Mathematical Evaluation of Conceptual Design Methods

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Rigor in Systems Engineering

- Much of Systems Engineering involves heuristic methods and best practices [17]
- Rigorous methods either don't exist or are not commonly used in many aspects of Systems Engineering
  - System Architecting [14]
  - Factors of Safety [16]
  - Requirements "margin" [18]
  - Risk Management [13]
  - Conceptual design [4][10]
- The methods that are commonly used lack a theoretical foundation—do we pay a price for using them?
- This research effort focuses on applying a rigorous theoretical framework (decision theory) to analyze conceptual design methods
- The decisions in play often have $billion implications

Normative vs. Descriptive Theory

- Normative theory examines how a design engineer *should* act when performing system design [7]

- Descriptive theory examines how a design engineer *does* act when performing system design [7]

- Our motivation is to develop normative theory to evaluate effectiveness of systems engineering methods
  - —Deliver more value to customer/user [9]
  - —Make more money [9]

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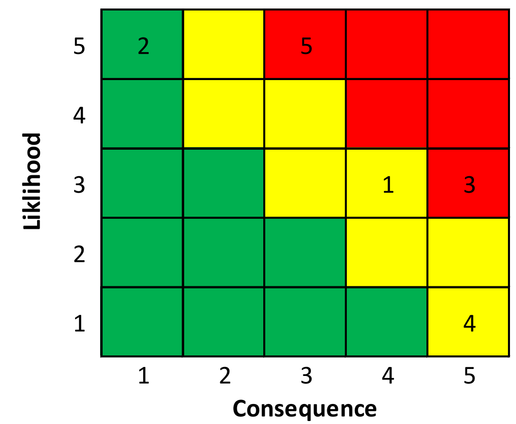
Example – Risk Management

- Given a set of risks and evaluation criteria…

	1	2	3	4	5
Probability	<1%	1-5%	5-20%	20-50%	50-100%
Impact	<$20k	$20k-$50k	$50k-$200k	$200k-$800k	>$800k

Risk	Probability	Consequence	Exposure
1	12%	$500k	$60k
2	98%	$99k	$97.02k
3	5%	$850k	$42.5k
4	0.95%	$10M	$95k
5	51%	$84k	$42.8k

- Build the risk matrix and prioritize…
  - —Priority is 3>5>1>4>2



- Applying decision theory by calculating expected value yields
  - —Priority is 2>4>1>5>3 … The exact opposite
  - —Cox [13] calls the risk matrix “worse than useless”

Conceptual Design

- Conceptual design performed early stages of design [1]
- System is typically being conceptualized at a high level
  - Architecture is not complete
  - System level attributes being evaluated
- Can be performed at any level in system decomposition [10]
  - System level
  - Subsystem
  - Component
- Decision is critical to final design outcome [1][15]

Research Questions

- Under what conditions does the Pugh Method lead to the best design?
- When the Pugh method does not lead to the best design, how much worse is the selected design?
- Under what conditions does the Quality Function Deployment lead to the best design?
- When the Quality Function Deployment method does not lead to the best design, how much worse is the selected design?

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Finding the Best Design

- The entire purpose of
  - Design methods [9]
  - Concept selection methods [10]
  - Trade studies [19]
- Pugh and QFD are a class of design/selection methods that [4][10]:
  - Ordinally rank designs from "best" to "worst"
  - Decompose design into a set of important attributes (cost, performance, etc)
  - Assume deterministic attribute values
- For these methods, finding the best design is a two step process [7]
  - Order the candidate design concepts from worst to best
  - Choose the best design concept

