29th Annual INCOSE international symposium

Orlando, FL, USA
July 20 - 25, 2019

Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions

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Edward Pohl, University of Arkansas

Parnell, G.S., Specking, E., Cilli, M., Goerger, S., & Pohl, E., "Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions, INCOSE International Symposium, Orlando, FL, July 20-25, 2019

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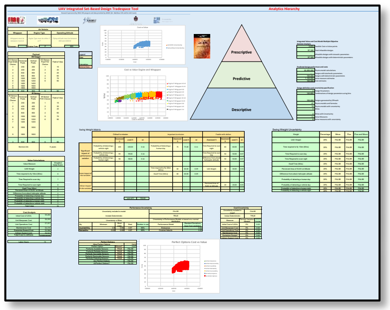
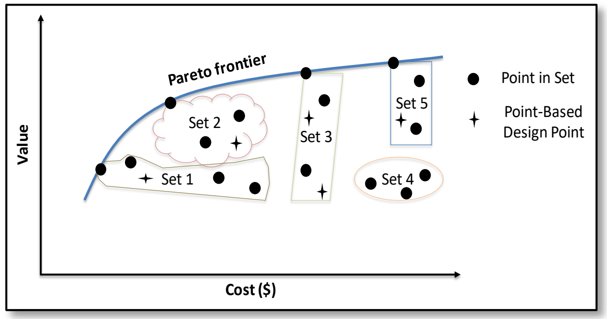
Bottom Line Up Front

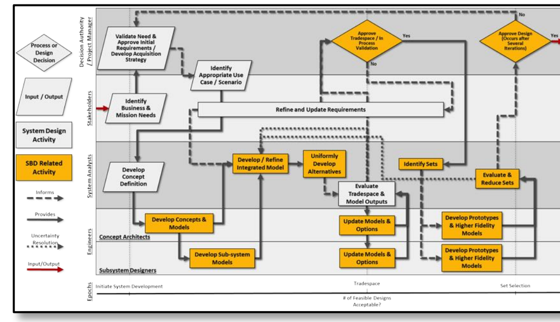
SBD UAV Demonstration Model



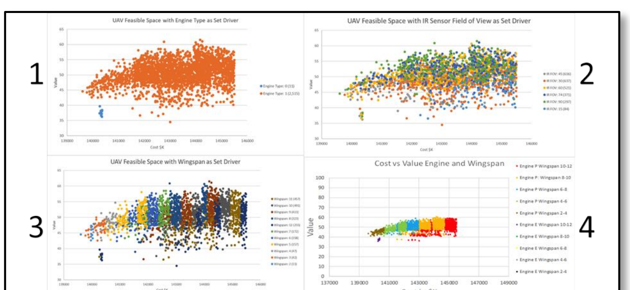
SBD vs. PBD



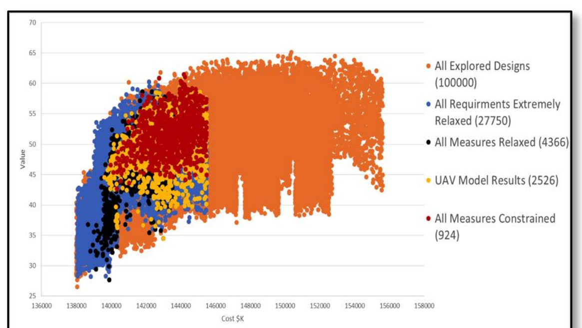
SBD Implementation



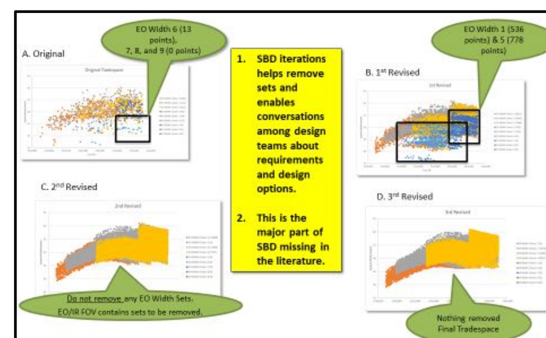
SBD Helps Assess Design Decisions



SBD Helps Assess the Impact of Requirements on the Feasible Tradepsace



SBD Helps to Inform System Engineers and Stakeholders



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- UAV Case Study
- Point-Based vs. Set-Based Design
- SBD Implementation
- Design Decision Evaluation
- Requirements Analyses
- System Engineers/Stakeholders Interactions
- SBD Challenges
- Future Research & Summary

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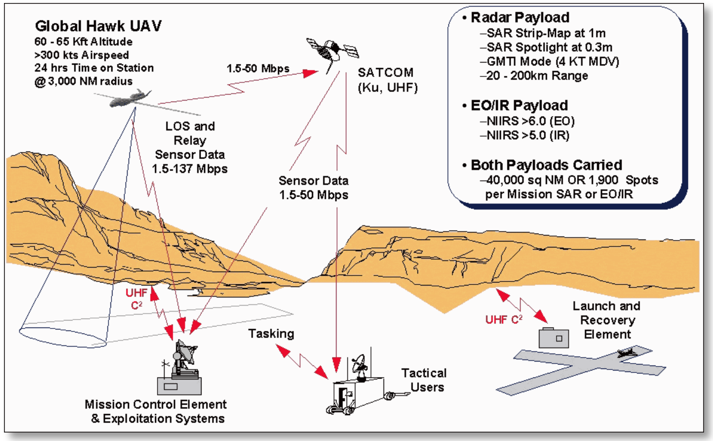
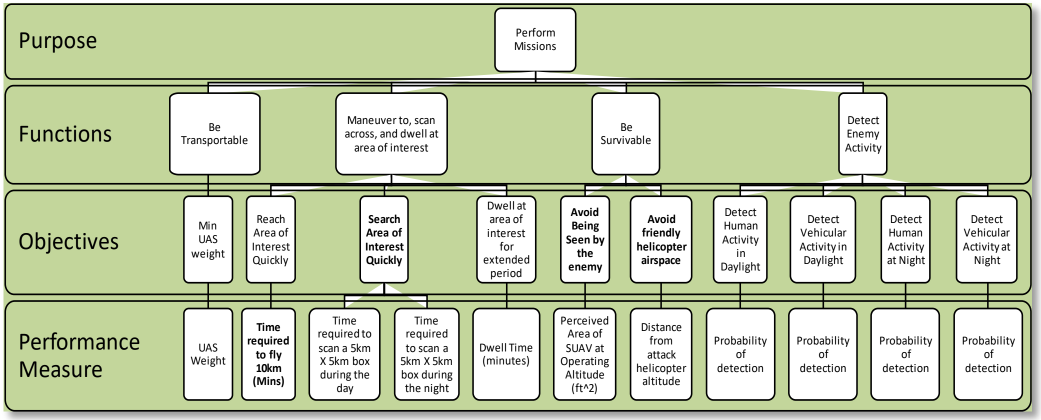
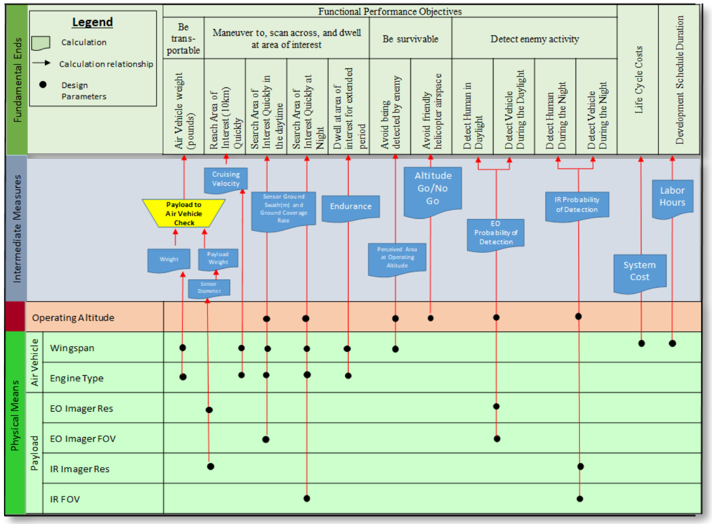
UAV Demonstration Data

1. **Using a notional UAV Case Study, this research applies the Trade-off Analytics Framework and SBD to the case study.**
2. **Seven design decisions were propagated through models to performance measures, value, and cost.**







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.

Synthesizing Results – Additive Value Model

1. **The first step is to develop a value curve for each performance measure that scales from a required performance level to an ideal performance level.**

2. **Any alternative that does not meet a requirement for any performance measure is considered infeasible.**

3. **For all feasible alternatives, the additive value model calculates each alternative's value.**

Note: There exist several utility and value models in addition to additive value model shown in this example.

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i)$$

where

v(x) is the alternative's value,

i = 1 to n is the number of the measure,

x_i is the alternative's score on the i^{th} measure,

$v_i(x_i)$ = is the single dimensional value of a score of x_i,

w_i is the weight of the i^{th} measure,

$$\sum_{i=1}^{n} w_i = 1$$

and (all weights sum to one).

The additive model assumes preferential independence. See Keeney & Raiffa, 1976, and Kirkwood, 1997 for additional models.

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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

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

Life Cycle Cost

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

We use a lifecycle cost model to estimate cost throughout the UAV's lifecycle.

Richards, J. (2018, March 15). UAV Demonstration Cost Model Meeting. (C. Small, Interviewer)
Small, C., Demonstrating Set-Based Design Techniques: A UAV Case study, Master's Thesis, Industrial Engineering, University of Arkansas, 2018

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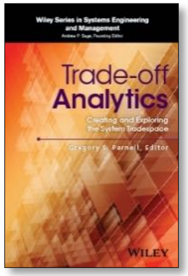
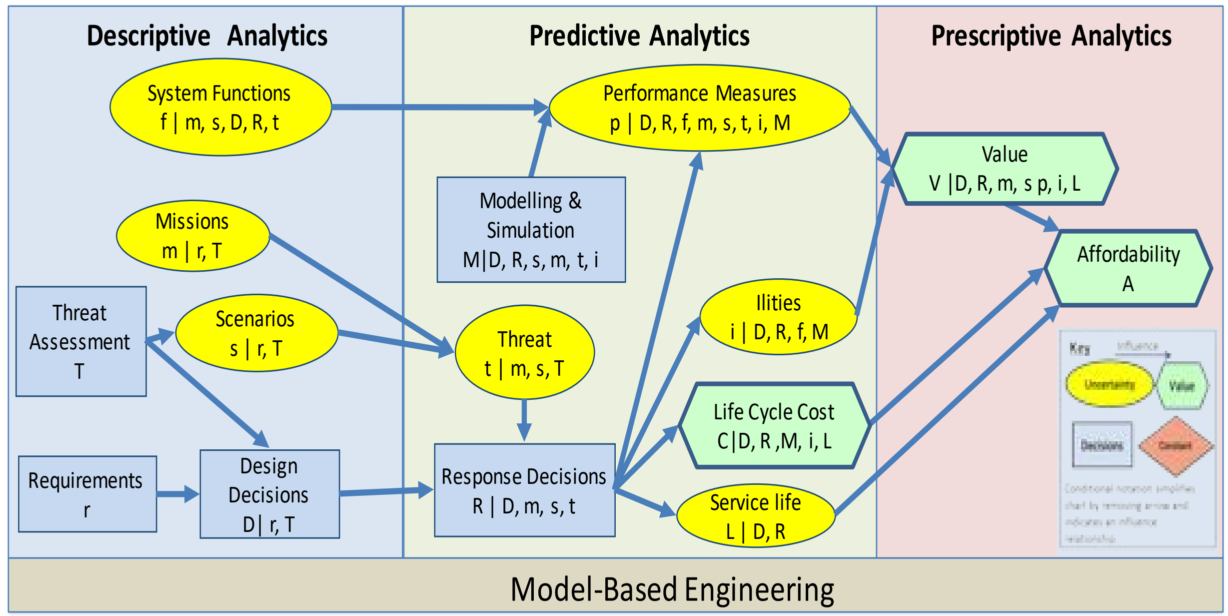
Developed Integrated Trade-Off Analytics Framework



1. **Describe integrated framework with analytics terms**
2. **Retain the sound mathematical foundation**
   a. **Multiple Objective Decision Analysis for value**
   b. **Life Cycle Cost**
   c. **Value and Cost Risk**
3. **Retain SIPmath for MC simulation**
4. **Identify sets to explore the tradespace**



The integrated model uses MBE to simultaneously assess the value, cost, and risk of the tradespace to identify affordable, efficient decisions.

