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A Value-Centric Tradespace Approach to Target System Modularization

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University of Virginia | ENGINEERING

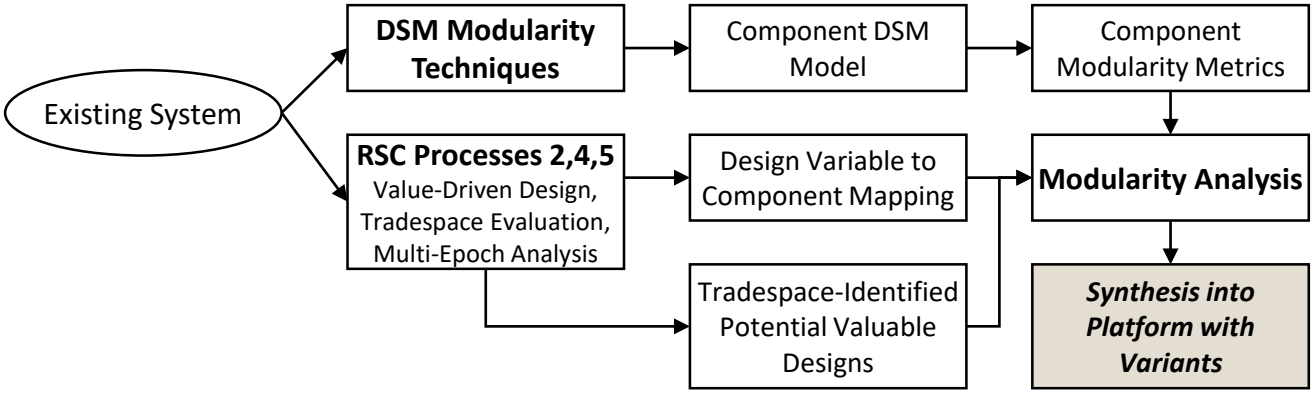
Design for Modularity?

Modularity is "a measure of the lack of technical interface connectivity between components of a system." (Sosa 2007)

- In a world of uncertainty and change, we may need changeable systems
- Modularity is often espoused as THE solution for achieving changeable systems
- But, modularity comes at a cost, and HOW and WHERE modularity is implemented matters
- Potential Benefits
  - Increasing overall economic value; aiding system flexibility and evolvability; increasing product variety; aid complexity management; mitigate uncertainties
- Potential Challenges
  - For high energy density systems: increases weight; increases cost; may result in lower performance
  - If weight, cost, and performance impact value, then *modularity might decrease value*

How can we *design for modularity* so that we can predictably *increase* value of our systems?

Approach



- Various techniques exist to address parts of "design for modularity"
- Intending to leverage two prior sets of techniques
  - Responsive Systems Comparison (RSC) – a tradespace-oriented technique for exploring potential value-driving designs
  - Dependency Structure Matrices (DSM) – a component matrix-oriented technique that can be analyzed using graph measures
- Combined, may offer structured and quantitative basis for identifying valuable modularity efforts
- Demonstrate on case study as proof of concept

Introduction to Case Study

The LifeTrac Tool

- Designed for 2 functions
  - Skid steer
    - Push, lift, and move material around a work site
  - Agricultural tractor
    - Provide tractive energy for pulling agricultural implements, such as tillage or seeding equipment, through a field
- Existing system
- Relatively simple design (n=47 elements, i=218 interactions)
- Design and costing info under open source license

