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Whole System Trades Analysis Tool (WSTAT) Overview

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U.S. DEPARTMENT OF ENERGY | National Nuclear Security Administration

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Introduction

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- Need to advance military capabilities within a stringent fiscal environment
- Crucial to clearly understand the relationships between capability goals and cost/schedule constraints within the realm of viable design choices
- Typically impossible to fully satisfy every goal of a program given competing requirements from multiple stakeholders
- Difficult tradeoffs must be made
- To illuminate these tradeoffs analytically, we employ a Multi-Objective Combinatorial Optimization approach in the Whole System Trades Analysis Tool (WSTAT)
  - efficiently explores the design space to find an optimal frontier of designs that achieve different balances between performance measures, affordability and schedule risk.
  - visualization and analysis capabilities allow this frontier to be explored by decision makers to answer a broad range of questions
- WSTAT is applied to a wide range of problem domains

  Infantry fighting vehicles – small robots – contingency bases – ships

WSTAT Purpose and Goals

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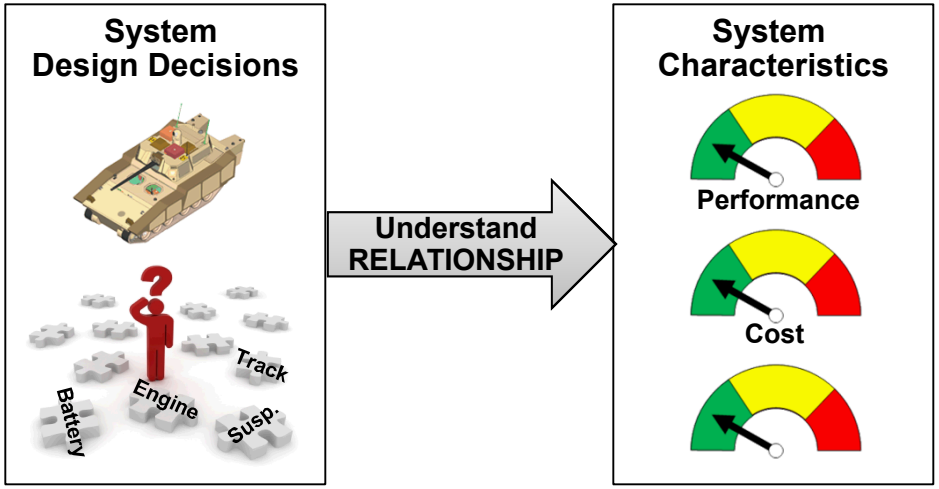
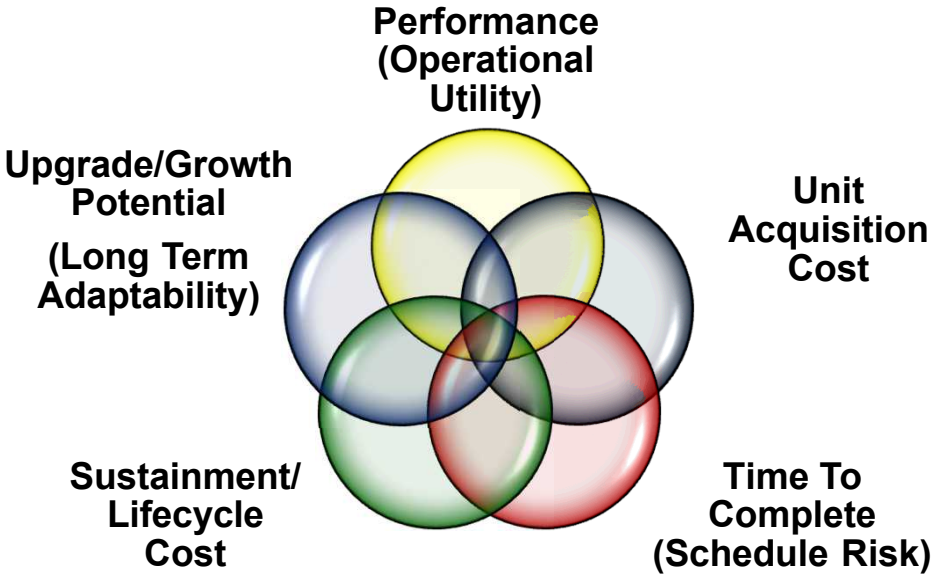
- Purpose
  - Model the relationship between design decisions & stakeholder value in order to inform and potentially influence requirements documents and associated specifications
  - Conduct cost informed trades analysis based on holistic design choices, while understanding the opportunity cost of each choice
- Process Goals
  - Generate many good alternatives
  - Stimulate healthy and informed debate
  - Provide foundation for a traceable and defendable decision
  - Build consensus (high level of commitment and shared understanding among team members and stakeholders)

Understanding the Problem





- System Decomposition
  - Understand the parts of the system that are tradable
- System Characteristics
  - Model relationship between system design decisions and system characteristics
- Challenges
  - Multiple dimensions of importance
  - Massive number of possible solutions (10^{20} – 10^{150} typical)
  - Constraints
  - 2^{nd} and 3^{rd} order interactions
  - Dependencies between subsystems

WSTAT Methodology

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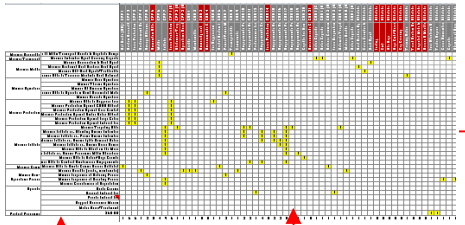
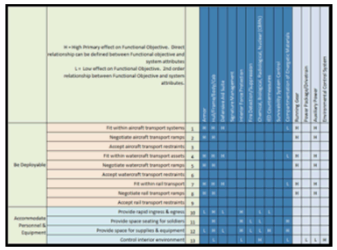
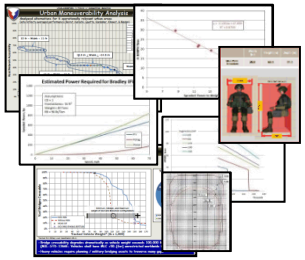
Map Requirements to Functional Objectives



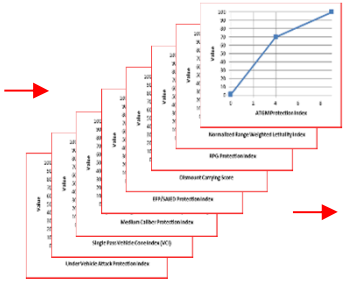
Map Functional Objectives to Product Structure



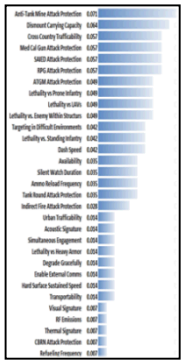
Define Metrics



Craft Value Functions

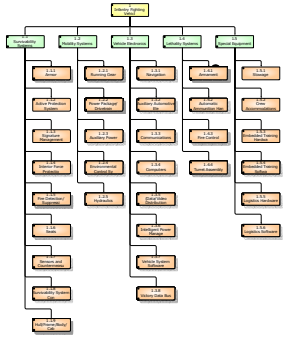


Determine Priority Weightings

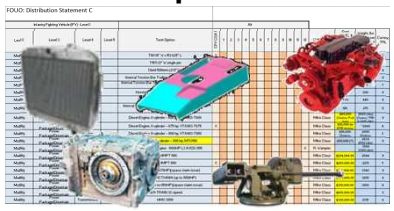


Develop Functional Objectives

Establish Product Structure

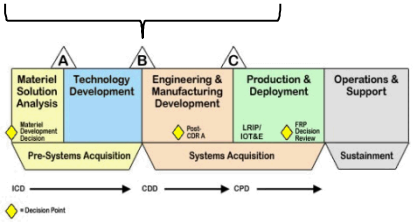


Identify Technology Options

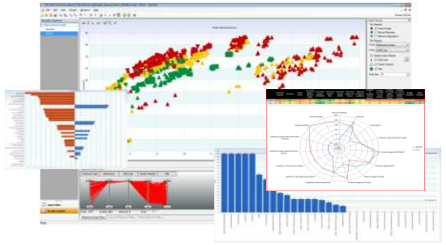


Multi-objective Optimization

Understand Needs/Requirements

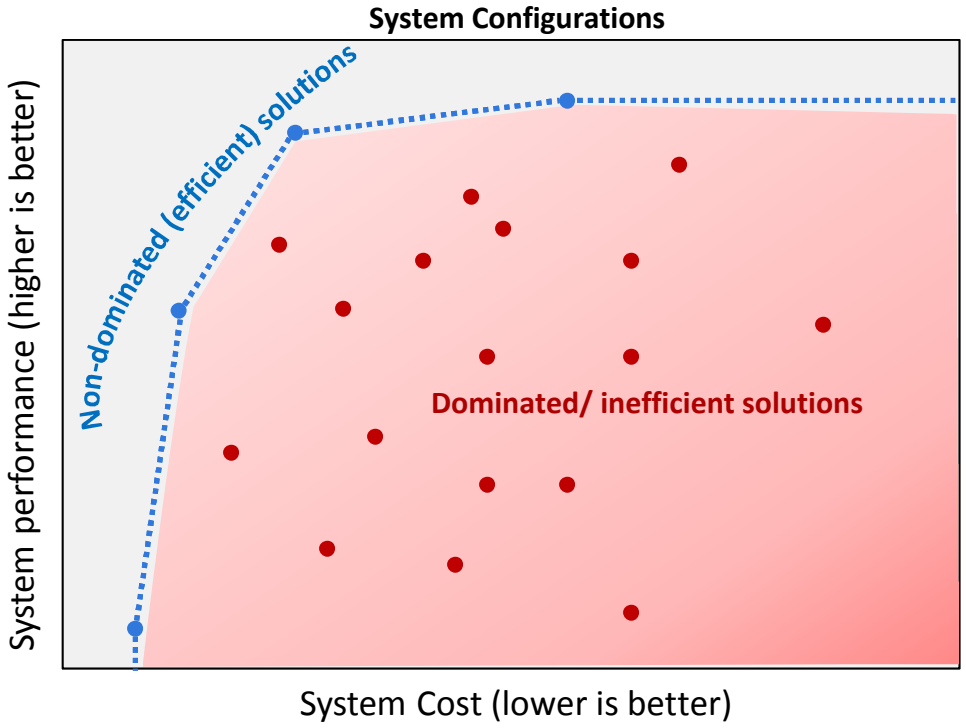


Generate Results & Conduct Analysis



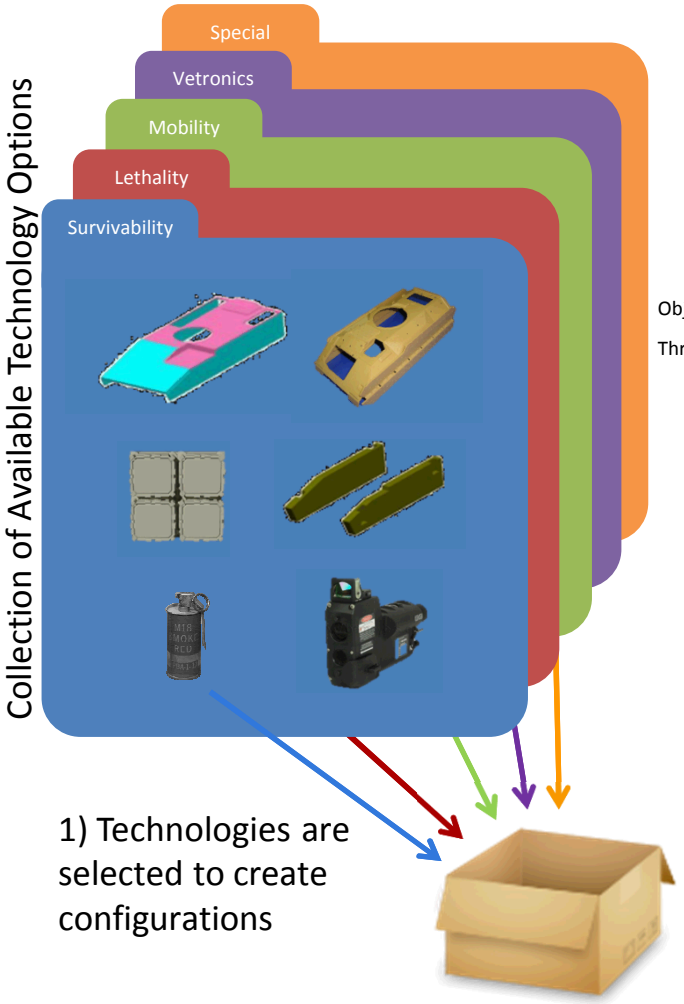
How WSTAT Works

- WSTAT looks at the design of a system, aggressively examining many potential configurations in an effort to meet multiple competing requirements and objectives
- WSTAT uses a multi-objective genetic algorithm to find design "sweet spots" that balance multiple competing criteria
  - Consider 2 criteria, cost and performance
  - **Non-dominated (Pareto efficient) solutions** identify optimal tradeoffs between competing criteria
  - Same idea applies when balancing more criteria, except in higher dimensions

