28th Annual INCOSE international symposium
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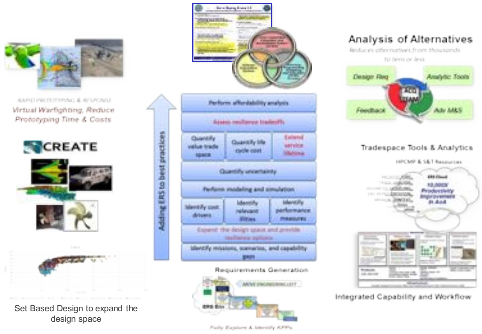
A UAV Case Study with Set Based Design

Colin Small, Dr. Greg Parnell, Dr. Simon Goerger, Dr. Ed Pohl, Dr. Matthew Cilli, Eric Specking, Zephan Wade

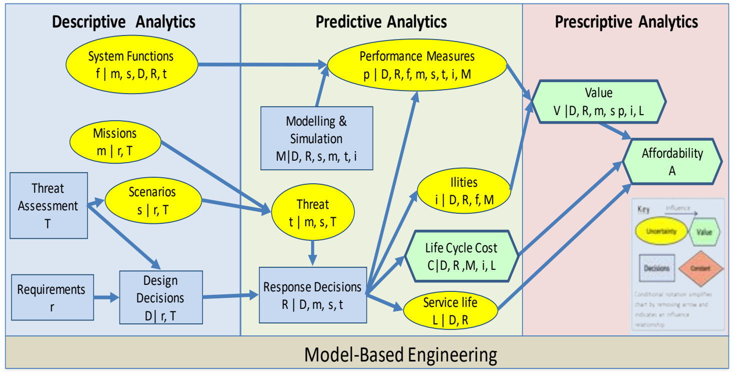
Bottom Line Up Front

This research provides a case study using ERS/ARDEC UAV data that demonstrates the potential of Set-Based Design trade-off analytics in system decision making for Engineered Resilient Systems.

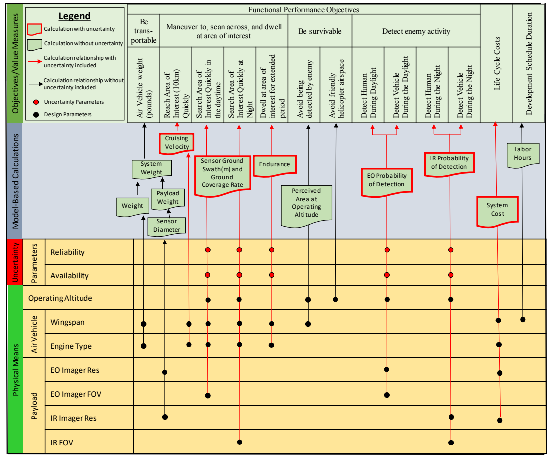
Incorporating ERS into AoAs



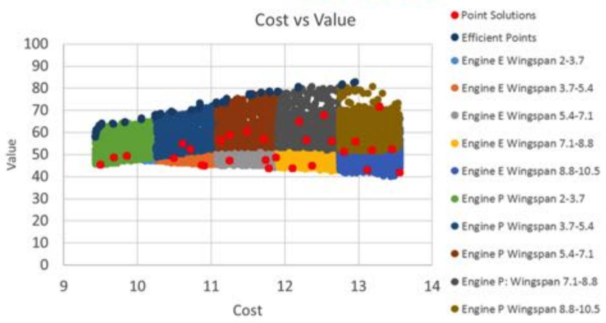
Trade-off Analytics Framework



Implementing Trade-off analytics framework and SBD in UAV Tradespace Tool



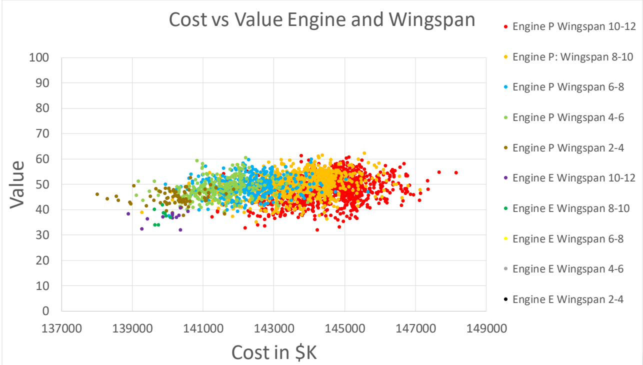
PBD vs. SBD



Small, C., Buchanan, R., Cilli, M., Parnell, G., Pohl, E., Wade, Z., "A UAV Case Study with Set-based Design," 28th Annual INCOSE International Symposium, 7-12 July 2018, Washington, DC.

Perfect Options

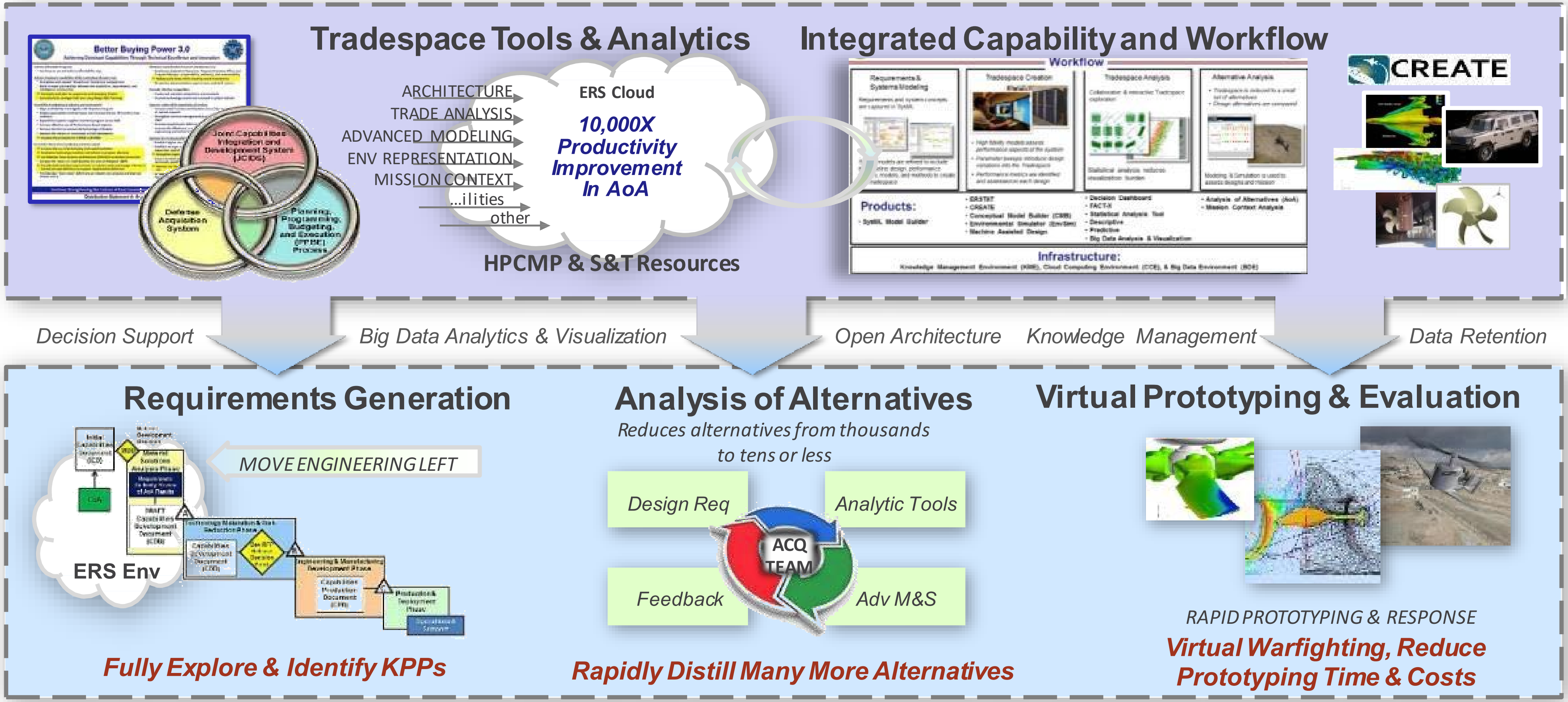
Effects of uncertainty on SBD



Overview

- Introduction
  - ERS
  - Trade-off Analytics Framework
  - Set Based Design
- Initial UAV Case Study
- UAV Tradespace Tool
  - Base model
  - Perfect Options
  - Uncertainty
- Conclusions
- Future Research

Engineered Resilient Systems (ERS)



Holland, J. P. (2015). Engineered Resilient Systems: Power of Advanced Modeling and Analytics in Support of Acquisition. NDIA 16th Science and Engineering Technology Conference. Springfield, VA.

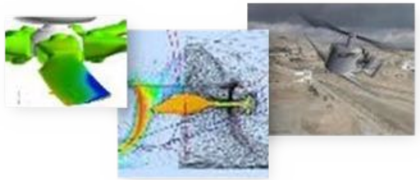
Engineered Resilient Systems (ERS) is a Department of Defense (DoD) Program focusing on the effective and efficient design of complex engineered systems. This thesis is funded by the ERS program.