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

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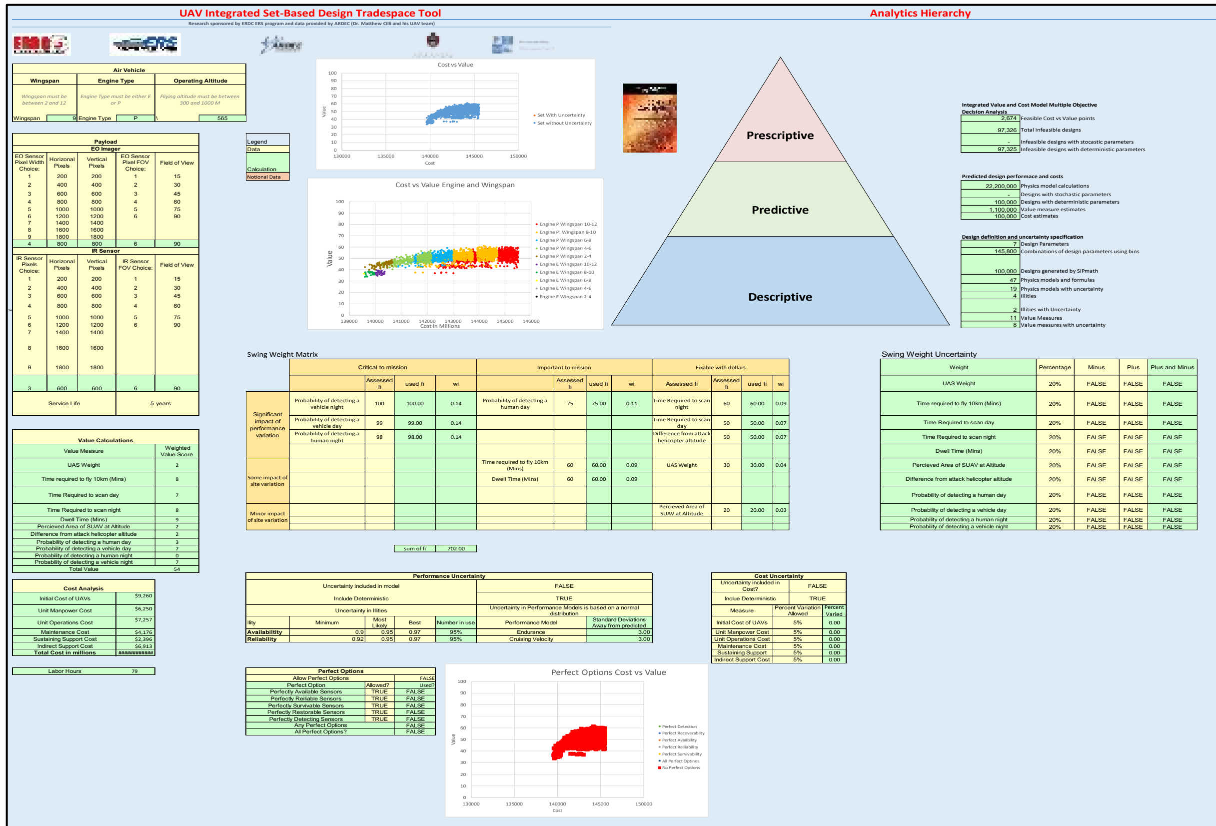
UAV Case Study Control Panel

1. **Using random numbers generated by SIPmath, the tradespace tool uniformly explores the design space (Monte Carlo simulation).**

2. **Using discrete and continuous design decisions, we simulated 100,000 designs in near-real time.**

3. **User selects the level of uncertainty on performance, cost, and preferences and the tool summarizes the cost vs. value.**

4. **This presentation uses the deterministic UAV model.**



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

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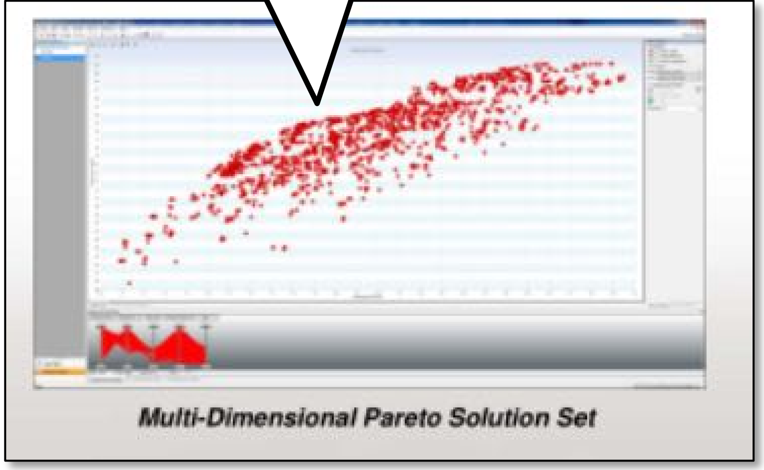
Point-Based Design Best Practices

1. **Develop integrated models to explore the tradespace**
2. **Use optimization to identify Pareto frontier in cost vs. value space, e.g.,**
   a. **Whole System Trades Analysis Tool (WSTAT)**
      i. **Sandia National Laboratory**
      ii. **Genetic Algorithm**
   b. **Advanced Collaborative Systems Optimization Modeler (ACSOM)**
      i. **Wayne State**
      ii. **IP with heuristic**
3. **Help identify promising point designs for next development phase**

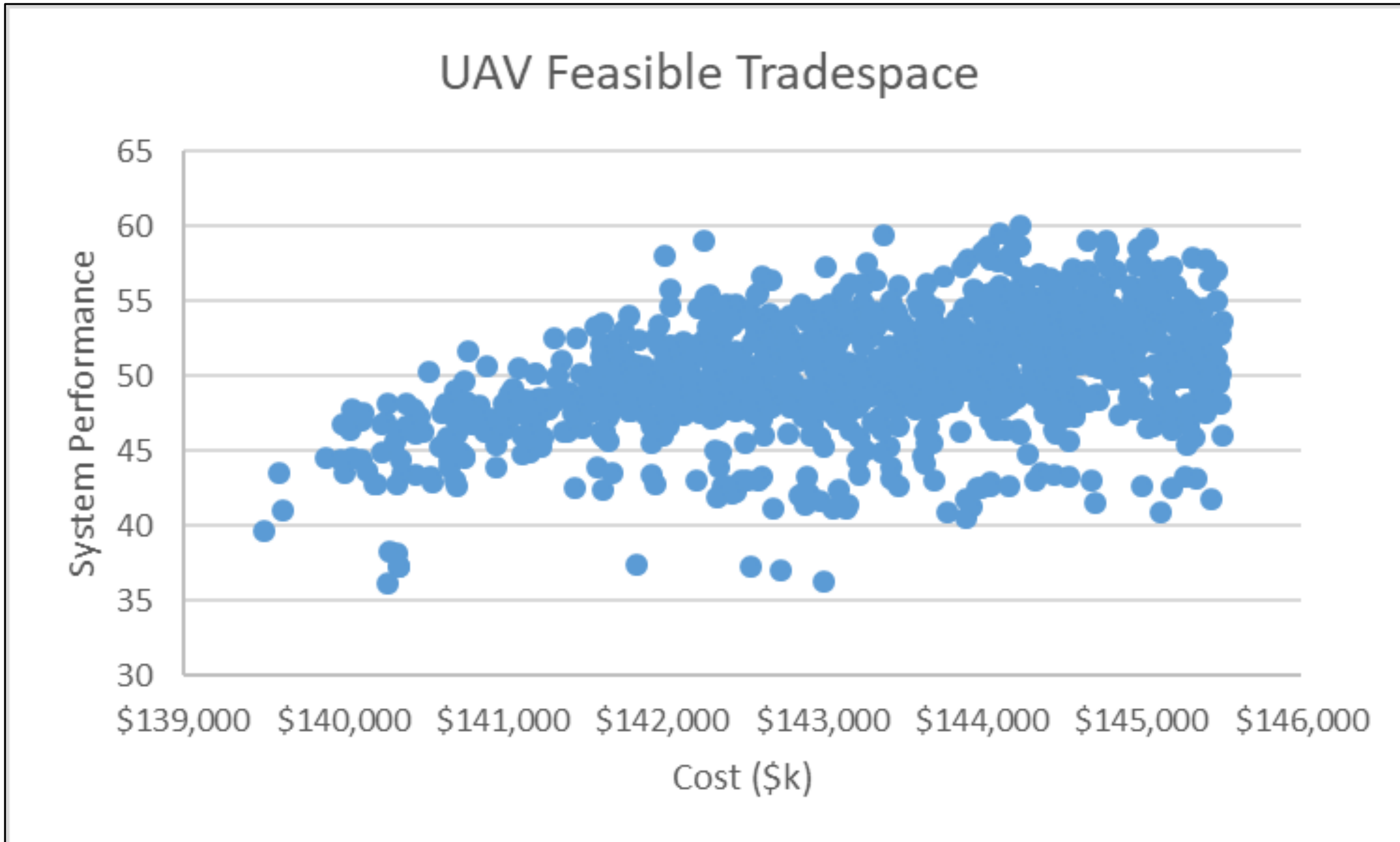
All points were "optimal" for a specific run.



https://www.sandia.gov/CSR/_assets/documents/WSTAT.pdf

Heuristic optimization techniques are used to find Pareto solutions, but optimality is not guaranteed due to significant non-linearity in the tradespace.

Tradespace Representation



1. **Monte-Carlo representation of the feasible tradespace helps to identify a Pareto Frontier.**
2. **Does not provide insights into how to assess design decisions or requirements.**

Specking, E., Shallcross, N., Parnell, G., Pohl, E., Goerger, S., Informing Early System Requirements and Design Decisions using Set-Based Design. Systems Engineering. (In progress 2019)

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Set-Based Design Distinctions

1. **"Considers large number of designs"**
2. **"Allow specialist to consider a design from their own perspective and use the intersection between individual sets to optimize a design"**
3. **"Establish feasibility before commitment"**
4. **Set-Based Design is a concurrent engineering alternative that provides improved stakeholder value through extensive uncertainty resolution and improved alternative designs**


The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster

Allen Ward • Jeffrey K. Liker • John J. Cristiano • Durward K. Sobek II

David J. Singer, PhD., Captain Norbert Doerry, PhD., and Michael E. Buckley

What is Set-Based Design?

