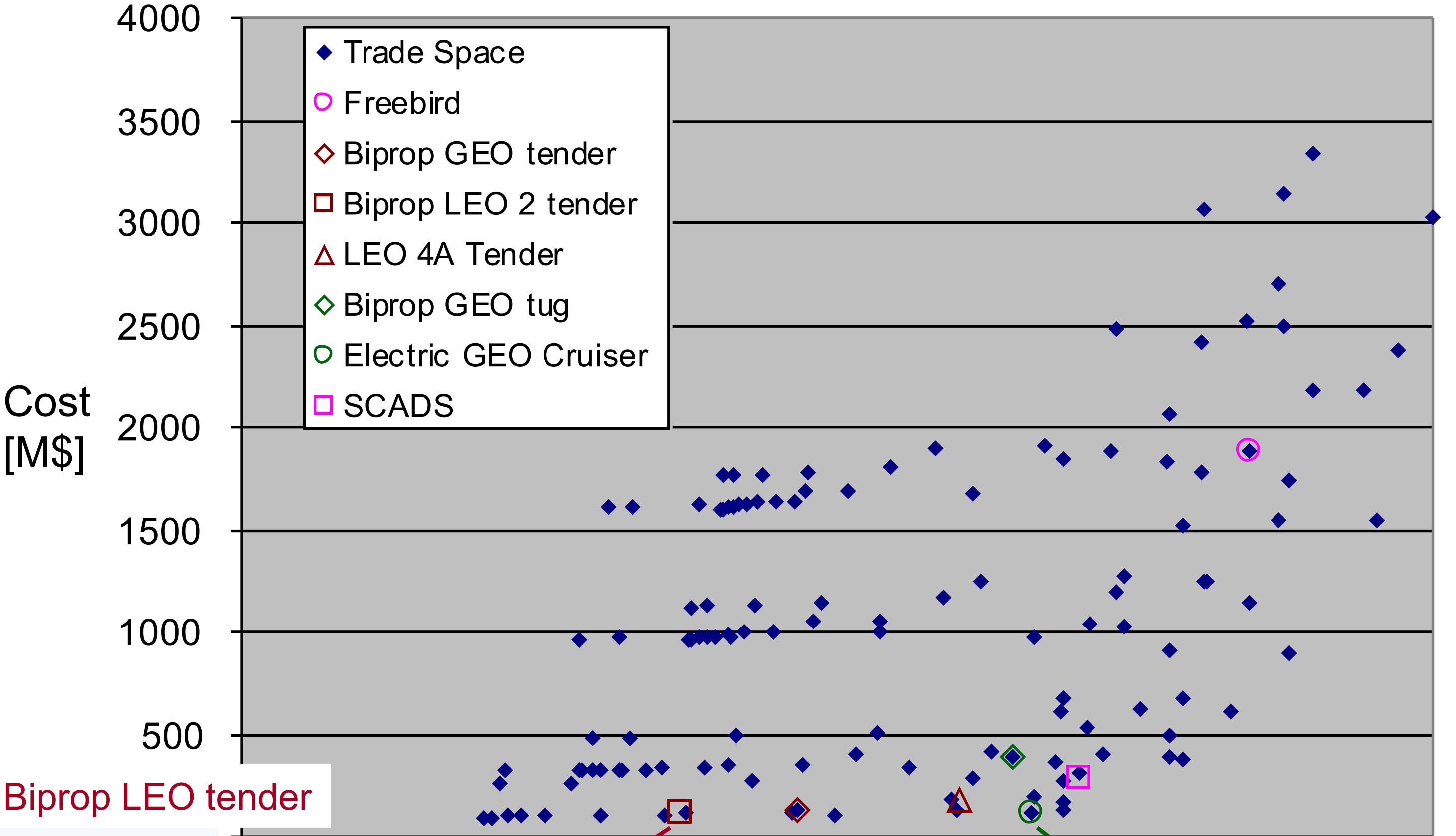
ΔV - Utility : where it can go



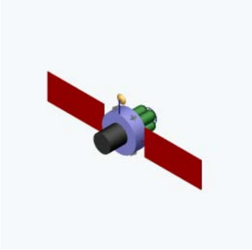
Payload mass utility: what it can handle



