Assessing Modularity-in-Use in Engineering Systems

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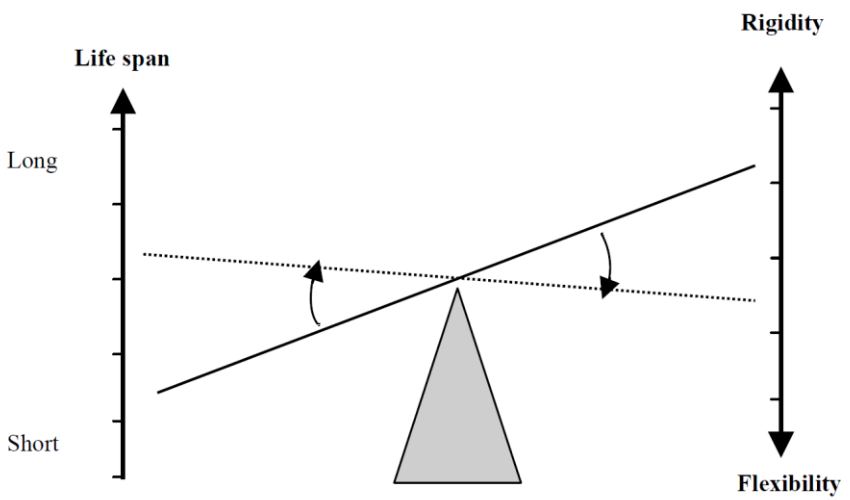
Modularity-in-Use

- Modularity-in-Use allows the **user** to reconfigure the system
- Distinct from Modularity-in-Design and Modularity-in-Manufacturing which benefit designers and producers
- Benefits to the user
  - **Flexibility**
  - Maintainability
  - Future cost savings
  - Increased lifespan
- Potential disadvantages
  - Higher initial cost
  - Reduced initial performance

Modular Products. Clockwise from top left: John Deere® Tractor, Izzy® Modular Office Furniture, Arleigh Burke Class Destroyer, Craftsman® Modular Power Tool Set.

System Flexibility

- Modularity-in-use provides system flexibility
- **Flexibility increases system lifespan**—environment changes but system remains useful
- As time progresses environmental uncertainty increases
  - Evolving threats
  - New deployment environments
  - Changing use cases
- Performance decreases in rigid systems as environment changes

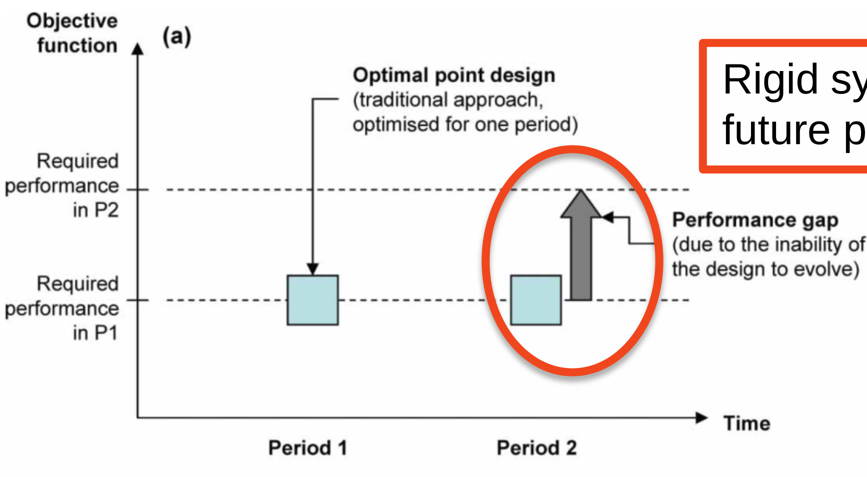


Relationship between flexibility and system lifespan. Credit: J.H. Saleh et al. (2002).