ABSTRACT

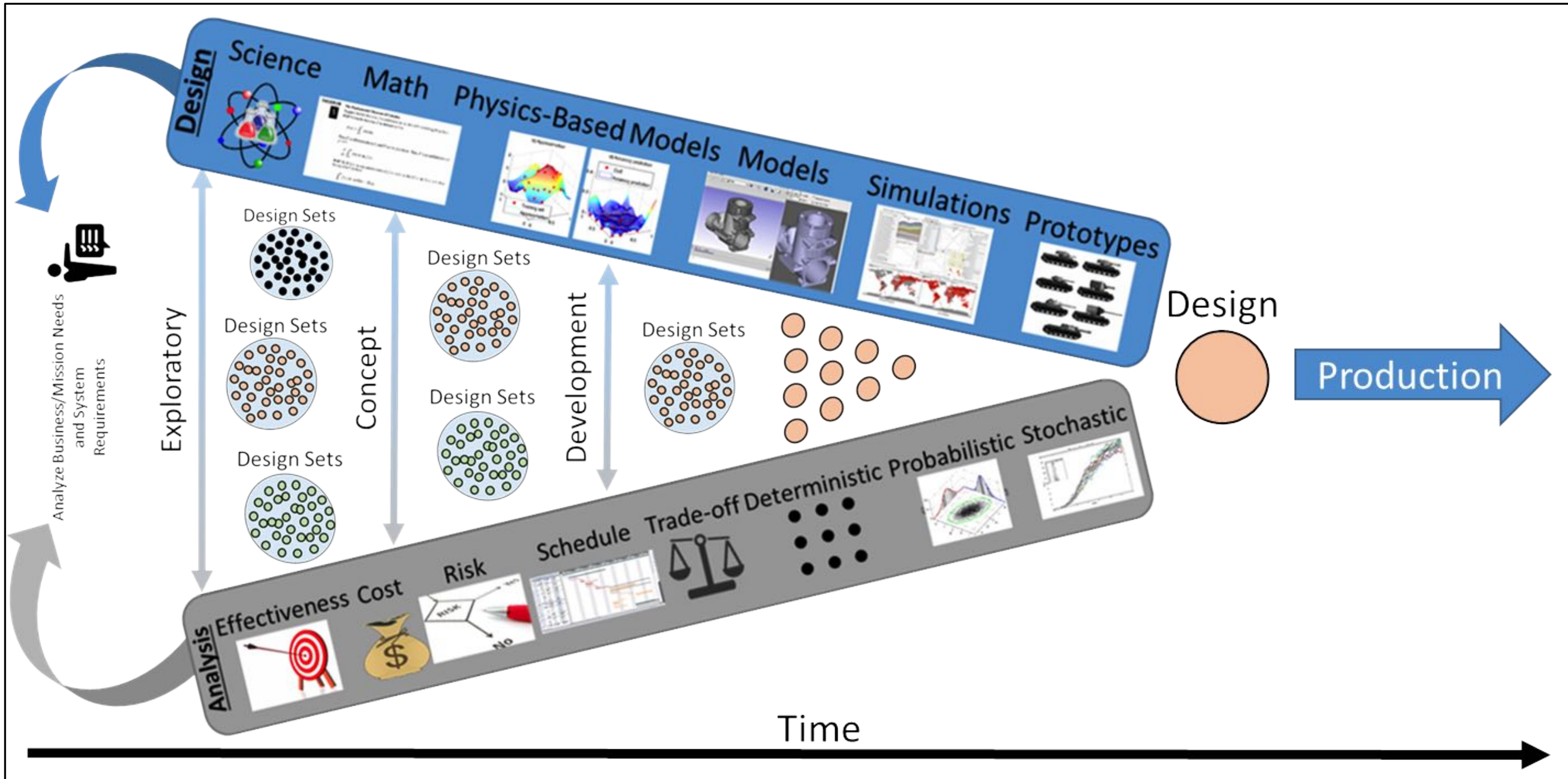
INTRODUCTION

D. J. Singer, N. Doerry, and M. E. Buckley, "What Is Set-Based Design?," Naval Engineers Journal, vol. 121, no. 4, pp. 31–43, 2009.

Commercial and government organizations have used Set-Based Design.

Literature lacks insights on how to implement SBD in a team-based environment.

SBD Visualization

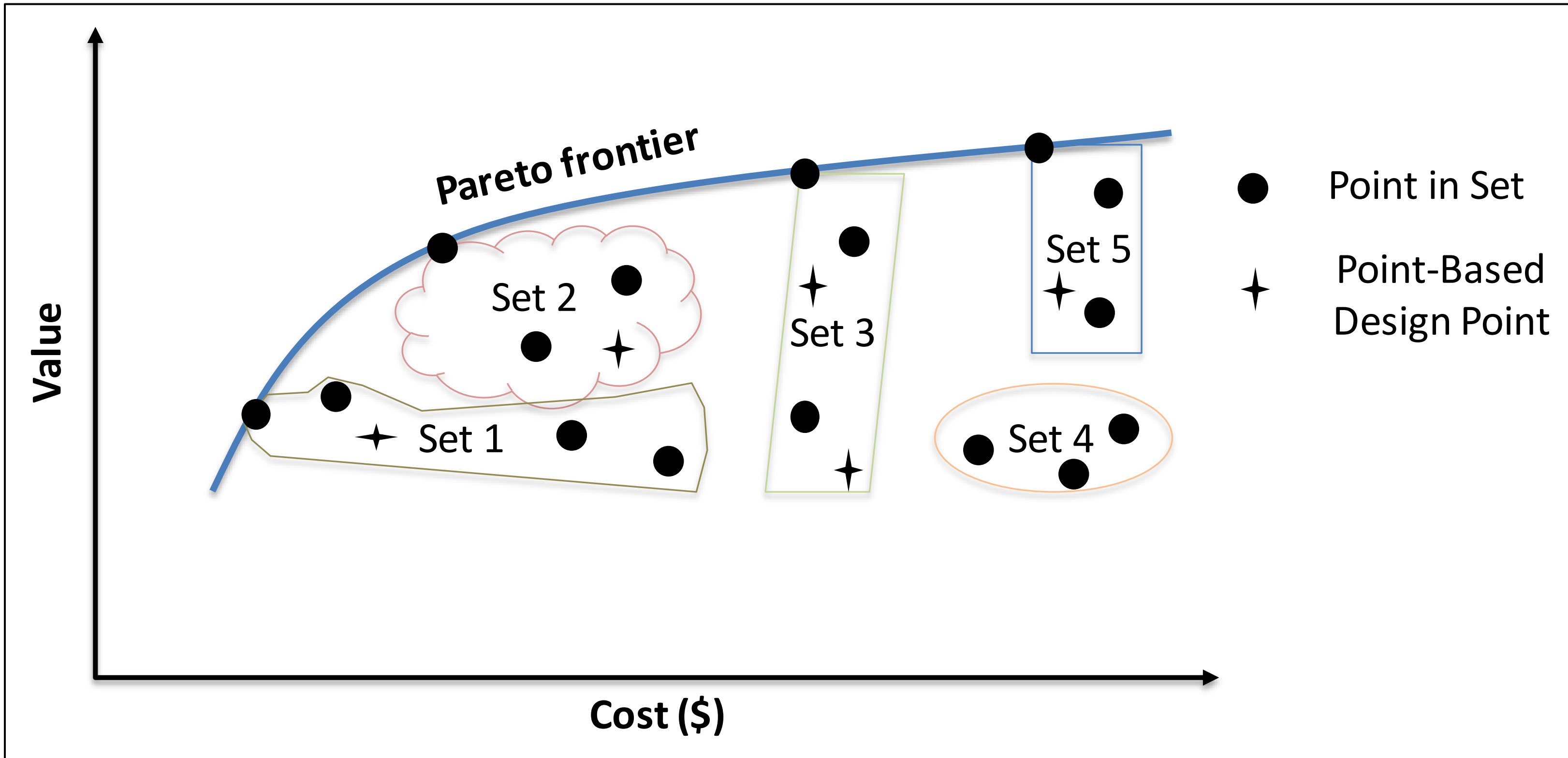


1. **Singer et al. do not provide how to perform SBD. This figure provides a visual representation that encompasses Singer et al.'s SBD characteristics.**

2. **SBD requires design and analysis techniques to perform uncertainty resolution and assess design feasibility on the large number of alternatives.**

Specking, E., Shallcross, N., Parnell, G., Pohl, E., Goerger, S., Informing Early System Requirements and Design Decisions using Set-Based Design. Systems Engineering. (In progress 2019)

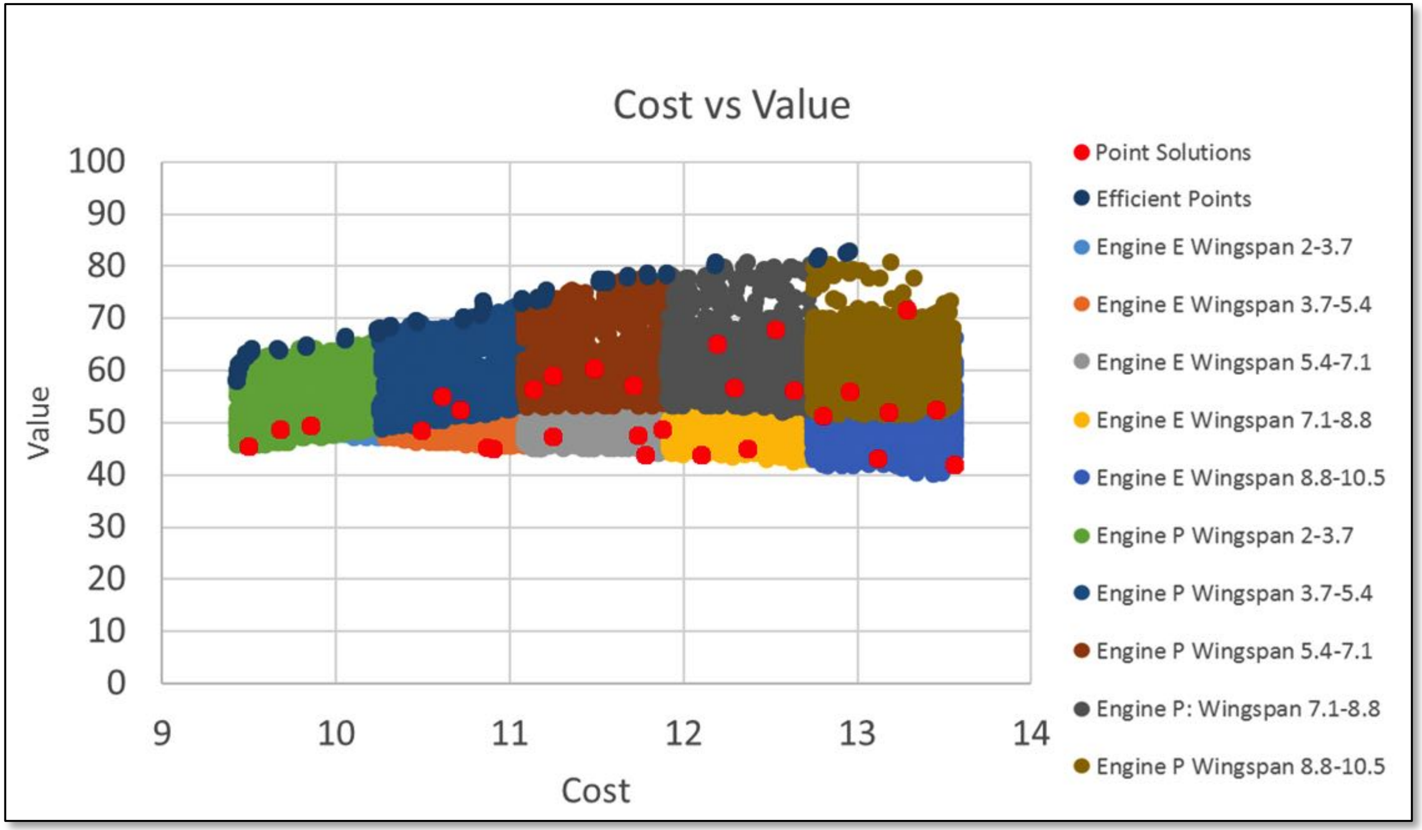
Trade-off Analytics with Point-Based vs. Set-Based Design



1. **Design points can be grouped in sets.**
2. **SBD seeks to identify the most promising sets.**

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

PBD vs. SBD In Practice



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

2. **In iteration 2 of the notional case study, SBD identified improved solutions compared to the original 32 point solutions.**

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.