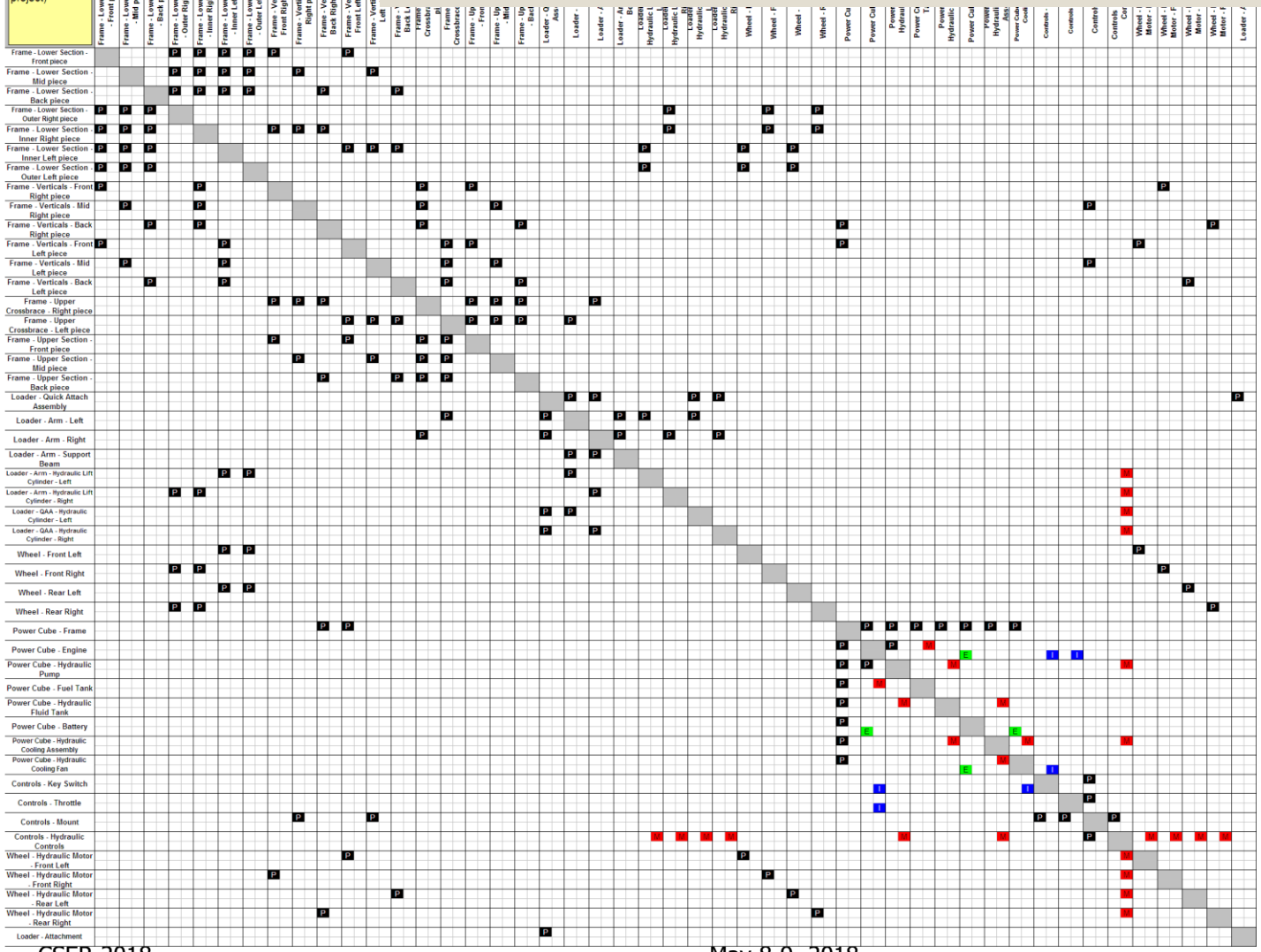
(Open-Ecology-Project, http://opensourceecology.org/wiki/LifeTrac)