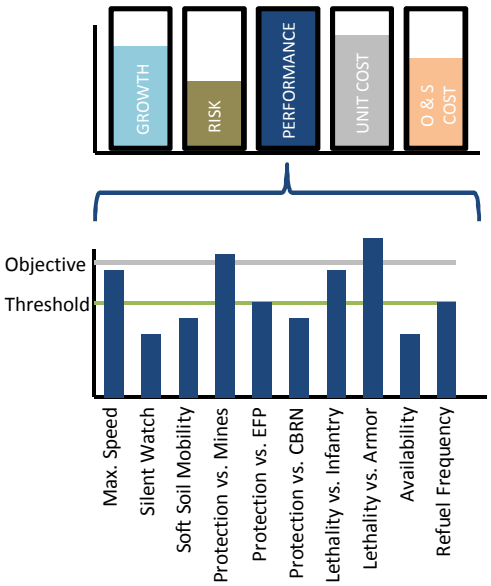


How WSTAT Works

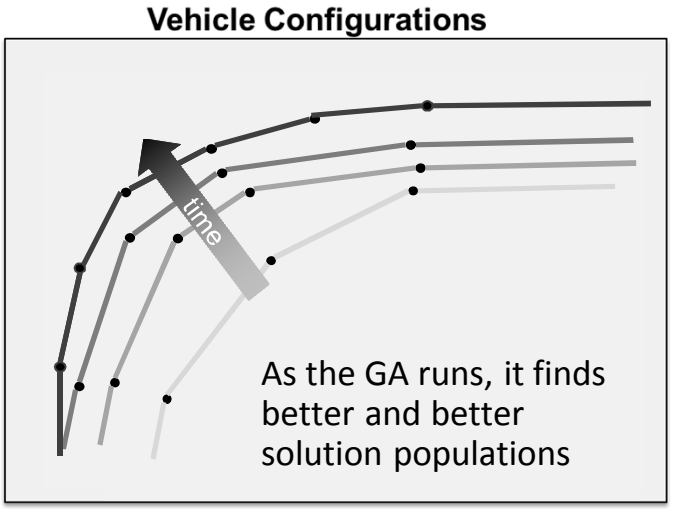
The WSTAT GA combines technology options into a system configuration, only keeping those configurations that best balance competing objectives



1) Technologies are selected to create configurations



2) Each configuration is scored in lower-level metrics that contribute to higher-level dimensions



3) Configurations are bred and mutated within a Genetic Algorithm (GA), evolving the population towards optimality

As evaluating all potential configurations is impossible, a genetic algorithm is used to identify a set of near-optimal solutions (typically several thousand)

WSTAT Uses

- Requirements analysis
- Tradeoff Analysis
  - Discover tradeoffs between technologies, requirements, attributes
- Assessing technology trends
  - e.g. in different price/weight ranges
- Comparing Solutions
  - Can compare government/contractor designs and non-developmental systems as well as optimized solutions
  - Pairwise/multiple solution comparison (radar, tornado, bar charts)
  - Priority weighting sensitivity analysis – how sensitive are the answers to different stakeholder perspectives?
  - Can include uncertainty in non-developmental systems
- Analyzing variations on a concept
  - Evaluating one-off design changes
  - Finding and analyzing dominating Pareto points
    - How can an existing design be made even better?
    - Where are the opportunities for the program to outshine non-developmental systems?
- Parametric analysis
  - E.g., how do things change if system weight grows?
- Family analysis
  - Analyze families of systems in one optimization, rather than optimizing single variants independently
  - Can incorporate cross-variant measures such as commonality

WSTAT V&V Activities

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- WSTAT is currently undergoing V&V
  - Army Materiel Systems Analysis Activity (AMSAA) is the V&V agency
    - Management WG, Performance WG, Data WG, Growth WG, Cost WG, Risk WG, Optimization WG, End-to-End WG
  - V&V Activities
    - Code review
    - Testing (functional, usability, sensitivity, stress)
    - Data V&V
    - SME panel review
    - Benchmarking where possible
  - Comprehensive software lifecycle management
    - CollabNet Teamforge
    - CollabNet Subversion (SVN)
- Verification of documentation
  - Requirements management plan
  - Configuration management plan
  - Intended use
    - Requirements traceability to intended use
  - Release plan
  - Automated testing logs
  - Training material
  - Development environment and processes
  - Analysis environment and configuration management processes

WSTAT V&V Completion:
~ December 2014

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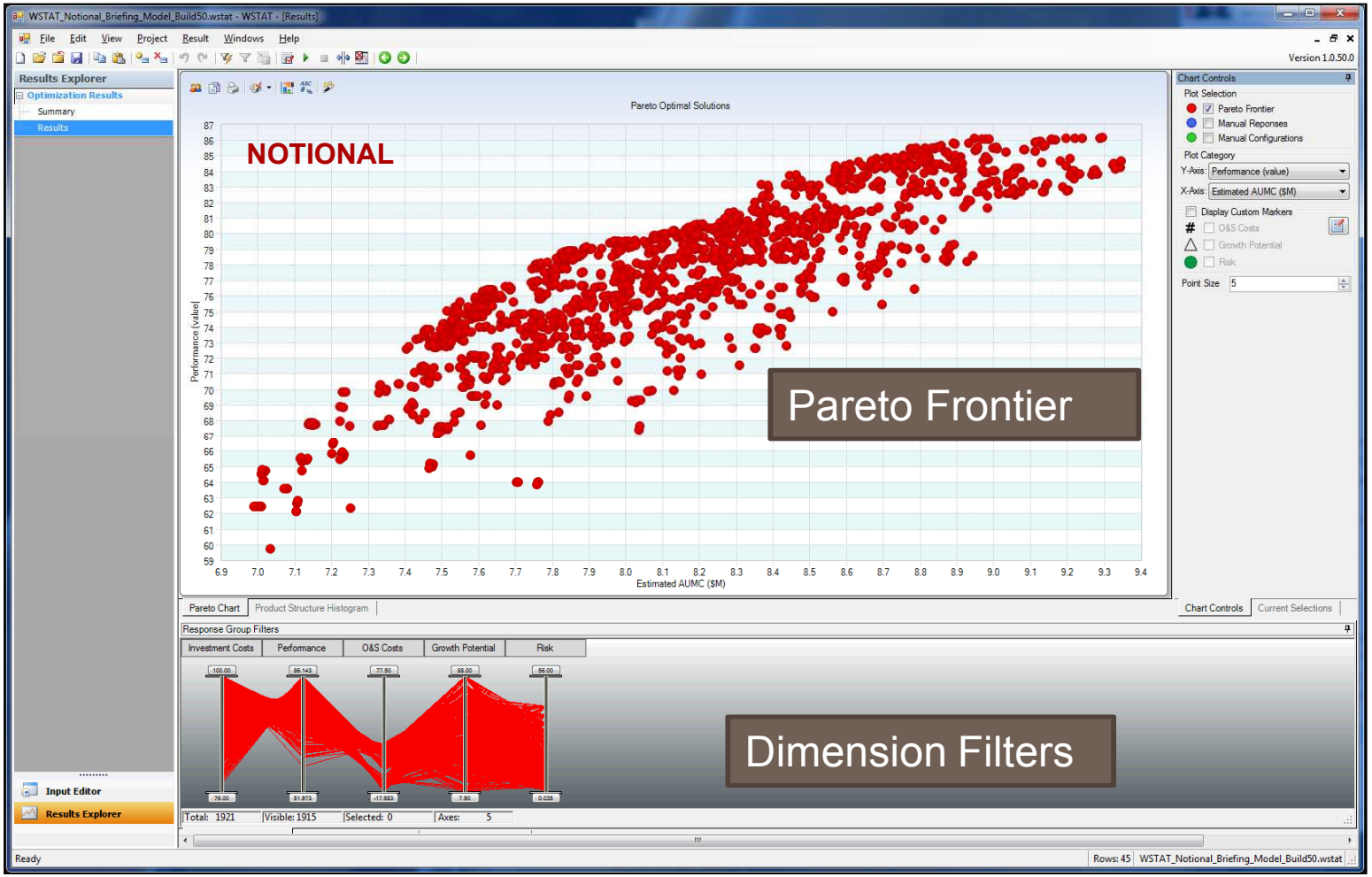
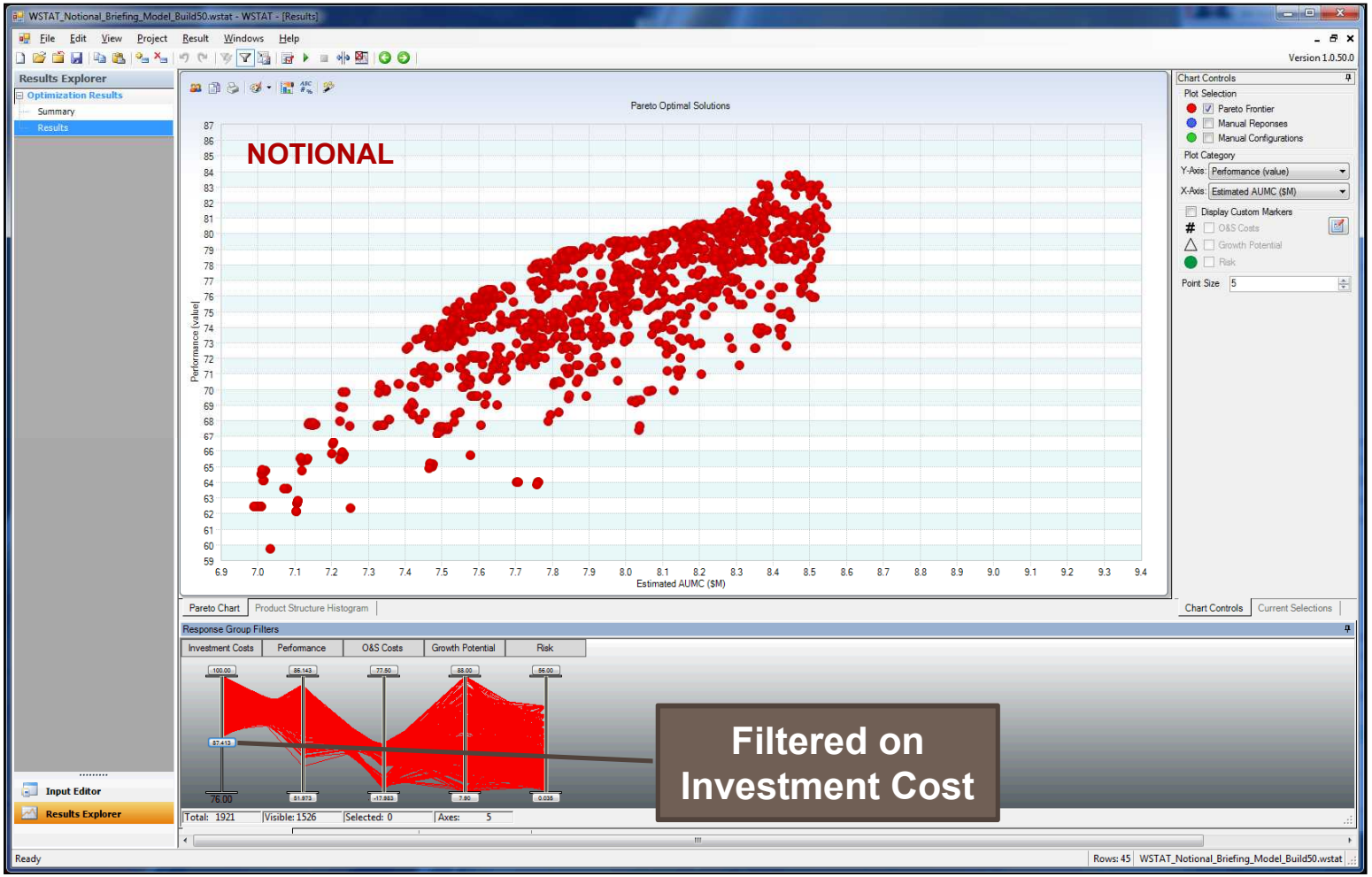
BASIC RESULTS