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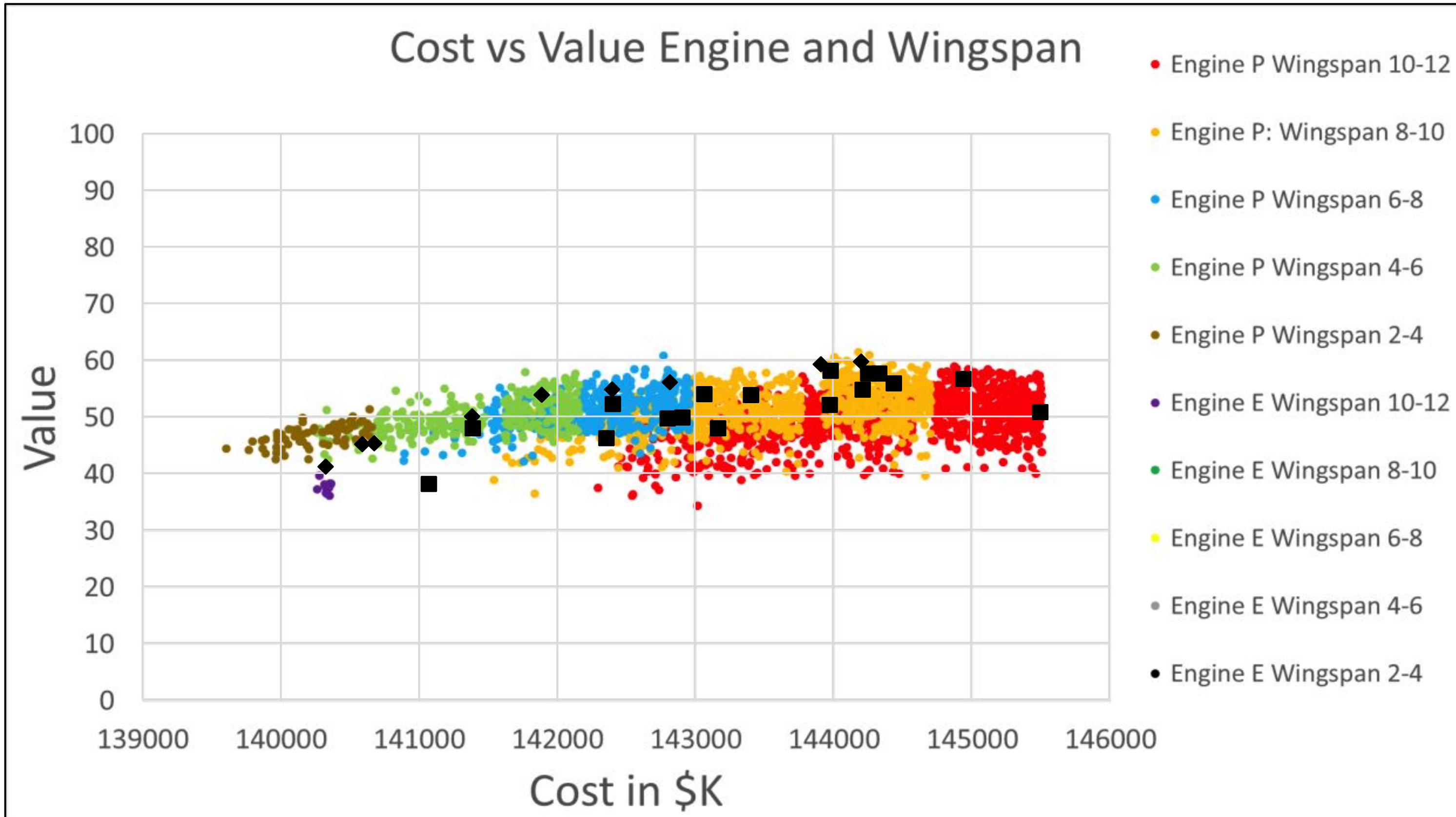
SBD TSE Validation Process

100,000 SBD Points with Genetic Algorithm Points



1. **Initial Goal: Use optimization to validate SBD.**
2. **Heuristic algorithms are commonly used to find efficient design points.**
3. **Validation process using Excel's genetic algorithm in Solver (evolutionary) coded into a custom macro to vary cost and find maximum value.**

TSE with SBD found 189 design points that dominated the genetic algorithm points!

Specking, E., Parnell, G., Pohl, E., Buchanan, R., "Evaluating a Set-Based Design Tradespace Exploration Process," 17th Annual Conference on Systems Engineering Research, April 3-4, 2019

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Design Sets

1. **Design decisions can be discrete or continuous**
2. **Performance calculated based on design decisions and scenarios**
3. **Types (mutually exclusive and collectively exhaustive)**
   a. **Design set drivers: fundamental design decisions that define platform characteristics for future missions**
   b. **Design set modifiers: design decisions that are "added on" to the platform and can be modified to adapt to new missions and/or scenarios**

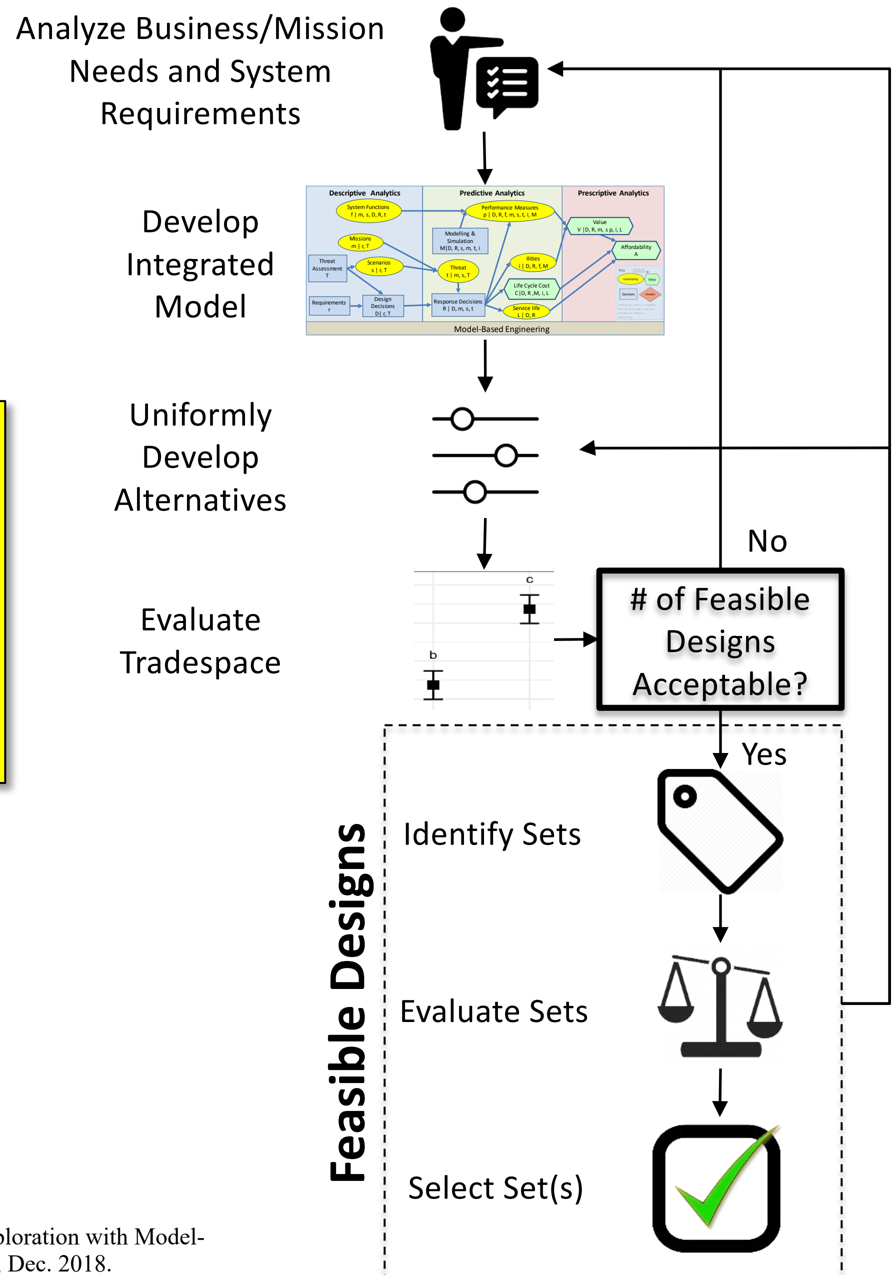
SBD requires a methodology to identify the set drivers.

Specking, E., Whitcomb, C., Parnell, G., Goerger, S., Pohl, E., Kundeti, N., "Literature Review: Exploring the Role of Set-Based Design in Trade-off Analytics," Naval Engineers Journal, American Society of Naval Engineers, Volume 130, Number 2, 1 June 2018, pp. 51-62.

Early Design SBD Process

1. **7 step process to use SBD with the Integrated Trade-off Analysis Framework in early system design.**

2. **Informs requirements and converges to a set of sets to carry to next design phase.**



Specking, E., Parnell, G., Pohl, E., and Buchanan, R., "Early Design Space Exploration with Model-Based System Engineering and Set-Based Design," *Systems,* vol. 6, no.4, p. 45, Dec. 2018.

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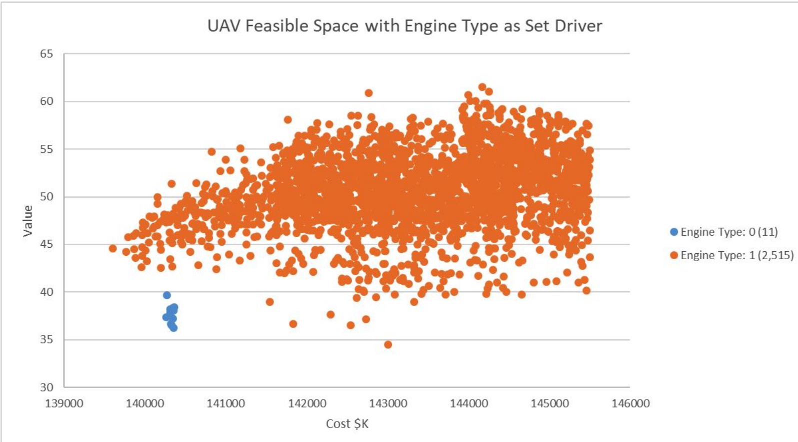
Assess Design Decisions with Sets

1



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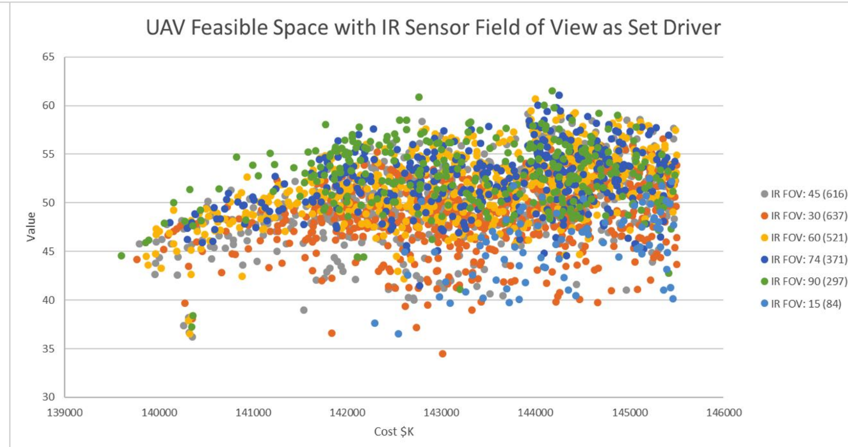

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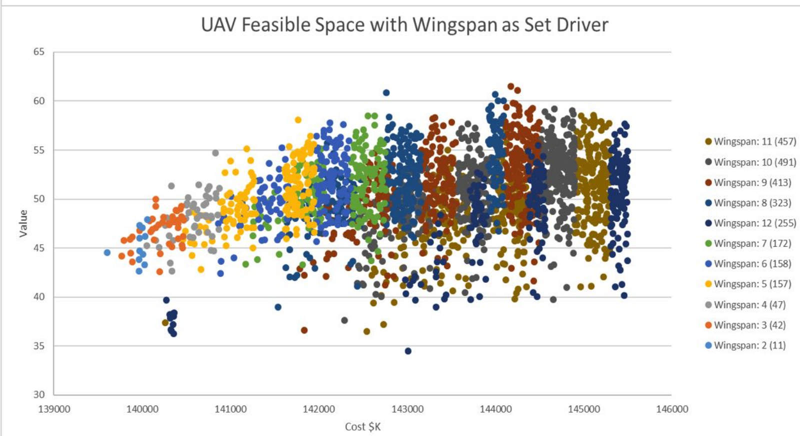

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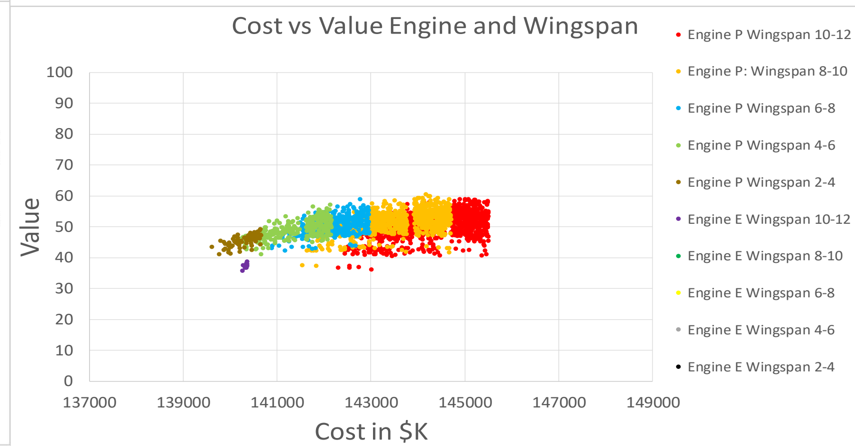

Sets provide insights about design decisions not obvious using points alone.

