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June 30 - July 3, 2014

Integrated Toolset and Workflow for Tradespace Analytics in Systems Engineering

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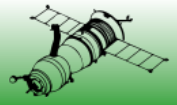
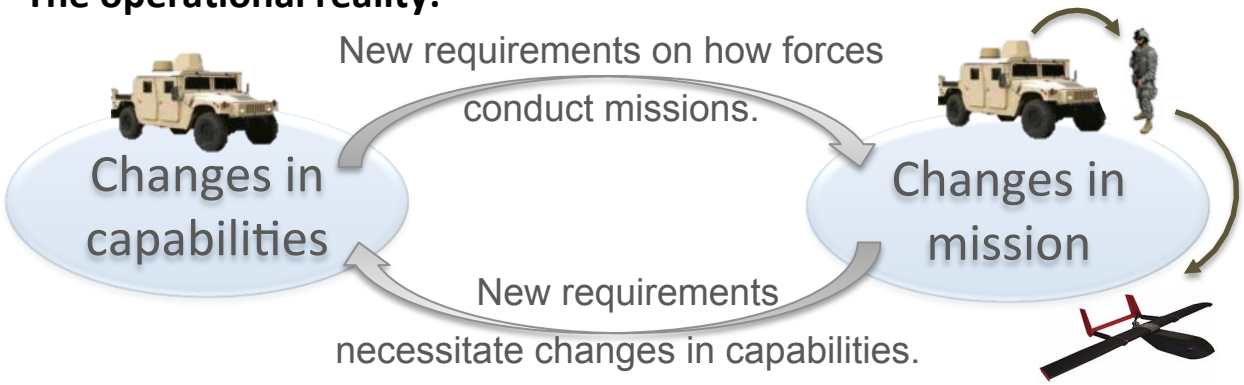



Motivation:
Engineering Resilient Systems

If you can do everything, you do not have to make choices.

So, you have to make those choices based on what you value most.

The operational reality:



Has led to:

"ERS will empower Pre-materiel analysis with significant impact on:
- *Requirements Generation*
- *Analysis of Alternatives*
- *Lifecycle Intelligence"*

~ Holland, ERS Overview Dec 2013

– Our goal –

How can we help system engineers design and analyze more effectively and rationally?

… in support of **Pre-Milestone A** Tradespace Analysis?

Tradespace Analysis for Early-Stage Design

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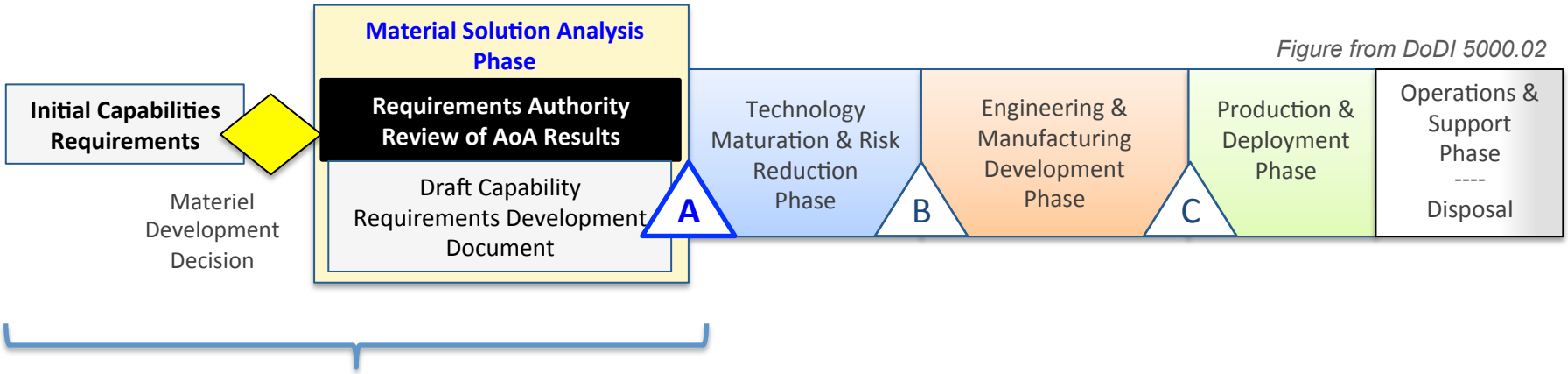

Figure from DoDI 5000.02

Objectives

- Identify, develop, and integrate a **design space environment and integrated workflow**
- Investigate how to **operationalize formalisms** into measureable and executable constructs
- … to support **Pre-Milestone A** Tradespace Analysis

Purpose

To support investigation and comparison of new methods and constructs for design exploration

To create flexible, rationally guided analyses in a way that allows the customer to quantify and visualize the impact of various requirements.