Pareto Frontier

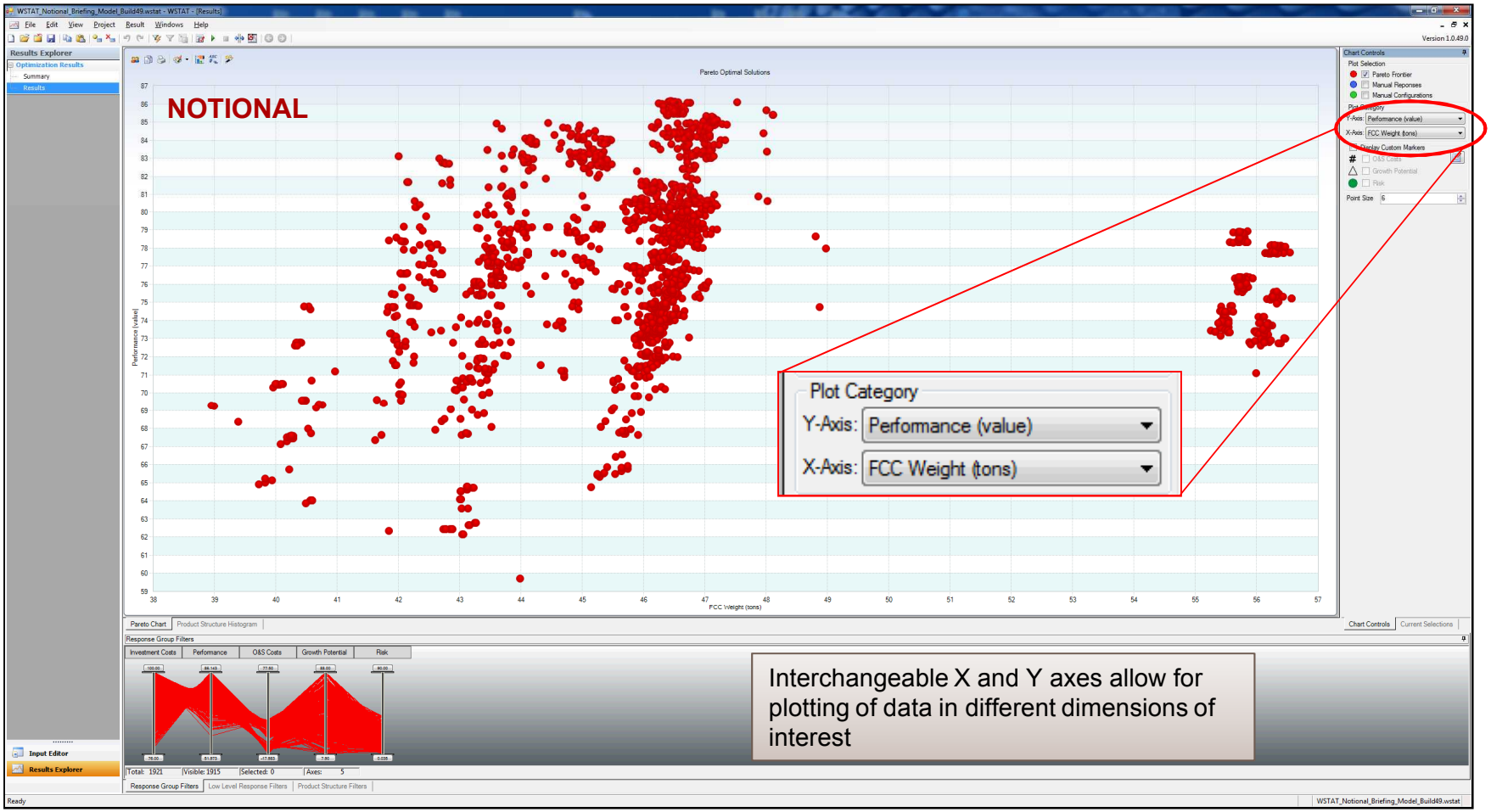


Filtering

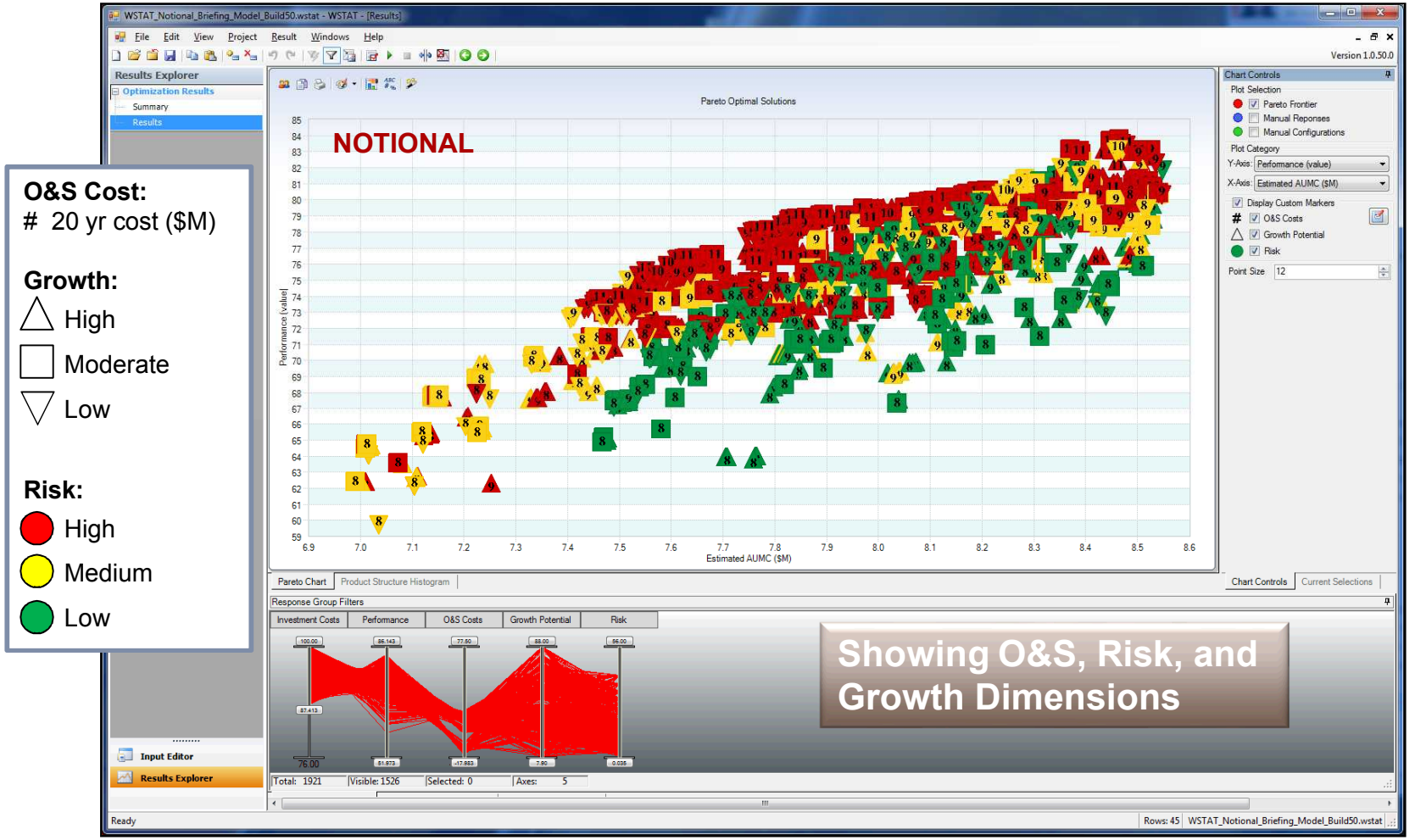


Can filter on individual objectives/requirements in the same manner as filtering the dimensions

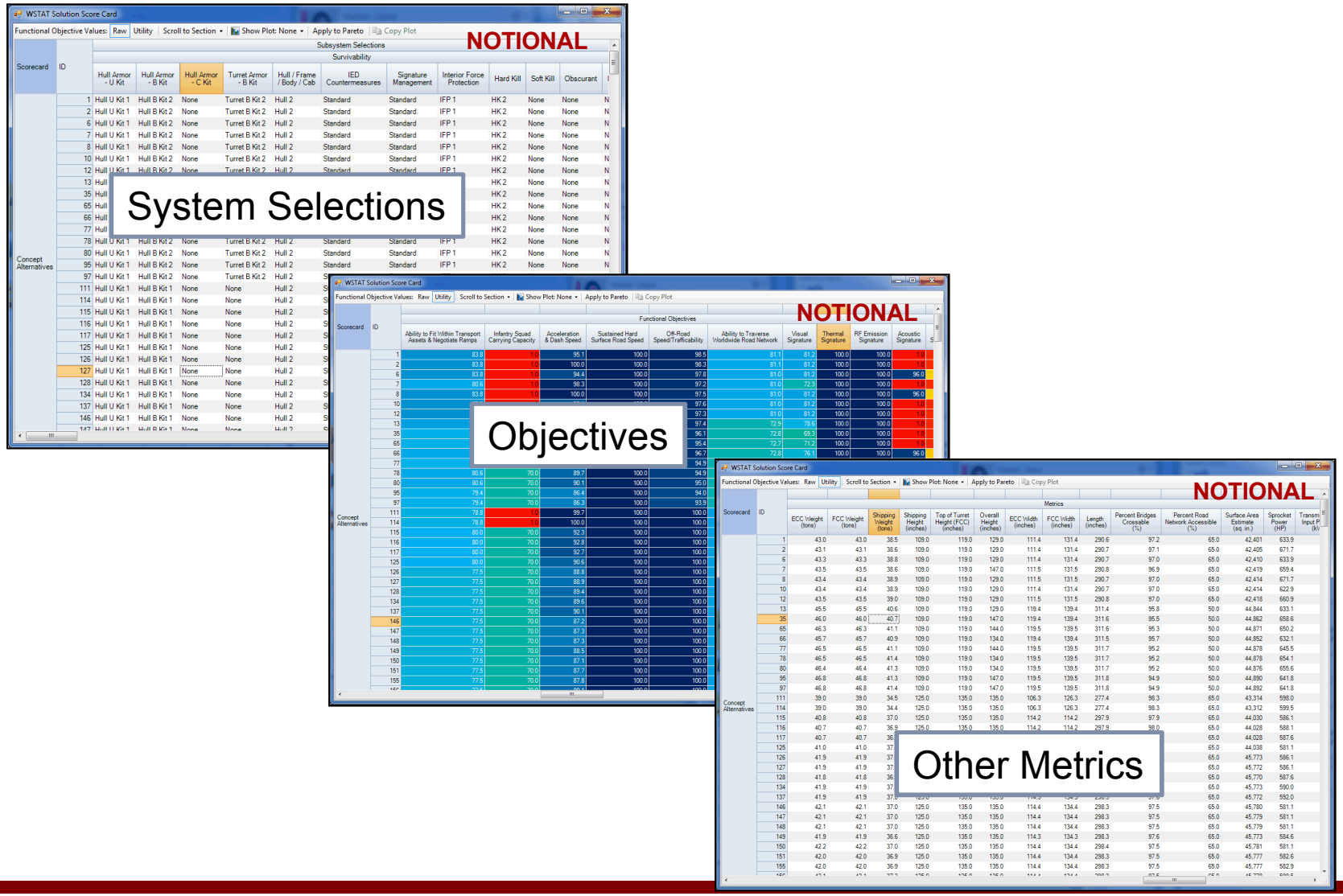
Pareto Frontier: Plot Categories



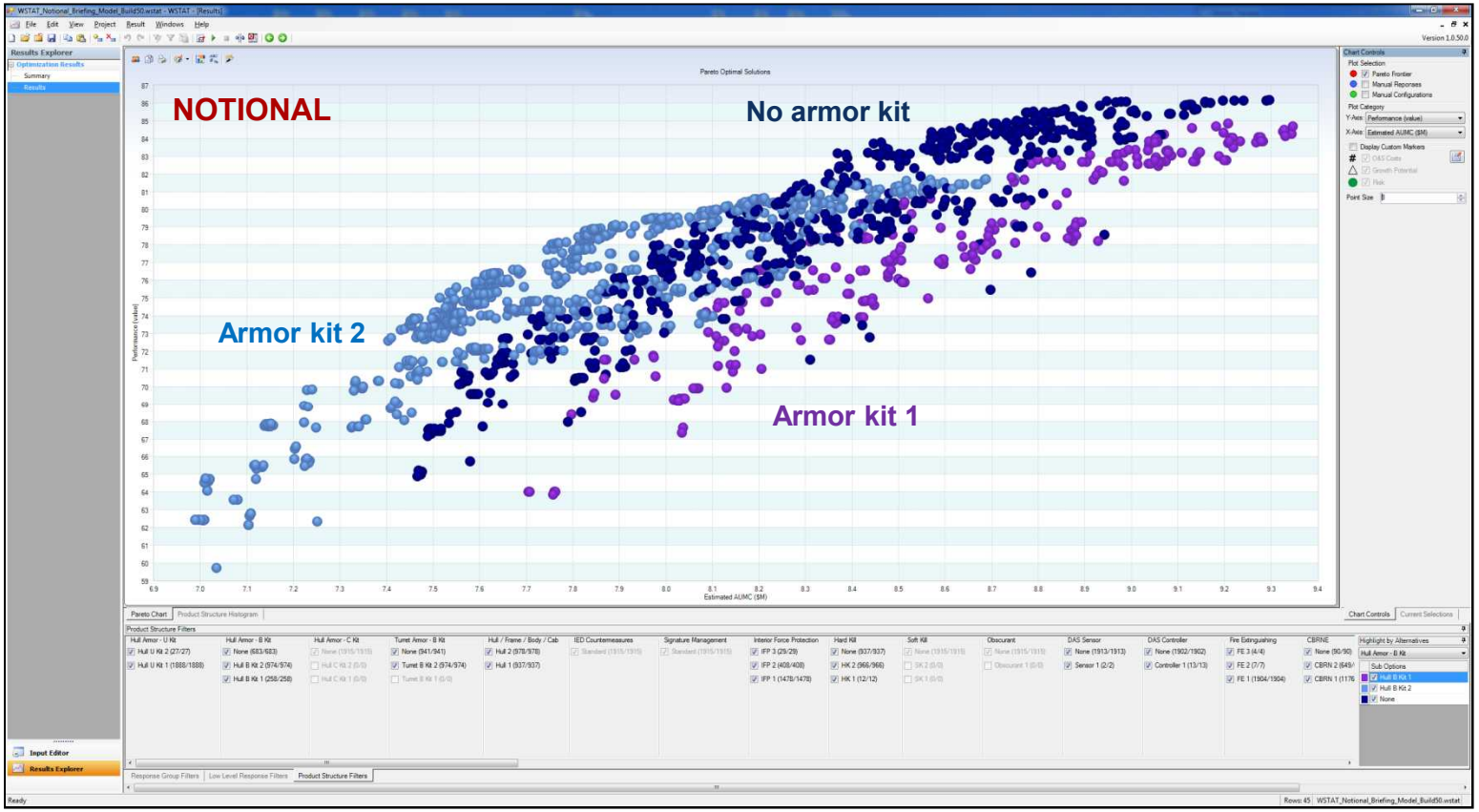
Multiple Dimensions



Scorecards


WSTAT Solution Score Card
NOTIONAL
System Selections
Objectives
Other Metrics

Product Structure Filters/highlighting



This screen allows the user to see the distribution of technology selections for all parts of the product structure in the Pareto frontier, and filter if needed.