1. **Less than 1% of blue engines are feasible (11 out of 500,000)**
2. **IR Sensor Field of View not a useful set driver (requires more analysis)**
3. **Wingspan may be a useful set driver**
4. **Combination of engine and wingspan provides additional information**

Parnell, G.S., Specking, E., Cilli, M., Goerger, S., & Pohl, E., "Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions, INCOSE International Symposium, Orlando, FL, July 20-25, 2019

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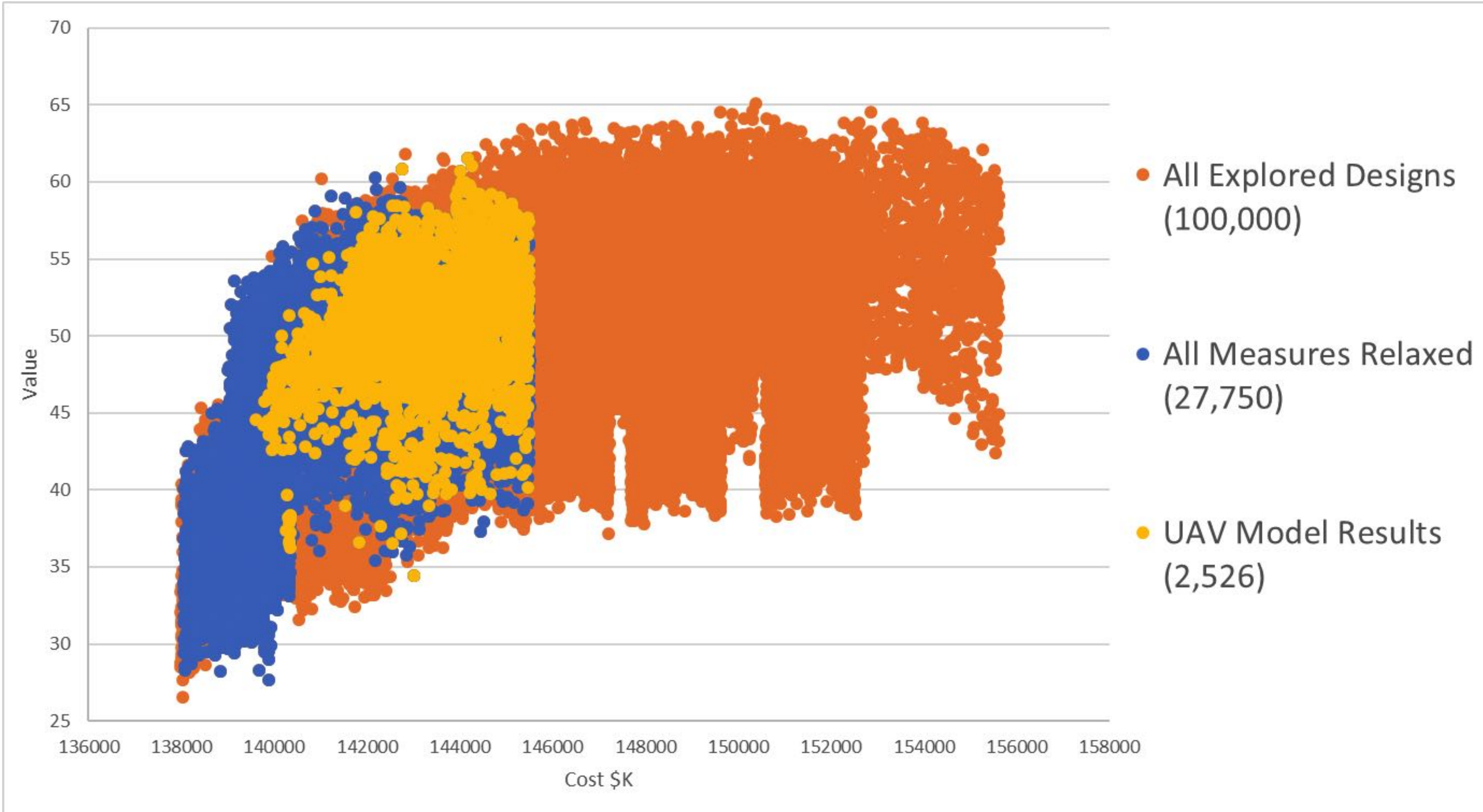
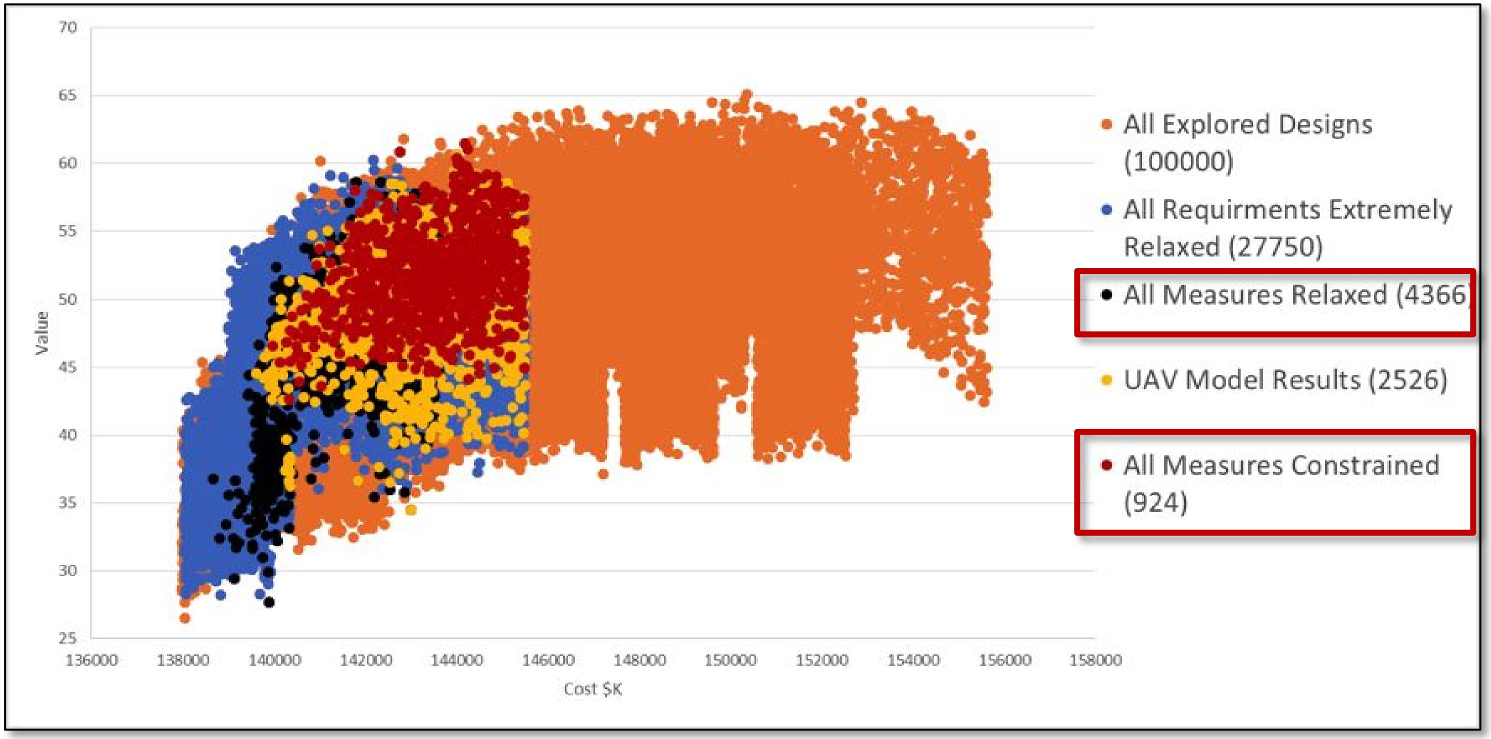
Requirements Analysis with SBD



Physics-based parametric models removed 72% of the tradespace (orange to blue). The remaining 28% is determined by requirements.

Parnell, G.S., Specking, E., Cilli, M., Goerger, S., & Pohl, E., "Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions, INCOSE International Symposium, Orlando, FL, July 20-25, 2019

Effects of Changes in All Requirements



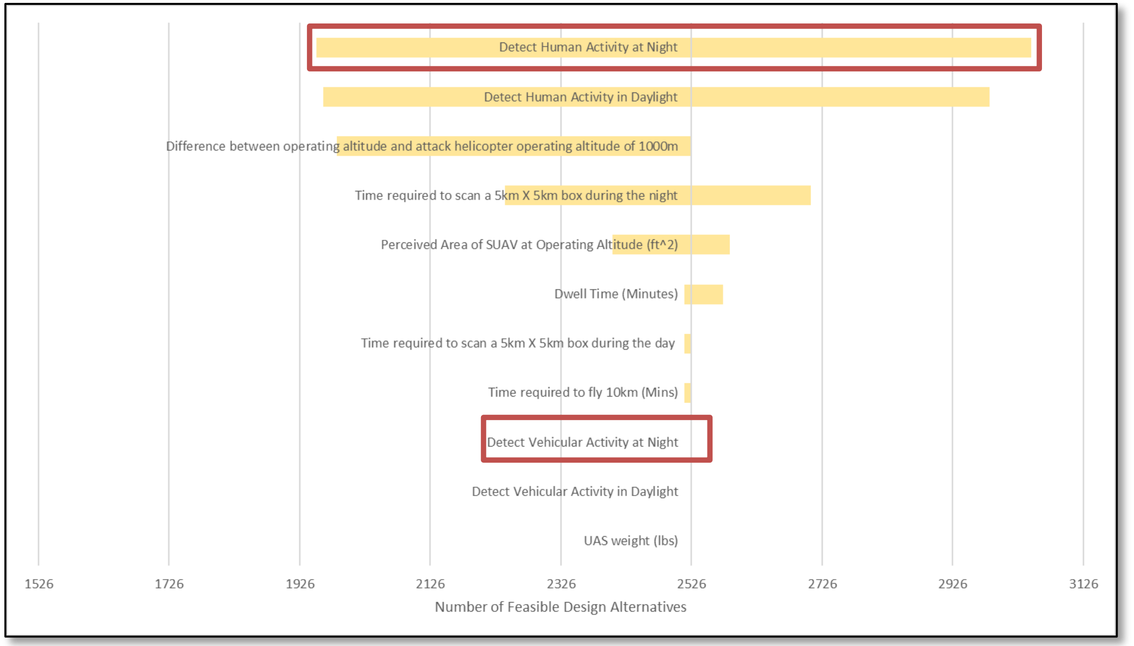
Varying all requirements dramatically changes the number of feasible designs (79% change – 924 to 4366).

1. **Relaxation: 4,366 feasible designs**
2. **Constrained: 924 feasible designs**

Parnell, G.S., Specking, E., Cilli, M., Goerger, S., & Pohl, E., "Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions, INCOSE International Symposium, Orlando, FL, July 20-25, 2019

Effects of individual requirement changes

Performance Measure	Relaxed	UAV Case Study	Constrained
UAS weight (lbs)	60	50	40
Time required to fly 10km (minutes)	20	15	10
Time required to scan a 5km X 5km box during the day (minutes)	220	200	180
Time required to scan a 5km X 5km box during the night (minutes)	220	200	180
Dwell Time (minutes)	30	60	90
Perceived Area of SUAV at Operating Altitude (ft^2)	18	16	14
Difference between operating altitude and attack helicopter operating altitude of 1000 m	0	0	250
Detect Human Activity in Daylight	0.5	0.6	0.7
Detect Vehicular Activity in Daylight	0.5	0.6	0.7
Detect Human Activity at Night	0.5	0.6	0.7
Detect Vehicular Activity at Night	0.5	0.6	0.7



Not all requirements have a significant impact on the feasible tradespace.