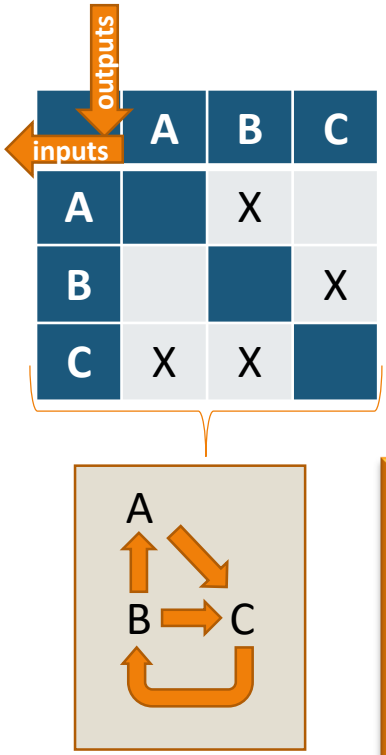
DSM Modularity Techniques

Constructing the DSM

Decompose existing system design into components and interactions

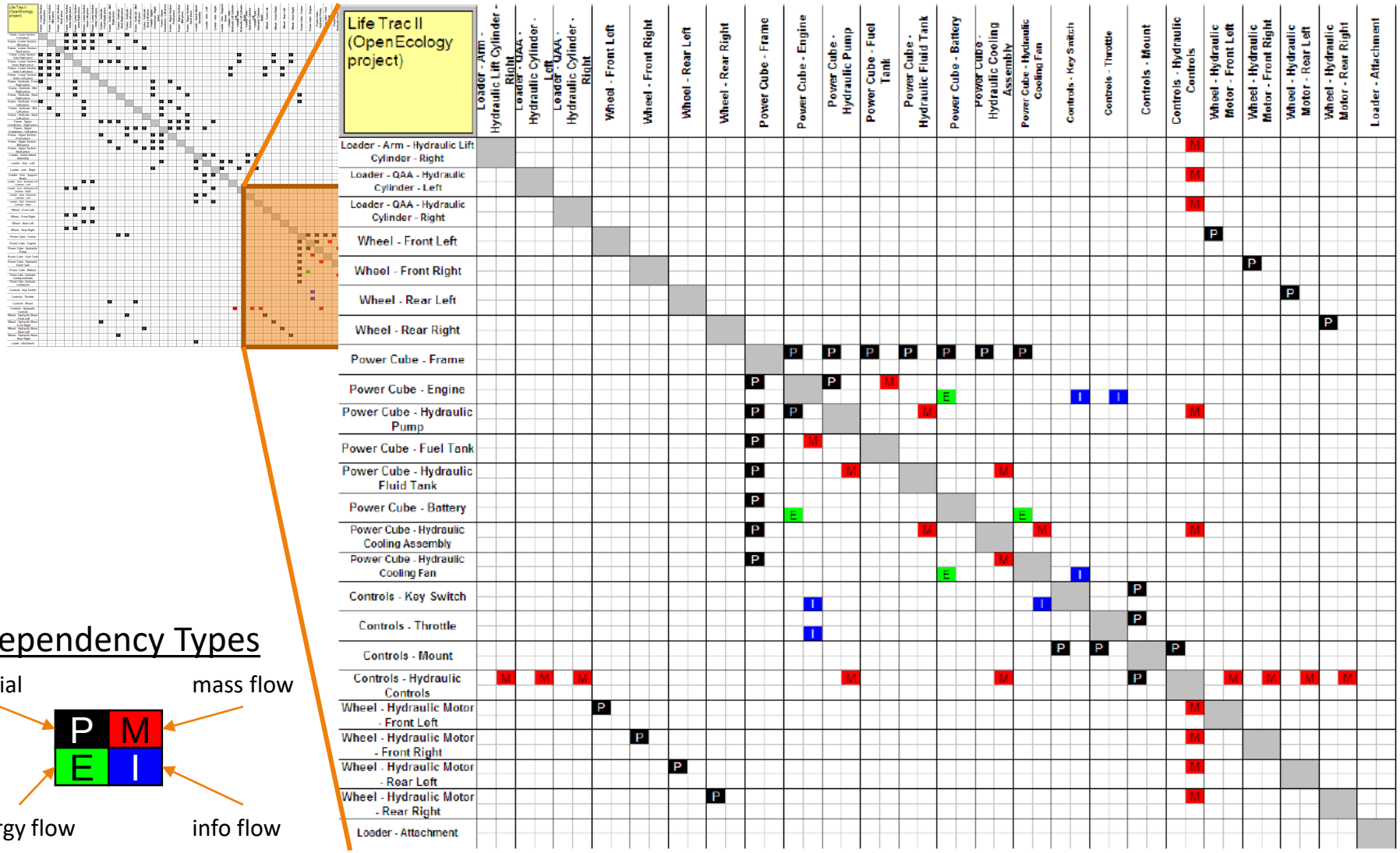
Life Trac II (OpenEcology project)