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USE CASES

Use cases

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- Requirements analysis
- Tradeoff Analysis (between technologies, requirements, attributes)
- Assessing technology trends (e.g. in different price/weight ranges)
- Comparing Solutions
  - Pairwise/multiple solution comparison (radar, tornado, bar charts)
  - Priority weighting sensitivity analysis
  - With uncertainty
- Analyzing variations on a concept
  - Manually changing technology choices
  - Finding and analyzing dominating Pareto points
- Parametric analysis
- Family analysis

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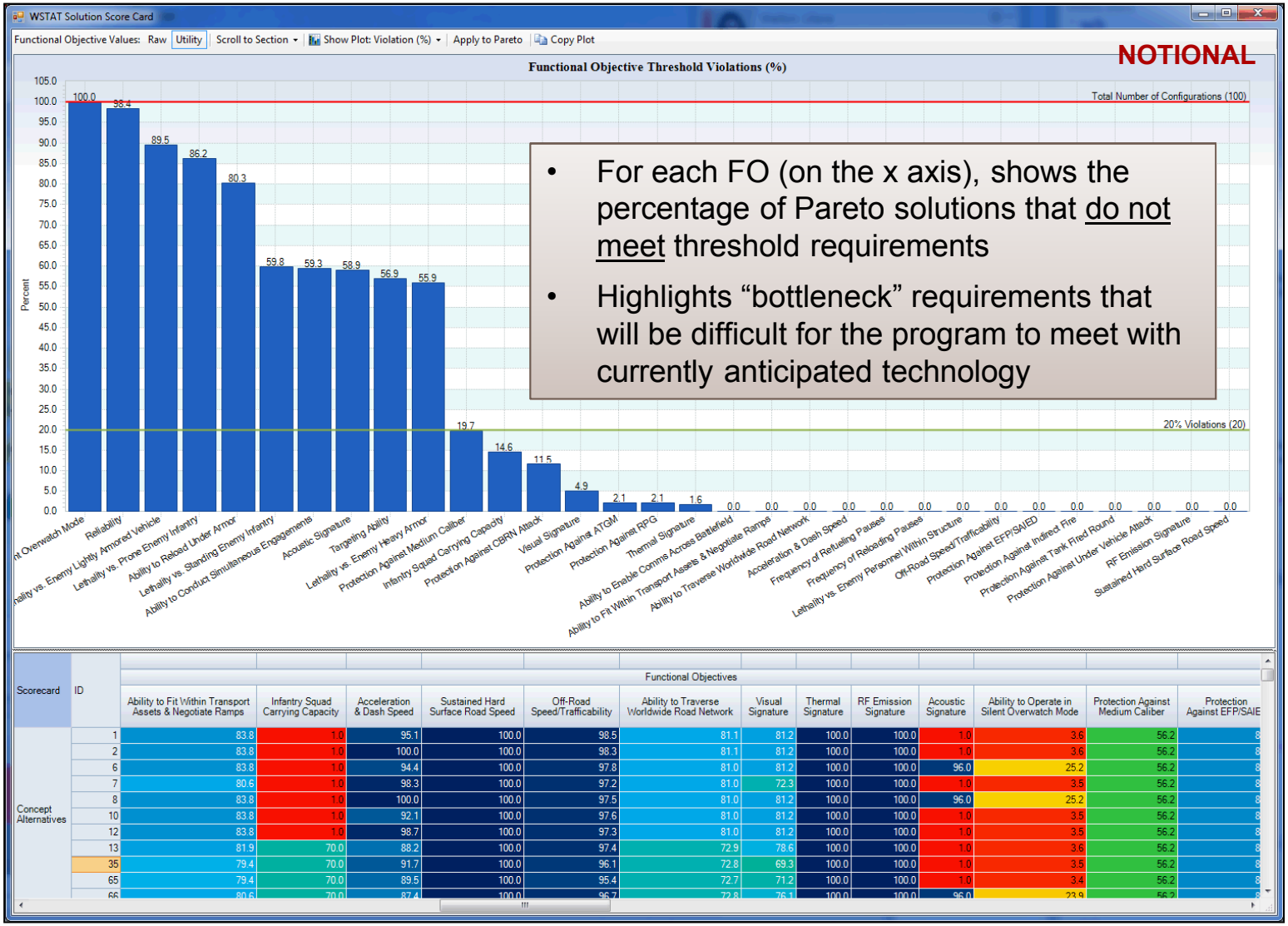
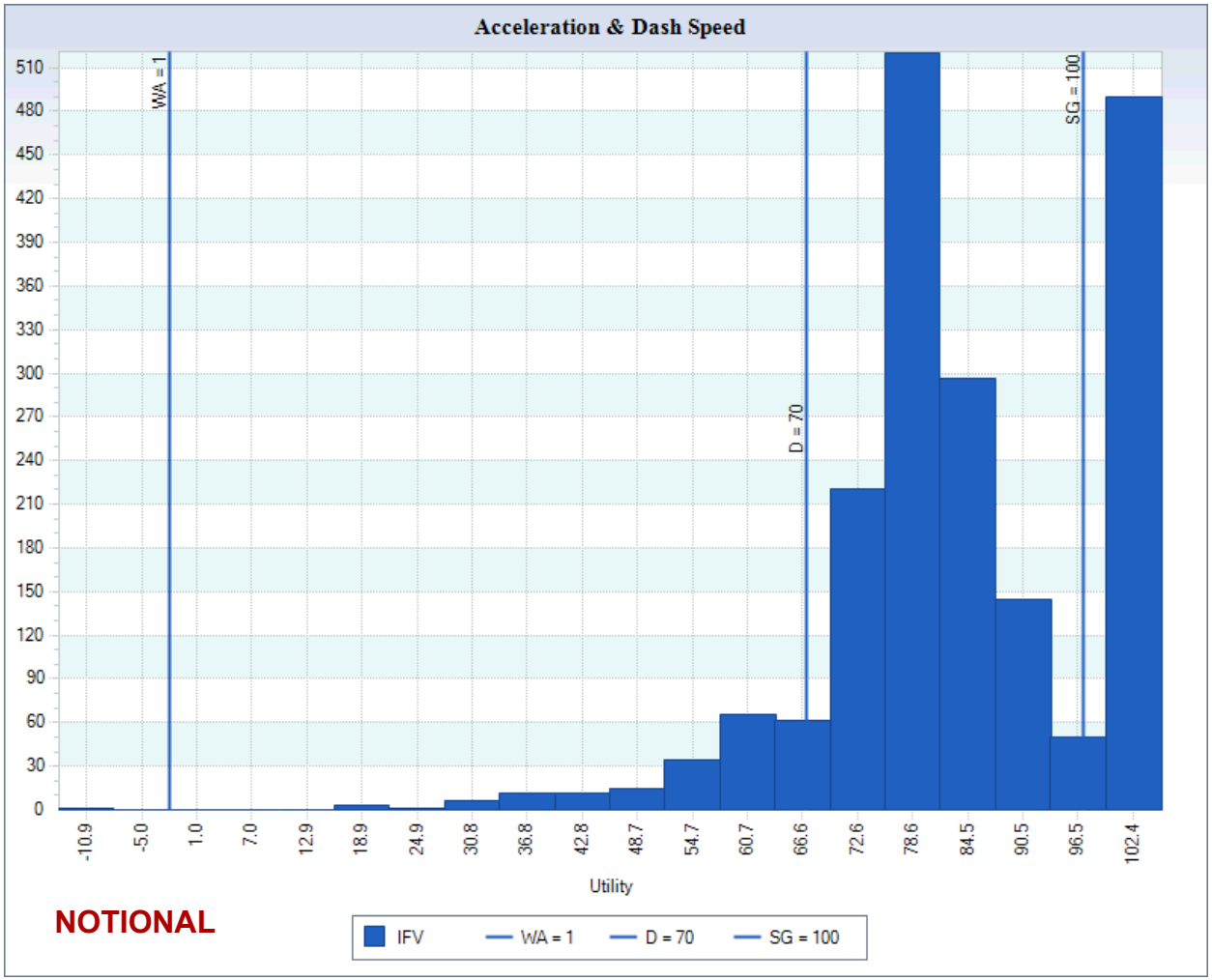
Requirement Violations



Scorecard	ID	Functional Objectives												
		Ability to Fit Within Transport Assets & Negotiate Ramps	Infantry Squad Carrying Capacity	Acceleration & Dash Speed	Sustained Hard Surface Road Speed	Off-Road Speed/Trafficability	Ability to Traverse Worldwide Road Network	Visual Signature	Thermal Signature	RF Emission Signature	Acoustic Signature	Ability to Operate in Silent Overwatch Mode	Protection Against Medium Caliber	Protection Against EFP/SAIE
Concept Alternatives	1	83.8	1.0	95.1	100.0	98.5	81.1	81.2	100.0	100.0	1.0	3.6	56.2	8
	2	83.8	1.0	100.0	100.0	98.3	81.1	81.2	100.0	100.0	1.0	3.6	56.2	8
	6	83.8	1.0	94.4	100.0	97.8	81.0	81.2	100.0	100.0	96.0	25.2	56.2	8
	7	80.6	1.0	98.3	100.0	97.2	81.0	72.3	100.0	100.0	1.0	3.5	56.2	8
	8	83.8	1.0	100.0	100.0	97.5	81.0	81.2	100.0	100.0	96.0	25.2	56.2	8
	10	83.8	1.0	92.1	100.0	97.6	81.0	81.2	100.0	100.0	1.0	3.5	56.2	8
	12	83.8	1.0	98.7	100.0	97.3	81.0	81.2	100.0	100.0	1.0	3.5	56.2	8
	13	81.9	70.0	88.2	100.0	97.4	72.9	78.6	100.0	100.0	1.0	3.6	56.2	8
	35	79.4	70.0	91.7	100.0	96.1	72.8	69.3	100.0	100.0	1.0	3.5	56.2	8
	65	79.4	70.0	89.5	100.0	95.4	72.7	71.2	100.0	100.0	1.0	3.4	56.2	8
	66	80.6	70.0	87.4	100.0	96.7	72.8	76.1	100.0	100.0	96.0	23.9	56.2	8

Objective Histograms



Use cases

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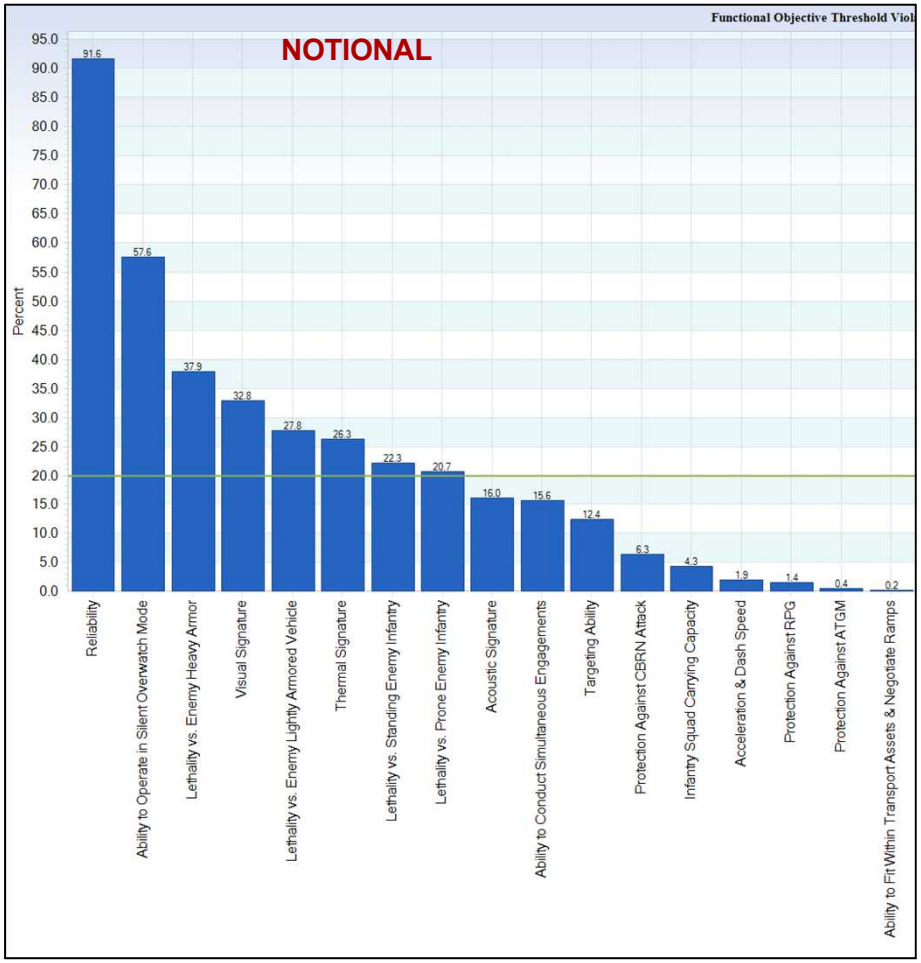
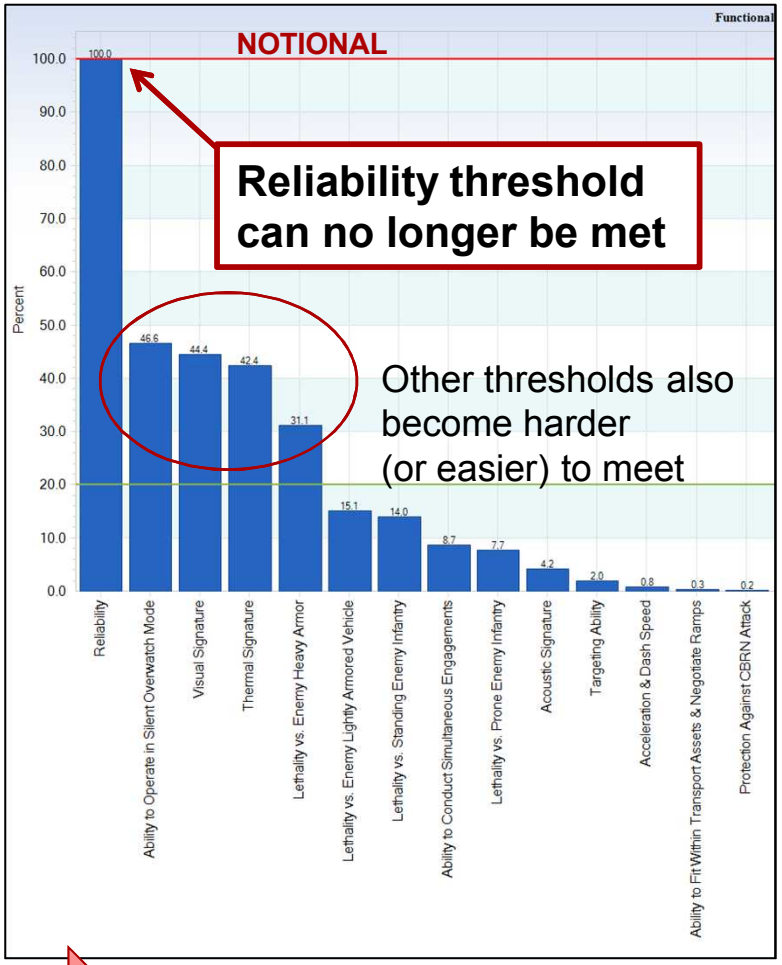
Meeting Specific Requirements

- By filtering to solutions that meet a certain level of performance for one or more requirements, WSTAT can help identify the different tradeoffs that are made in terms of:
  - Other requirements
  - Technology choices
  - System attributes/characteristics
- Some general insights that might be gained from this type of analysis include:
  - Which requirements make other requirements difficult to fulfill
  - Identification of subsystems and technology selections which are most relevant to the requirements of interest
  - Whether meeting certain requirements will drive toward solutions that have particular characteristics

Meeting Specific Requirements: Requirement Tradeoffs





Unfiltered

Apply filter

Squad Capacity at Objective

Same idea can be applied with objective histograms
- e.g., how does meeting certain requirements change the performance distribution of other requirements?