This work was performed as part of the Systems Engineering Research Center RT-46 Tradespace and Affordability project.

Developing an Integrated Workflow Process

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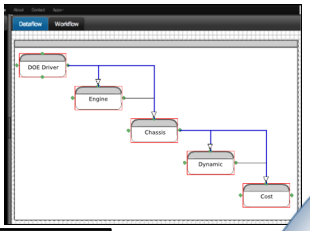
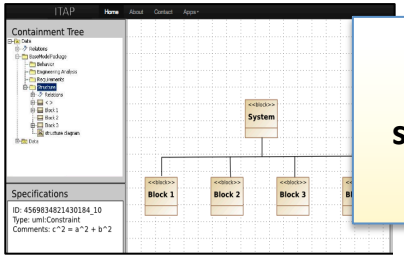
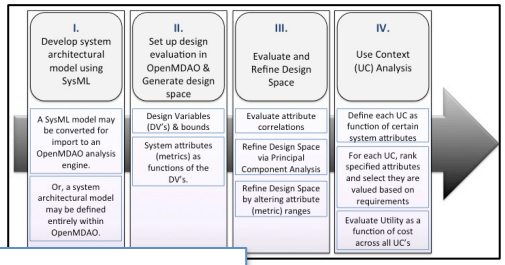
To guide design exploration & investigate methods to operationalize and execute foundation formalisms

SysML & OpenMDAO

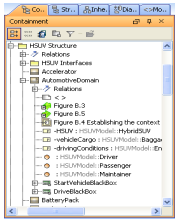


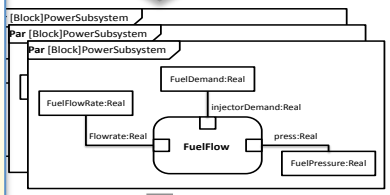


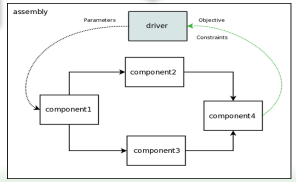
I.
Identify Open-source Technologies & Toolsets



II.
Develop Rationally Guided Workflow

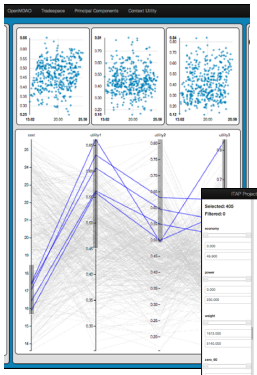


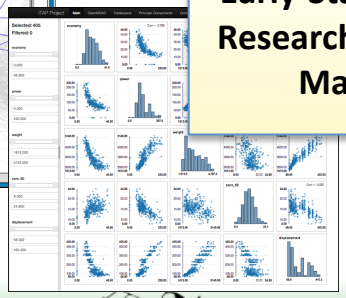


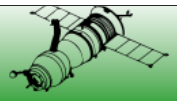


III.
Create Flexible, Open Architecture to Support Workflow

IV.
Integrate with Analysis Methods to Support Early-Stage Analytical Research and Method Maturation







SE Tools Overview

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Architecting / Conceptualization

- Analysis of Needs
  - Capture Customer Reqs & Gaps
  - 7MP Tools / Affinity Diagrams
  - Project Primer
- Synthesis of Solutions
  - QFD / SME inputs
  - MADM
  - TOPSIS
  - Morph Matrix
- Architecture Selection & Evaluation
  - SysML
  - System WBS

Analysis / Arch. Trade Studies

OpenMDAO → Monte Carlo / Tradespace Exploration / Sensitivity Analysis → Model Execution / Data Manager (Distributed Processing) → Save Data for Offline Analysis