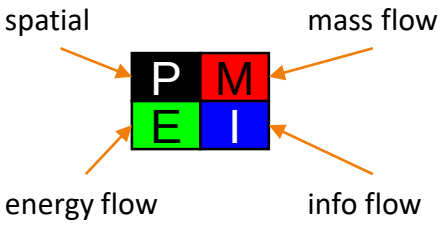


DSM Modularity Techniques

Constructing the DSM (2)



Dependency Types



DSM Modularity Techniques
Calculating Modularity Metrics

Graph-based metrics can be used to screen through DSM space for "modular" points

Connectedness

Degree modularity for component i

$$M(D)_i = 1 - \frac{D_i}{n-1}$$

Distance from other components

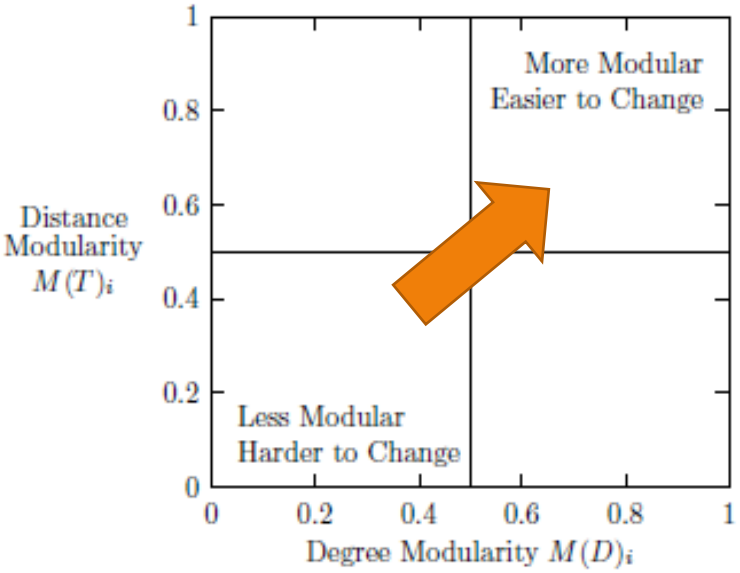
Distance modularity for component i

$$M(T)_i = \frac{T_i}{n(n-1)}$$

n = number of components
D_i = Freeman degree for component i
T_i = Freeman farness for component i

Sosa 2007

- Quantitative means for identifying components that are:
  - "easy" to separate from other components
  - Have fewer linkages to other components
- Other modularity metrics may be appropriate as well



Value-Driven Tradespace E&A

Defining Values for Success

2 Main User Types

	Construction	Agriculture
2 Different Contexts (each)	1. Demanding needs 2. Balanced needs	3. Row spacing 24” 4. Row spacing 30”
LifeTrac “Concept”:	*needs a “skid steer”*	*needs a “tractor”*

Identify *attributes* as value criteria to determine successful system for each user type

	Attribute	Measurement	Units	U = 0 (Least acceptable)	U = 1 (Most desirable)	Epoch 1	Epoch 2	Epoch 3	Epoch 4
Construction	Material capacity	Maximum load	pounds	1200	2000	0.0	0.5		
	Maneuverability	Vehicle width	inches	96	72	0.0	0.2		
	Lifting capacity	Breakout force	pounds	1500	2500	0.0	0.3		
Agriculture	Efficiency	Work rate	acres/hr	2	6			1	1
	Row spacing	<constraint>	inches	n/a	n/a			24	30