Space Tug Tradespace Exploration



Biprop LEO tender

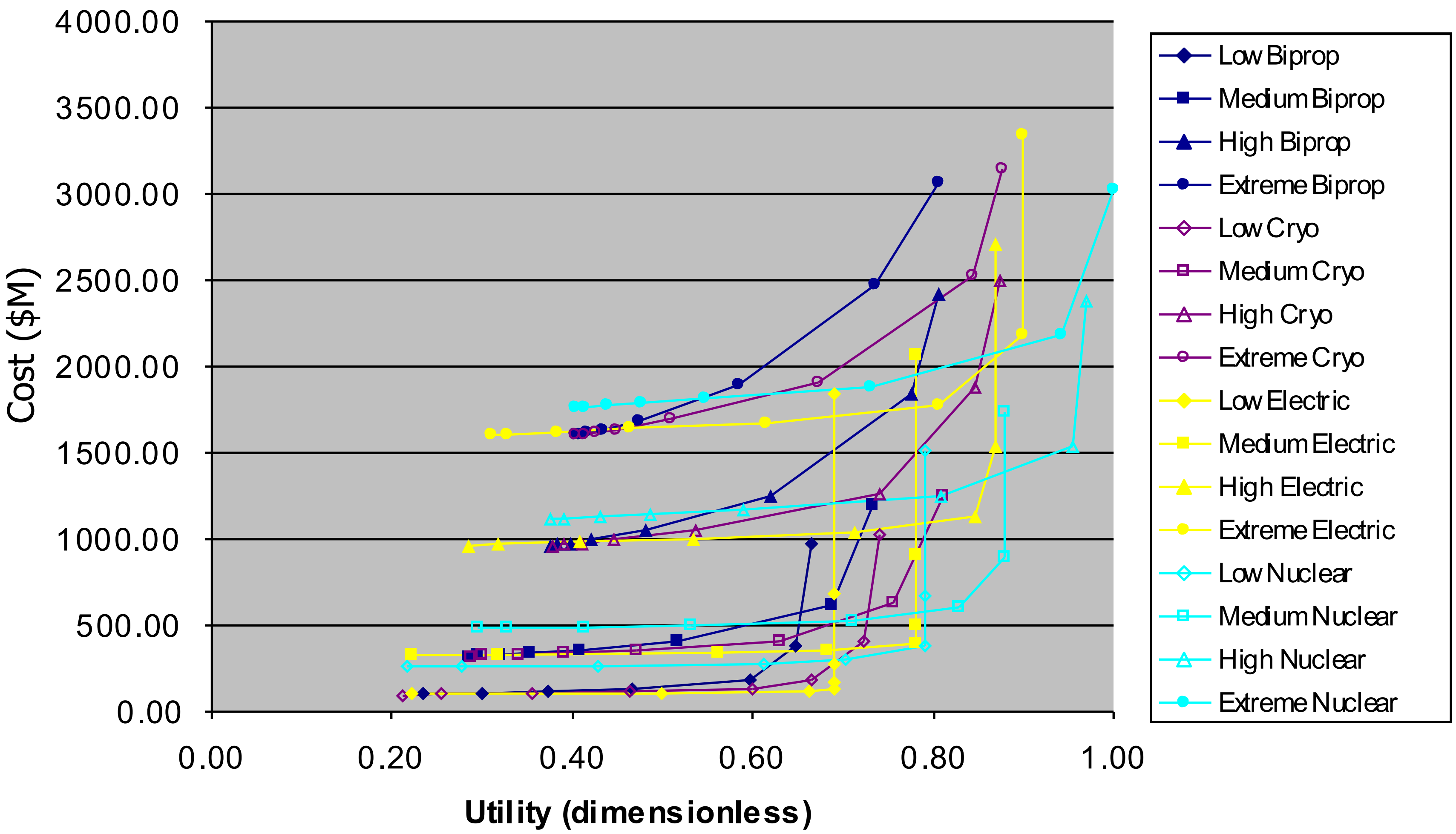


680.18 kg dry mass; 1403.6 kg wet mass
Reasonable size and mass fraction

Electric GEO Cruiser

711 kg dry mass, 1112 kg wet mass
Includes return of tug to safe orbit
A reasonable, versatile system