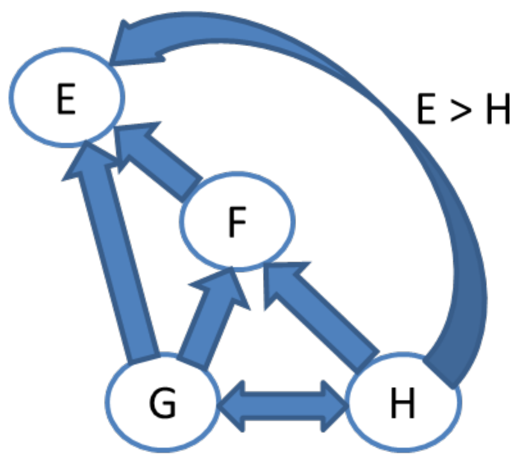
Pugh Method Explained

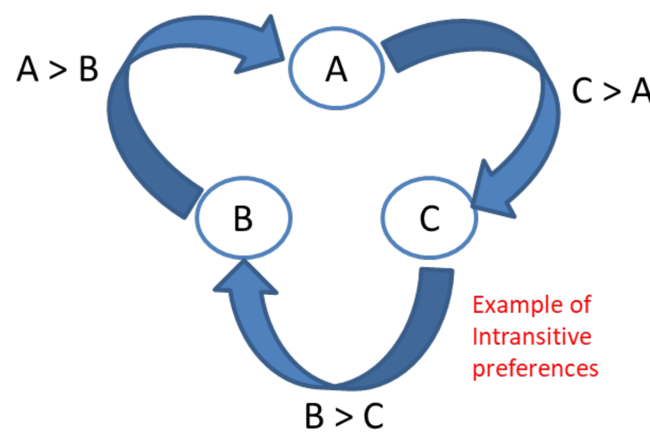
- Pugh method of controlled convergence (PuCC) is widely use concept selection methodology [9]
- Example: 3 design concepts (A, B, C) and 3 attributes of interest (power, cost and volume)
- Procedure [4]
  1. Select a datum concept
  2. Build a matrix of designs/attributes
  3. Rate each attribute of each design against the datum and better (+), worse (-) or same (o)
  4. Aggregate the scores of each design concept into an aggregate score $\sum Better(+) - \sum Worse(-)$
  5. Evaluate matrix, eliminate weak designs
  6. Add new design concepts
  7. Repeat

	Design A	Design B	Design C
Power (W)	DATUM	+	-
Cost ($)		-	-
Volume (ft^3)		+	+

Assumptions and Inconsistencies in Pugh

- Minimum Assumptions used to evaluate Pugh [2][4]
  - Reflexivity of ordering
  - Completeness of ordering
  - Transitivity of ordering
- Other assumptions are made, but not necessary to show inconsistencies in Pugh method
- Inconsistent result defined as design choice that is
  - Not the best design
  - Intransitive ordering

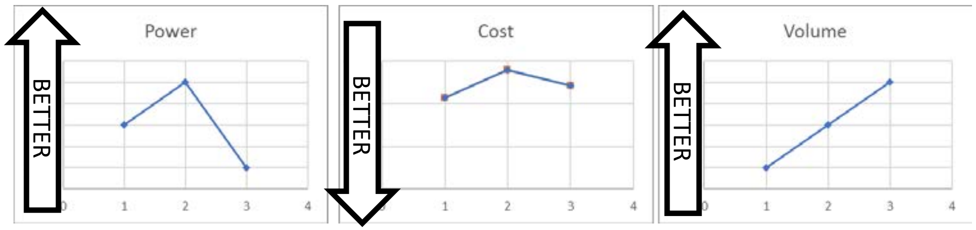




Pugh Inconsistency Example

- Select the best microwave
- 3 Attributes
  - —Power (more is preferred)
  - —Cost (less is preferred)
  - —Volume (more is preferred)
- Selected design is solely based on selected datum rather than the attributes

	Design A	Design B	Design C
Power (W)	1100	1200	1000
Cost ($)	106.99	139.99	121.53
Volume (ft^3)	1.2	1.3	1.4



	Design A	Design B	Design C
Power (W)		+	-
Cost ($)	DATUM	-	-
Volume (ft^3)		+	+

B is best

	Design A	Design B	Design C
Power (W)	-		-
Cost ($)	+	DATUM	+
Volume (ft^3)	-		+

C is best

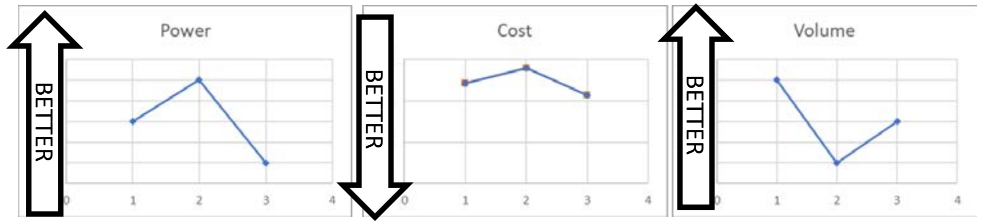
	Design A	Design B	Design C
Power (W)	+	+	
Cost ($)	+	-	DATUM
Volume (ft^3)	-	-	

A is best

Pugh Inconsistency Example 2

- Select the best microwave
- 3 Attributes
  - —Power (more is preferred)
  - —Cost (less is preferred)
  - —Volume (more is preferred)

	Design A	Design B	Design C
Power (W)	1100	1200	1000
Cost ($)	121.53	139.99	106.99
Volume (ft^3)	1.4	1.2	1.3



- Differences between A and B are hidden from the decision-maker by the matrix structure

		A is Datum	B is Datum	C is Datum
power	B>A>C	B>A>C	B>A=C	B=A>C
cost	B>A>C	B>A>C	B>A=C	B=A>C
volume	A>C>B	A>C=B	A=C>B	A>C>B

