SAND2013-8516C

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Vehicle Trade Studies with Commonality

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U.S. DEPARTMENT OF ENERGY | NNSA

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Outline

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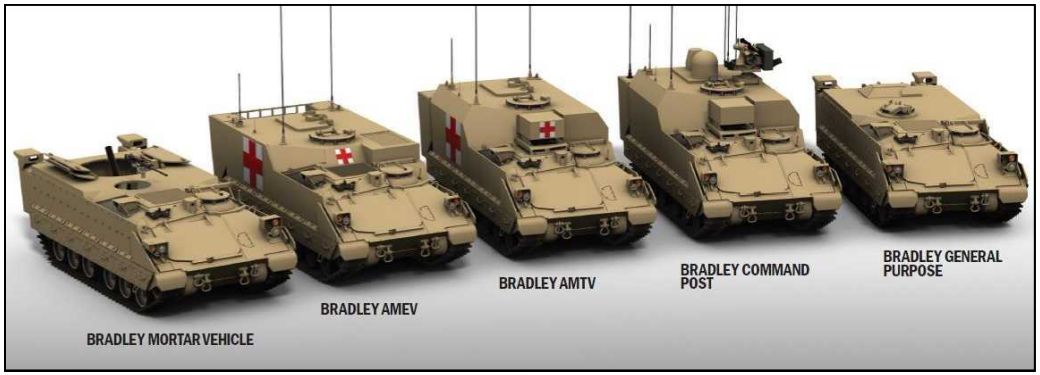
- Commonality Overview
  - In military systems
  - Why it's useful
  - In Whole Systems Trade Analysis Tool (WSTAT)
- Commonality Measures
  - Binary, Harmonic, Linear
  - Hybrid
  - On Multiple Parts
- Post-Hoc Commonality Analysis
- Integrated Commonality Analysis

Commonality Overview

Work Sponsor: Program Executive Office Ground Combat Systems
Project Lead: Shatiel Edwards (PEO GCS)
Sandia Team: Alexander Dessanti, John Eddy, Jack Gauthier, Stephen Henry, Matt Hoffman, Hai Le, Darryl Melander, Frank Muldoon, Adam Pierson, Liliana Shelton



The Armored Multi-Purpose Vehicle (AMPV) program is modernizing its fleet of aging M113s to family of Bradley variants. These variants need to perform as well as possible in their various missions roles. Yet they also need to have a high degree of overlap in their component parts

The Robotic Systems Joint Program Office (RS JPO) currently maintains a very diverse fleet of unmanned ground vehicles. This presents significant challenges (for example, in maintenance and training). If possible, they desire a consolidated fleet of robots with common parts and control systems while maintaining the ability to perform different mission roles