Trade Space Analysis



Hits a "wall" of either physics (can't change!) or utility (can)

Non-Dominance

- Non-Dominance, Pareto Frontier
- Multiobjective Optimization
  - Preferences enter <u>aposteriori</u>

History – Vilfredo Pareto

- **Born in Paris in 1848** to a French Mother and Genovese Father
- Graduates from the **University of Turin** in 1870 with a degree in **Civil Engineering**
  - Thesis Title: “The Fundamental Principles of **Equilibrium** in Solid Bodies”
- While working in Florence as a Civil Engineer from 1870-1893, Pareto takes up the study of philosophy and politics and is one of the **first to analyze economic problems with mathematical tools**.
- In 1893, Pareto becomes the Chair of Political Economy at the **University of Lausanne in Switzerland**, where he creates his two most famous theories:
  - Circulation of the Elites
  - **The Pareto Optimum**
    - ***“The optimum allocation of the resources of a society is not attained so long as it is possible to make at least one individual better off in his own estimation while keeping others as well off as before in their own estimation.”***
    - **Reference:** Pareto, V., *Manuale di Economia Politica*, Societa Editrice Libraria, Milano, Italy, 1906. Translated into English by A.S. Schwier as *Manual of Political Economy*, Macmillan, New York, 1971.

Properties of optimal solution

$\mathbf{x}^*$ optimal if $\mathbf{J}\left(\mathbf{x}^*\right) \geq \mathbf{J}(\mathbf{x})$ (maximization)

for $\mathbf{x}^* \in S$ and for $\mathbf{x} \neq \mathbf{x}^*$

⇨ This is why multiobjective optimization is also sometimes referred to as vector optimization

$\mathbf{x}^*$ must be an efficient solution

$\mathbf{x} \in S$ is efficient if and only if (iff) its objective vector (criteria) J($\mathbf{x}$) is non-dominated

A point $\mathbf{x} \in S$ is efficient if it is not possible to move feasibly from it to increase an objective without decreasing at least one of the others

Dominance (assuming maximization)

Let $\mathbf{J}^1, \mathbf{J}^2 \in \mathbb{R}^z$ be two objective (criterion) vectors.

$$J^i = \begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ J_z \end{bmatrix}$$

Then **J¹** dominates **J²** (weakly) iff

$$\mathbf{J}^1 \geq \mathbf{J}^2 \quad \text{and} \quad \mathbf{J}^1 \neq \mathbf{J}^2$$

More precisely: $J_i^1 \geq J_i^2 \quad \forall\, i \quad \text{and} \quad J_i^1 > J_i^2 \quad \text{for at least one } i$

Also **J¹** strongly dominates **J²** iff

$$\mathbf{J}^1 > \mathbf{J}^2$$

More precisely: $J_i^1 > J_i^2 \quad \forall\, i$

Dominance - Exercise

max{range}	[km]
min{cost}	[$/km]
max{passengers}	[-]
max{speed}	[km/h]

Multiobjective Aircraft Design

#1	#2	#3	#4	#5	#6	#7	#8
7587	6695	3788	8108	5652	6777	5812	7432
321	211	308	278	223	355	401	208
112	345	450	88	212	90	185	208
950	820	750	999	812	901	788	790

Which designs are non-dominated ? (5 min)

Concept Question 6

- Which airplane designs are non-dominated?
  - 5,6 and 7
  - 1, 3, 4 and 8
  - 1, 2, 3, 4 and 8
  - 2, 3, 5, and 6
  - 1, 3, 4, and 7
  - Need more information to answer

- Answer Concept Question 6 (see supplemental files)

Procedure

Algorithm for extracting non-dominated solutions:
Pairwise comparison

#1		#2	Score #1	Score #2
7587	>	6695	1	0
321	>	211	0	1
112	<	345	0	1
950	>	820	1	0
			2	vs 2

Neither #1 nor #2 dominate each other

#1		#6	Score #1	Score #6
7587	>	6777	1	0
321	<	355	1	0
112	>	90	1	0
950	>	901	1	0
			4	vs 0