An ***epoch*** is a time period of fixed context and needs

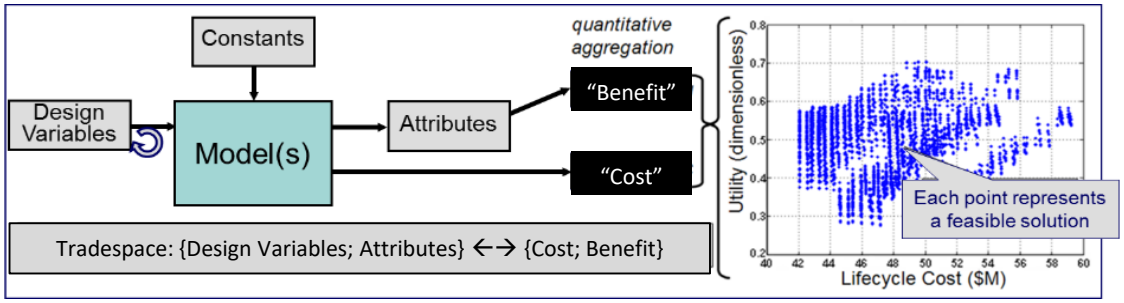
Value-Driven Tradespace E&A

Enumerating and Generating Tradespaces

Propose factors in your control that DRIVE value attributes

Design Vector		Attributes				
Variable	**Range**	**Material capacity**	**Maneuver ability**	**Lifting capacity**	**Efficiency**	**Row spacing**
Bucket width	[56-84] inches	X	X			
Available hydraulic power	[4-40] HP	X		X		
Engine power	[4-40] HP				X	
Vehicle width	72,90 inches					X

Use models to generate **data** to explore relationships

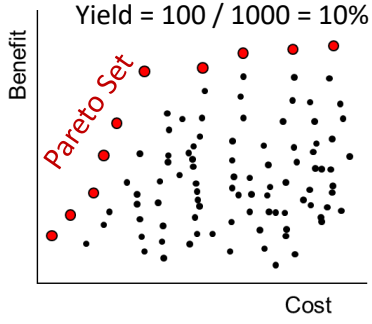


Value-Driven Tradespace E&A

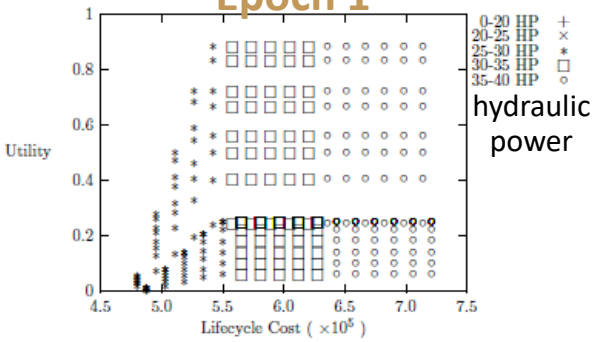
Exploring Tradespaces

Tradespace	Feasible Designs	Acceptable Designs U(X) ≥ 0
Skid steer, full soln. (epoch 1)	592	256
Skid steer, partial soln. (epoch 2)	592	256
Tractor, 30 in (epoch 3)	296	256
Tractor, 24 in (epoch 4)	296	272