Meeting Specific Requirements: System Attribute Tradeoffs

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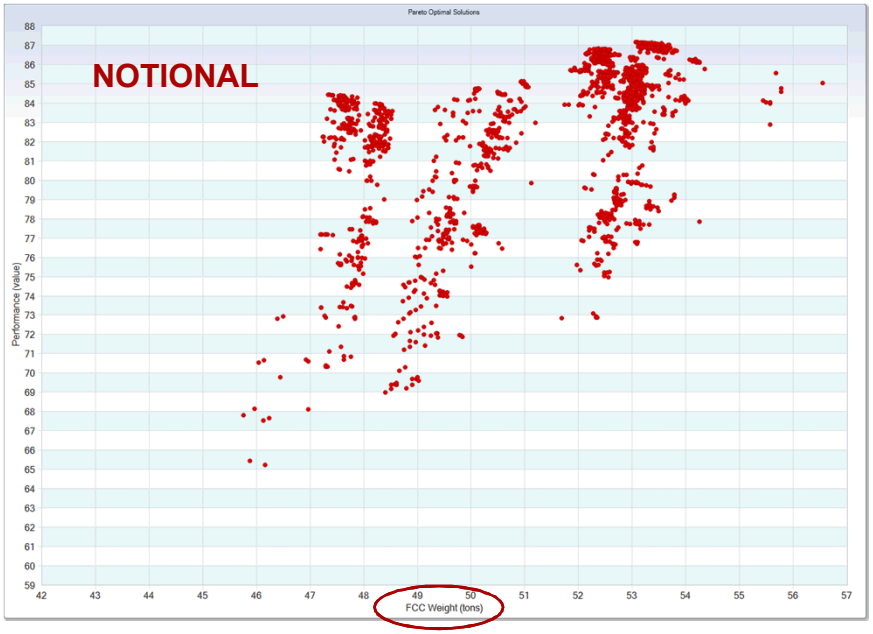
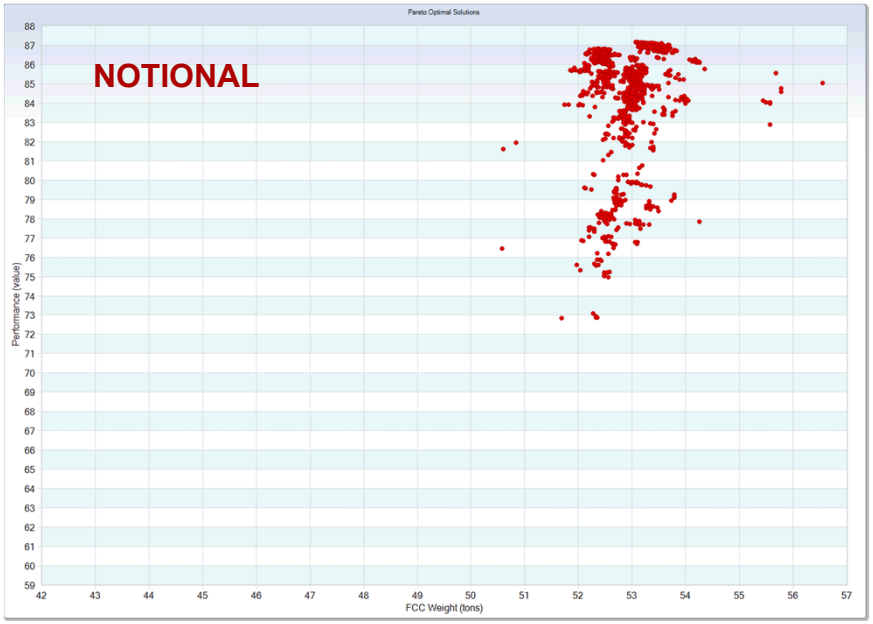
System Weight Trends



Unfiltered

Apply filter



Survivability requirements at Threshold

Meeting certain requirements can drive the system to have certain attributes;
in this example, meeting survivability requirements means the system must be heavier

Correlations Between Goals

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- For any dimension or individual objective/requirement, solutions can be ranked against one another in terms of utility
- Solutions that are relatively very good in one measure may be bad in another
  - E.g. highest performance solutions tend to have poor schedule risk
- Or, some measures may be largely sensitive to the same things and will rise and fall together.

- Can look at correlations between rankings to tease out relationships between measures
  - E.g. cost rank is strongly negatively correlated with performance rank
  - Acceleration is strongly positively correlated with top speed

Use cases

- Requirements analysis
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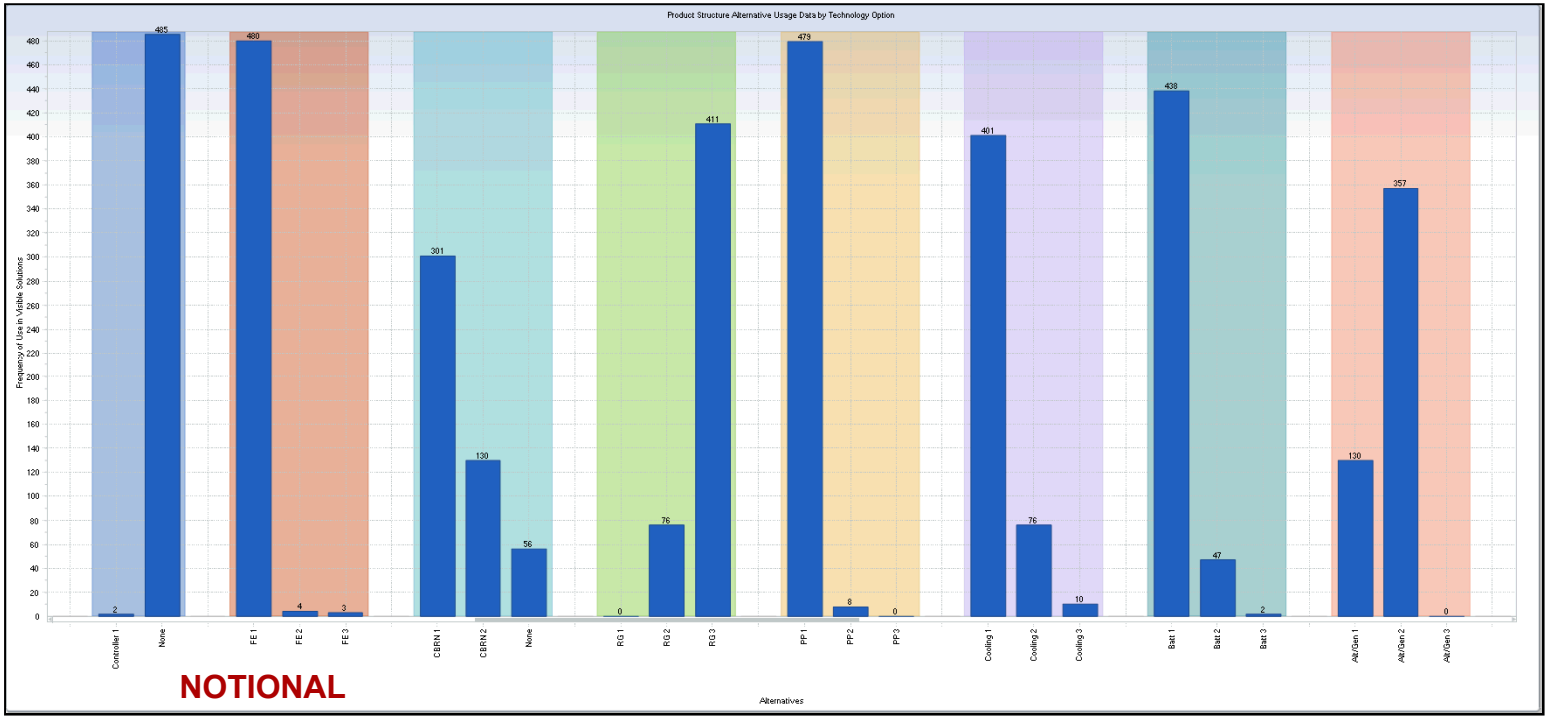
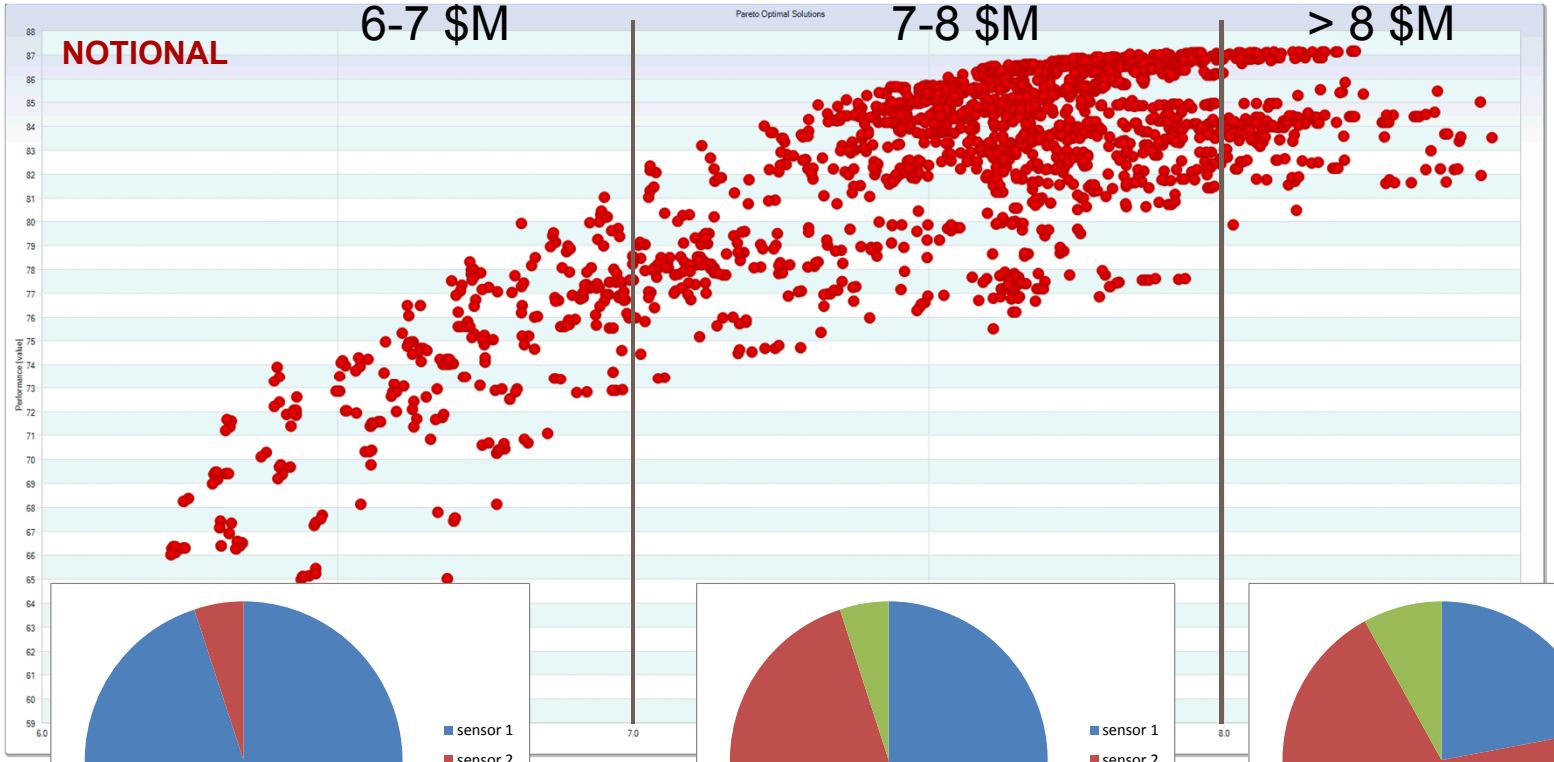
Product Structure Histogram

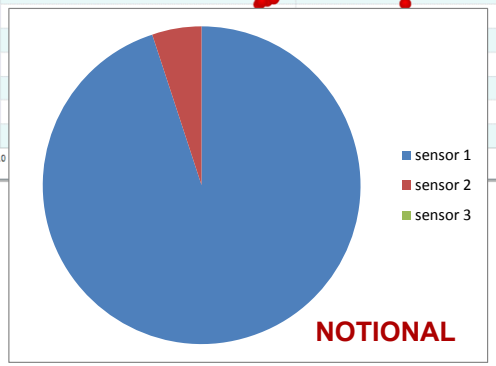


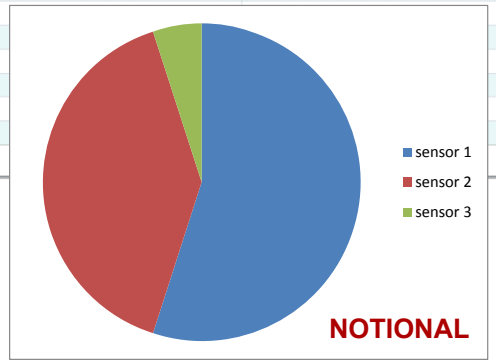
This screen allows the user to see the frequency of technology selections for all parts of the product structure in the set of Pareto frontier solutions.

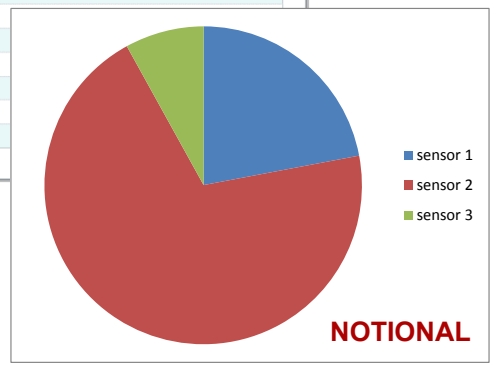
Technology trends: Cost

Example: What sensor technology trends exist as we allow the cost of the system to grow from 6 to 8.5 $M?