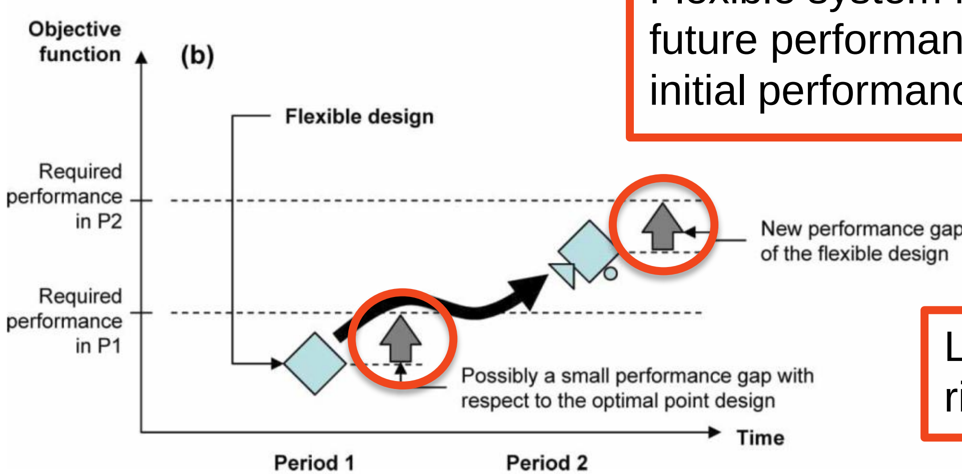
Challenge: assessing the value of increased flexibility due to Modularity-in-Use

Performance Risk Reduction

Performance Risk: the possibility of a future performance gap—quantified by future performance variance or probability of meeting required performance threshold.



Rigid system has high future performance risk



Flexible system has low future performance risk but initial performance tradeoff

Lower future performance risk results in longer lifespan

Difference in performance over time in rigid vs flexible system. Credit: Saleh et al. (2009).

Flexibility Assessment Process

Identify Environment / Use Parameters
- Elements beyond control
- Potentially probabilistic

Define System Architecture
- Elements within designer's control
- May change with modular reconfiguration

Model System Performance
- Measure one or more Key Performance Parameters
- Modeled modular system reconfigures

Performance Metric e.g. P(kill)

Repeat for All Design Options

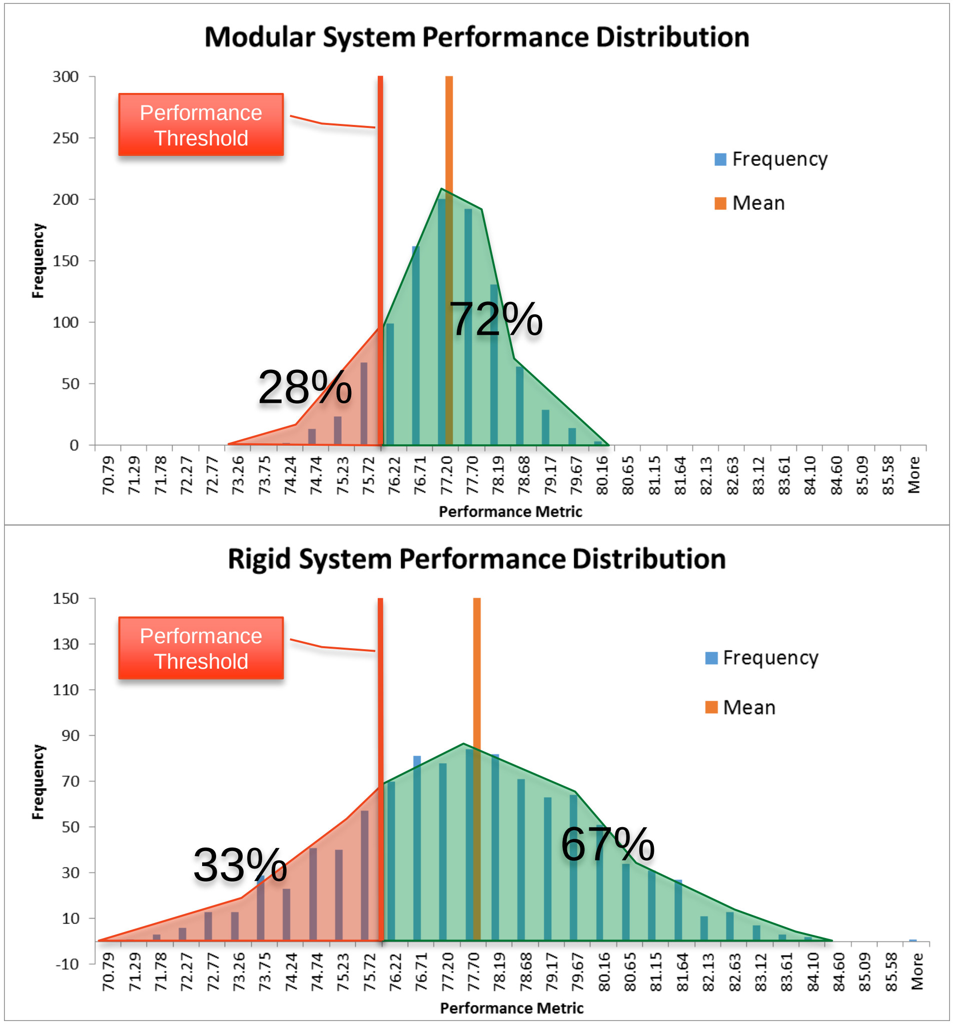
Simulate Future Uncertainty
- Monte Carlo simulation
- Future environment / use parameters probabilistic
- Model of modular system adapts with changing parameters to maximize performance