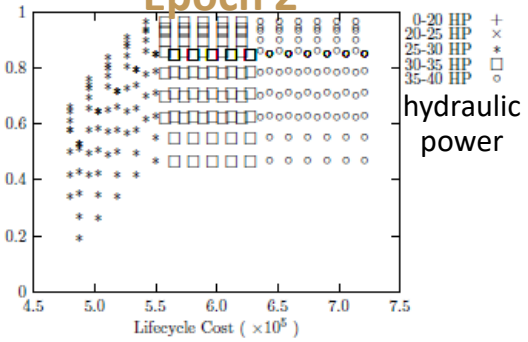
Tradespace Concept



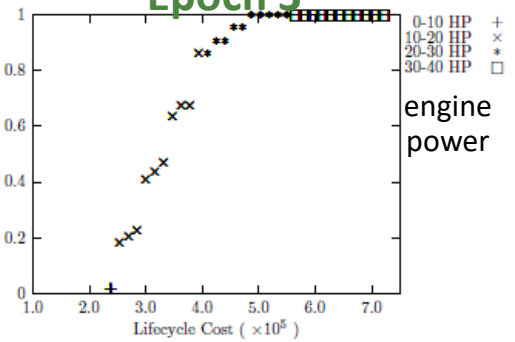
Epoch 1



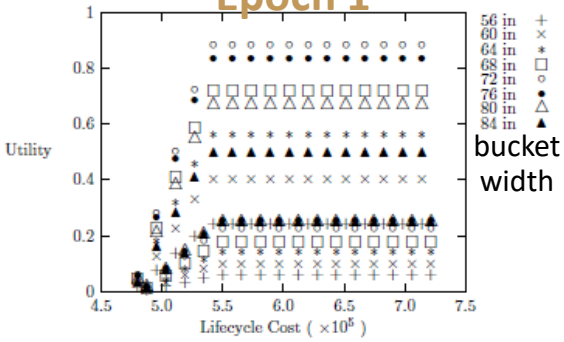
Epoch 2



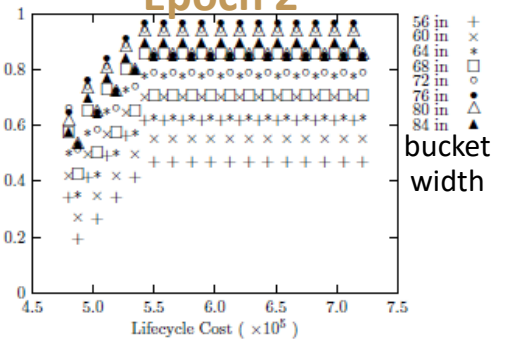
Epoch 3



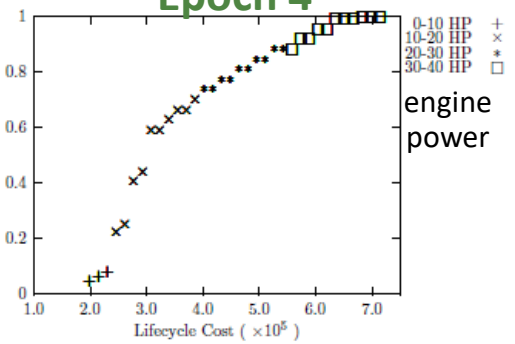
Epoch 1



Epoch 2

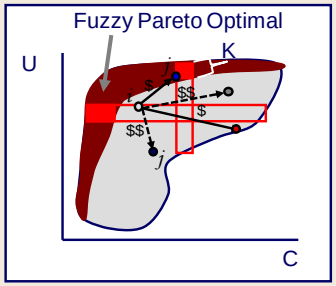


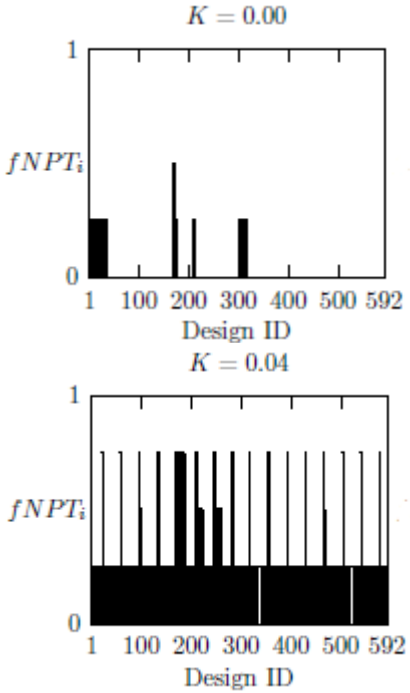
Epoch 4



Value-Driven Tradespace E&A
Analyzing Across Epochs

Tradespace Concept





fNPT is the fuzzy Normalized Pareto Trace

Design ID	Fuzzy Pareto Number	Hydraulic / Engine Power (HP)	Vehicle Width (in)	Bucket Width (in)
22	0.01	25	72	56
59	0.01	25	72	60
96	0.01	25	72	64
133	0.01	25	72	68
134	0.01	26	72	68
135	0.04	27	72	68
136	0.04	28	72	68
170	0.01	25	72	72
171	0.01	26	72	72
172	0.01	27	72	72
173	0.01	28	72	72
174	0.01	29	72	72
175	0.04	30	72	72
176	0.04	31	72	72
177	0.04	32	72	72
178	0.04	33	72	72
179	0.04	34	72	72
180	0.04	35	72	72
181	0.04	36	72	72
182	0.04	37	72	72
183	0.04	38	72	72
184	0.04	39	72	72
185	0.04	40	72	72
207	0.01	25	72	76
208	0.01	26	72	76
209	0.01	27	72	76
210	0.01	28	72	76
211	0.01	29	72	76
244	0.01	25	72	80
245	0.01	26	72	80
246	0.01	27	72	80
247	0.01	28	72	80
281	0.01	25	72	84
282	0.01	26	72	84
283	0.01	27	72	84
318	0.04	25	90	56
355	0.04	25	90	60
392	0.04	25	90	64
429	0.04	25	90	68
466	0.04	25	90	72
503	0.04	25	90	76
504	0.04	26	90	76
540	0.04	25	90	80
541	0.04	26	90	80
577	0.04	25	90	84
578	0.04	26	90	84
Min		25	72	56
Max		40	90	84
Variance		18.4	60.3	48.5