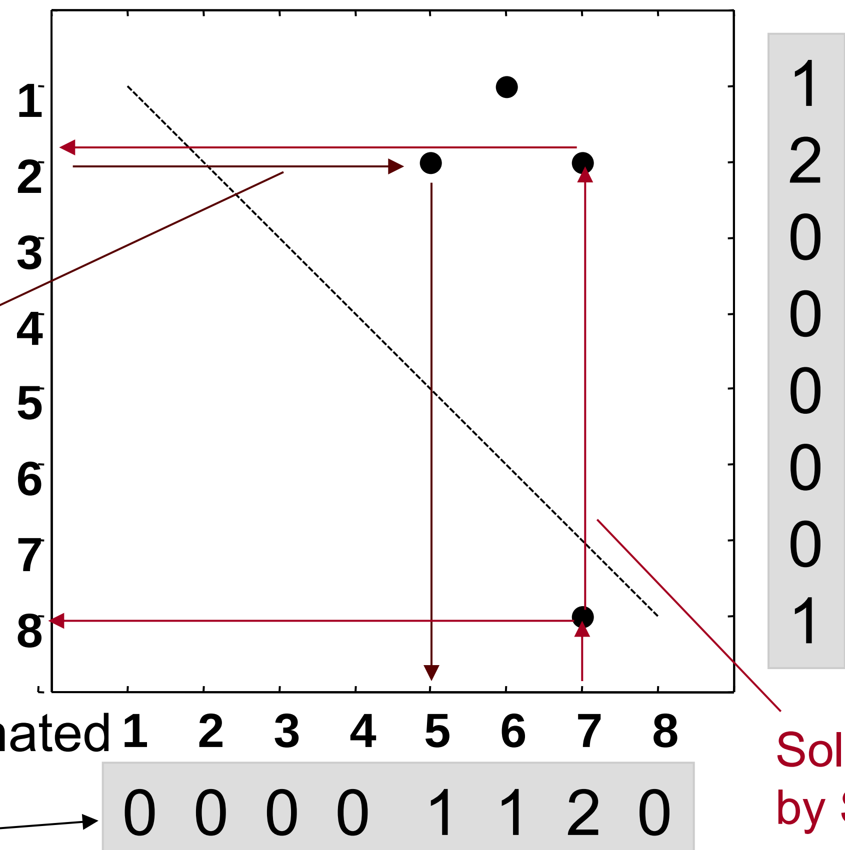
Solution #1 dominates solution #6

In order to be dominated a solution must have a ”score” of 0 in pairwise comparison

Domination Matrix

Shows which solution dominates which other solution (horizontal rows) and (vertical columns)