	Design A	Design B	Design C
Power (W)		+	-
Cost ($)	DATUM	+	-
Volume (ft^3)		-	-

B is best

	Design A	Design B	Design C
Power (W)	-		-
Cost ($)	-	DATUM	-
Volume (ft^3)	+		+

B is best

	Design A	Design B	Design C
Power (W)	+	+	
Cost ($)	+	+	DATUM
Volume (ft^3)	+	-	

A is best

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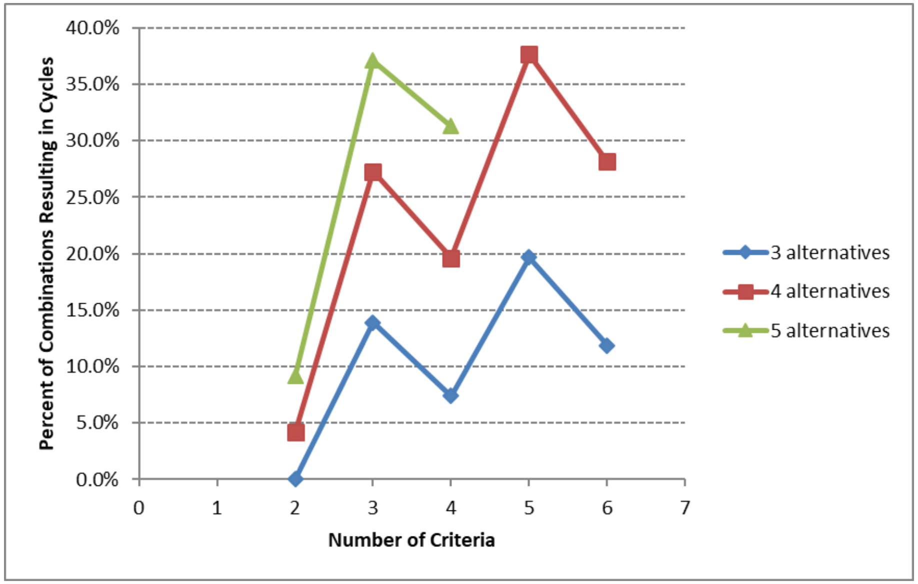
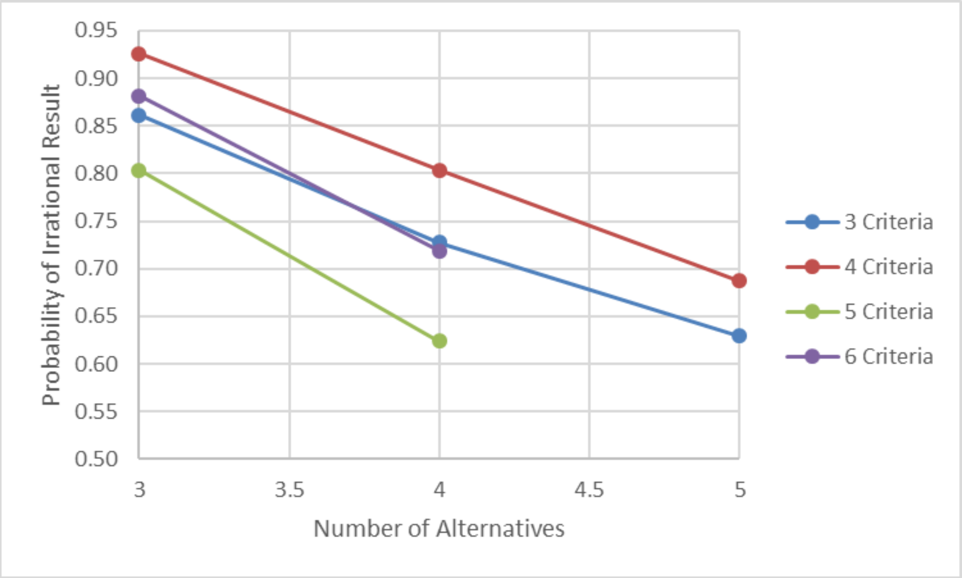
How Likely Are These Problems?

- Exhaustive , brute force computation of potential outcomes (not simulation) yields
  - —Likelihood increases as dimensionality increases
  - —Even numbers of attributes is less likely to exhibit behavior
- However, the best design cannot be identified
- We just know that the method can't reliably help us find it