Use tradespace metrics to identify “good” designs across epochs

Used to find *passively robust solutions*, upon which we will seek to add *active responses* (via modularity) to improve net attractiveness of solutions

Connecting Tradespace Analysis back to DSM Analysis

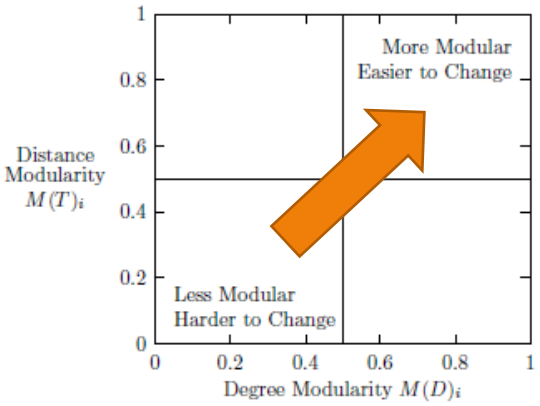
Associate DSM ***components*** with ***design variables***

		Design Variable			
		Skid Steer		Tractor	
i	Determined Component	Bucket Width	Hydraulic Power	Vehicle Width	Engine Power
1	Frame - Lower Section - Front piece			X	
2	Frame - Lower Section - Mid piece			X	
3	Frame - Lower Section - Back piece			X	
20	Loader - Arm - Left		X		
21	Loader - Arm - Right		X		
23	Loader - Arm - Hydr. Lift Cyl. - Left		X		
24	Loader - Arm - Hydr. Lift Cyl. - Right		X		
25	Loader - QAA - Hydr. Cyl. - Left		X		
26	Loader - QAA - Hydr. Cyl. - Right		X		
32	Power Cube - Engine		X		X
33	Power Cube - Hydr. Pump		X		X
42	Controls - Hydr. Controls		X		X
43	Wheel - Hydr. Motor - Front Left				X
44	Wheel - Hydr. Motor - Front Right				X
45	Wheel - Hydr. Motor - Rear Left				X
46	Wheel - Hydr. Motor - Rear Right				X
47	Loader - Attachment	X			

This table will allow us to **link design variables of interest** (i.e. those that we may want to *CHANGE* to maintain high Pareto Trace) **to DSM components**, which we can analyze in terms of potential modularity

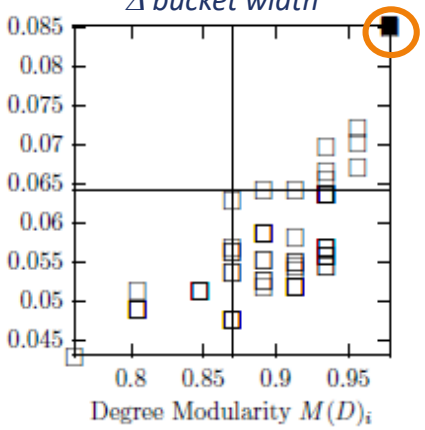
Modularity Analysis

Highlight ***selected components*** associated with design variables to see degree of modularity