Measure Flexibility
- Future performance risk quantified by negative performance variance
- Assess differences in mean design performance & negative performance risk
- Examine performance in specific futures

Assessing future performance risk reduction due to system flexibility under uncertainty

Flexibility Measurement

- Risk quantified by performance variance
- Calculate probability system will meet performance threshold
- Distribution average represents expected value of performance
- Example scenario: rigid system has higher average performance but greater variance
- Example performance threshold: 76
- Modular system has 72% probability of meeting or exceeding threshold
- Rigid system has 67% probability
- 5% lower than modular system despite higher average performance
- Test performance under specific future scenarios



Two Hypothetical Systems Compared: example tradeoff between expected performance and variance.

Modularity-in-Use Case Study

- Objective: provide decision maker greater insight into how each design performs in uncertain future
- Product: modular water bottles with solid food storage containers
- Performance Model: Multi-Attribute Decision Matrix
- Use Parameters: user's weights of product attributes
    - Liquid capacity
    - Solid Capacity
    - Weight
    - Pill Tray
    - Cost
- Performance Metric: single utility score
- Four products evaluated
    - Small, medium, and large rigid bottles
    - Modular bottle

Case Study Performance Model

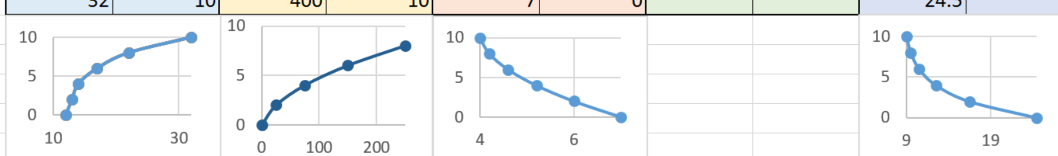
Identify Environment / Use Parameters
- Elements beyond control
- Potentially probabilistic

Define System Architecture
- Elements within designer's control
- May change with modular reconfiguration

Model System Performance
- Measure one or more Key Performance Parameters
- Modeled modular system reconfigures

- Environment / Use Parameters defined as user's perceived importance of product attributes
- System Architecture defined by physical attributes of the product
- Utility score calculated based on attribute weights and raw attribute data
- Relationships between attribute weights, raw data, and utility defined a priori