1. **<u>Detect Human Activity at Night</u>: Impacts the number of feasible designs**
2. **<u>Detect Vehicular Activity at Night</u>: No impact on the number of feasible designs**

Parnell, G.S., Specking, E., Cilli, M., Goerger, S., & Pohl, E., "Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions, INCOSE International Symposium, Orlando, FL, July 20-25, 2019

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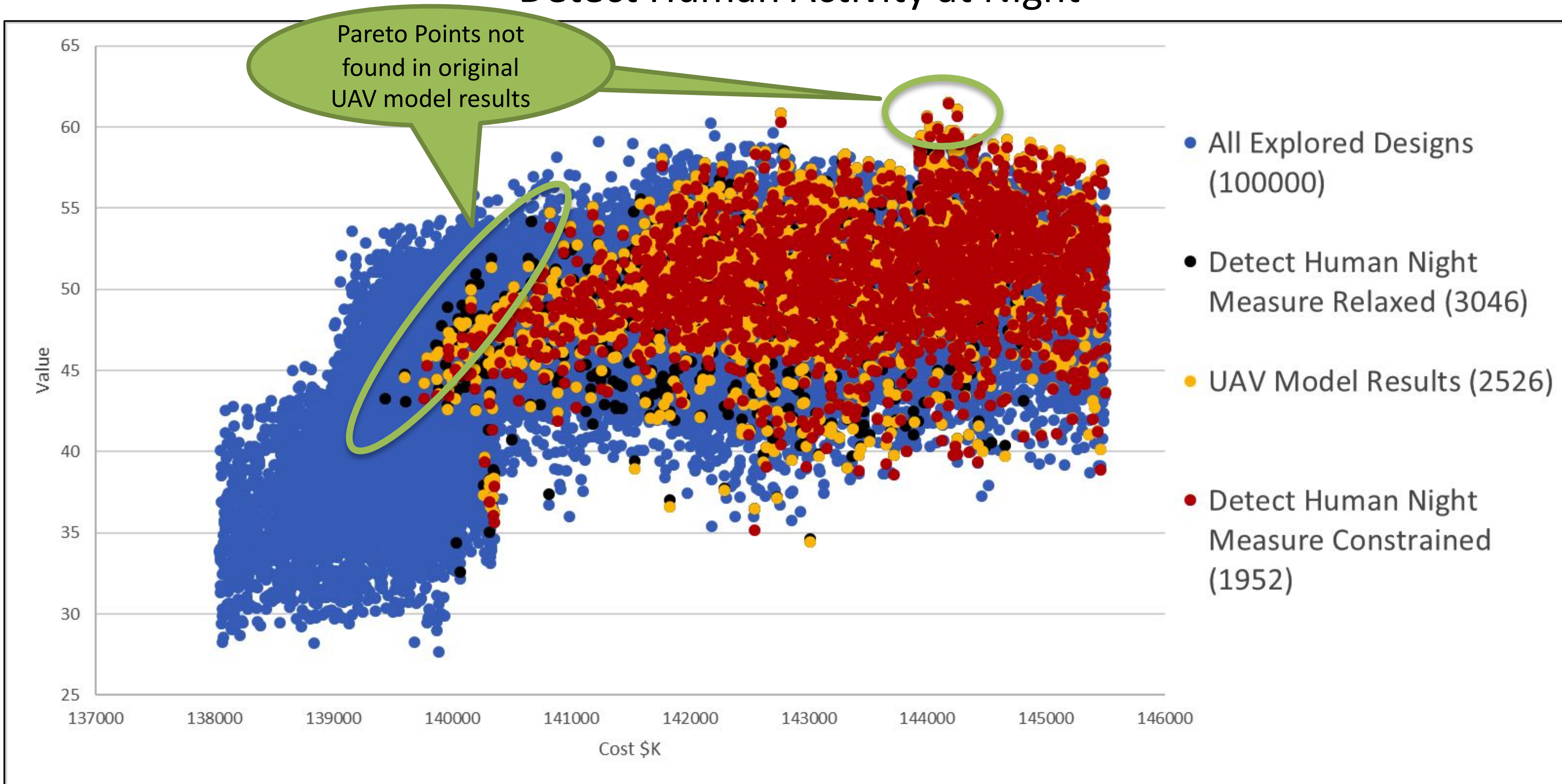
Evaluating the Design Space

Detect Human Activity at Night



Changing the tradespace has the potential to generate Pareto solutions not found in the original analysis.

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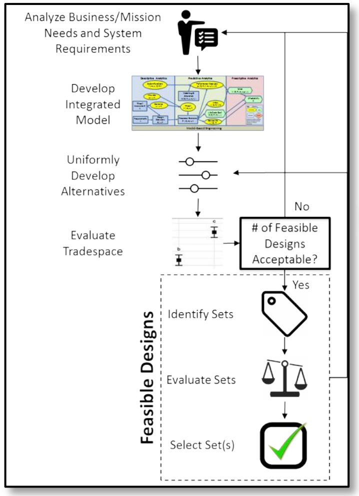
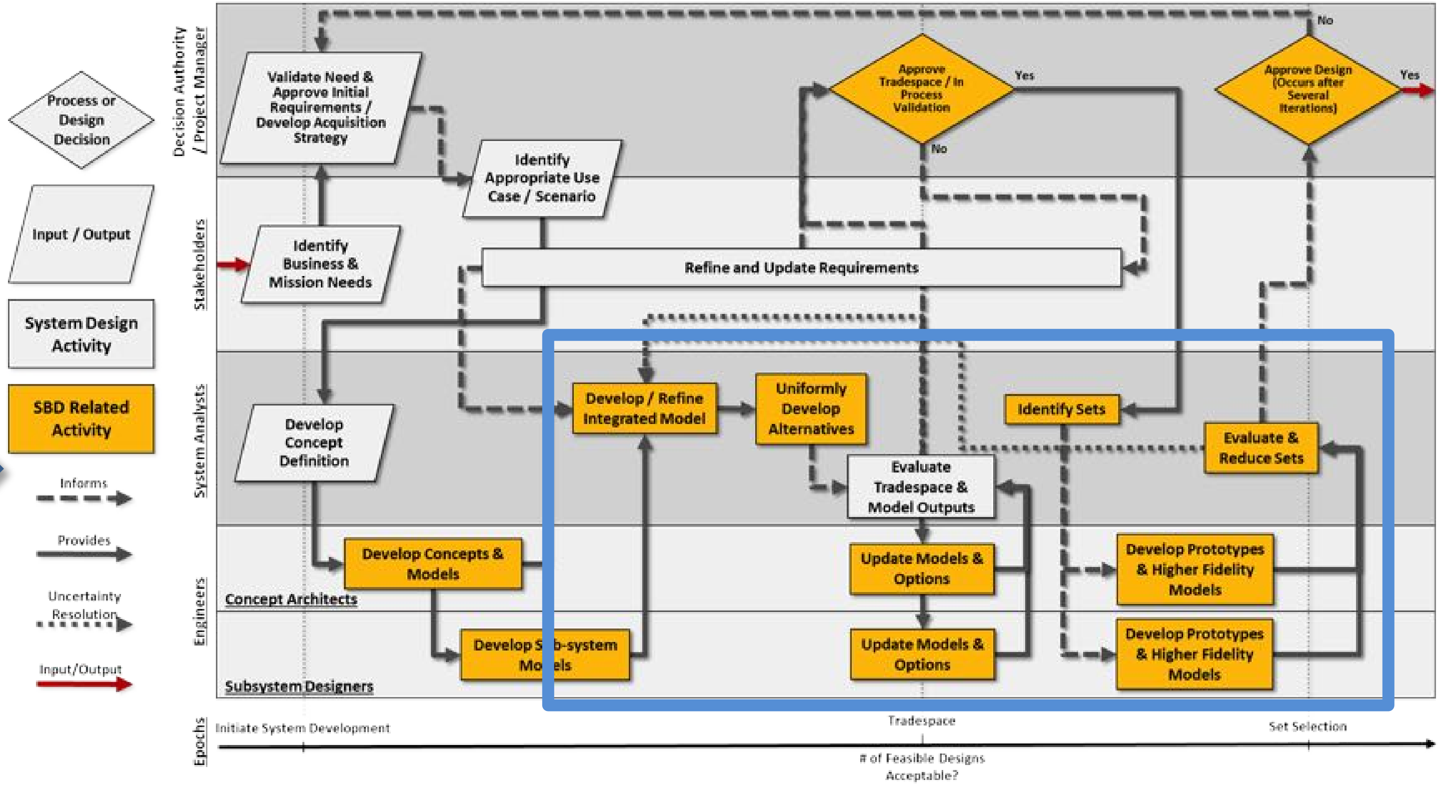
Early Design SBD Process

System Analysis View (Technical)



System Engineering View (Socio-technical)



SBD requires greater analytical effort than traditional PBD methods. The added cost is justified by the potential for increased program resilience under uncertainty and greater potential to develop better system designs.

This process captures the <u>right information</u> from the <u>right people</u> at the <u>right time</u> and executes the <u>analytics in near real-time</u>.

Specking, E., Parnell, G., Pohl, E., and Buchanan, R., "Early Design Space Exploration with Model-Based System Engineering and Set-Based Design," *Systems,* vol. 6, no.4, p. 45, Dec. 2018.

Specking, E., Shallcross, N., Parnell, G., Pohl, E., Goerger, S., Informing Early System Requirements and Design Decisions using Set-Based Design. Systems Engineering. (In progress 2019)

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Example of removing dominated design decision options with EO sensor design teams interaction.

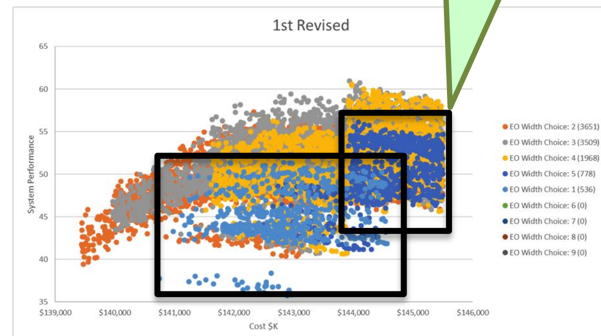
EO Width 6 (13 points), 7, 8, and 9 (0 points)

A. Original

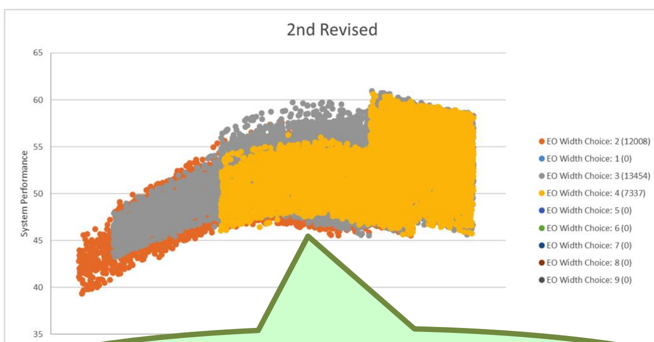
1. **SBD iterations helps remove sets and enables conversations among design teams about requirements and design options.**
2. **This is the major part of SBD missing in the literature.**

EO Width 1 (536 points) & 5 (778 points)

B. 1st Revised

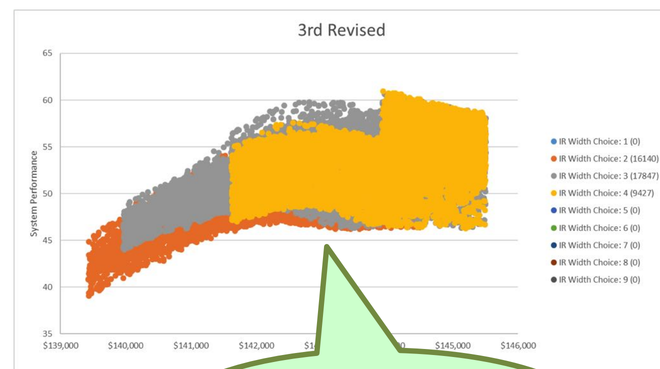


C. 2nd Revised



Keep remaining EO Width Sets (2, 3, & 4).
Remove EO/IR FOV sets based upon separate analysis.