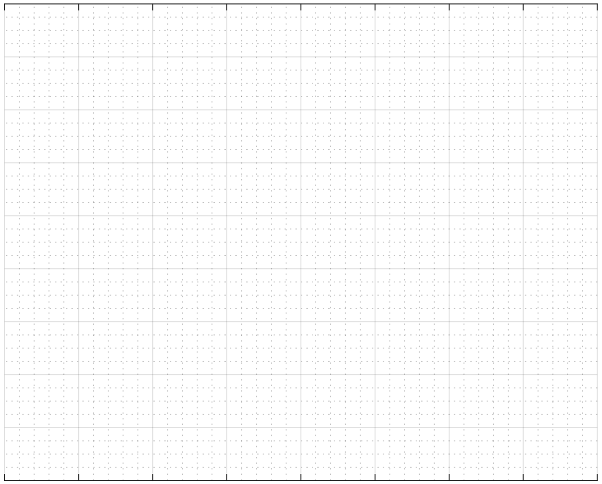


Simulating a Linear Value Model

- Pugh recommends suboptimal design at least 30% of the time

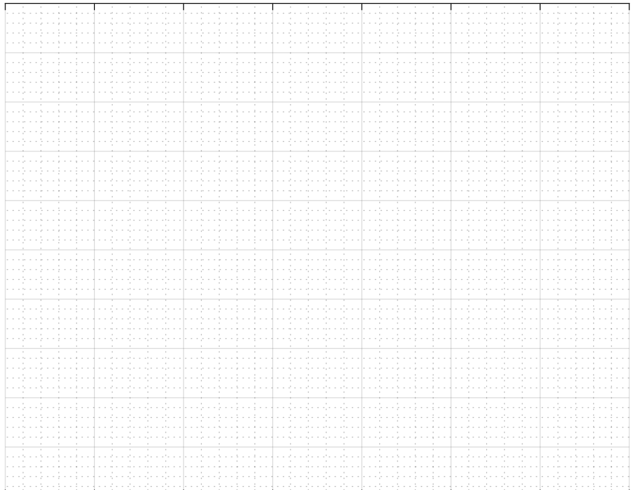
- Pugh can recommend the worst design

- Expected loss in utility is 5-10%
  - Linear, equally weighted value model is best case
  - No realistic set of attributes is linear



Unequally Weighted Attributes

One attribute 5x more important than others



One attribute 10x more important than others

Future Work

- Extend analysis methodology to non-linear value models
  - Common example: Cost-benefit ratio with discounting
- Analyze iteration in Pugh concept selection
- Use framework to evaluate QFD

Questions

- Thank you for your time and attention!
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References

1. Blanchard, Benjamin S., and W. J. Fabrycky, *Systems Engineering and Analysis* (New Jersey: Pearson Prentice Hall, 2011), pg. 49.
2. Kenneth Joseph Arrow, Social Choice and Individual Values (New York, NY: John Wiley and Sons, Inc., 1951).
3. George A. Hazelrigg, “The Implications of Arrow’s Impossibility Theorem on Approaches to Optimal Engineering Design”, Journal of Mechanical Design, Vol. 118 (1996): 161-164.
4. Stuart Pugh, “Concept Selection: A Method that Works”, Proceedings of the International Conference on Engineering Design (1981): 497-506.
5. Johannes F. Jacobs, Ibo van de Poel and Paricia Osswijer, “Clarifying the Debate on Selection Methods for Engineering: Arrow’s Impossibility Theorem, Design Performances and Information Basis”, Research in Engineering Design, vol. 25 (2014): 3-10.
6. Itzhak Gilboa, *Theory of Decision Under Uncertainty* (New York, NY: Cambridge University Press, 2009): pg. 51-64.
7. Martin Peterson, An Introduction to Decision Theory (New York, NY: Cambridge University Press, 2017).
8. R. Duncan Luce and Howard Raiffa, *Games and Decisions: Introduction and Critical Survey* (New York, NY: John Wiley and Sons, 1957)
9. Hazelrigg, George A., *Fundamentals of Decision Making: For Engineering Design and Systems Engineering* (Pearson Education, 2012).
10. Don Clausing, Total Quality Development: A Step-by-Step Guide to World Class Concurrent Engineering (New York, NY: ASME Press, 1994).
11. Thoman L. Saaty, *Group Decision Making: Drawing Out and Reconciling Differences* (Pittsburgh, PA: RWS Publications, 2008).
12. Donald G. Saari, Decisions and Elections: Explaining the Unexpected (New York, NY: Cambridge University Press, 2001).
13. Cox, Louis Anthony Jr., *Breakthroughs in Decision Analysis* (Hoboken, NJ: John Wiley and Sons, Inc., 2015).
14. Mark W. Maier and Eberhardt Rechtin, *The Art of Systems Architecting* (Boca Raton, FL: CRC Press, 2009).
15. Barry W. Boehm, Software Engineering Economics (Englewood Cliffs, NJ: Prentice-Hall Inc., 1981).
16. Henry Petroski, Invention by Design: How Engineers Get from Thought to Thing (Cambridge, MA: Harvard University Press, 1996).
17. Griffin, Michael, “How Do We Fix Systems Engineering?”, 61st International Astronautical Congress (2010)
18. National Aeronautics and Space Administration, *NASA Systems Engineering Handbook*, NASA/SP-2007-6105
19. Department of Defense, *Defense Acquisition Guidebook*, 2017