Commonality Overview

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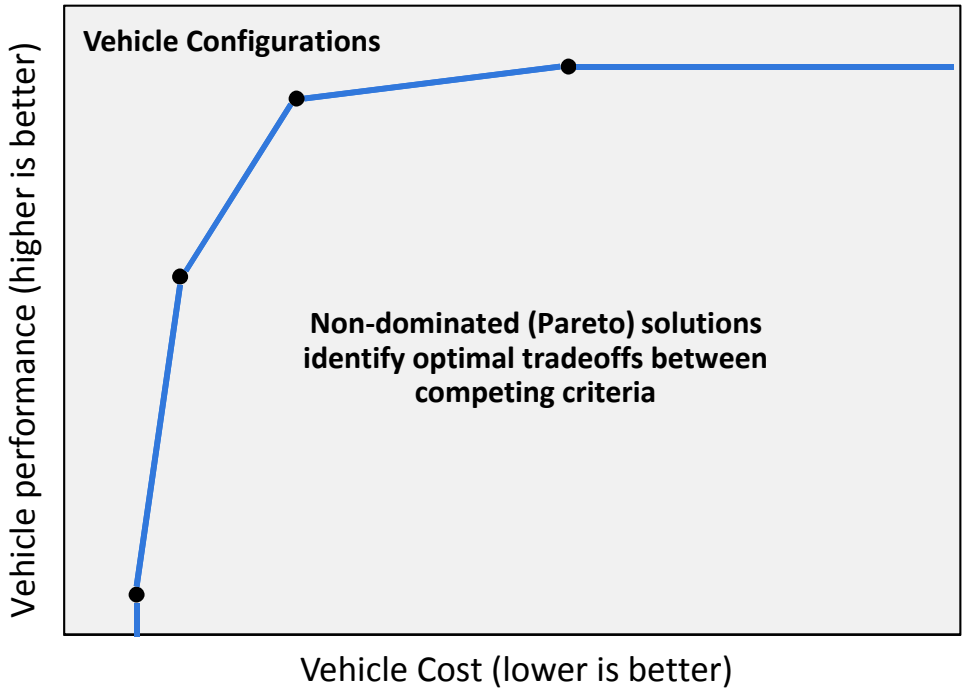
- What do we mean by commonality?
  - When considering multiple vehicle variants in a family of vehicles (FoV), commonality simply refers to using the same parts (technology options) within the vehicles' product structure.
  - For example, using the same engine, suspension, battery system, or camera across a family of vehicles performing different tasks.
- Why is commonality useful?
  - Spare parts can be used in multiple variants
  - Repairs, training, and operations are more consistent
  - Economies of scale
- Tension between commonality and specialization
  - When seeking the absolute best performance for a variant, this often leads to configurations that are highly specific to that variant's needs.
  - Commonality is at odds with the tendency, presenting both mathematical and political challenges

WSTAT Introduction

Whole Systems Trade Analysis Tool

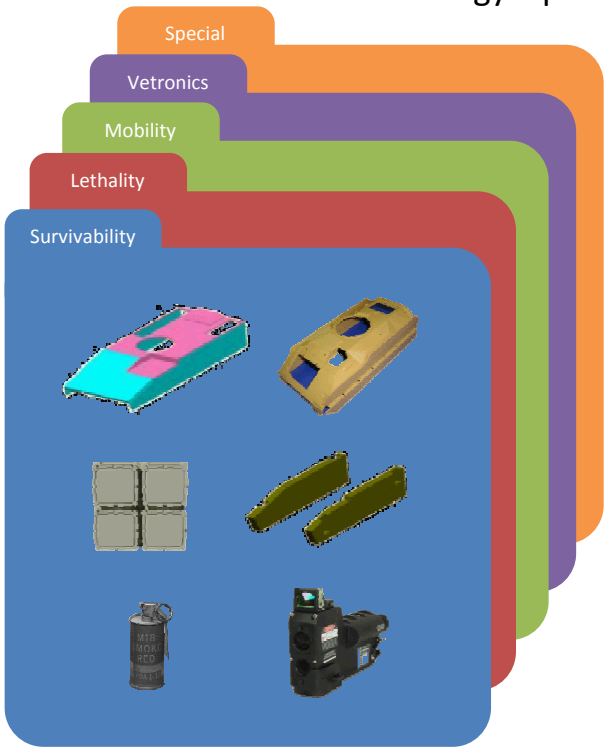
- WSTAT looks at the design of a single vehicle, aggressively examining many potential configurations in an effort to meet multiple competing requirements and objectives.
- WSTAT uses multi-objective optimization to find design "sweet spots." You can't just look at one aspect (such as cost) like nothing else matters.
  - Consider only 2 criteria, cost and performance
  - Same idea applies when balancing more criteria, except that higher-dimensional spaces are required