D. 3rd Revised



Nothing removed
Final Tradespace

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Summary of Tradespace Refinement Results for All Design Teams

Decision Options Removed

Design Decision	Tradespace: Initial	Tradespace: 1st Revised	Tradespace: 2nd Revised
Wingspan			
Engine Type	E		
Operating Altitude	600 – 1000		
EO Sensor Width	6 – 9	1, 5	
EO Sensor Field of View		15	30
IR Sensor Width	6 – 9	1, 5	
IR Sensor Field of View		15	30

Final Tradespace

Design Decision	Final Decision Options
Wingspan	2 – 12
Engine Type	P
Operating Altitude	300 – 599
EO Sensor Width	2, 3, 4
EO Sensor Field of View	45, 60, 75, 90
IR Sensor Width	2, 3, 4
IR Sensor Field of View	45, 60, 75, 90

1. **Conversations with design teams about requirements and design options should be held with each team of subject matter experts.**
2. **SBD Iteration is repeated until a final tradespace selected dependent upon the project schedule.**

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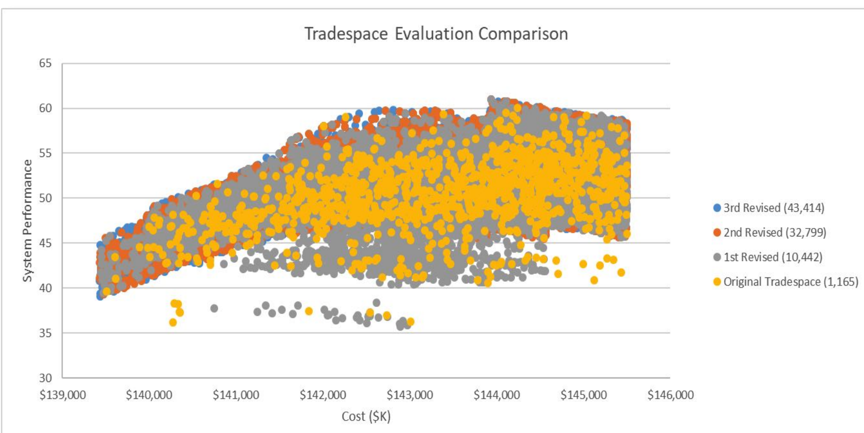
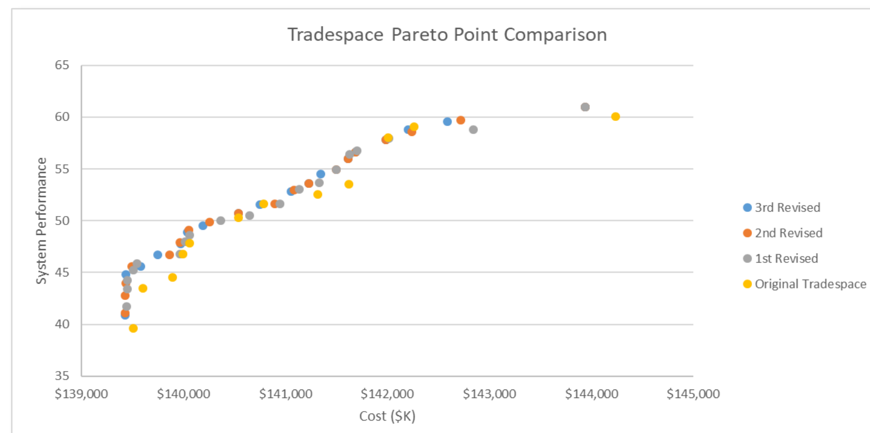
Impact of Tradespace Refinement

Tradespace	Counts			Percentages	
	Sampled	Feasible	Pareto Points	Feasible (of Sampled)	Pareto Points (of feasible)
Initial	100000	1165	12	1.2%	1.03%
1st Revised	100000	10442	19	10.4%	0.18%
2nd Revised	100000	32799	19	33%	0.06%
3rd Revised	100000	43414	18	43%	0.04%





Pareto frontier is not dramatically effected by tradespace refinement process. This demonstrates that SBD finds good design alternatives no matter the feasible space.

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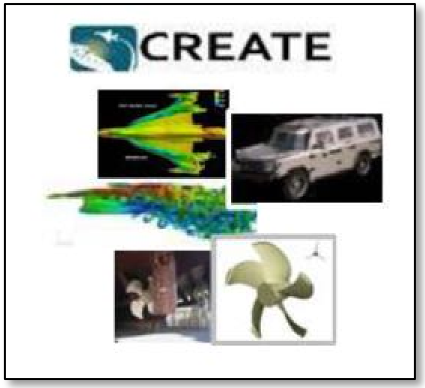
Overview

- UAV Case Study
- Point-Based vs. Set-Based Design
- SBD Implementation
- Design Decision Evaluation
- Requirements Analyses
- System Engineers/Stakeholders Interactions
- SBD Challenges
- Future Research & Summary

Challenges using SBD

1. PBD to SBD culture change
2. Rapid assessment of complex design solutions for viability
3. Mission effects generation and assessment on larger sets of alternatives using M&S
4. Storage, sustainment, and access to large data sets (e.g., tera, peta, exa, etc.) for extended periods of time (decades)
5. Data set linkage across domains and specialties
6. Mathematically sound and repeatable processes for down selecting and grouping viable systems into representative bins for presentation to decision makers



Revised from Specking, E., Whitcomb, C., Parnell, G., Goerger, S., Pohl, E., Kundeti, N., "Literature Review: Exploring the Role of Set-Based Design in Trade-off Analytics," Naval Engineers Journal, American Society of Naval Engineers, Volume 130, Number 2, 1 June 2018, pp. 51-62.

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Future Research

Development of a Model-Based System Engineering Framework suitable for SBD that includes:

1. **Integrated modeling of value, cost, and risk**
2. **Multi-resolution M&S**
3. **Uncertainty resolution**
4. **High fidelity supportability models**
5. **High fidelity cost models**

Look for strategic partners to help integrate SBD into your system engineering processes.

For example, SBIR research.

Proceedings of the American Society for Engineering Management 2019 International Annual Conference
E. Schott, E-H. Ng, H. Keathley, and C. Krejci eds.

INTEGRATING SET-BASED DESIGN INTO THE DEPARTMENT OF DEFENSE ACQUISITIONS SYSTEM TO INFORM PROGRAMMATIC DECISIONS

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Abstract
Over the years, the Department of Defense (DoD) has implemented several significant modifications to its acquisition process with the goal of producing timely and cost-effective systems. These changes, however, have done little to curb major design problems, delays and cost overruns to programs. Many DoD acquisition programs use Point-Based Design (PBD) approaches in system development, frequently resulting in premature design decisions resulting in subsequent schedule delays, and cost overruns. Delays and increased costs are a result of the time-consuming activities undertaken to fix the selected PBD solution prior to the resolution of key technology and budget uncertainties. Set-Based Design (SBD) is a concurrent system design and analysis alternative to PBD, which systematically resolves program uncertainties early in the design phase, potentially reducing the need for costly and inefficient redesign activities. In application, SBD evaluates multiple design concepts for a longer period of time into the design process, while simultaneously resolving requirements and design uncertainties. Commercial manufacturing and defense related industries have successfully employed SBD in product development (PD). This success suggests that a DoD feasibility and integration assessment of an SBD process for PD of a large-scale DoD acquisition programs is required. This research reviews current DoD acquisition processes, provides a strategic framework for SBD integration into these processes, and identifies critical integration challenges for future research. This paper concludes that integration of SBD into major DoD acquisition processes is both feasible and economical, as well as a credible and defensible methodology for making complex design decisions under uncertainty.

Keywords
Set-Based Design, Defense Acquisition, Decision Analysis, Model-Based Systems Engineering, Uncertainty Resolution, Tradespace Exploration

Introduction
The United States Department of Defense (DoD) currently invests trillions of dollars into weapon system research, development, and acquisition (United States Government Accountability Office, 2017). Responsibility for this significant investment lies with an equally large and complex defense acquisition system; a system that has periodically implemented significant changes to address the root causes of costly systemic problems and risks. Since the 1990s, the Government Accountability Office (GAO) has identified DoD weapon system acquisitions as a high-risk area. The reason for this perpetual designation lies within a history of significant and unanticipated cost and schedule growth, resulting in numerous Nunn-McCurdy cost breaches (United States Government Accountability Office, 2013). To address these continuing issues, the DoD published Department of Defense Instruction (DoDI) 5000.02 for the Operation of the Defense Acquisition System. This document significantly increased emphasis on

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Demonstrating Set-Based Design Concepts in Support of U.S. Army Acquisition Decisions

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Summary

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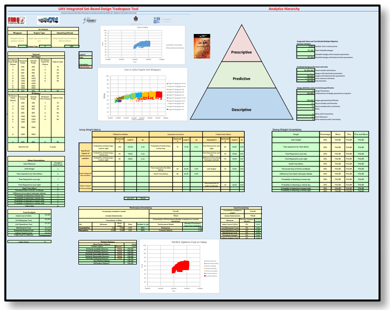
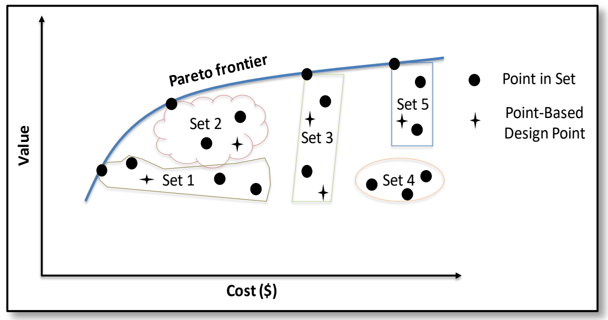
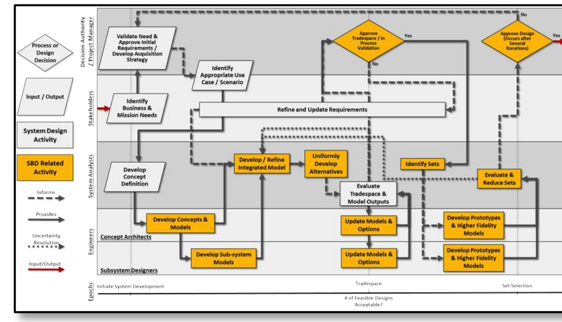
SBD UAV Demonstration Model