An Engineered Resilient System

- "A resilient engineered system is able to successfully complete its planned mission(s) in the face of a disruption (environmental or adversarial), and has capabilities allowing it to successfully complete future missions with evolving threats"

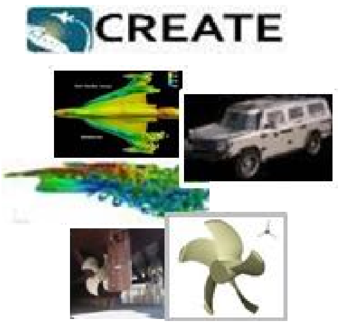
Specking, E., Cilli, M., Parnell, G., Wade, Z., Cottam, B., & Small, C. (2017). *Tech Report: Graphical Representaiton of Resilient Engineered Systems.*

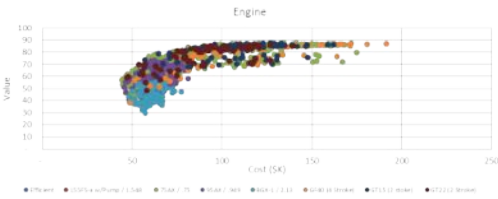
Model Based Systems Engineering



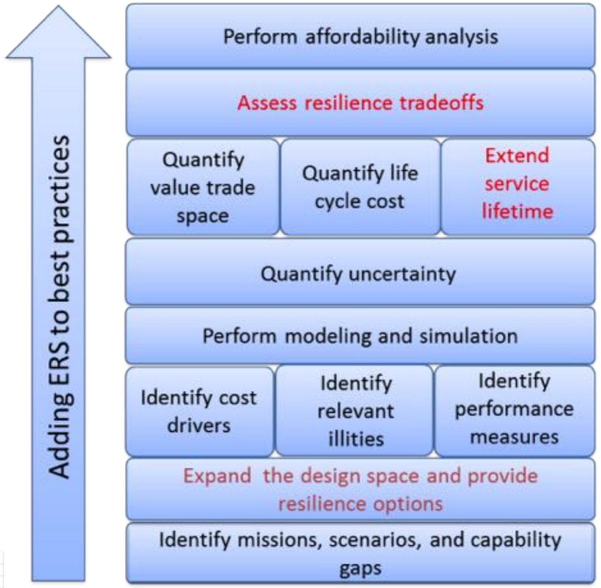
RAPID PROTOTYPING & RESPONSE

Virtual Warfighting, Reduce Prototyping Time & Costs

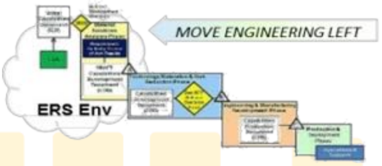




Set Based Design to expand the design space



Requirements Generation



Fully Explore & Identify KPPs

Analysis of Alternatives

Reduces alternatives from thousands to tens or less

Tradespace Tools & Analytics

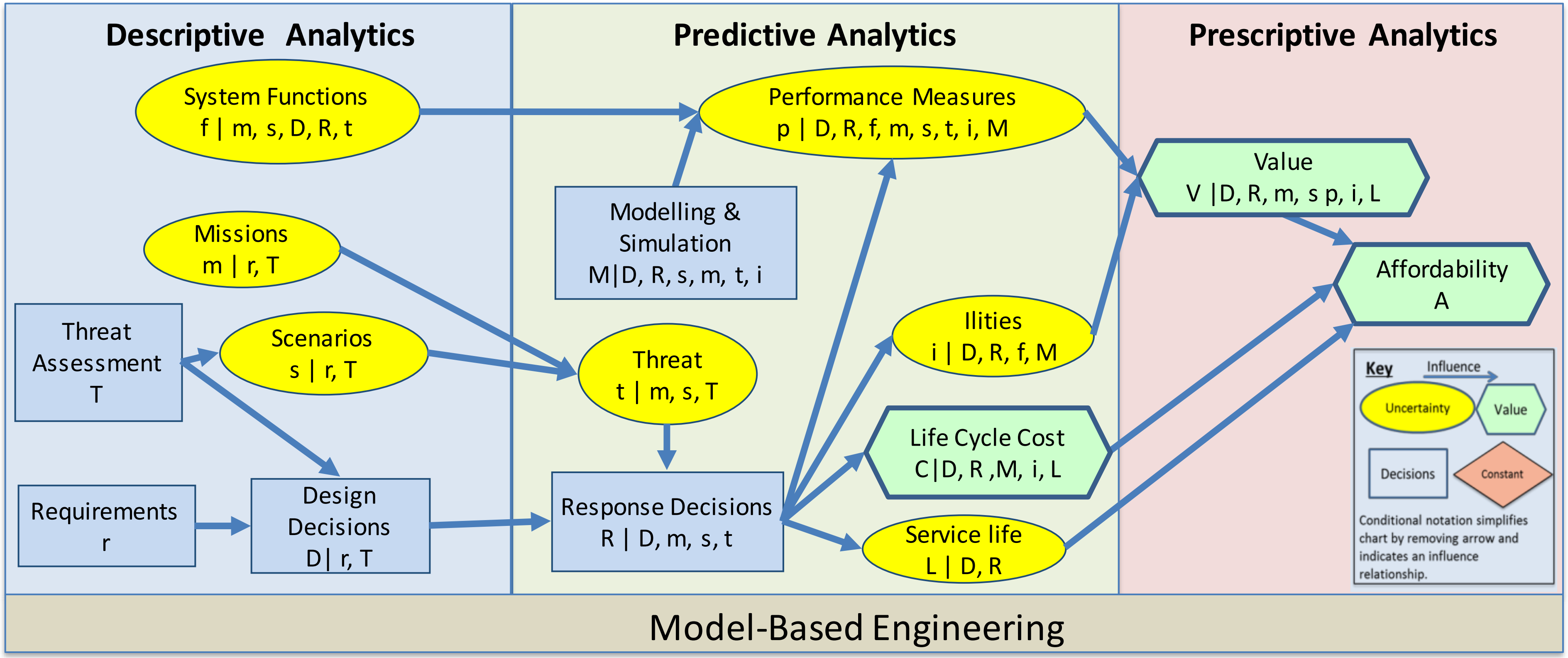
HPCMP & S&T Resources

Integrated Capability and Workflow

Small, C., Parnell, G., Pohl, E., Goerger, S., Cottam, C., Specking, E., Wade, Z., (2018) Engineering Resilience for Complex Systems. In: Madni A., Boehm B., Ghanem R., Erwin D., Wheaton M. (eds) Disciplinary Convergence in Systems Engineering Research. Springer, Cham, pp. 3-15

The DoD and ERS seek to leverage the capabilities of model based engineering and set based design to improve decision making in AoAs.

Integrated Trade-off Analytics Framework

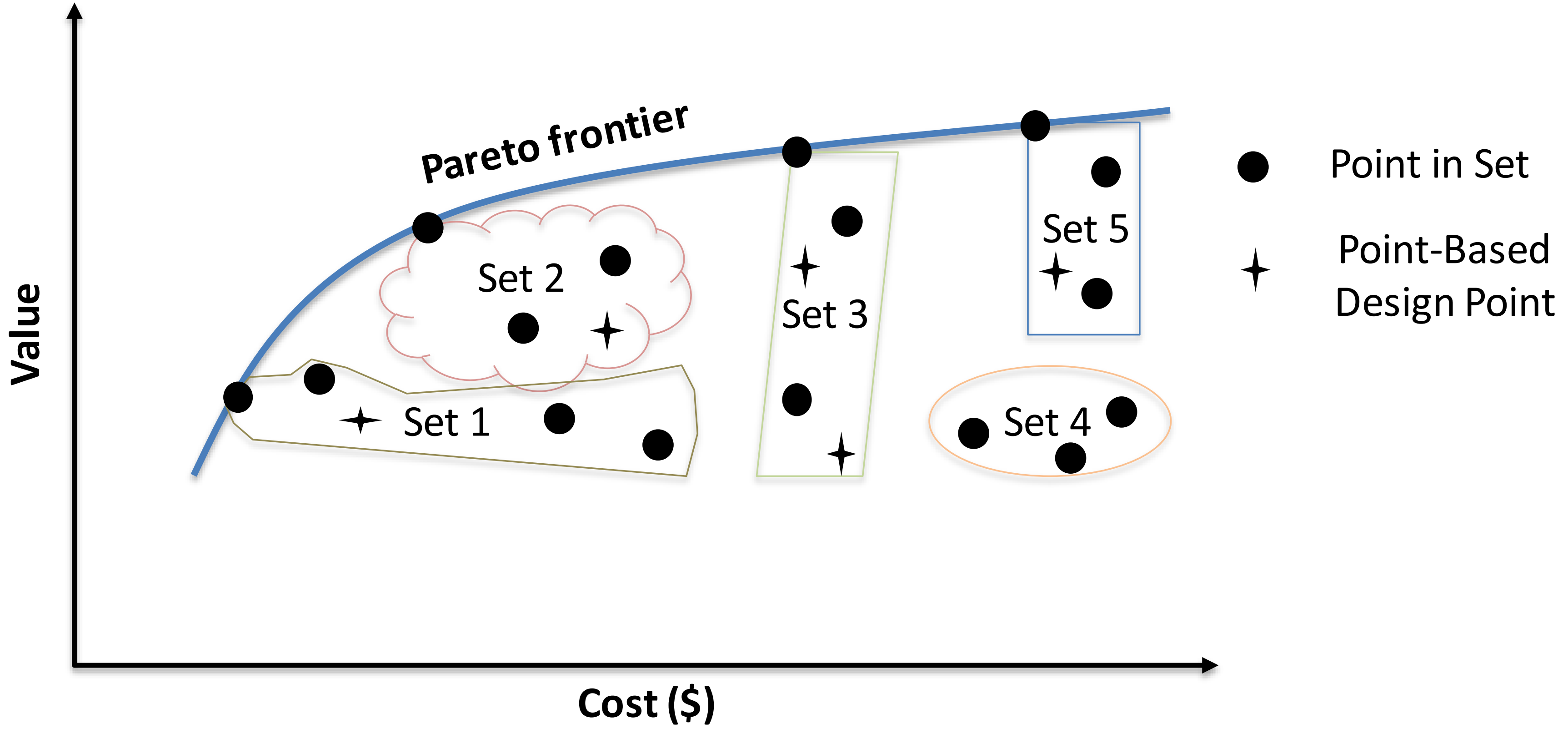


Modified from MacCalman, Alexander D., Gregory S. Parnell and Sam Savage. "An Integrated Model for Trade-off Analysis." Parnell, Gregory S. Trade-off Analytics: Creating and Exploring the System Tradespace. Wiley, 2016

Small, C., Parnell, G., Pohl, E., Goerger, S., Cottam, C., Specking, E., Wade, Z., (2018) Engineering Resilience for Complex Systems. In: Madni A., Boehm B., Ghanem R., Erwin D., Wheaton M. (eds) Disciplinary Convergence in Systems Engineering Research. Springer, Cham, pp. 3-15

Trade-off analytics requires descriptive, predictive, and prescriptive analytics using Model Based Engineering.

Set-Based Design



Wade, Z., Parnell, G., Goerger, S., Pohl, E., Specking, E. “Designing Engineered Resilient Systems Using Set-Based Design” 16th Annual Conference on Systems Engineering Research, Charlottesville, Virginia, May 8-9, 2018

Set-based design allows for further exploration of the design space over point-based design.

Set Drivers and Modifier

- In set based design, design decisions are split into two categories.
  - Set Drivers
  - Set Modifiers
- The sets in Set-Based design are determined by the set drivers.

Small, C., Parnell, G. S., Buchanan, R., Cilli, M., Pohl, E., Goerger, S., & Wade, Z. (2018). A UAV Case Study with Set-Based Design. *28th Annual INCOSE International Symposiu.* Washington,DC: International Council on System Engineering.