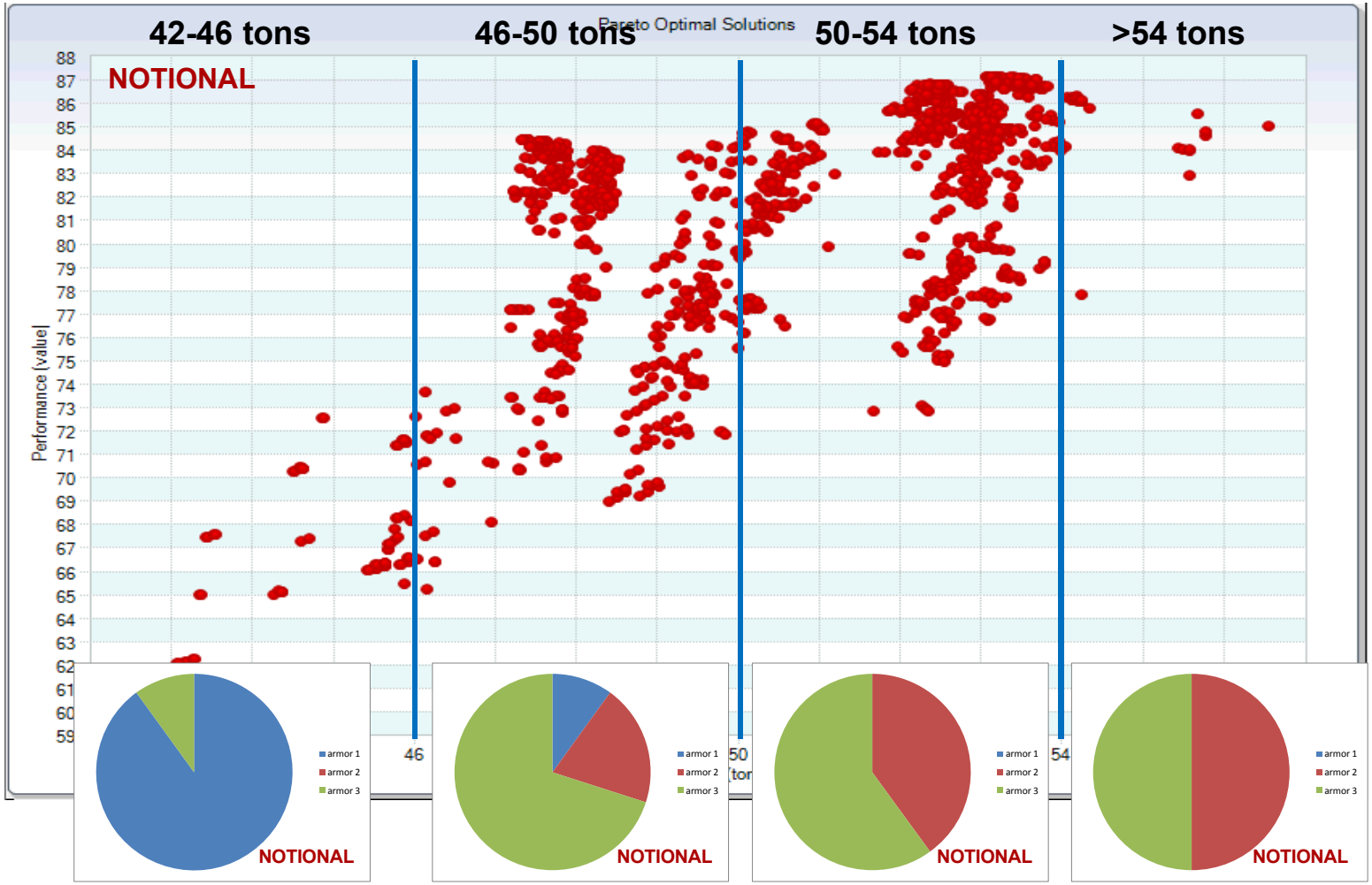






Technology trends: Weight

Example: what armor technology trends exist as we allow the weight of the system to grow from 42 to 57 tons?



Use cases

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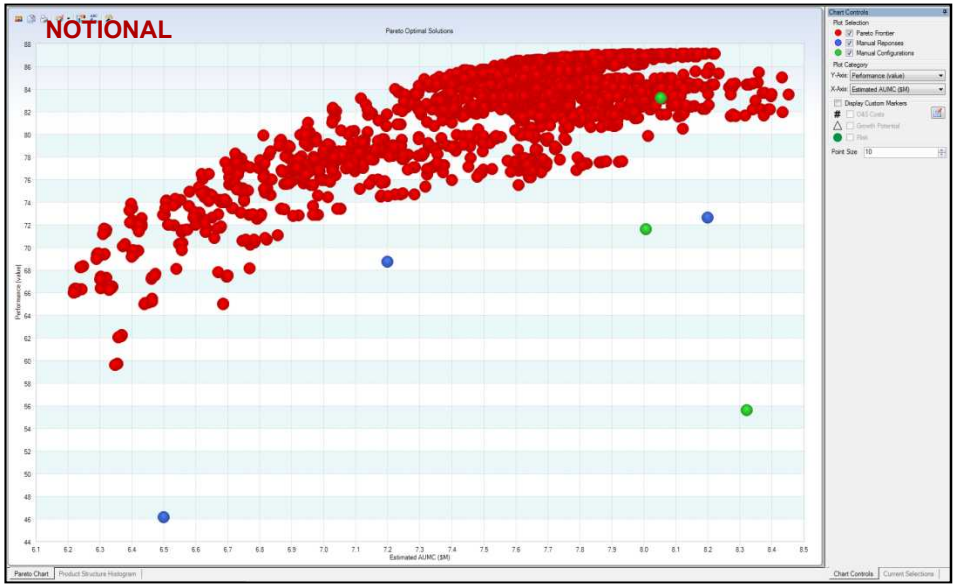
Manual Solutions

- Ability to manually define solutions gives decision makers the freedom to explore additional concepts beyond those in the Pareto set, e.g.,
  - Government Engineering Designs
  - Contractor Designs
  - Existing/non-developmental systems
- Two types of manual solutions:
  - Manual Responses
    - Product Structure and/or technology options not within scope of model, but attributes/performance have been measured in a manner consistent with the value function(s) so they can still be plotted and compared in value space.
  - Manual Configurations
    - Specific configurations that can be defined with the existing product structure (e.g. specific design concepts) for consideration and analysis
- Allows comparison of manual solutions with each other and with Pareto points



Pairwise Solution Comparison: Tornado Plots

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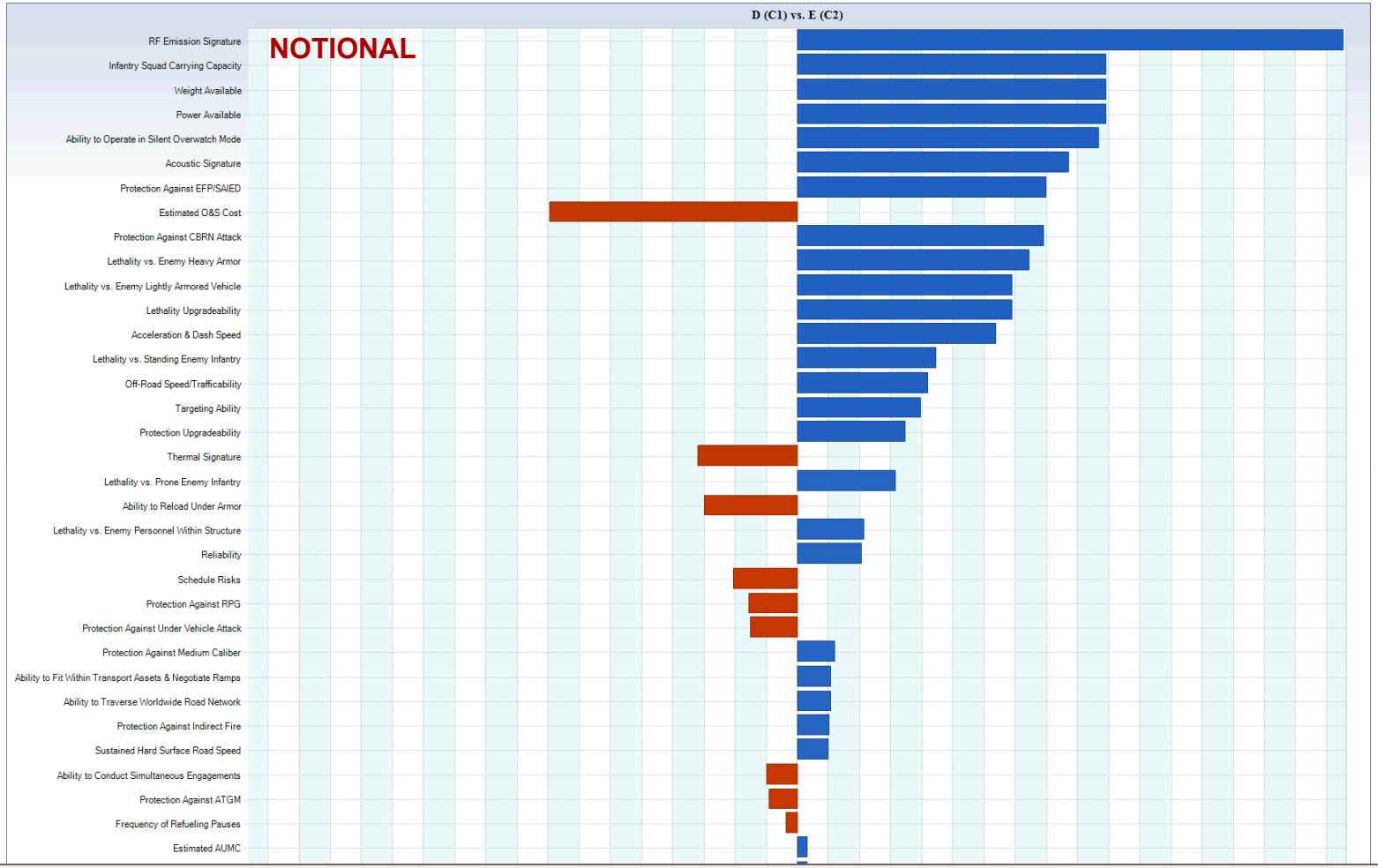
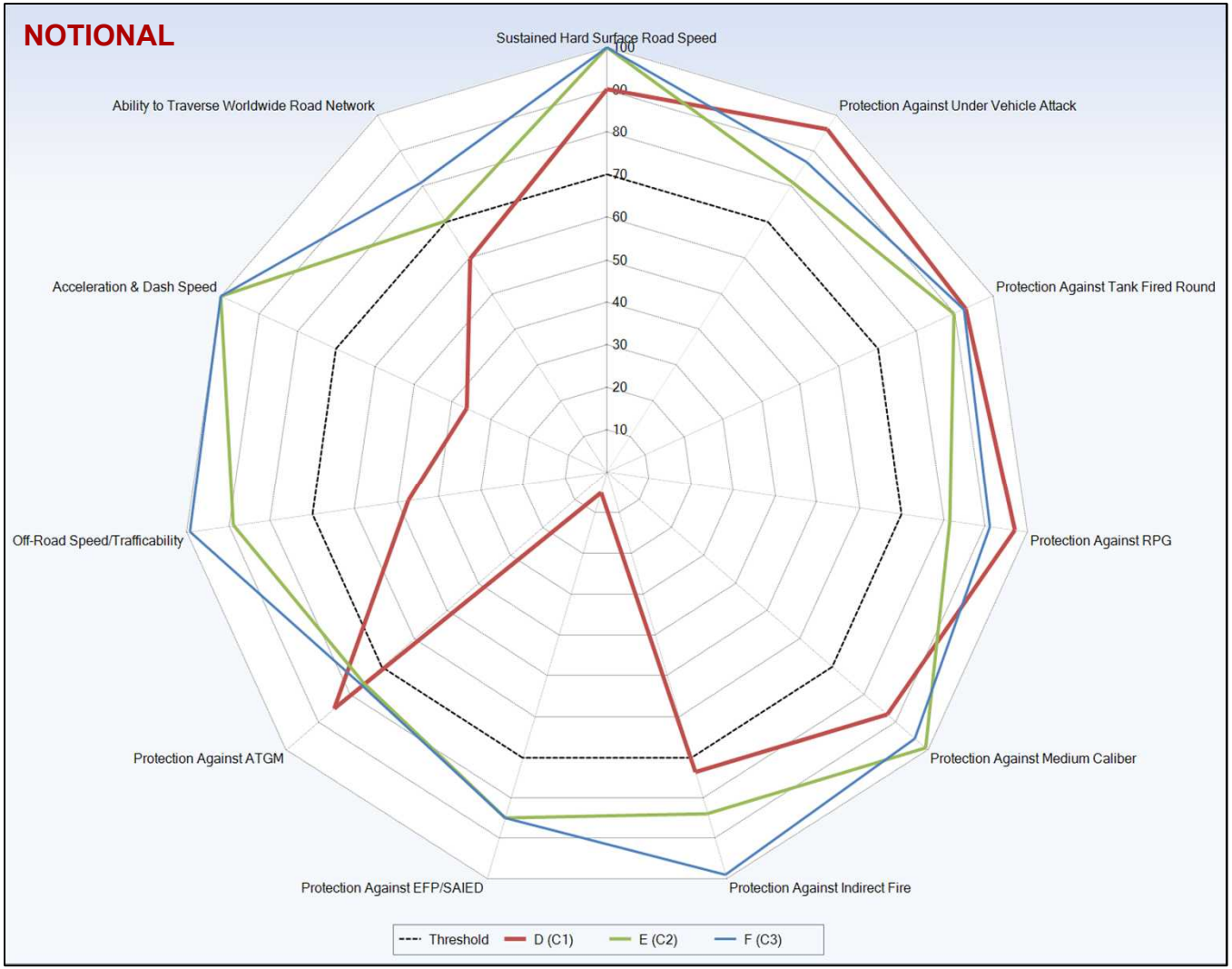