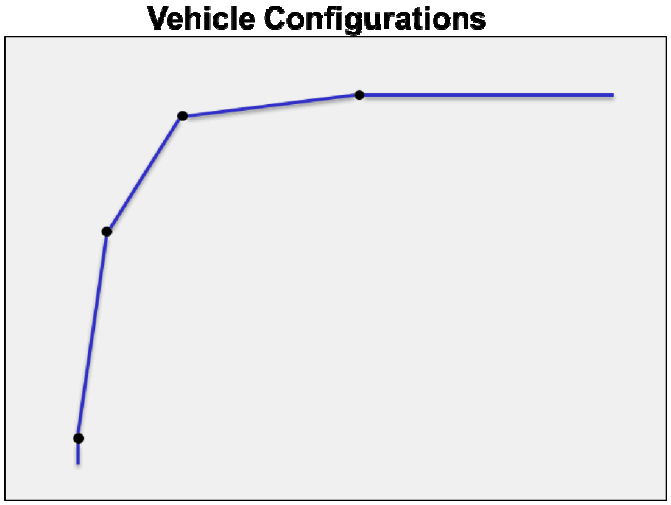
WSTAT Introduction

- WSTAT combines appropriate technology options into a single vehicle configuration, keeping those configurations that best balance competing objectives

Collection of Available Technology Options



Technologies are selected to create configurations

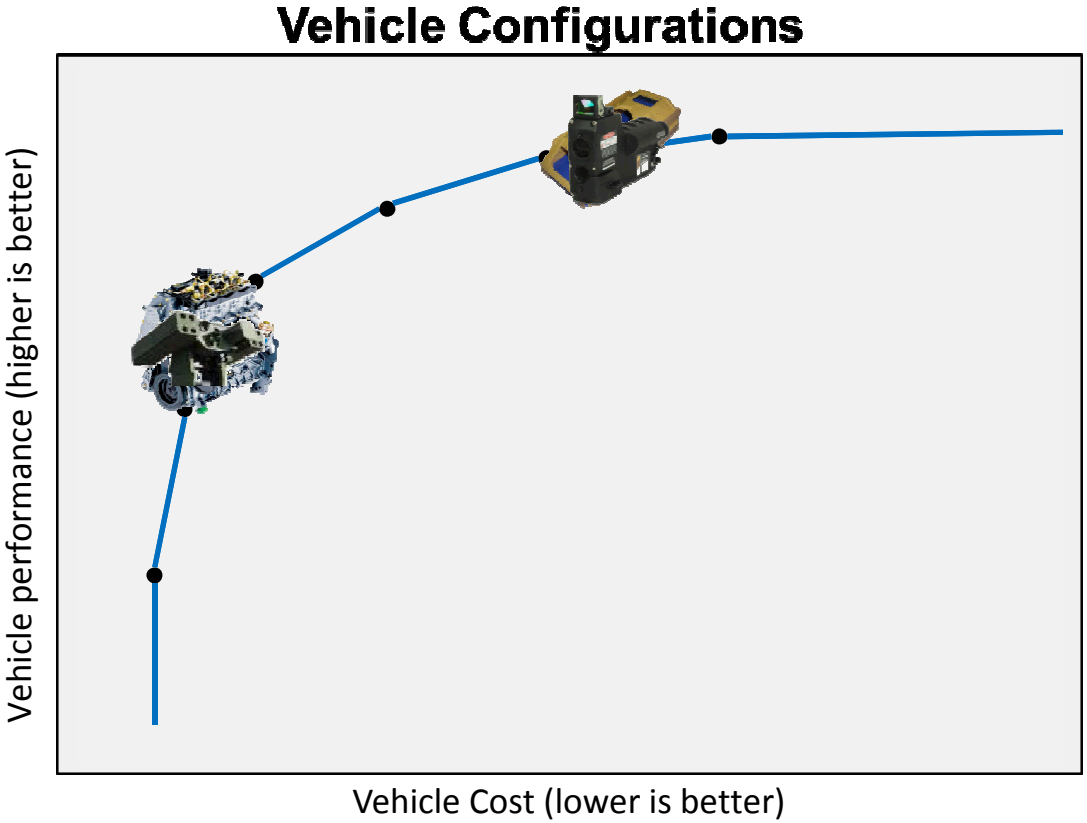


Configurations are scored in 5 value dimensions:

- Performance
- Procurement Cost
- O&S Cost
- Risk (immaturity of technologies)
- Growth (future modification potential)

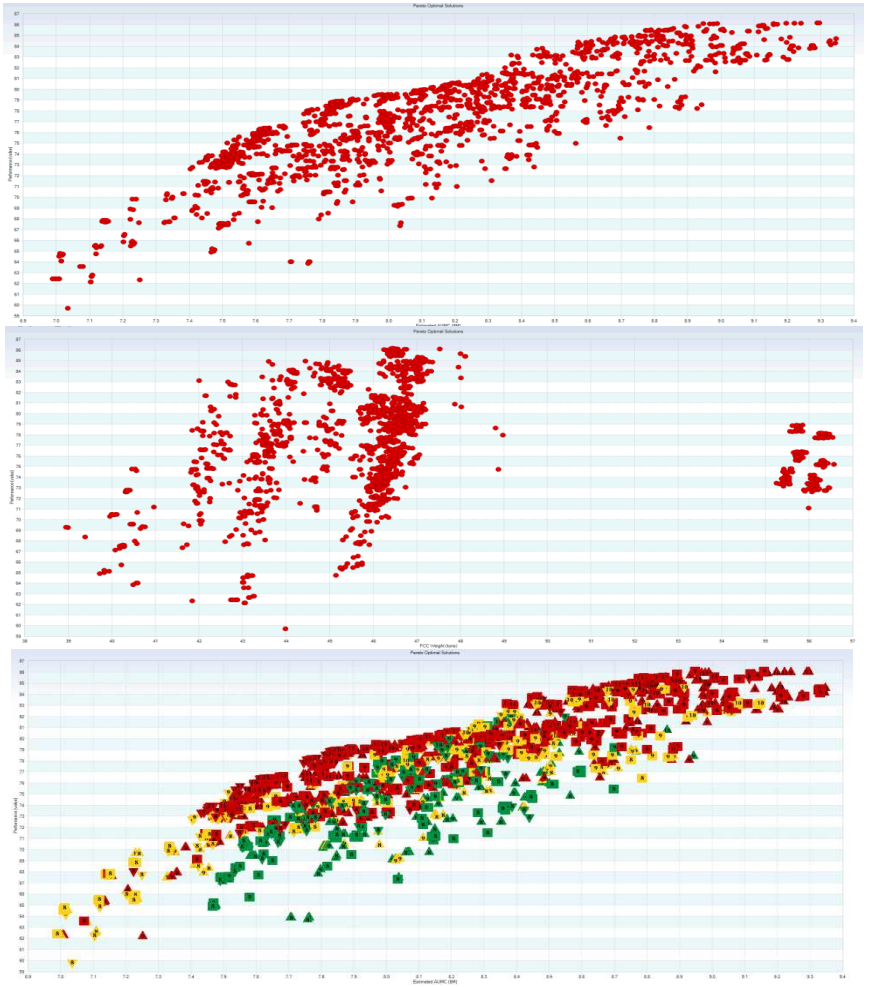
WSTAT Introduction

- WSTAT utilizes a genetic algorithm to search for the configurations that optimally balance the 5 dimensions of performance, procurement cost, O&S cost, risk, and growth
- Finds new solutions by mixing, matching, and mutating aspects of the best solutions found so far
- As it runs, the algorithm finds better and better solution populations



WSTAT Pareto Visualization

- For a single vehicle, WSTAT typically generates around 2000 Pareto optimal configurations
- These configurations can be viewed in multiple ways, including along any two of the 5 objective dimensions
- Can also view all 5 dimensions of optimality simultaneously with coloring and symbols
- WSTAT provides a multitude of advanced methods for filtering and interrogating the solution space

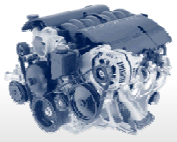
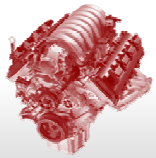