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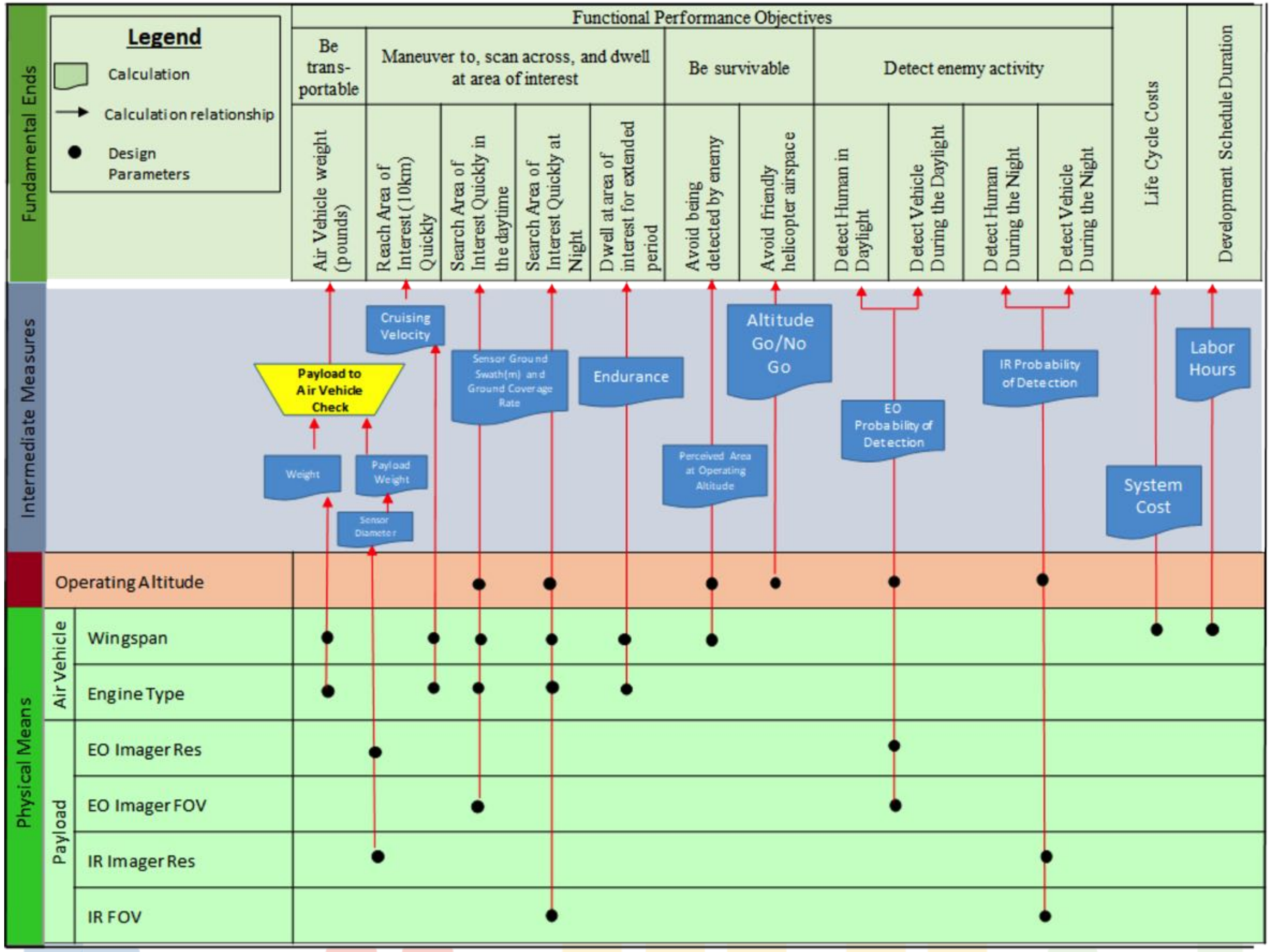
UAV Case Study



Cilli, Matthew. "Decision Framework Approach Using the Integrated Systems Engineering Decision Management (ISEDM) Process." *Model Center Engineering Workshop, Systems Engineering Research Center (SERC)*. 31 July 2017.

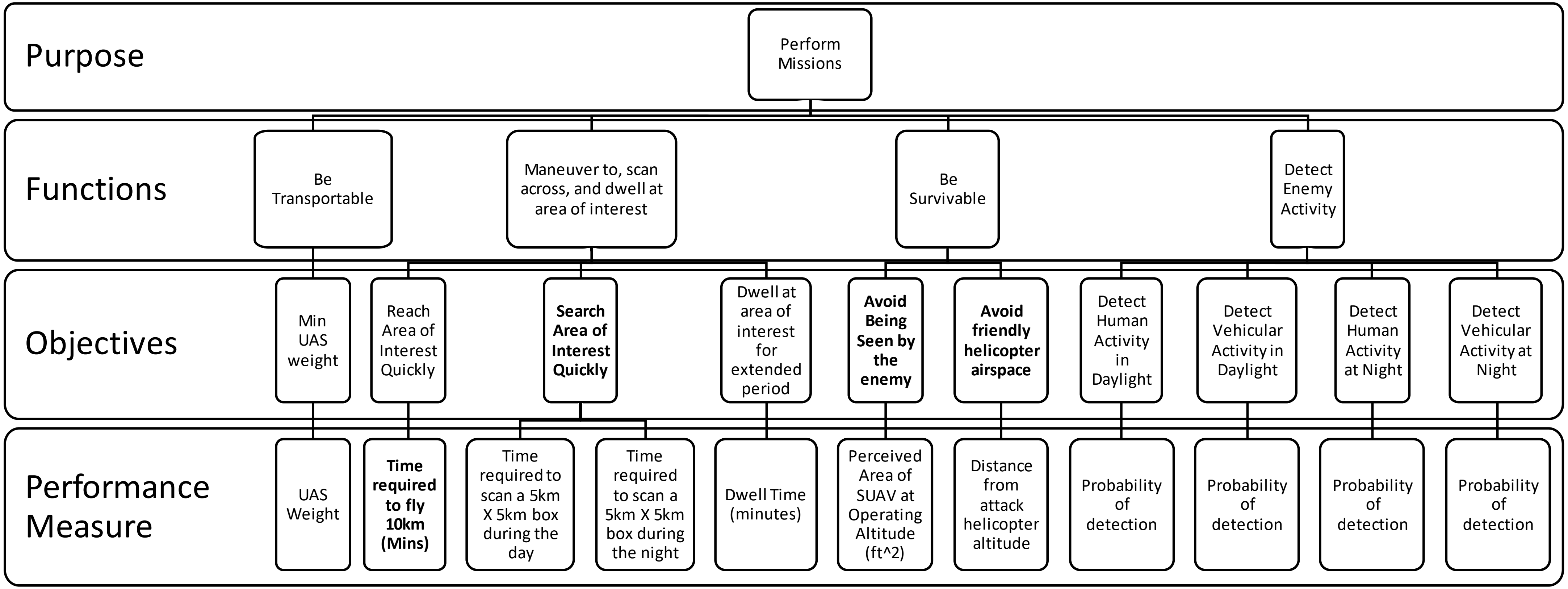
Using a UAV Case Study developed by Dr. Cilli at ARDEC, this research has applied the Trade-off Analytics Framework and set based design to the case study.
In the initial case study, 7 design decision were propagated through physics-based models to performance measures and cost.

UAV Case Study Design Decisions

Design Choice	Options	
Engine	Discrete Choice: • Electric	• Piston
Wingspan	Continuous choice: • 2 ft. to 12 ft.	
Operating Altitude	Continuous choice: • 300 m. to 1000 m.	
Electro-Optical (EO) Sensor Resolution	Discrete Choice: • 200 Pixels X 200 Pixels • 400 Pixels X 400 Pixels • 600 Pixels X 600 Pixels • 800 Pixels X 800 Pixels	• 1000 Pixels X 1000 Pixels • 1200 Pixels X 1200 Pixels • 1400 Pixels X 1400 Pixels • 1600 Pixels X 1600 Pixels • 1800 Pixels X 1800 Pixels
EO Sensor Field of View	Discrete Choice: • 15 Degrees • 30 Degrees • 45 Degrees	• 60 Degrees • 75 Degrees • 90 Degrees
Infrared (IR) Sensor Resolution	Discrete Choice: • 200 Pixels X 200 Pixels • 400 Pixels X 400 Pixels • 600 Pixels X 600 Pixels • 800 Pixels X 800 Pixels	• 1000 Pixels X 1000 Pixels • 1200 Pixels X 1200 Pixels • 1400 Pixels X 1400 Pixels • 1600 Pixels X 1600 Pixels • 1800 Pixels X 1800 Pixels
IR Sensor Field of View	Discrete Choice: • 15 Degrees • 30 Degrees • 45 Degrees	• 60 Degrees • 75 Degrees • 90 Degrees

In the Case study there are seven design decisions propagated to value and cost.

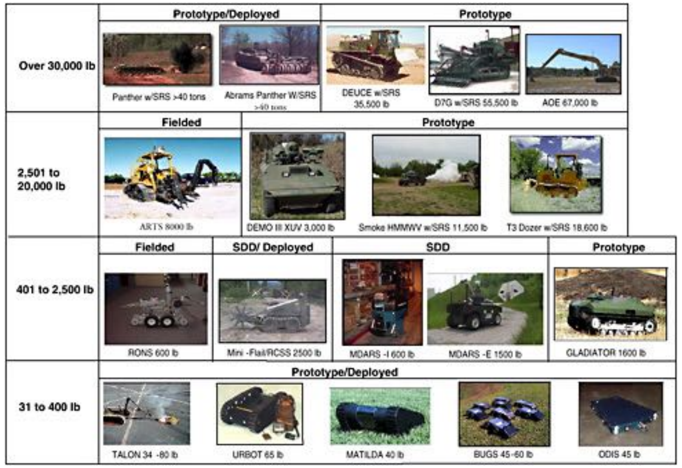
Case Study Value Measures



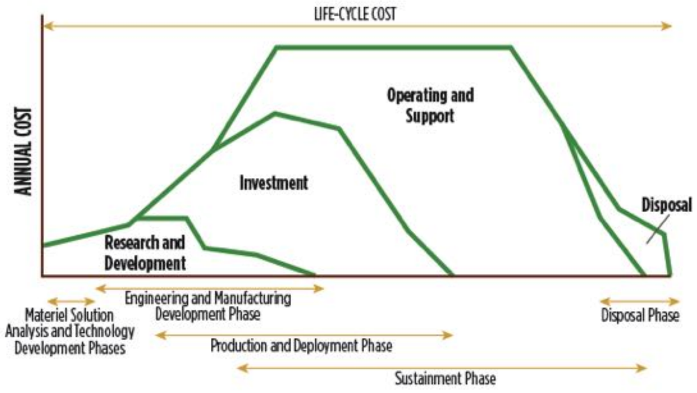
In the Case study there 4 functions with 11 performance measures.