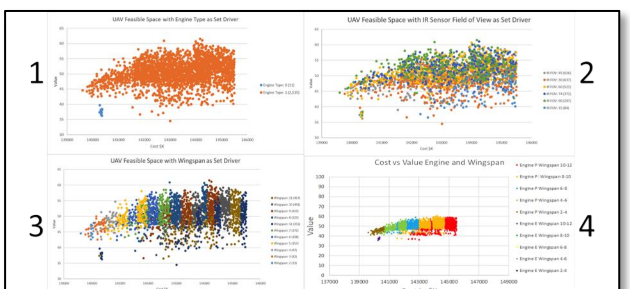
SBD vs. PBD



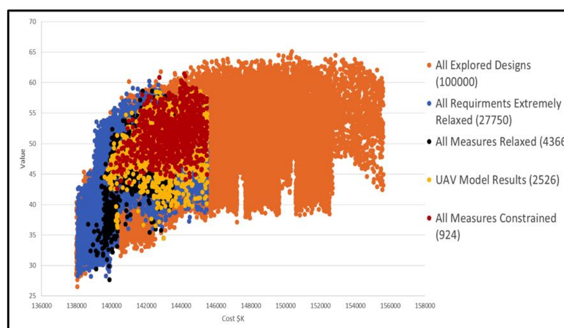
SBD Implementation



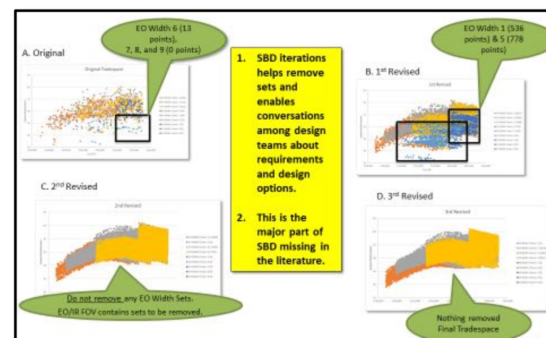
SBD Helps Assess Design Decisions



SBD Helps Assess the Impact of Requirements on the Feasible Tradepsace



SBD Helps to Inform System Engineers and Stakeholders



SBD Process for Early Design

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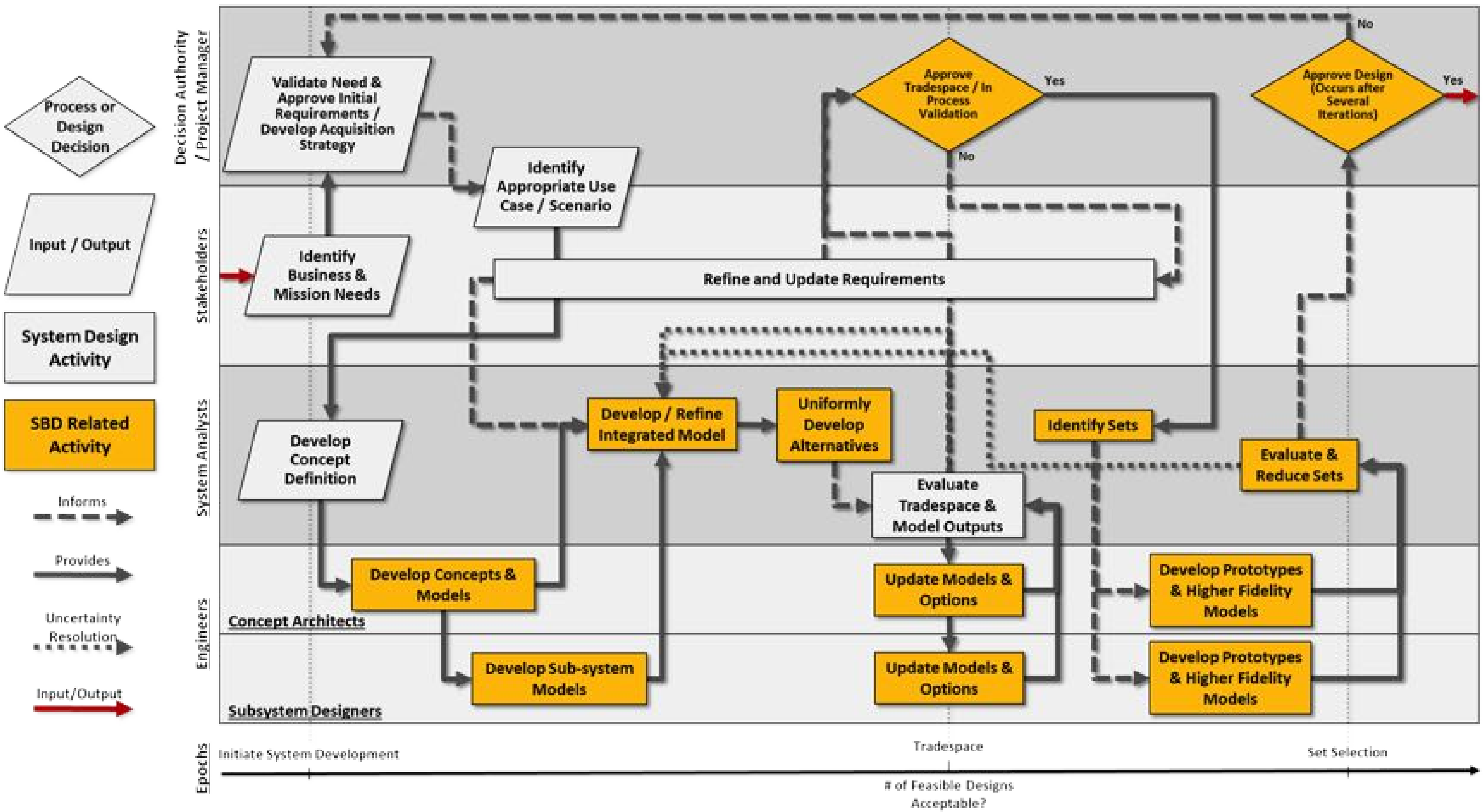

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Requirement Change Overview

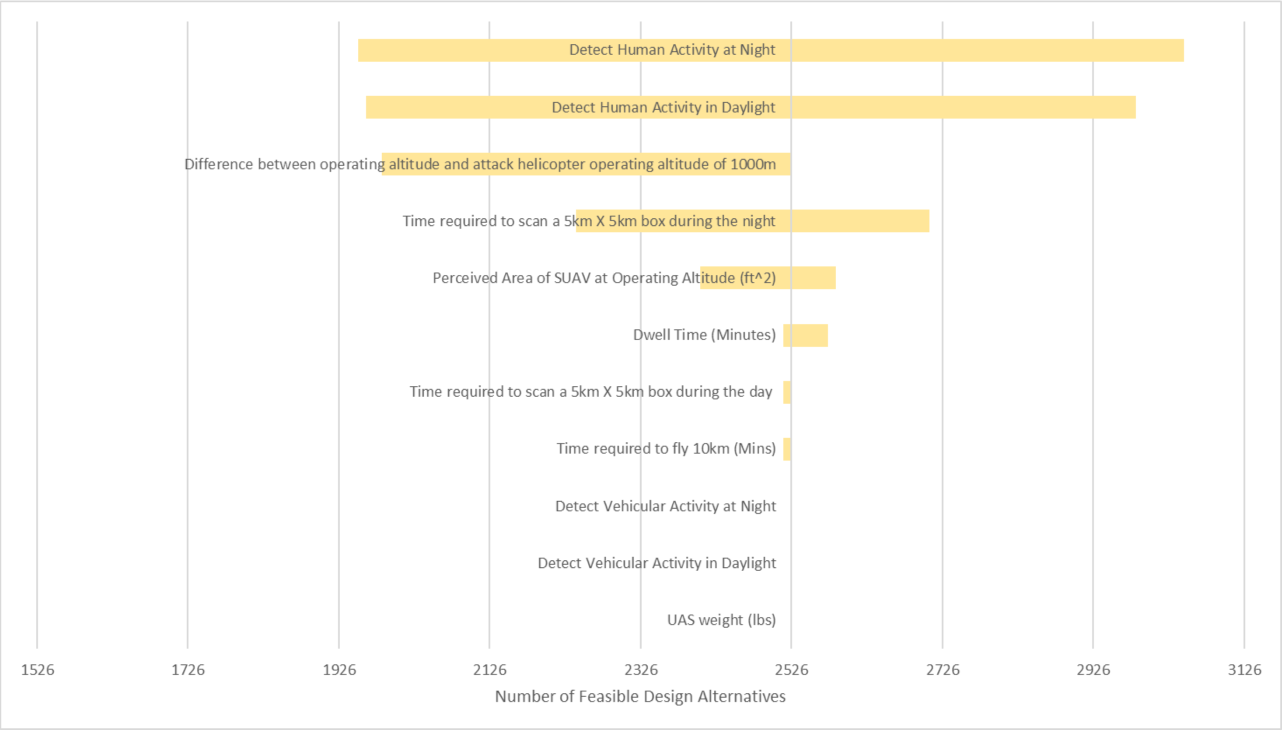
Scenario	Feasible Designs
All Explored Designs	100000
All Requirements Extremely Relaxed	27750
All Measures Relaxed	4366
UAV Model Results	2526
All Measures Constrained	924

Measure	Relaxed	Constrained	Difference
UAS weight (lbs)	2526	2526	0
Time required to fly 10km (Mins)	2526	2515	11
Time required to scan a 5km X 5km box during the day	2526	2515	11
Time required to scan a 5km X 5km box during the night	2709	2241	468
Dwell Time (Minutes)	2574	2515	59
Perceived Area of SUAV at Operating Altitude (ft^2)	2585	2405	180
Difference between operating altitude and attack helicopter operating altitude of 1000m	2526	1983	543
Detect Human Activity in Daylight	2983	1962	1021
Detect Vehicular Activity in Daylight	2526	2526	0
Detect Human Activity at Night	3046	1952	1094
Detect Vehicular Activity at Night	2526	2526	0

Parnell, G.S., Specking, E., Cilli, M., Goerger, S., & Pohl, E., “Using Set-Based Design to Inform System Requirements and Evaluate Design Decisions, INCOSE International Symposium, Orlando, FL, July 20-25, 2019

Infeasibility

- Physics
  - Appropriate payload (Max payload ≥ total payload weight)
- Requirements (minimum acceptable)
  - UAV Weight (total payload weight)
  - Probability of detecting human day
  - Probability of detecting human night
  - Time required to scan box during day
  - Time required to scan box during night
- All others produce all feasible solutions no matter decision variables combination



1. Both analyses are consistent.

2. The payload weight effects requirements, but the total UAV weight does not effect feasibility

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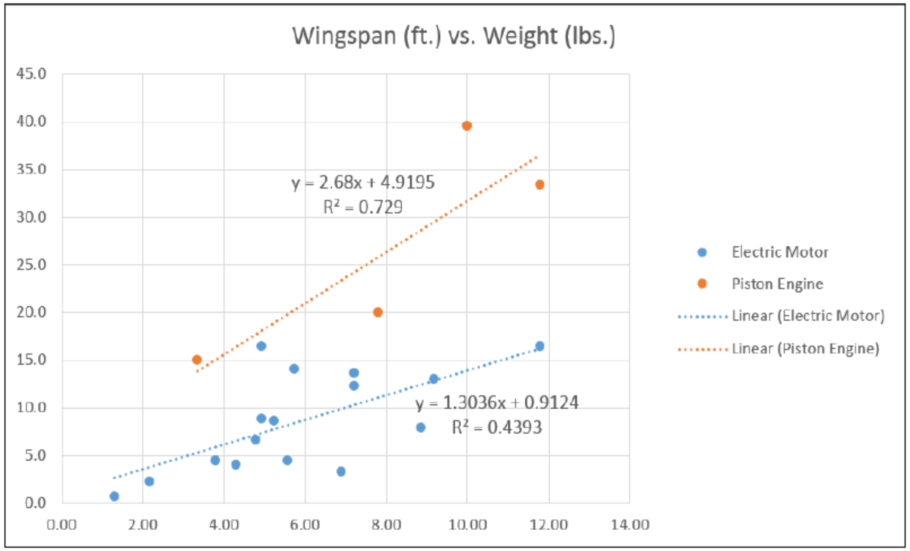
Infeasibility Based upon Physics



Fly Weight

$If\ Electric\ Engine: Fly\ Weight\ (lbs.) = Wingspan * 1.3 + 0.91$

$if\ Piston\ Engine: Fly\ Weight\ (lbs.) = Wingspan * 2.68 + 4.92$

Max Payload

$If\ Electric\ Engine: Max\ Payload\ (lbs.) = FlyWeight * 0.18$

$If\ Piston\ Engine: Max\ Payload\ (lbs.) = FlyWeight * 0.31$

$Total\ Payload\ Weight = Sensor\ Weight + Communications\ Weight$

$Communications\ Weight = notionally\ assumed\ 0.5\ lbs.$

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

1. **EO Sensor selection effects the UAV payload weight.**
2. **Appropriate Payload = total payload weight < Max payload**

Engine Type P; Wingspan 12 Appropriate Payload (part of value cal)

IRWidth EOWidth

FALSE	1	2	3	4	5	6	7	8	9
1	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
2	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
3	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
4	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
5	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
6	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
7	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
8	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
9	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

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Infeasibility Based upon Requirements

$$\textit{Fly Weight}$$

$$\textit{If Electric Engine: Fly Weight (lbs.)} = \textit{Wingspan} * 1.3 + 0.91$$

$$\textit{if Piston Engine: Fly Weight (lbs.)} = \textit{Wingspan} * 2.68 + 4.92$$

$$\textit{Max Payload}$$

$$\textit{If Electric Engine: Max Payload (lbs.)} = \textit{FlyWeight} * 0.18$$

$$\textit{If Piston Engine: Max Payload (lbs.)} = \textit{FlyWeight} * 0.31$$

$$\textit{Total Payload Weight} = \textit{Sensor Weight} + \textit{Communications Weight}$$

$$\textit{Communications Weight} = \textit{notionally assumed } 0.5 \textit{ lbs.}$$

Key

Top 50 percentile of value function	3.348514
Minimum requirement ≤ 50th Percentile of value function	49.17342
≤ Minimum requirement	129.0705

1. **If an UAV is feasible based upon physics, minimum requirements can still make a physics based feasibility, infeasible.**

2. **EO Sensor selection effects models provided by sensor design team.**

Total payload weight

IRWidth	EOWidth 1	2	3	4	5	6	7	8	9
1	1	1	2	3	5	8	12	17	23
2	1	2	3	5	8	12	17	23	30
3	2	3	5	8	12	17	23	30	39
4	3	5	8	12	17	23	30	39	49
5	5	8	12	17	23	30	39	49	61
6	8	12	17	23	30	39	49	61	75
7	12	17	23	30	39	49	61	75	91
8	17	23	30	39	49	61	75	91	109
9	23	30	39	49	61	75	91	109	129

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