Commonality Measures

- Consider a Family of Vehicles (say, with 4 variants) and a single tech option for which we wish to measure commonality. What are some possible measures?
- Binary
  - $C_b = \begin{cases} 1 & \text{if } \mathbf{all} \text{ variants use same tech option} \\ 0 & \text{otherwise} \end{cases}$
- Harmonic
  - $C_h = \frac{1}{\text{number of different tech options used}}$
- Linear
  - $C_l = \frac{max(\text{number of variants using the same tech option})}{\text{total number of variants}}$

Strict, all or nothing

Allows for partial commonality

	Variant 1	Variant 2	Variant 3	Variant 4	C_b	C_h	C_l
FoV:					**0.00**	**0.50**	**0.75**

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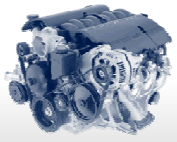
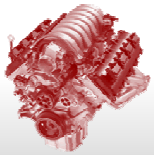
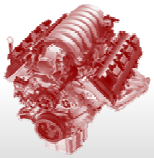
FoV:					**0.00**	**0.50**	**0.50**

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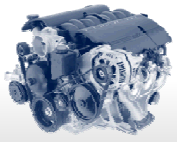
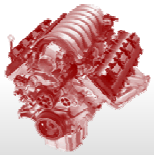
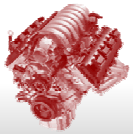
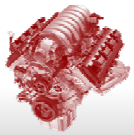
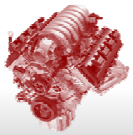
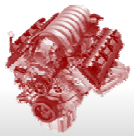
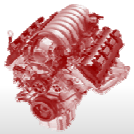
	Variant 1	Variant 2	Variant 3	Variant 4	C_b	C_h	C_l
FoV:					**0.00**	**0.33**	**0.50**

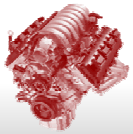
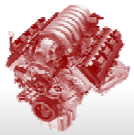
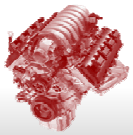
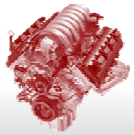
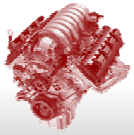
Commonality Measures

- When looking at these families together, issues with each commonality becomes apparent.

	Variant 1	Variant 2	Variant 3	Variant 4	C_b	C_h	C_l
FoV 1:					**1.00**	**1.00**	**1.00**
FoV 2:					**0.00**	**0.50**	**0.75**
FoV 3:					**0.00**	**0.50**	**0.50**
FoV 4:					**0.00**	**0.33**	**0.50**
FoV 5:					**0.00**	**0.25**	**0.25**

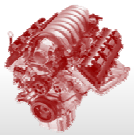
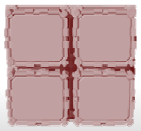
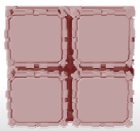
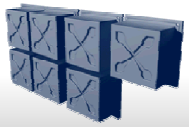
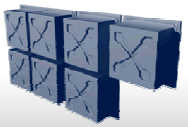
Commonality Measures

- Mixed commonality measure blends the harmonic and linear and addresses these issues
  - $C_m = \begin{cases} \frac{C_h + C_l}{2} & \text{if } \frac{C_h + C_l}{2} > \frac{1}{\text{number of variants}} \\ 0 & \text{otherwise} \end{cases}$

	Variant 1	Variant 2	Variant 3	Variant 4	C_b	C_h	C_l	C_m
FoV 1:					**1.00**	**1.00**	**1.00**	**1.00**
FoV 2:					**0.00**	**0.50**	**0.75**	**0.62**
FoV 3:					**0.00**	**0.50**	**0.50**	**0.50**
FoV 4:					**0.00**	**0.33**	**0.50**	**0.42**
FoV 5:					**0.00**	**0.25**	**0.25**	**0.00**