Visualize

D3, Raphael → Visualization Manager

Document

Report Generation | Save Plots | Markup





A Focus on Web-Based Collaborative & Open Source Technologies

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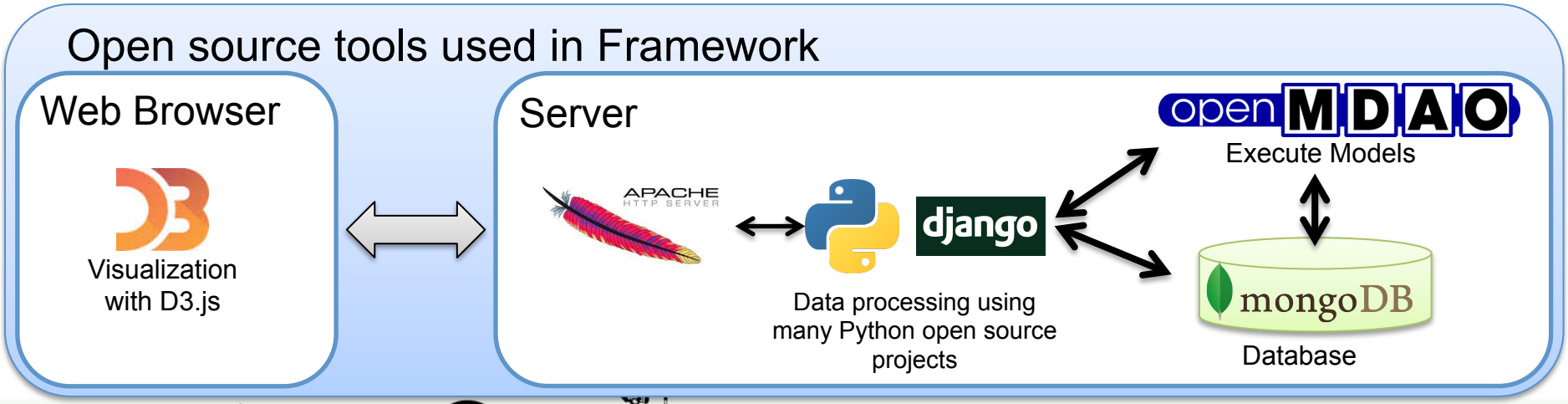
- **Collaboration**
  - Complex Systems Engineering problems require teams working together
    - Geographically disperse teams may complicate knowledge sharing and result in longer latencies
  - Web-based tools can provide a backbone for these teams to better integrate their knowledge leading to better communication
- **Open source**
  - The community of developers and practitioners contribute back to the central repository so everyone continues to benefit
  - Open tools and standards promote interoperability and extensibility across problem domains

Open source tools used in Framework



Supporting Framework and Workflow

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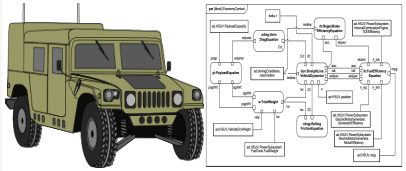
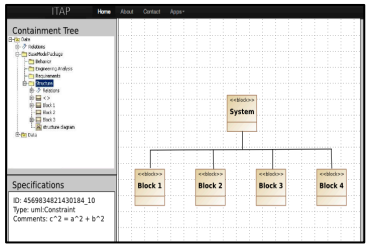
Design Concept Architecture → **Executable Model** → **CSV or Database** → **Subset CSV or Database**

SysML System Design Architecture



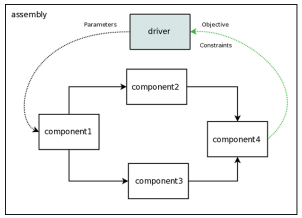
Documents problem.

Informs parametric models for quantitative evaluation.



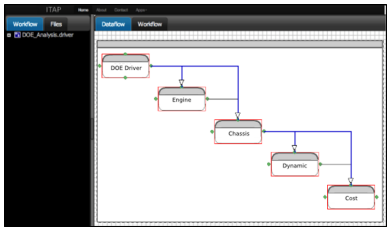
In-browser SysML motivates making model executable to increase its overall utility in the design process .

Parametrics & OpenMDAO



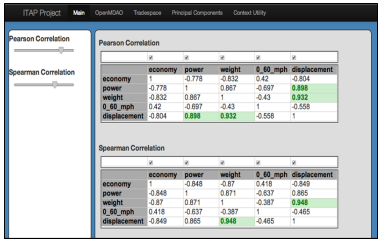
Analysis parametrics from SysML or brought into process from other sources.

Evaluate design alternatives using OpenMDAO.



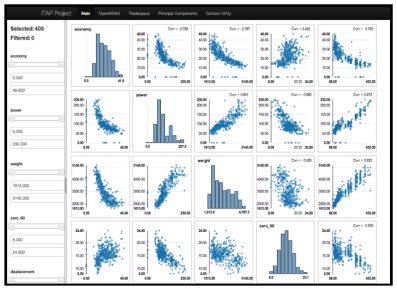
In-browser Design Structure Matrix Representation using OpenMDAO can interface with SysML Parametric Constraints.