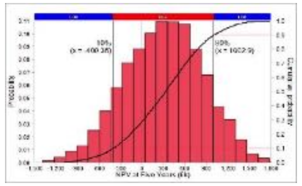
DoD Analysis of Alternatives

Point Design Concepts and Architectures

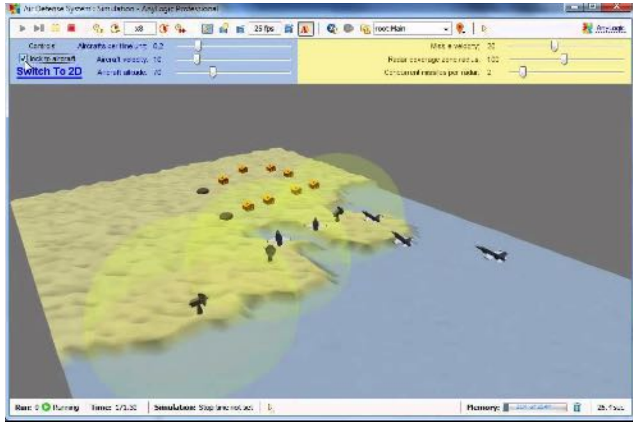


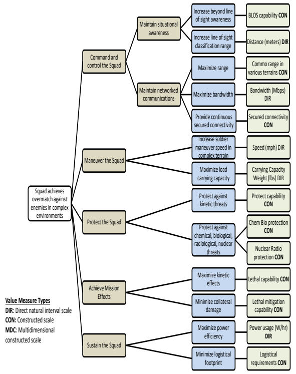
Life Cycle Cost Model





Capability and Military Value Models





Risk Analysis Models

Impact	Risk Management Actions		
Significant	Considerable management required	Must manage and monitor risks	Extensive management essential
Moderate	Risks may be worth accepting with monitoring	Management effort worthwhile	Management effort required
Minor	Accept risks	Accept, but monitor risks	Manage and monitor risks
	Low	Medium	High
		Likelihood	

In many traditional AoAs, different groups such as cost analysts, capability analysts, risk analysts, or other groups perform the analysis on different areas of the AoA.

Case Study Changes

Iteration	Model	Descriptive	Predictive	Prescriptive
1	Initial Case Study			
2	Multiple Changes	The case study was redeveloped from the ground up and given new design choices.	And entirely new set of physics models was used. The only remaining model was the probability of detection.	A completely new value model and new cost model.
3	Design Choices	The set of design choices was expanded as new combinations of sensors were added.	None	None
4	Value Model	None	None	Preferences on value curves were changed. Changing preferences for alternatives.
5	Value Model	None	None	The value curves were changed once more to allow more feasible solutions.
6	Value Model	None	New calculation for distance to attack helicopter added or all alternatives.	A new value measure (distance from attack helicopter) was added.
7	Design Choices	New alternatives for sensor FOV were added and altitude options were reduced after a discussion with Dr. Ham.	None	None
8	Swing Weights	None	None	Swing weights were changed after a discussion with Dr. Ham.
9	Cost Model	None	Cost model was changed to a lifecycle cost model.	None

- Similar to real world AoAs, the case study changed several times
- However, the integrated and simultaneous MBE methodology is robust to changes.

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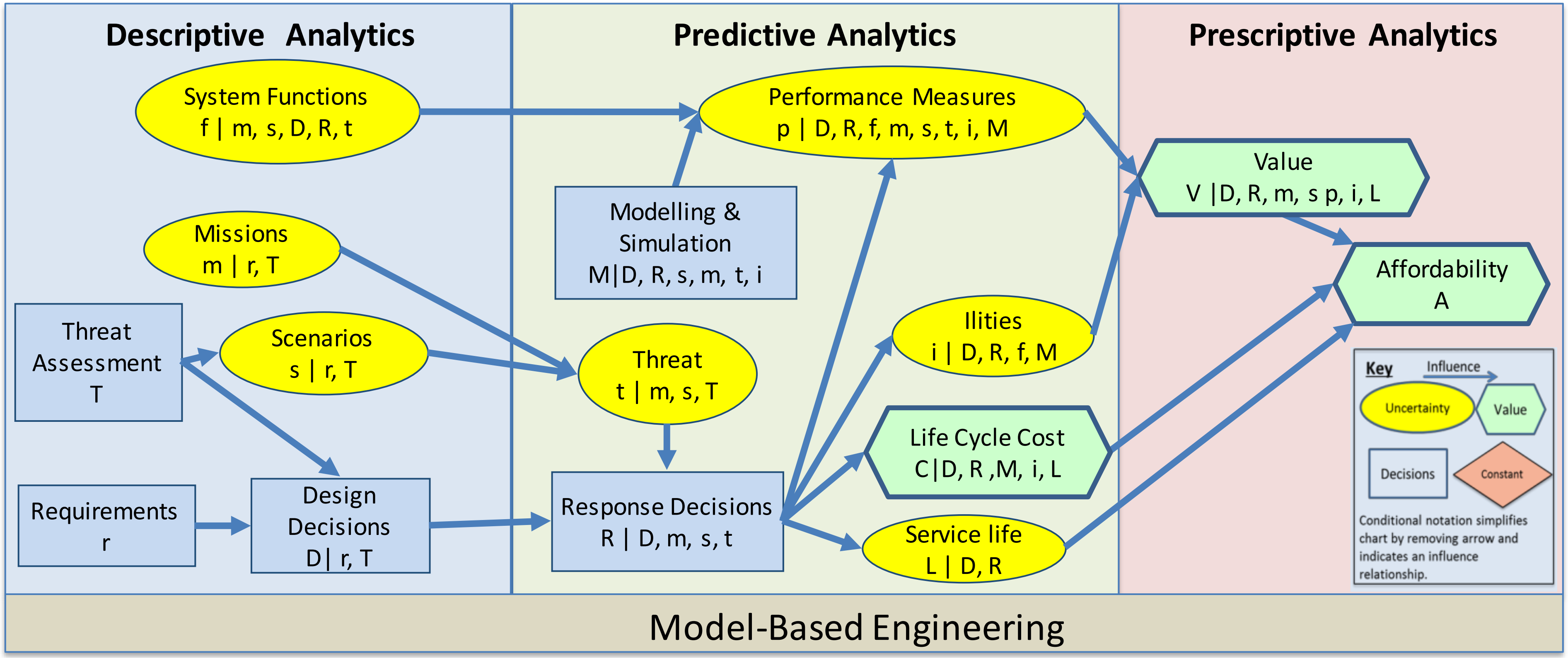
Influence Diagram for Integrated Trade-off Analytics: Current Status



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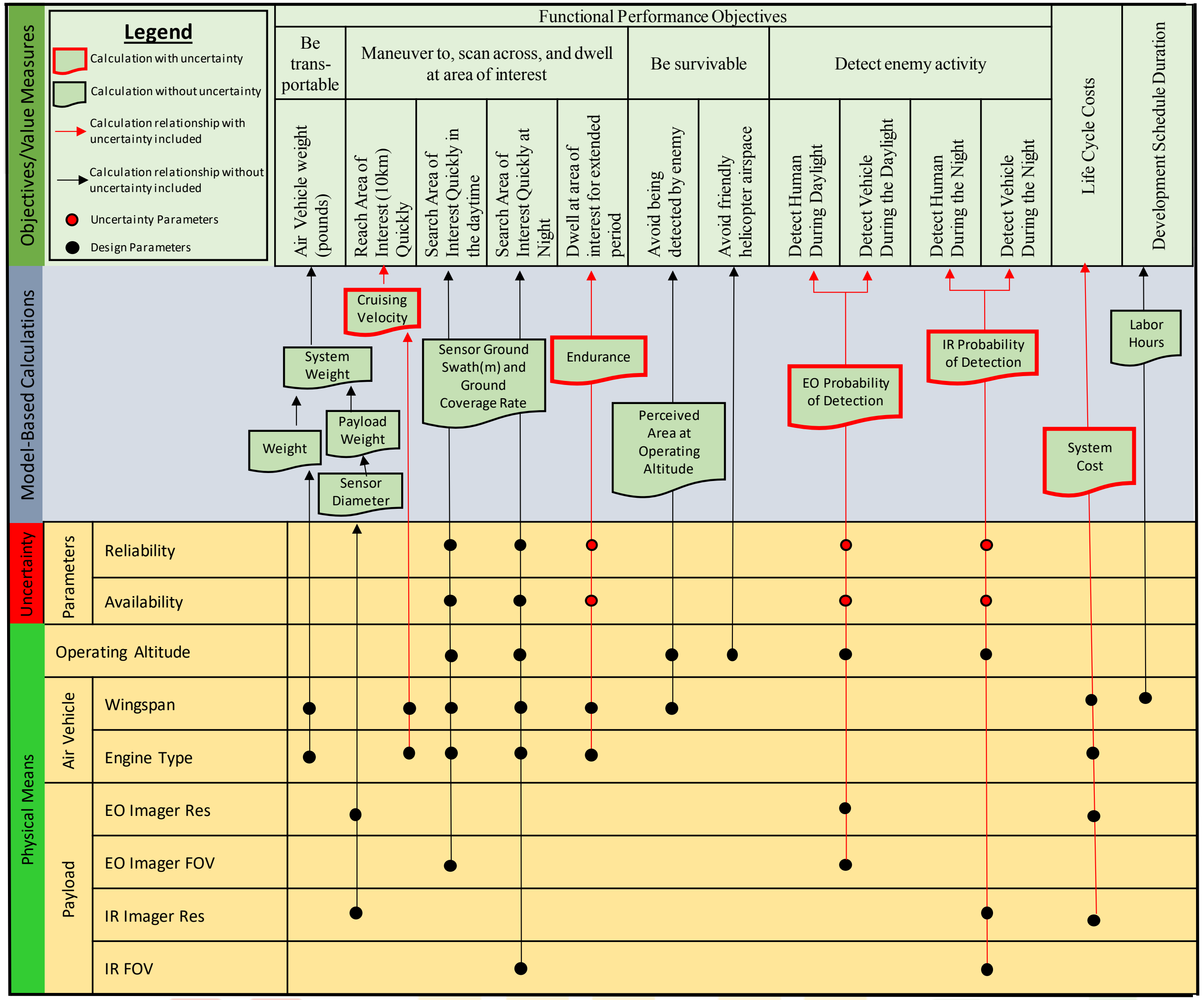
We have expanded the case study and analysis to include the entire trade-off analytics framework.