Commonality Measures

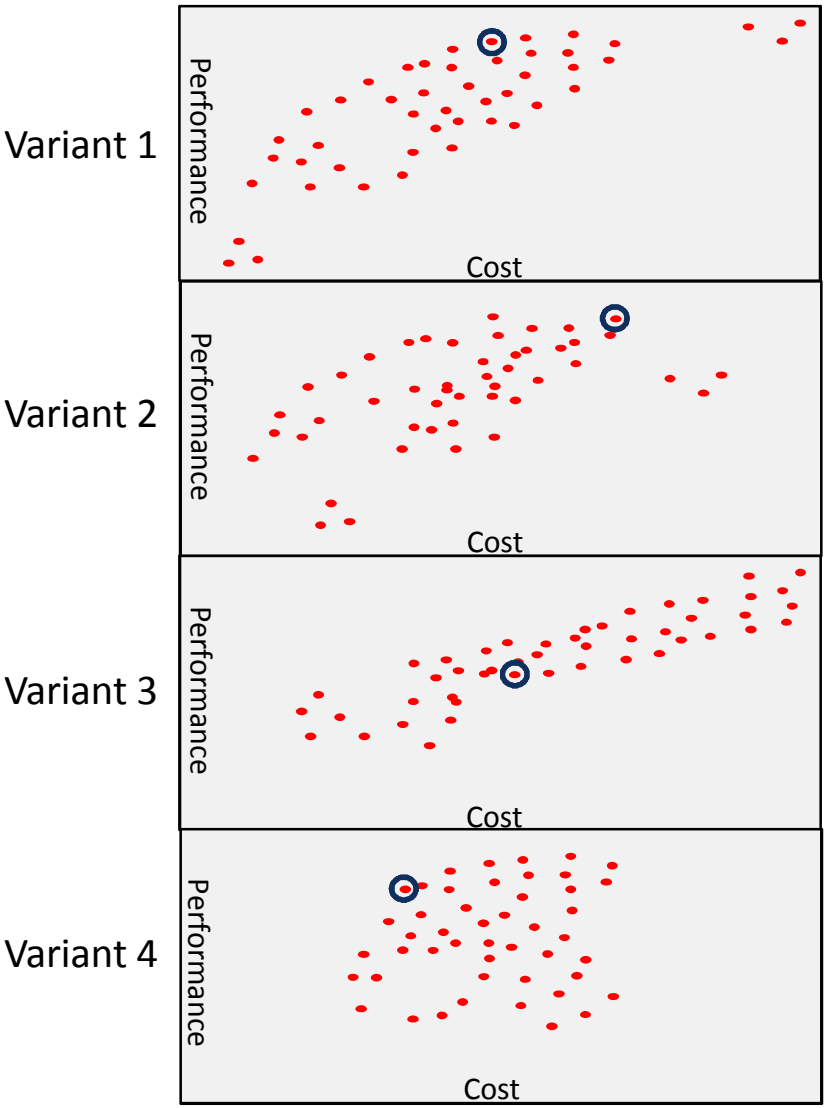
- This idea can be trivially extended to consider multiple tech options within each family
- Weightings can be applied to the commonality measure of each tech option
  - Based on cost of that item
  - Based on importance of that item

FoV:	Variant 1	Variant 2	Variant 3	Variant 4	C_m	w
Engine					**0.62**	**0.75**
Armor					**0.50**	**0.25**