Row Σ



j-th row indicates how many solutions j-th solution dominates

Solution 2 dominates Solution 5

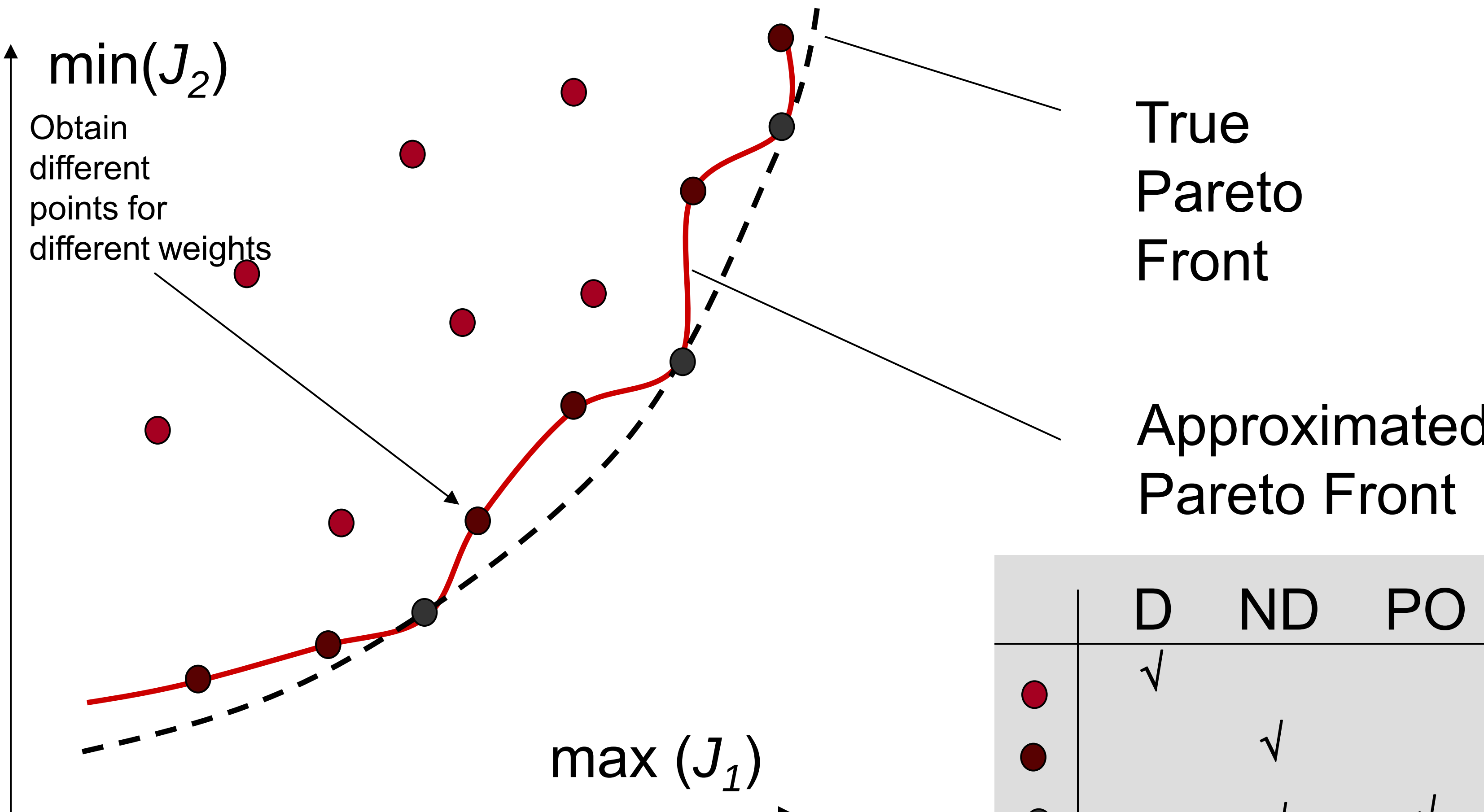
Solution 7 is dominated by Solutions 2 and 8

k-th column indicates by how many solutions the k-th solution is dominated

Column Σ

Non-dominated solutions have a zero in the column Σ!

Pareto-Optimal vs. non-dominated



	D	ND	PO
●	√		
●		√	
●		√	√

All pareto optimal points are non-dominated
Not all non-dominated points are pareto-optimal

It's easier to show dominatedness than non-dominatedness !!!

Preliminary Design Review (PDR)

- **What is the purpose of PDR?**
  - Explain what concept and system architecture was chosen
  - Explain why it was chosen – *approve this as the design baseline*
  - Compare it against the rejected alternatives
  - Show some quantitative analysis that gives confidence that the requirements as stated at the SRR and derived since then can be met
  - Describe the results of any risk reduction experiments / prototypes
  - Preview detailed design phase leading up to CDR

Preliminary Design Review

The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. It will show that the correct design options have been selected, interfaces have been identified, approximately 10 percent of engineering drawings have been created, and verification methods have been described. PDR occurs near the completion of the preliminary design phase (Phase B) as the last review in the Formulation phase.

Image Source: http://f4e.europa.eu/Downloads/News/01_cryoplant_web-140120151200-Large.jpg.

NASA SE Handbook (2007), p.177

Summary Lecture 5: Concept Selection

- During Conceptual Design
  - Use Pugh-Matrix Selection
    - When detailed mathematical models not yet available, but qualitative understanding exists
- During Preliminary Design
  - Use Utility Analysis
    - Especially for non-commercial systems where NPV may not be easy to calculate
  - Use Non-dominance
    - Generate many designs for each concept, apply Pareto filter