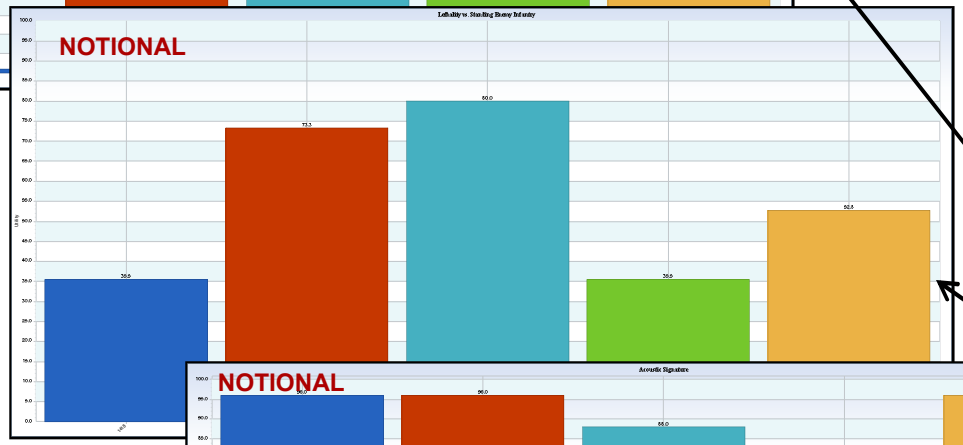
For any 2 configurations, shows percent win/loss in each functional objective

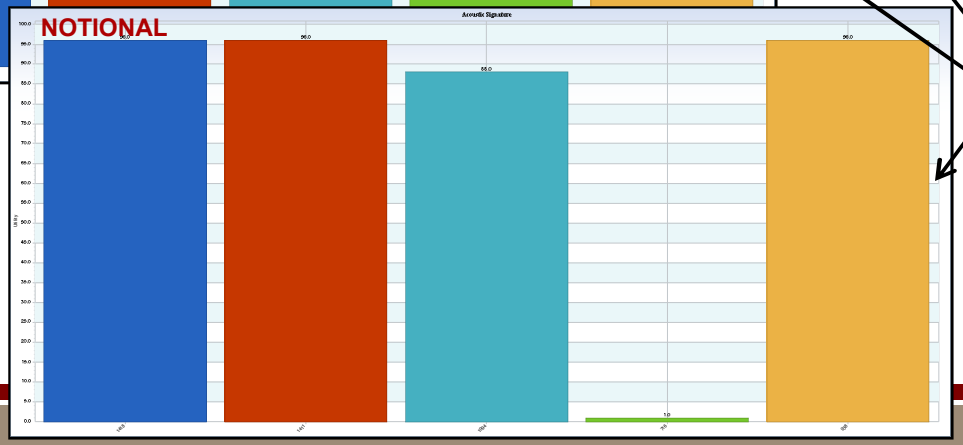
Multi-Solution Comparison: Radar Charts

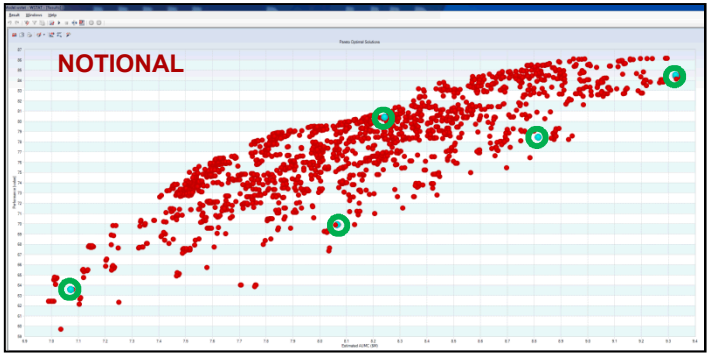


Functional Objective Bar Charts

Head-to-head comparison of multiple solutions for a given FO – e.g., for comparing solutions in an AoA





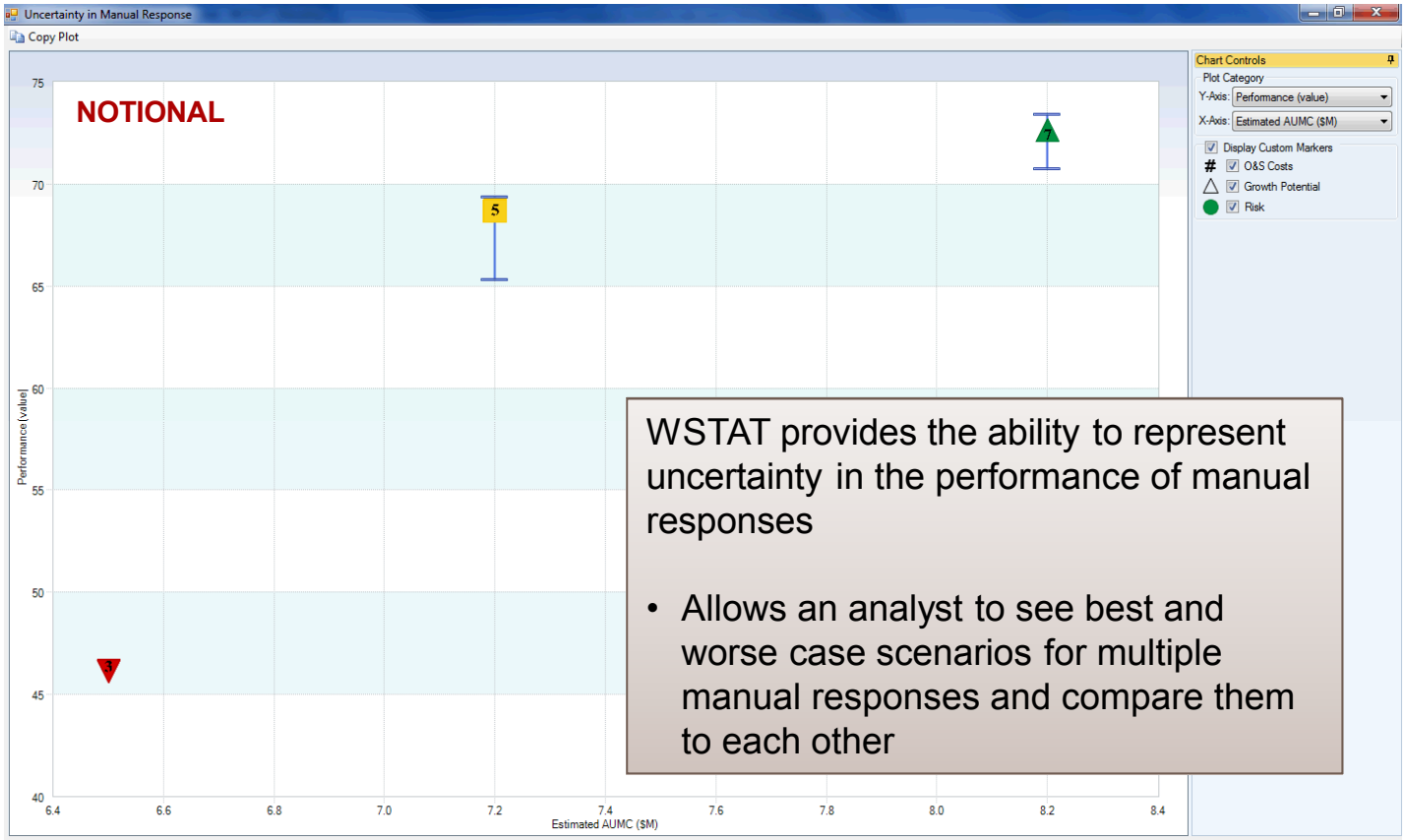


Compares multiple solutions side by side, focusing on one functional objective at a time, e.g.,

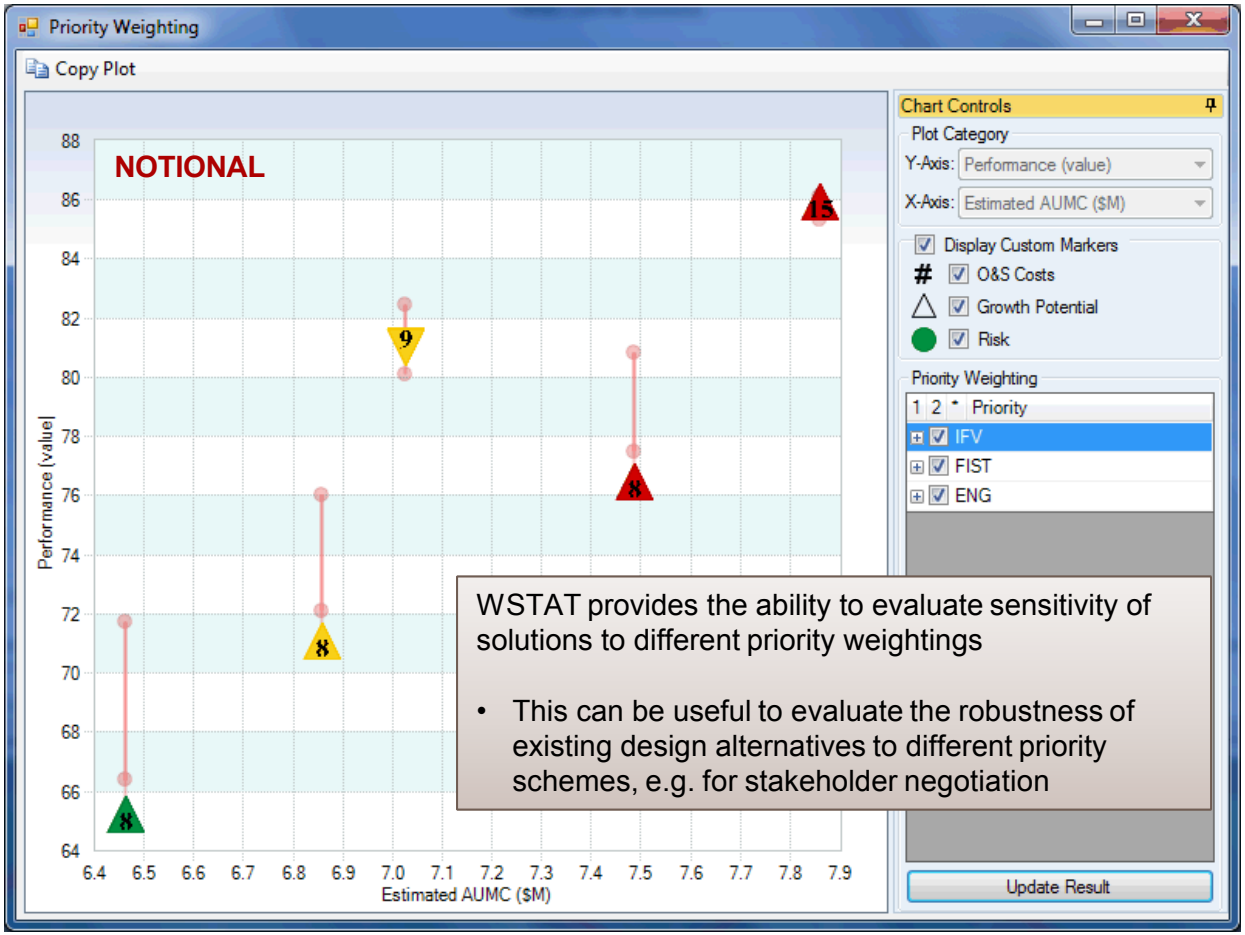
- Infantry Squad Carrying Capacity
- Lethality vs. Standing Enemy Infantry
- Acoustic Signature

(each bar is one of the selected solutions)