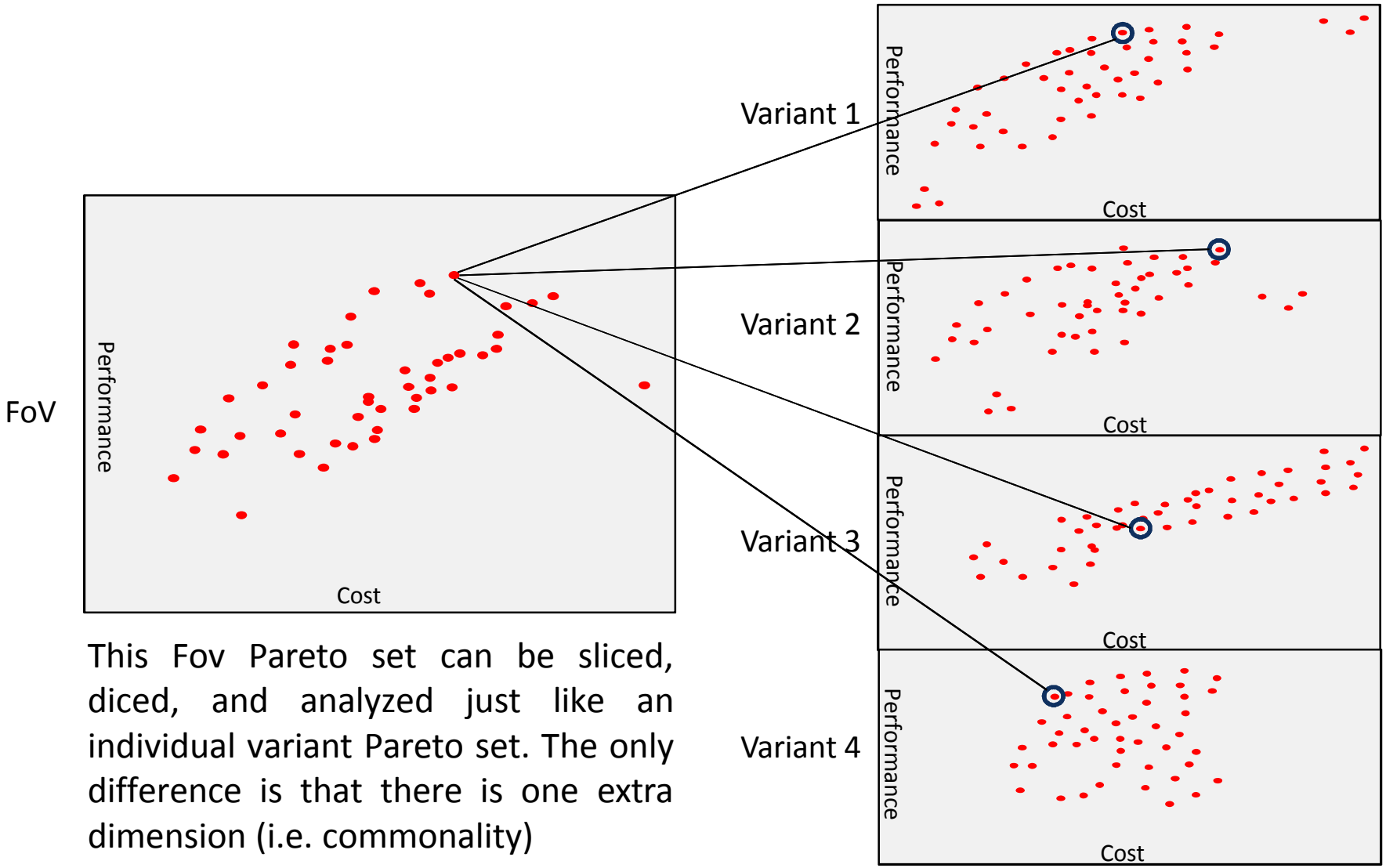
- FoV Commonality = $(0.62 \cdot 0.75) + (0.5 \cdot 0.25) = \mathbf{0.59}$

“Post-Hoc” Commonality Analysis

- This approach considers commonality as a post-processing step to traditional WSTAT analysis
- Individual Pareto solutions are acquired separately for each vehicle variant
- A family of vehicles is then formed by choosing exactly 1 Pareto solution from each variant.
- Since each variant has ≈ 2000 solutions, even a 4-variant family cannot be explicitly enumerated ($2000^4 = 1.6 \times 10^{13}$ possible families)
- We use a genetic algorithm to find FoV Pareto solutions in 6 objective dimensions (5 from WSTAT in aggregated form, plus commonality)
- Simple linear constraint enforces that exactly 1 Pareto solution from each family is chosen