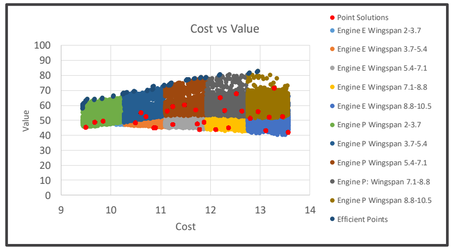
UAV Case Study Updated Assessment Flow Diagram

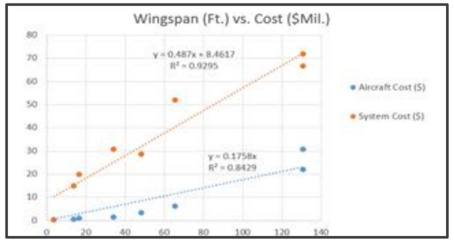


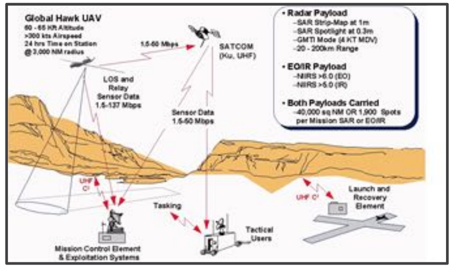
We have included uncertainty in the performance, cost, and preferences. In addition, we have included a life cycle cost model as well as included resilience in the performance calculations.

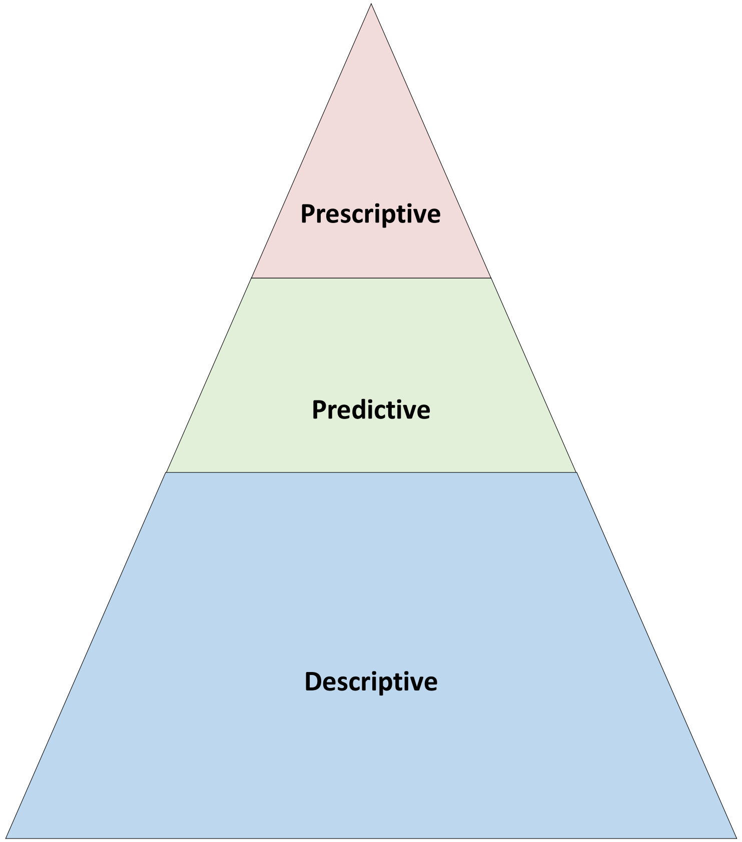
Small, C., Demonstrating Set-Based Design Techniques: A UAV Case study, Master's Thesis, Industrial Engineering, University of Arkansas, 2018

Trade-Off Analytics Hierarchy









Integrated Value and Cost Model
Multiple Objective Decision Analysis

2,576	Feasible Cost vs Value points
97,424	Total infeasible designs
95,549	Infeasible designs with stocastic parameters
1,874	Infeasible designs with deterministic parameters

Predicted design performace and costs

21,900,000	Physics model calculations
98,070	Designs with stochastic parameters
1,930	Designs with deterministic parameters
1,100,000	Value measure estimates
100,000	Cost estimates

Design definition and uncertainty specification

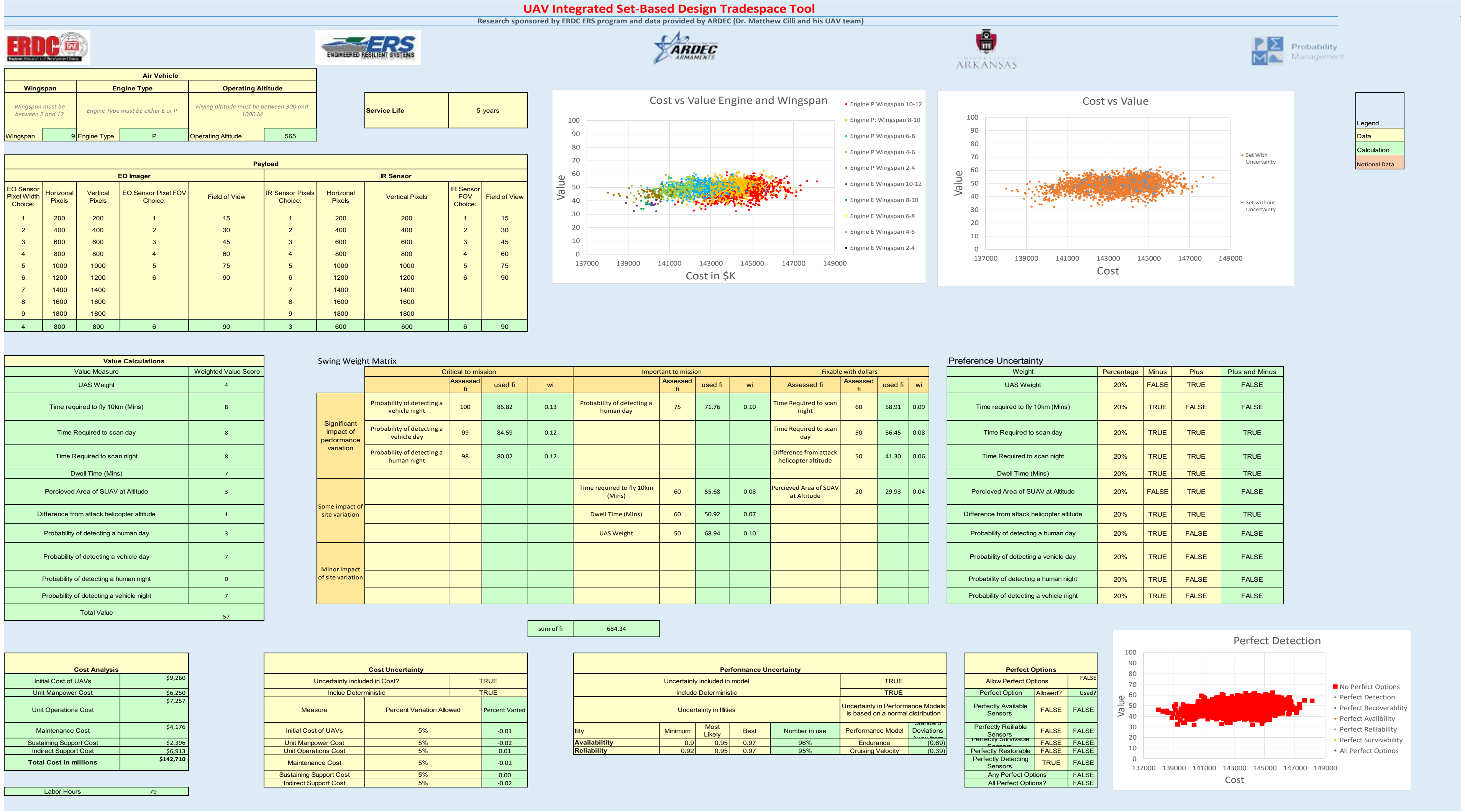
7	Design Parameters
145,800	Combinations of design parameters using bins
100,000	Designs generated by SIPmath
47	Physics models and formulas
19	Physics models with uncertainty
4	Illities
2	Illities with Uncertainty
11	Value Measures
8	Value measures with uncertainty

Using Excel and an Excel add-in called SIPmath from Probability Management, this research has created an integrated tradespace tool to apply the analytics framework and explore set-based design.

Small, C., Buchanan, R., Cilli, M., Parnell, G., Pohl, E., Wade, Z., “A UAV Case Study with Set-based Design,” 28th Annual INCOSE International Symposium, 7-12 July 2018, Washington, DC.