Manual Response Uncertainty



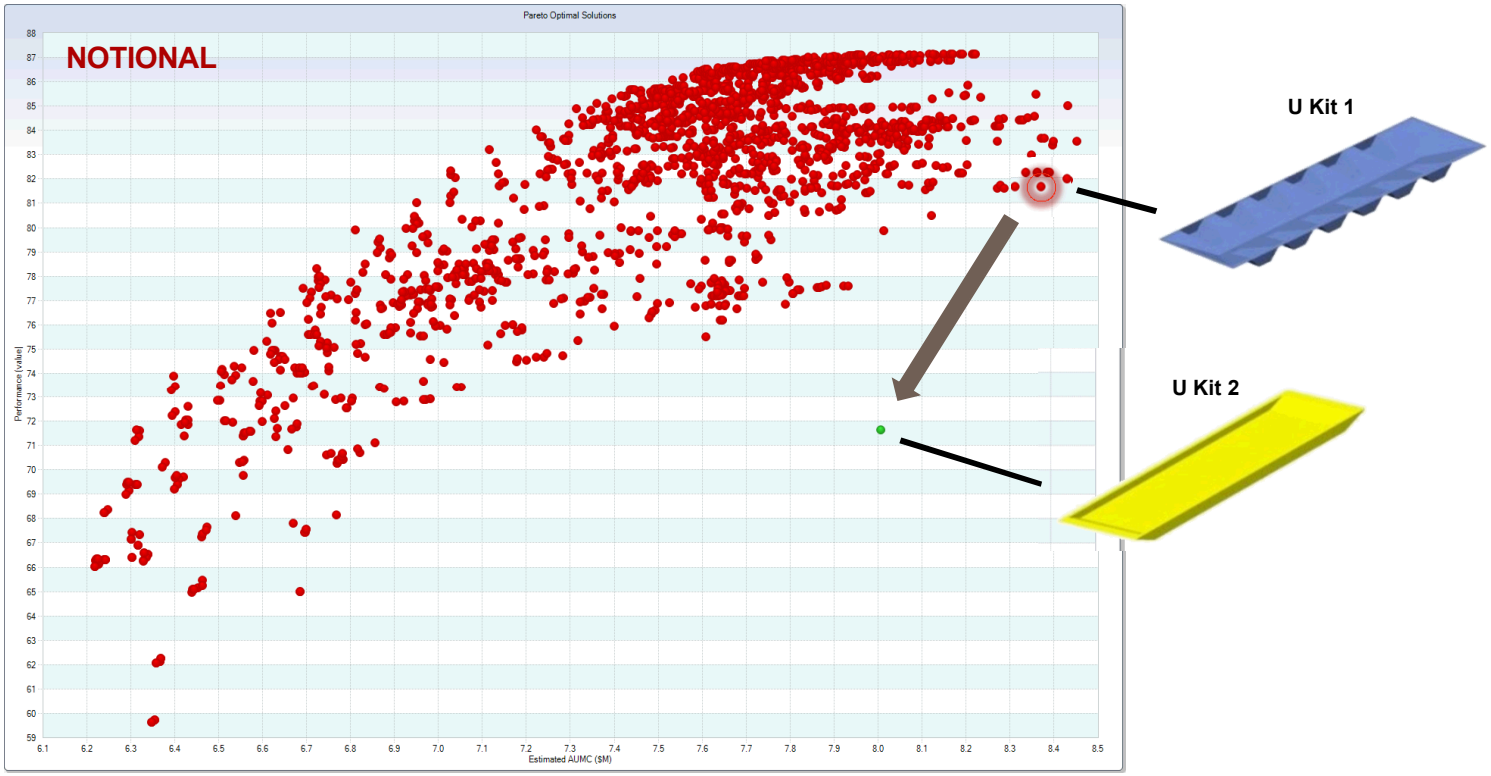
Priority Weights Sensitivity



Use cases

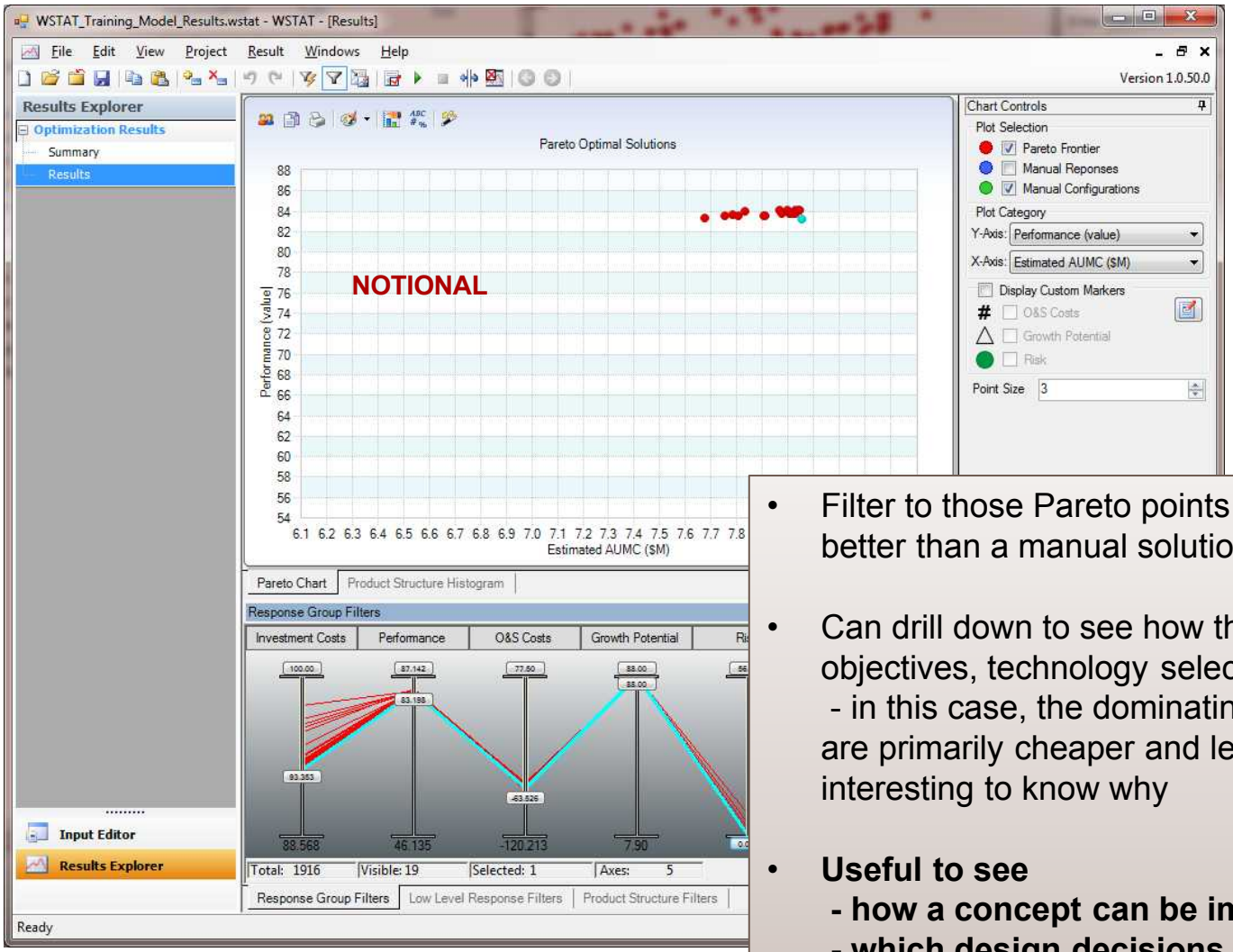
- Requirements analysis
- Tradeoff Analysis (between technologies, requirements, attributes)
- Assessing technology trends (e.g. in different price/weight ranges)
- Comparing Solutions
  - Pairwise/multiple solution comparison (radar, tornado, bar charts)
  - Priority weighting sensitivity analysis
  - With uncertainty
- Analyzing variations on a concept
  - Manually changing technology choices
  - Finding and analyzing dominating Pareto points
- Parametric analysis
- Family analysis

One-off technology variation analysis



Proposed technology changes can easily be represented within a manual configuration, and the effects of the change can be assessed (e.g. by looking at changes in performance, system metrics such as weight and power draw, etc.)

Domination analysis



- Filter to those Pareto points that are equal to or better than a manual solution in every dimension
- Can drill down to see how they compare in specific objectives, technology selections, etc.
  - in this case, the dominating Pareto solutions (red) are primarily cheaper and less risky, and it would be interesting to know why
- **Useful to see**
  - **how a concept can be improved**
  - **which design decisions might cause the system to outperform non-developmental options**

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Parametric Analysis

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- Occasionally it is useful to run multiple models and compare their output.

- E.g., if weight growth is expected to be an issue, parametrically increase the untraded/baseline weight across multiple models.
- Can tell you how things would change if the extra weight were factored in.
  - Attribute trends
    - as weight is added, does it choose to shed weight where possible, or add horsepower to compensate?
  - Requirements trends
    - does it start to have difficulty meeting mobility requirements? Or maybe because of the added engine load it has difficulty with heat signature?
  - Technology trends
    - Do certain heavy technology options, or lower-power engines, fall out of favor? Do heavier-duty (and more expensive) suspensions become necessary?

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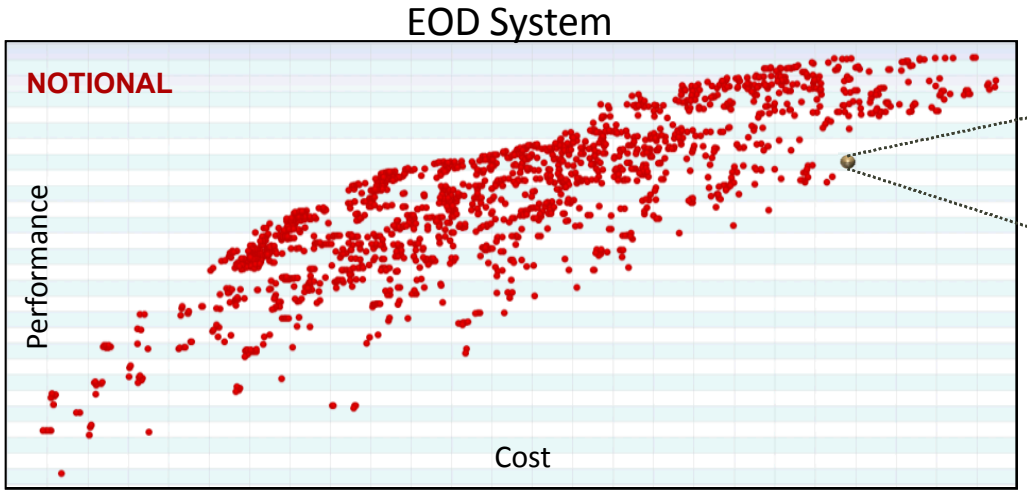
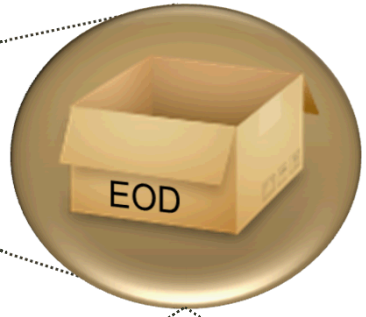
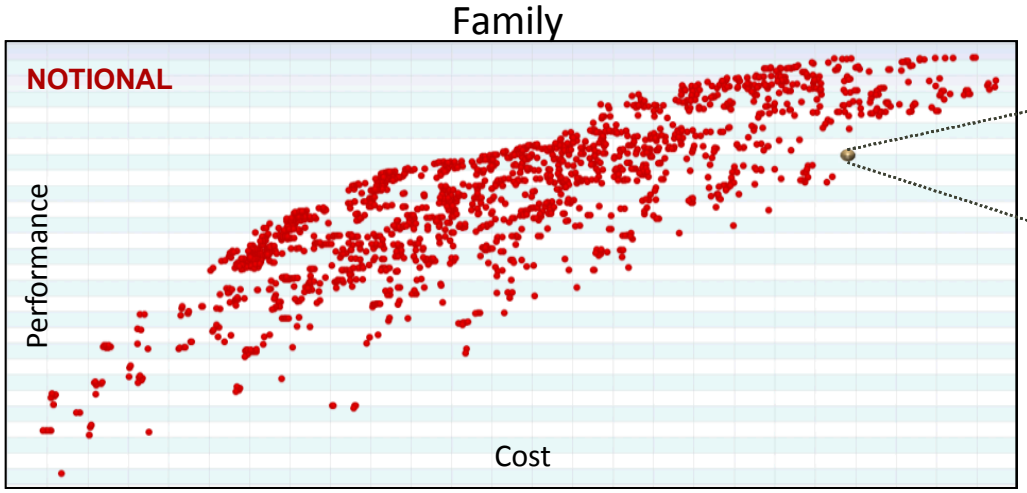
WSTAT Conventional Single-System Optimization

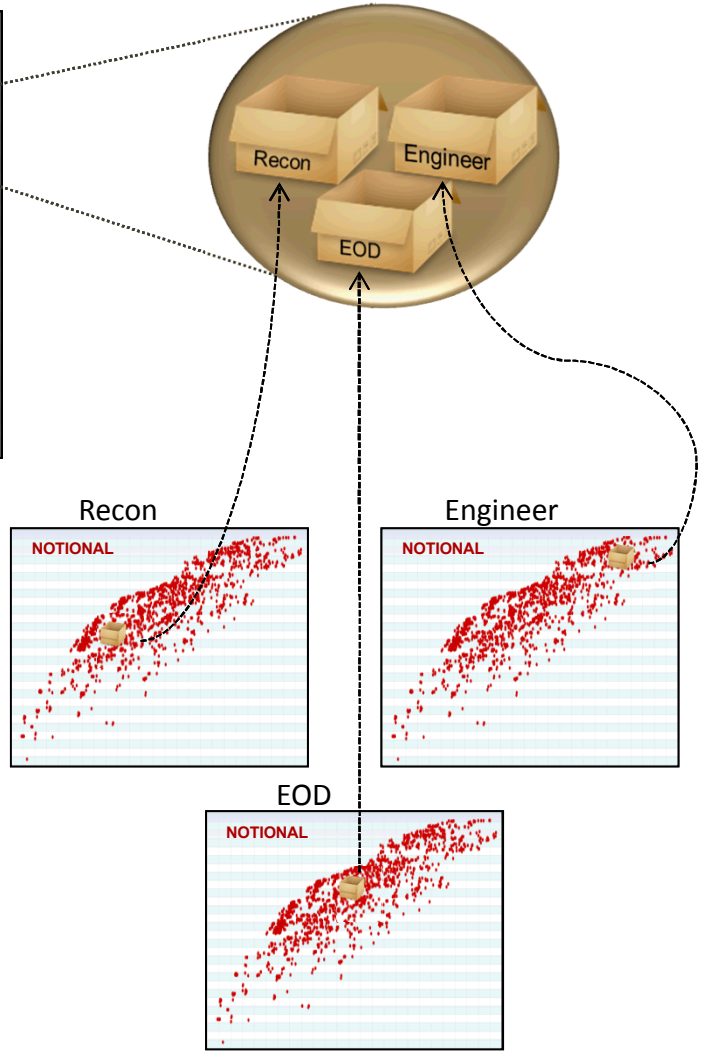




- Traditionally, WSTAT generates optimal configurations for a single system
- Each dot represents a single system configuration having optimal tradeoffs in multiple competing dimensions
- Each dot has knowledge about the components (Tech Options) that were chosen for that configuration

WSTAT Family-Level Optimization





- In a family version of WSTAT each dot represents an optimal family of systems, best balancing the needs of each family member
- The performance, cost, etc. of the family are determined via the contributions of the family members.
- New objectives that only make sense at a family level – such as commonality – can now be assessed.

Conclusion

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- Exploring tradeoffs between program goals based on possible design decisions can provide insight in all phases of the R&D and acquisition processes.
  - helps to shape and/or refine requirements so they are mutually achievable, or highlight those that require more technology development
  - highlights promising technologies in different attribute ranges
  - allows evaluation of the relative merits of existing design concepts and non-developmental systems
    - screening candidate concepts for an Analysis of Alternatives (AoA)
    - supporting source selection decisions
  - suggests ways that existing design concepts might be improved