“Post-Hoc” Commonality Analysis



This Fov Pareto set can be sliced, diced, and analyzed just like an individual variant Pareto set. The only difference is that there is one extra dimension (i.e. commonality)

“Post-Hoc” Commonality Summary

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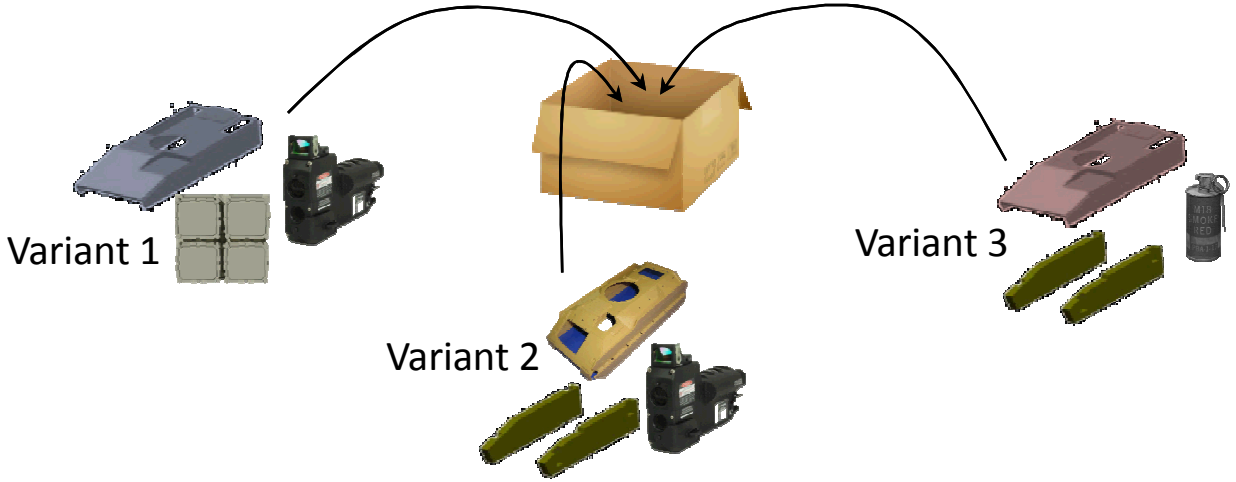
- Advantages
  - Approaching commonality from this perspective allows for quick development
    - FoV-level GA is very simple
    - WSTAT output can be used directly without modification
  - Analysis is fast, as we have effectively decomposed the problem
    - Each variant optimized independently with FoV optimized afterwards
- Disadvantages
  - Decomposing the problem in this manner limits the FoV solutions that you can acquire (you leave out families that excel in commonality but sacrifice in the other 5 dimensions)
  - Commonality doesn’t drive variant optimization choices
  - In some contexts, this might actually be desired (i.e. you’d like commonality, but not at the expense of individual variants)

Integrated Commonality Analysis

- Where the “post-hoc” approach followed a natural decomposition of the problem, this approach solves for the entire FoV Pareto set at once.
- Here all components from all variants are “placed in the box”



- Objective functions are natively at the FoV level. Commonality is just another objective

Integrated Commonality Summary

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- Advantages
  - Much richer search space allows FoV Pareto solutions that could not be gotten by post-hoc approach
  - Commonality plays a part in the tradeoffs governing the design of each variant
  - Since all objectives are at an FoV level, other family level metrics besides commonality could be easily incorporated
- Disadvantages
  - Much richer search space means algorithm could get bogged down
  - Much more difficult development task

Summary

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- Commonality and military fleets
- Measures for commonality
- Post-hoc vs. integrated commonality

Questions?