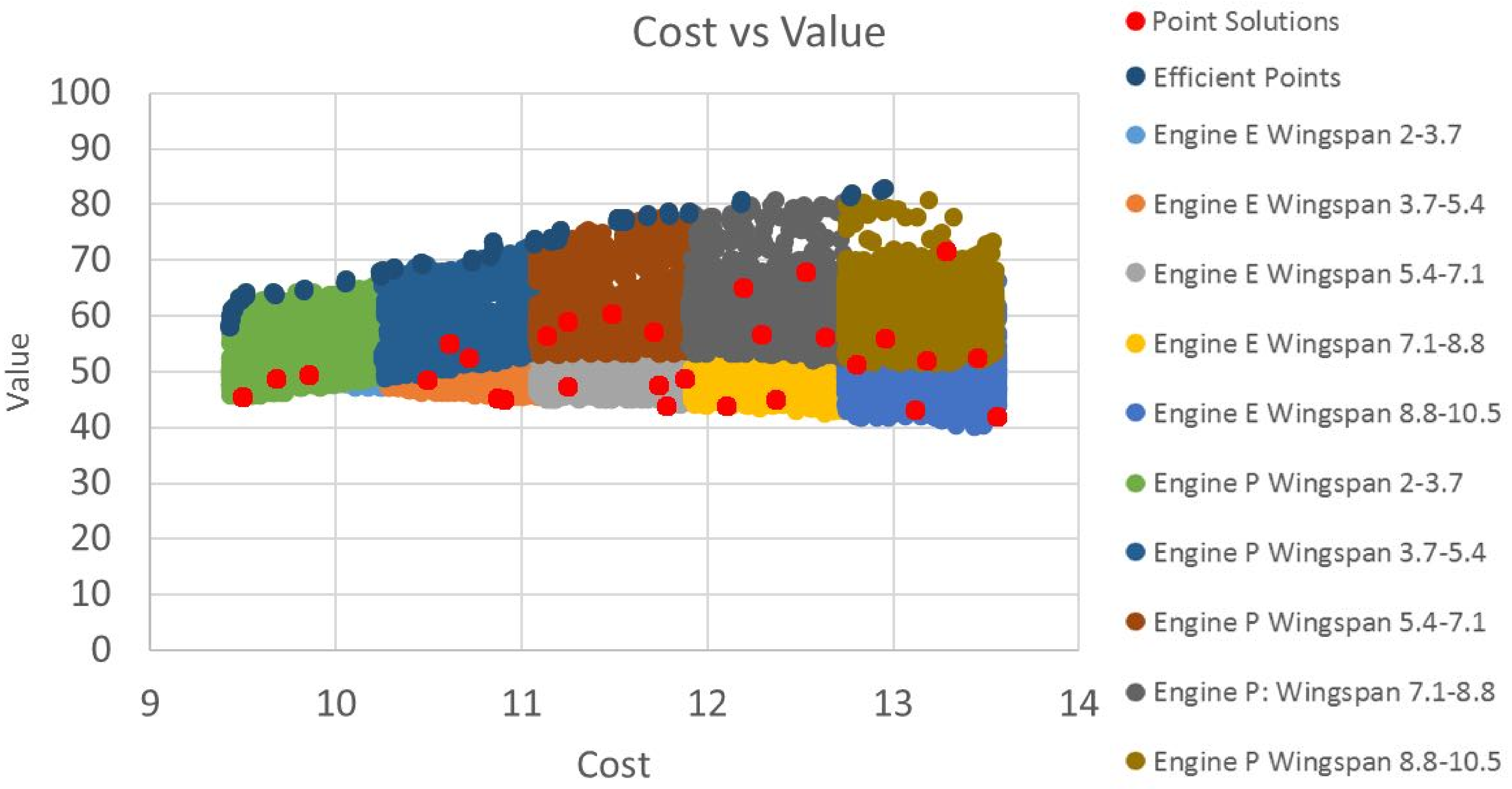
Analytics hierarchy provides transparency into the complexity of the trade-off analytics

UAV Tradespace Tool



Using random numbers generated by SIPmath, the tradespace tool uniformly explores the entire design space.
In addition, the control panel allows the user to select the level of uncertainty on performance, cost, and preferences.

PBD vs. SBD

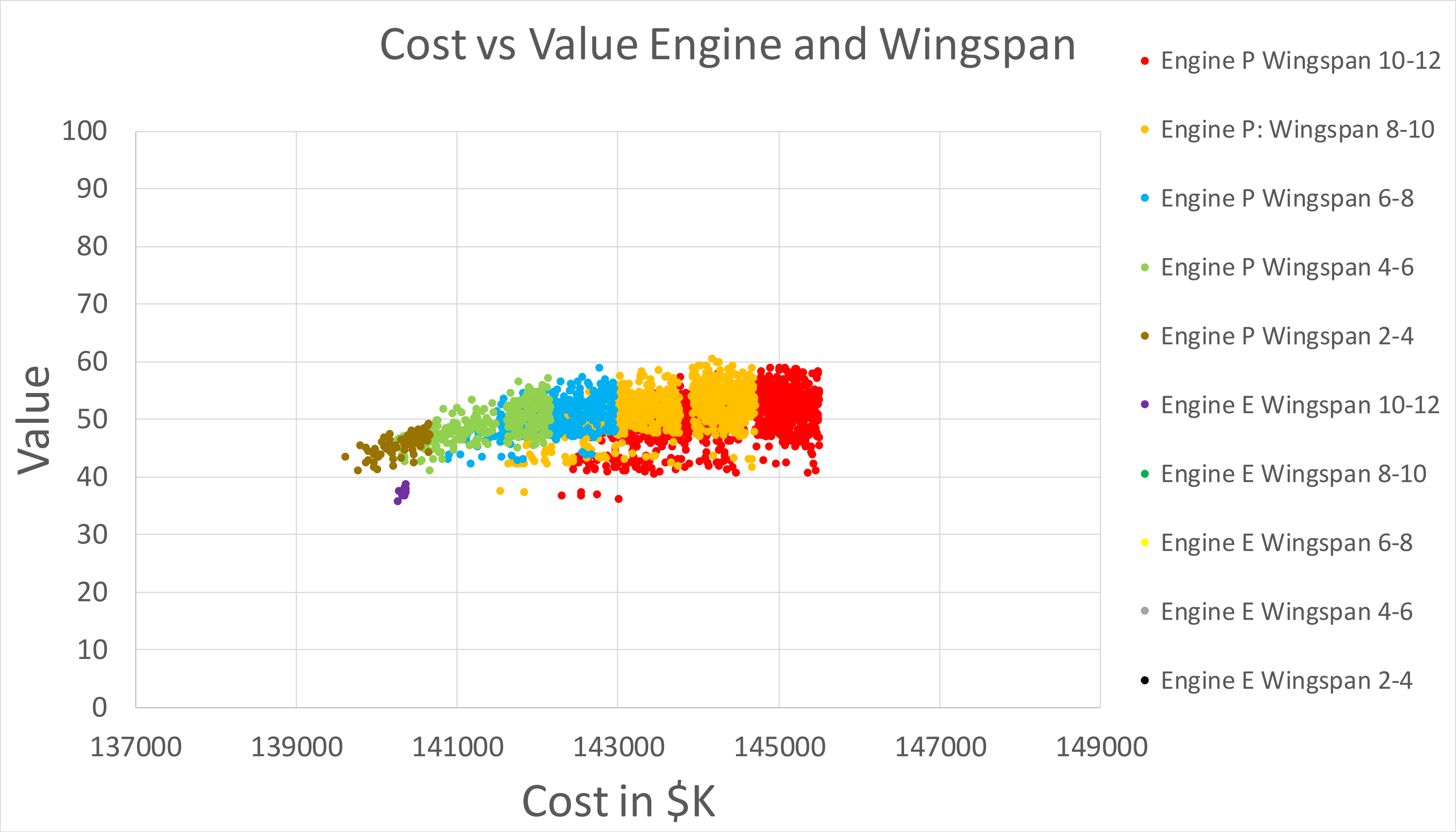


Sets are determined by engine type and wingspan. Deterministic analysis shows the value vs cost for the 10 sets.

Small, C., Buchanan, R., Cilli, M., Parnell, G., Pohl, E., Wade, Z., "A UAV Case Study with Set-based Design," 28th Annual INCOSE International Symposium, 7-12 July 2018, Washington, DC.

In iteration 2 of the case study, set-based design identified improved solutions compared to a finite number of point solutions.

Value Vs Cost



Throughout the changes, sets are still determined by engine type and wingspan. Deterministic analysis shows the value vs cost for the 10 sets.

Life Cycle Cost Model

Hardware Cost

$$Air\ Vehicle\ Recurring\ Unit\ Cost\ (\$K\ 2013) = FlyWeight * 1.002$$
$$Air\ Frame\ Unit\ Recurring\ Cost\ (\$K\ 2013) = PayloadWeight * 5.607$$
$$Propulstion\ Unit\ Recurring\ Cost\ (\$K\ 2013) = (FlyWeight - PayloadWeight) * 1.808$$
$$Payload\ Average\ Unit\ Cost\ (\$K\ 2013) = 0.5 * AirFrameUnitCost$$
$$Total\ Hardware\ Cost(\$K\ 2013) = TotalGroundStation + AirVehicleUnitCost + PayloadAverageCost + PropulsionUnitCost + AirFrameUnitCost$$

Support Costs

$$Unit\ Level\ Manpower\ Cost\ (\$K\ 2013) = 250 * 0.5 * NumberOfSystems$$
$$Unit\ Operations\ Cost\ (\$K\ 2013) = (24676 + 0.8286 * 1156 * TotalAirCraftInventory) * 1/10$$
$$Maintenance\ Cost\ (\$K\ 2013) = \begin{pmatrix} 41223 + 0.1261 * AirElementsWeight * \\ AgeOfAircraft * TotalAircraftInventory \end{pmatrix} * \frac{1}{10}$$
$$Sustaining\ Support\ Cost\ (\$K\ 2013) = TotalHours\verb|^|0.7303 * NumberOfSystems$$
$$Indirect\ Support\ Cost\ (\$K\ 2013) = 2777 * e^{(0.01824 * NumberOfSystems)}$$

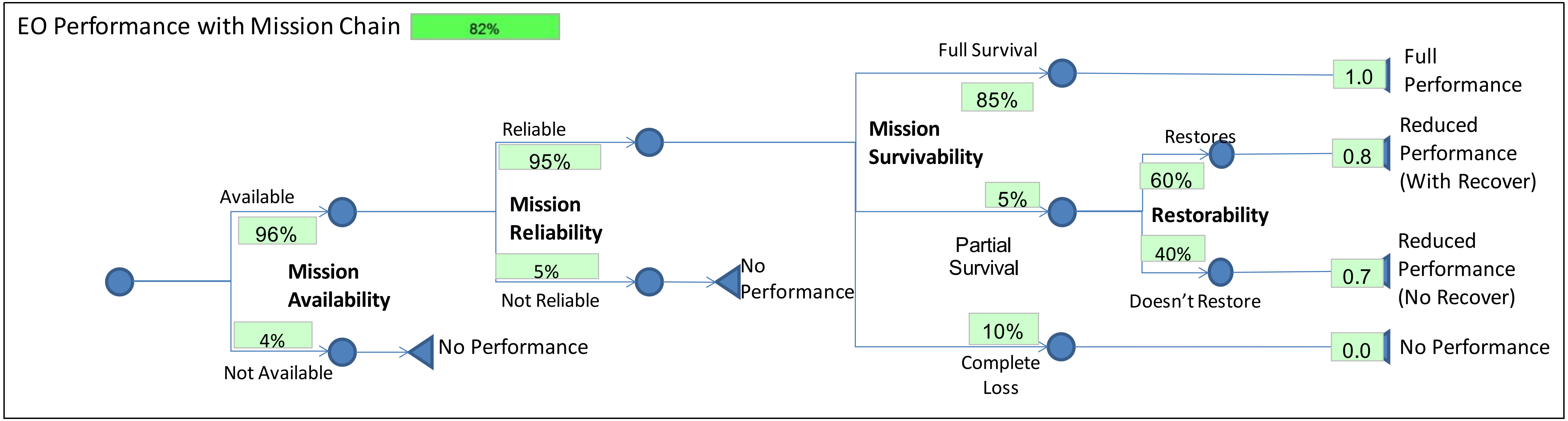
Life Cycle Cost

$$Life\ Cycle\ Cost\ (\ \$K\ 2013) = TotalHardwareCost * NumberOfSystems + (Unit\ Level\ Manpower\ Costs + Unit\ Operations\ Costs + Maintenance\ Cost + Sustaining\ Support\ Cost + Indirect\ Support\ Cost) * Service\ Life$$

To explore the lifecycle of the we have expanded the cost model to a lifecycle cost model.