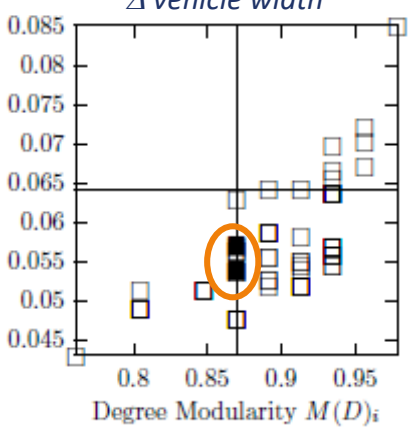
Attachment Module

Δ bucket width



Frame Modules

Δ vehicle width



Attachment module is "easy" so can execute during ***production or use***

Frame module is "hard" so can execute during ***production only***

All components
Selected components

Transition rules (using these modules) connect designs into a ***tradespace network***

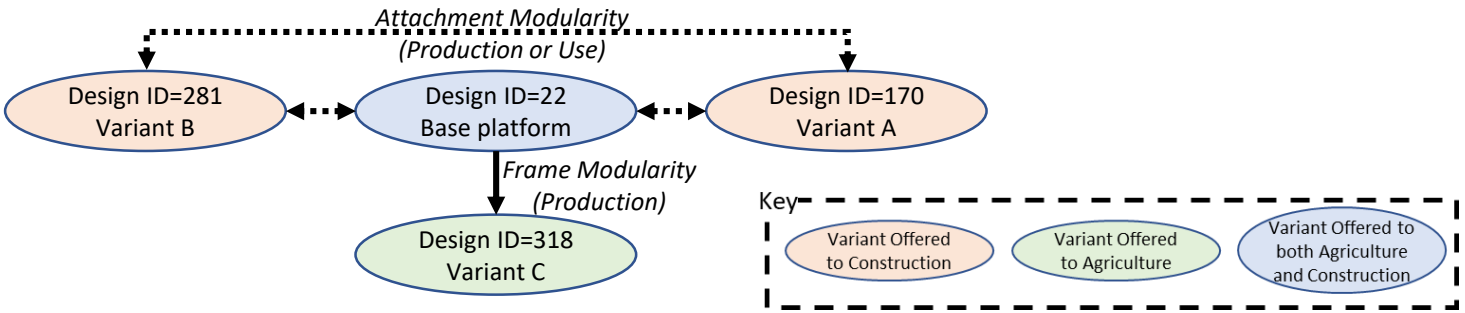
Design ID	Hydraulic/Engine Power (HP)	Vehicle Width (in)	Bucket Width (in)	Reachable Via	Reachable Phase
22	25	72	56	Baseline	
170	25	72	72	Attachment Module	Production or Use
281	25	72	84	Attachment Module	Production or Use
318	25	90	56	Frame Modules	Production only
466	25	90	72	Attachment and Frame Modules	Production or Use
577	25	90	84	Attachment and Frame Modules	Production or Use

Synthesis into Platform with Variants

				Construction		
Design ID	Hydraulic/Engine Power (HP)	Vehicle Width (in)	Bucket Width (in)	Epoch 1	Epoch 2	Product Offering
577	25	90	84	0.079	0.645	
170	25	72	72	0.060	0.662	Best ✓
281	25	72	84	0.031	0.579	Better ✓
22	25	72	56	0.016	0.341	Good ✓
466	25	90	72	0.015	0.512	
318	25	90	56	0.004	0.191	

			Agriculture		
Design ID	Hydraulic/Engine Power (HP)	Vehicle Width (in)	Epoch 3	Epoch 4	Product Offering
22, 170, 281	25	72	unacceptable	0.809091 ✓	Yes, all three
318, 466, 577	25	90	1 ✓	unacceptable	Just 318

Select a subset of designs that are ***reachable via modularity*** to define a ***platform*** with variants



Discussion

- Through a case study, it was shown how the RSC framework could be used to indicate which design variables could change as a result of different use scenarios and preference sets and how to trace those changing design variables to the affected system components.
- This tracing was then combined with network centrality measures of component modularity to indicate to what degree those components supported modular changeability to achieve the different desired levels of design variables.
- The output from this can then be used to focus the modularity efforts of system designers.
- While only qualitatively considered, a connection was made between component modularity and system path enablers and transitions paths.
- The approach showed that a structured means for leveraging tradespaces with DSM-based analyses can help to develop a product strategy that incorporates both passive and active means for achieving value across users and contexts.

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Thank you for your attention!

Questions?

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