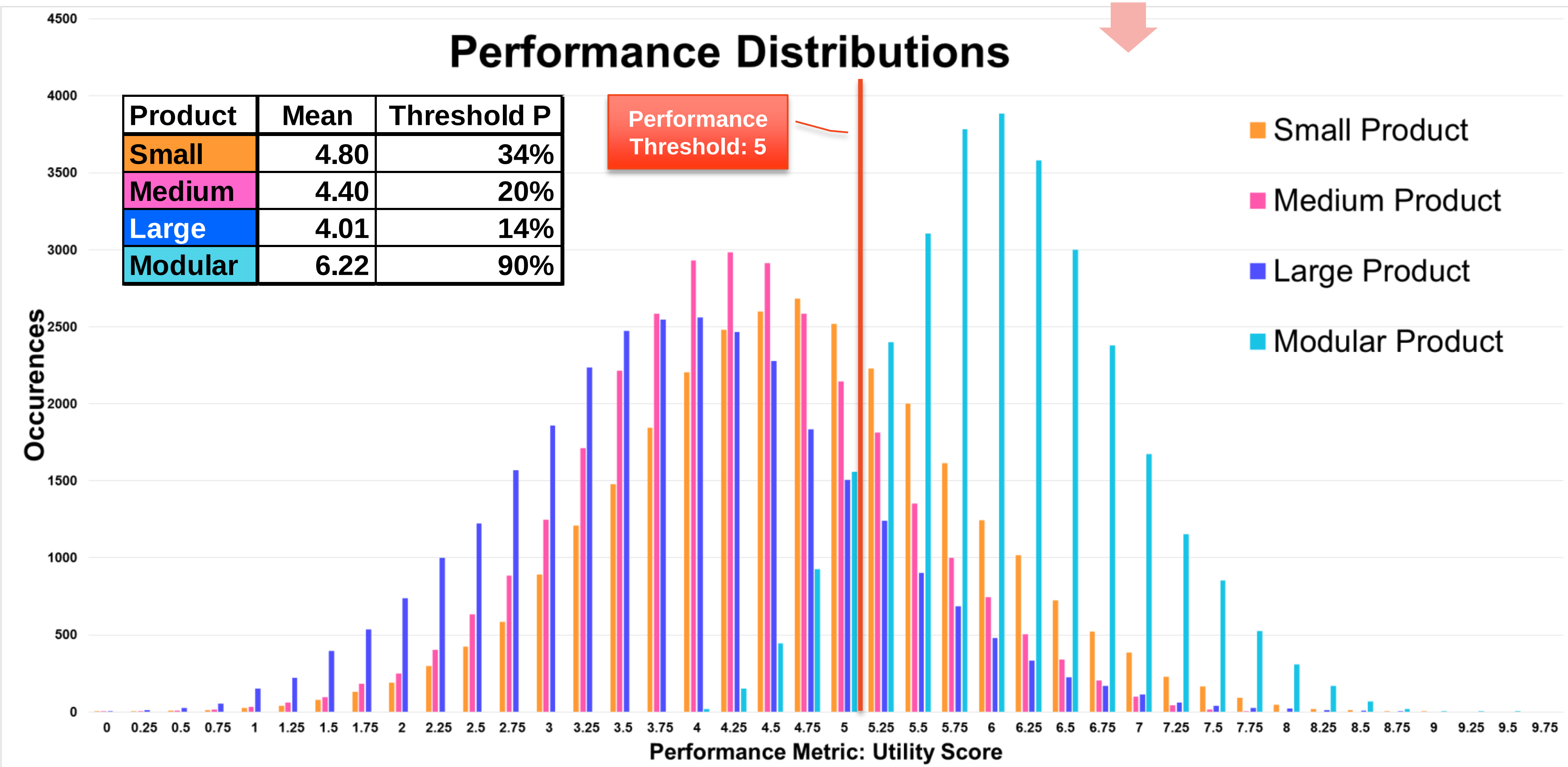
Weight	50		50		50		50		50	
	Liquid Capacity		Solid Capacity		Weight		Pill Tray		Cost	
	Oz	Scale	cc	Scale	oz	Scale	Y/N	Scale	$	Scale
	x	v(x)	x	v(x)	x	v(x)	x	v(x)	x	v(x)
	12	0	0	0	4	10	0	0	9	10
	13	2	25	2	4.2	8	1	10	9.5	8
	14	4	75	4	4.6	6			10.5	6
	17	6	150	6	5.2	4			12.5	4
	22	8	250	8	6	2			16.5	2
	32	10	400	10	7	0			24.5	0



Attributes, relative weight, and relationships between each attribute and utility normalized from 0 to 10.