Richards, J. (2018, March 15). UAV Demonstration Cost Model Meeting. (C. Small, Interviewer)

Incorporating Mission Resilience in Performance Measures



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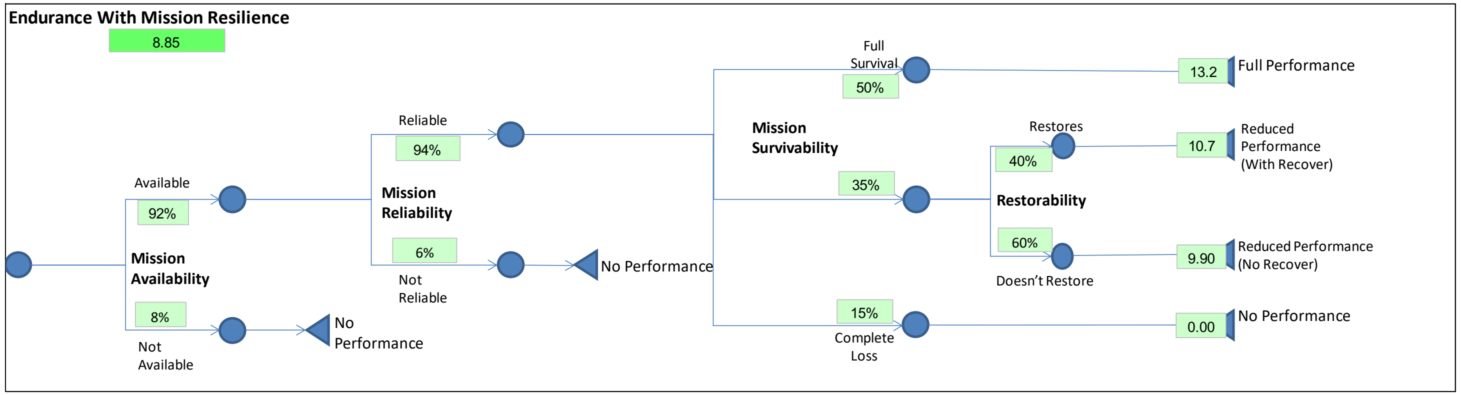
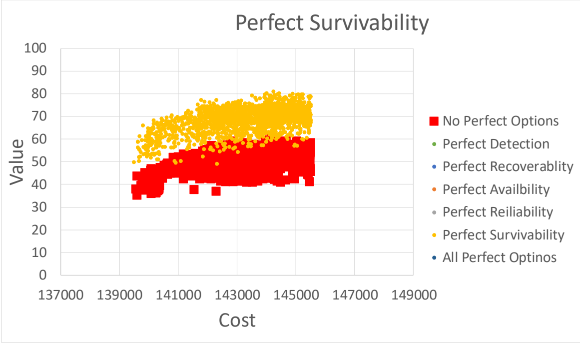
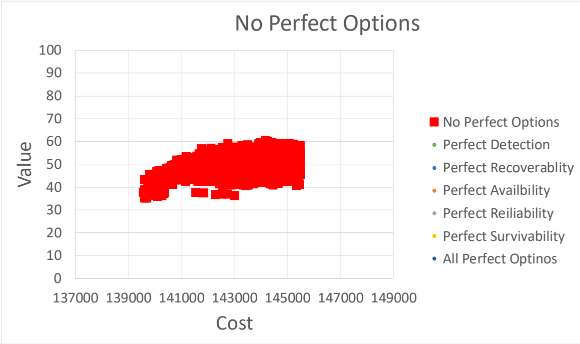
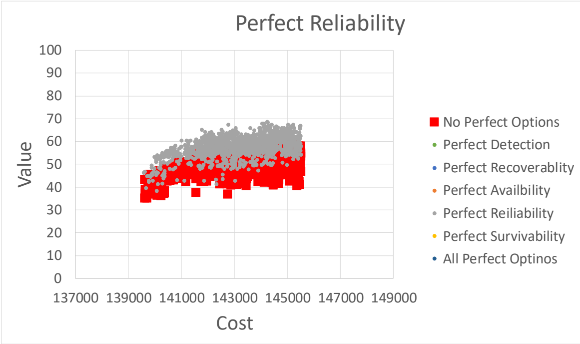
Using probability trees, we have incorporated mission resilience into endurance and probability of detection performance calculations.

Perfect Options









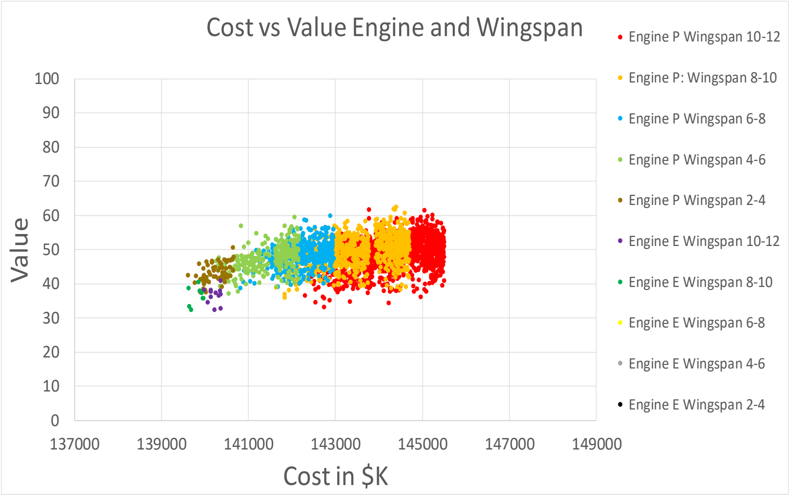
Analyzing the effect of perfect ilities provides insight into resilience response decisions.

Small, C., Demonstrating Set-Based Design Techniques: A UAV Case study, Master's Thesis, Industrial Engineering, University of Arkansas, 2018

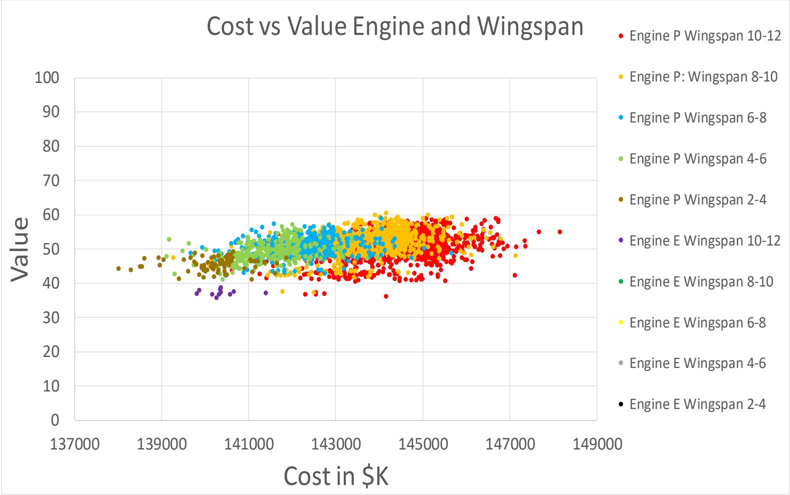
Uncertainty

- In this research uncertainty has been incorporated into three areas:
  – Performance
    - Through physics based models
    - Through the ilities
  – Cost model
    - In each of the cost types
  – Preferences
    - In the un-normalized elicited swing weights

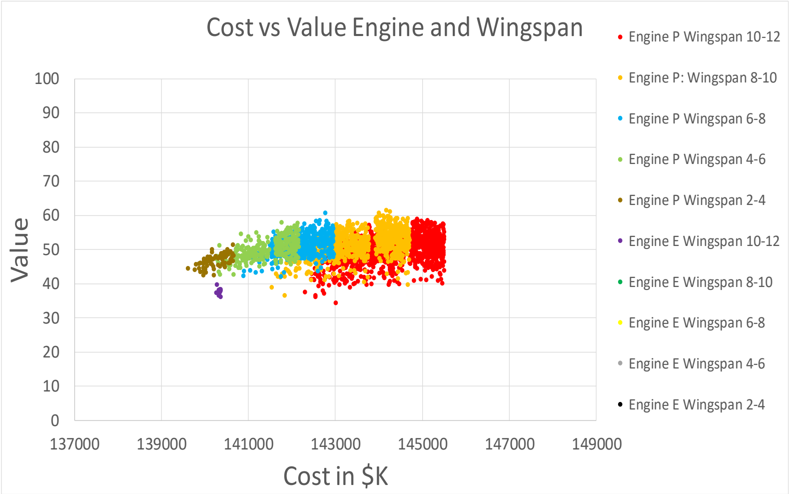
Uncertainty



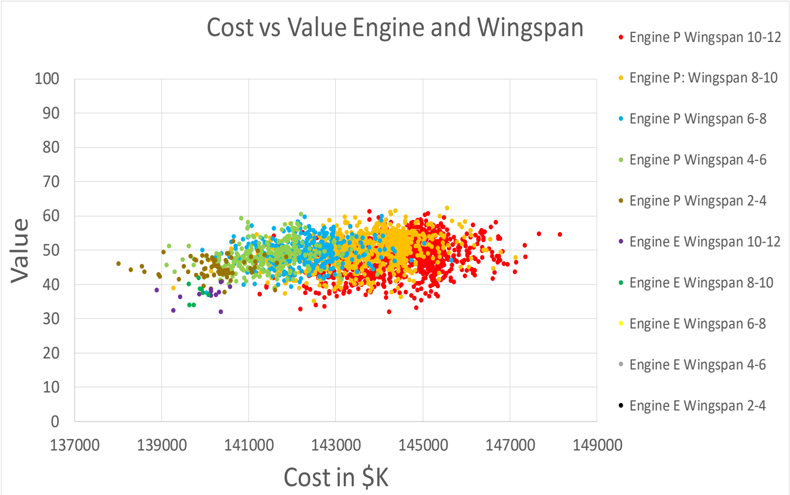
Cost Uncertainty



Performance Uncertainty



Preference Uncertainty



All Uncertainty

- Overall incorporating uncertainty increases the overlap in sets, making them harder to distinguish like real world systems that can have wide ranges of uncertain performance and cost.
- Some sets are impacted by different types of uncertainty more than others