Simulation of Uncertainty

Weights defined by uniform random variables → 30,000 future scenarios simulated → Modular product reconfigured in each trial to maximize utility → Performance data collected → Specific future scenarios evaluated



Product	Mean	Threshold P
Small	4.80	34%
Medium	4.40	20%
Large	4.01	14%
Modular	6.22	90%

Simulation output. The modular product dominates in terms of both mean performance and probability of meeting the performance threshold

Sensitivity Analysis

- User can compare performance under different future scenarios
- Modular product dominated on average
- Small product may still be desirable if Cost and Weight become relatively more important in the future
- Choose the Small product if this is a concern

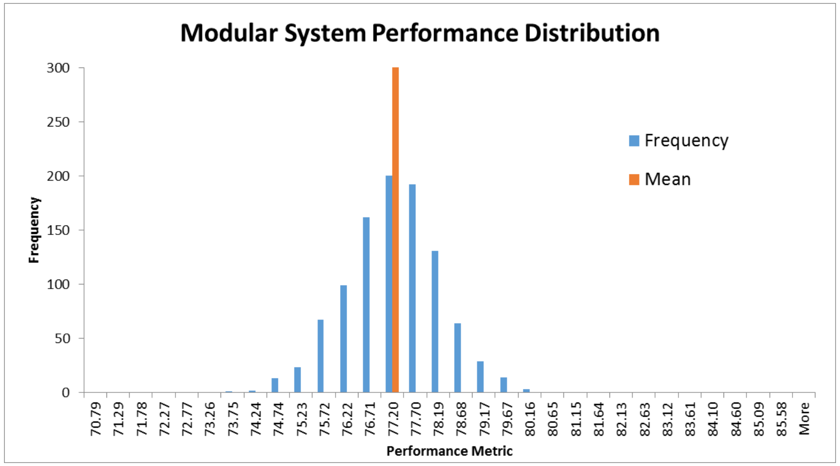
Modular vs. Small - When is Modular Better?												
		Cost										
	0	0	10	20	30	40	50	60	70	80	90	100
Weight	0	1	1	1	1	1	1	1	1	1	1	1
	10	1	1	1	1	1	1	1	1	1	1	1
	20	1	1	1	1	1	1	1	1	1	1	1
	30	1	1	1	1	1	1	1	1	1	1	1
	40	1	1	1	1	1	1	1	1	1	1	1
	50	1	1	1	1	1	1	1	1	1	1	0
	60	1	1	1	1	1	1	1	1	1	0	0
	70	1	1	1	1	1	1	1	1	0	0	0
	80	1	1	1	1	1	1	1	0	0	0	0
	90	1	1	1	1	1	1	0	0	0	0	0
	100	1	1	1	1	1	0	0	0	0	0	0

Analysis conducted by altering Cost and Weight attribute weights while holding others constant. The Small product outperforms the Modular product when both are relatively more important.

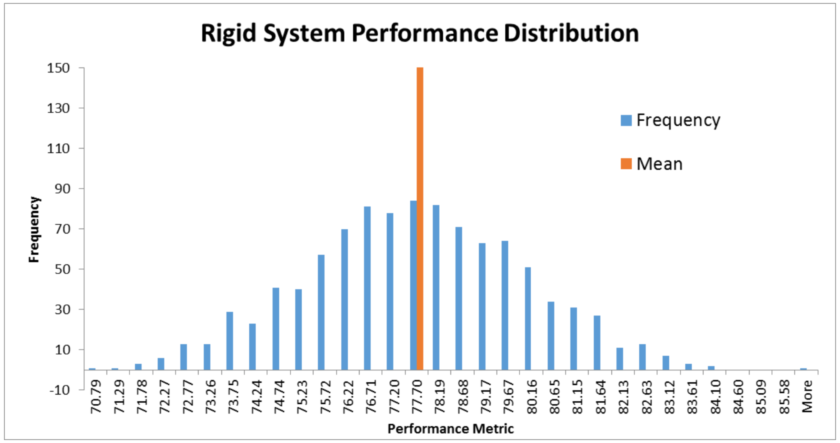
Summary

- Benefits of modularity can be assessed by measuring performance risk
- Performance risk measured through simulation of system performance under uncertainty
- Minimizing performance risk results in longer system lifespan
  - Better equipped force
  - Future cost savings

Flexibility granted by Modularity-in-Use can be assessed by measuring future performance risk to the user



Lower performance risk in modular system
⇒ Longer system lifespan



Higher average performance in rigid system but higher performance risk
⇒ Shorter system lifespan