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Contributions

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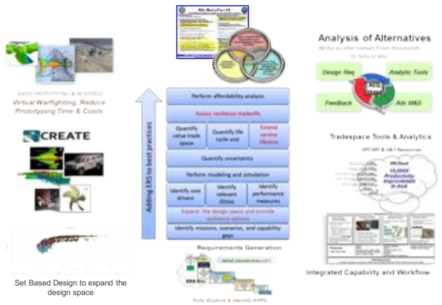
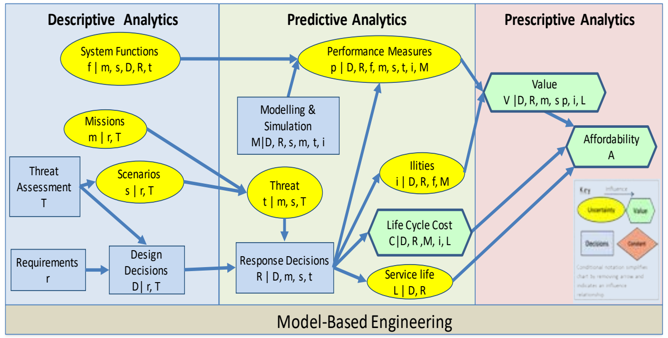
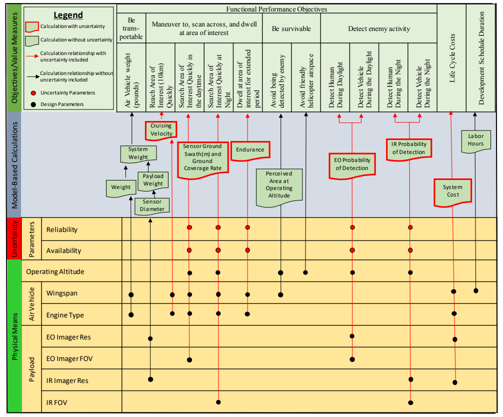


Trade-off Analytics Framework



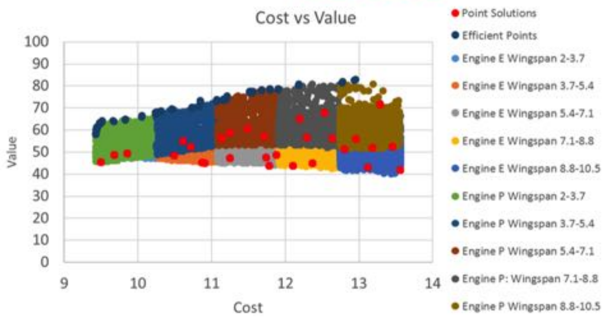
Implemented Trade-off analytics framework and SBD



Methodology is robust to changes

Design Choice	Options	
Engine	Discrete Choice: • Electric	 • Piston
Wingspan	Continuous choice: • 2 ft. to 12 ft.	
Operating Altitude	Continuous choice: • 300 m. to 1000 m.	
Electro-Optical (EO) Sensor Resolution	Discrete Choice: • 200 Pixels X 200 Pixels • 400 Pixels X 400 Pixels • 600 Pixels X 600 Pixels • 800 Pixels X 800 Pixels	• 1000 Pixels X 1000 Pixels • 1200 Pixels X 1200 Pixels • 1400 Pixels X 1400 Pixels • 1600 Pixels X 1600 Pixels • 1800 Pixels X 1800 Pixels
EO Sensor Field of View	Discrete Choice: • 15 Degrees • 30 Degrees • 45 Degrees	 • 60 Degrees • 75 Degrees • 90 Degrees
Infrared (IR) Sensor Resolution	Discrete Choice: • 200 Pixels X 200 Pixels • 400 Pixels X 400 Pixels • 600 Pixels X 600 Pixels • 800 Pixels X 800 Pixels	• 1000 Pixels X 1000 Pixels • 1200 Pixels X 1200 Pixels • 1400 Pixels X 1400 Pixels • 1600 Pixels X 1600 Pixels • 1800 Pixels X 1800 Pixels
IR Sensor Field of View	Discrete Choice: • 15 Degrees • 30 Degrees • 45 Degrees	 • 60 Degrees • 75 Degrees • 90 Degrees

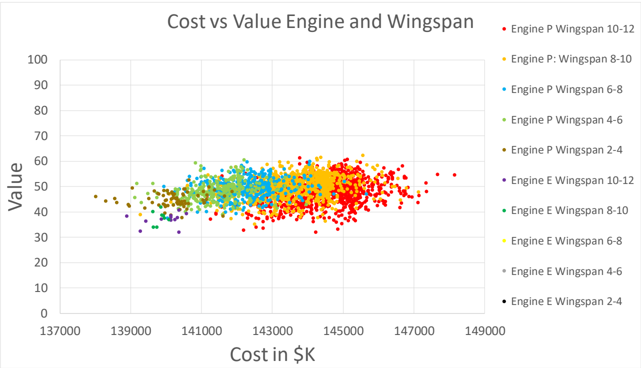
PBD vs. SBD



Small, C., Buchanan, R., Cilli, M., Parnell, G., Pohl, E., Wade, Z., "A UAV Case Study with Set-based Design," 28th Annual INCOSE International Symposium, 7-12 July 2018, Washington, DC.

Perfect Options

Effects of uncertainty on SBD



Due in large part to this research, the creator of the UAV case study has begun to incorporate major portions of this methodology and Set-Based Design within his systems engineering trade-off analysis for the ARDEC. (Cilli, 2018)

Small, C., Demonstrating Set-Based Design Techniques: A UAV Case study, Master's Thesis, Industrial Engineering, University of Arkansas, 2018

Overview

- Introduction
  - ERS
  - Trade-off Analytics Framework
  - Set Based Design
- Initial UAV Case Study
- UAV Tradespace Tool
  - Base model
  - Perfect Options
  - Uncertainty
- Conclusions
- Future Research

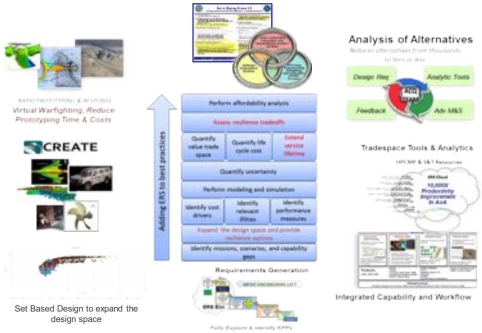
Future Work

- There are four major areas for future research:
  - In this study the sets drivers were determined by using a heuristic method by looking at the impact of design decisions on the cost and value tradespace. To increase the feasibility of set-based design methodology, a repeatable, mathematical method of defining set-drivers needs to be developed.
  - The ability to generate the efficient frontier needs to be validated through comparison with genetic algorithms.
  - The resilience options research needs to be expanded to include explicit resilience options as well as the cost of resilience options.
  - In support of the ERS research effort at ERDC this tradespace tool will be implemented in an online trade-off analytics tool (TradeBuilder).

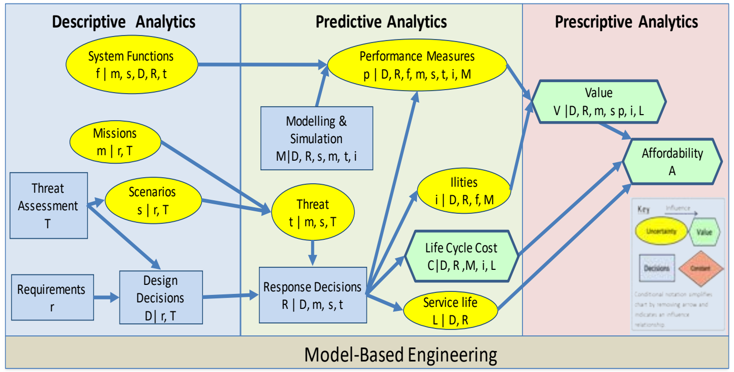
Questions

My thesis provides a case study using ERS/ARDEC UAV data that demonstrates the potential of Set-Based Design trade-off analytics in system decision making for Engineered Resilient Systems.

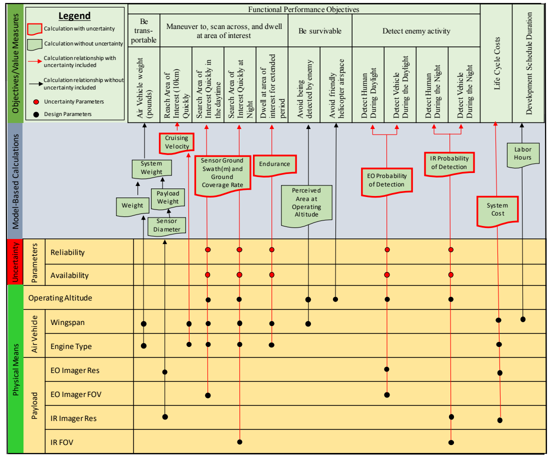
Incorporating ERS into AoAs



Trade-off Analytics Framework

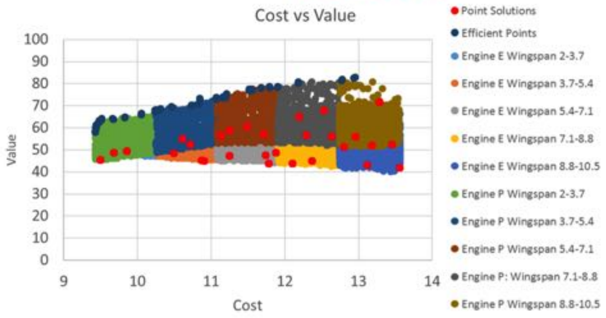


Implementing Trade-off analytics framework and SBD in UAV Tradespace Tool



Effects of uncertainty on SBD

PBD vs. SBD



Small, C., Buchanan, R., Cilli, M., Parnell, G., Pohl, E., Wade, Z., "A UAV Case Study with Set-based Design," 28th Annual INCOSE International Symposium, 7-12 July 2018, Washington, DC.

Perfect Options