Tradespace Analytical Refinement & Visualization



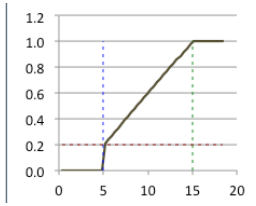
Evaluate attribute correlations.

Reduce visualization burden.

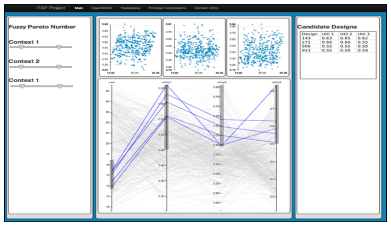


Collaborative, interactive Tradespace exploration through visualization tools.

Needs Context Analysis



Flexible, requirements based analysis using Multi-Attribute Utility Theory.



Begins to operationalize dimensions of '**Robustness**'.

Interactive exploration of key stakeholder needs.

Insights can carry forward to higher-fidelity design or requirements refinement.

Parametric Execution for Tradespace Generation

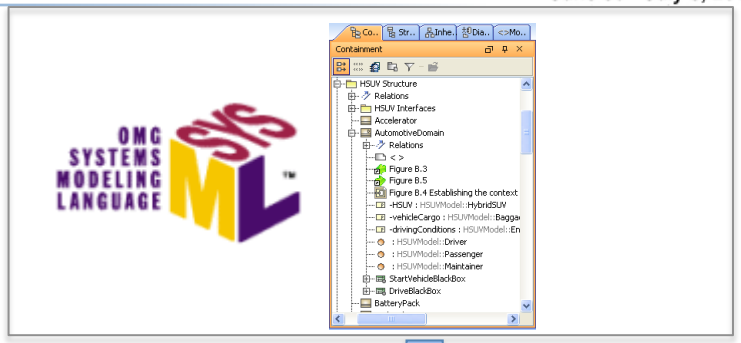
OpenMDAO is an open-source Multidisciplinary Design Analysis and Optimization (MDAO) framework in development by NASA

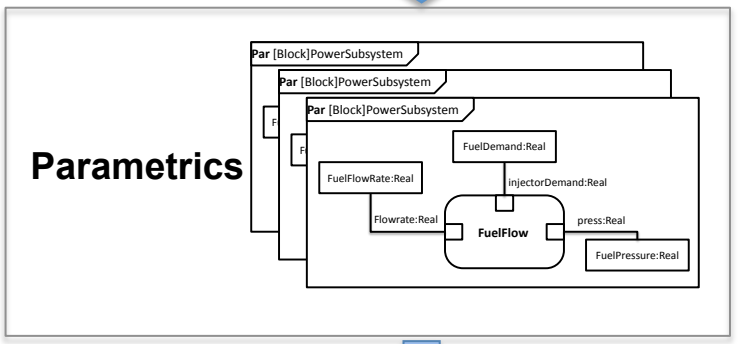
- Controls the execution order of different analyses
- Intelligently handles unit conversions for design variables between analyses

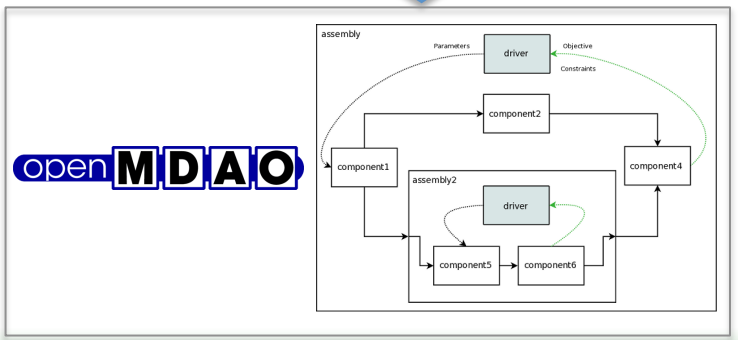
Process to extract SysML parametrics for OpenMDAO execution

1. Parse SysML model for relevant parametric information
   - Design variables – units, flow
   - Parametric equations – execution order
2. Create OpenMDAO components from parametrics
   - Connect the components through the appropriate design attributes
3. Execute top level driver to explore the tradespace
   - Driver can be a Design of Experiments, or optimizer

Resulting tradespace data is saved to a database and retrieved later for additional analysis

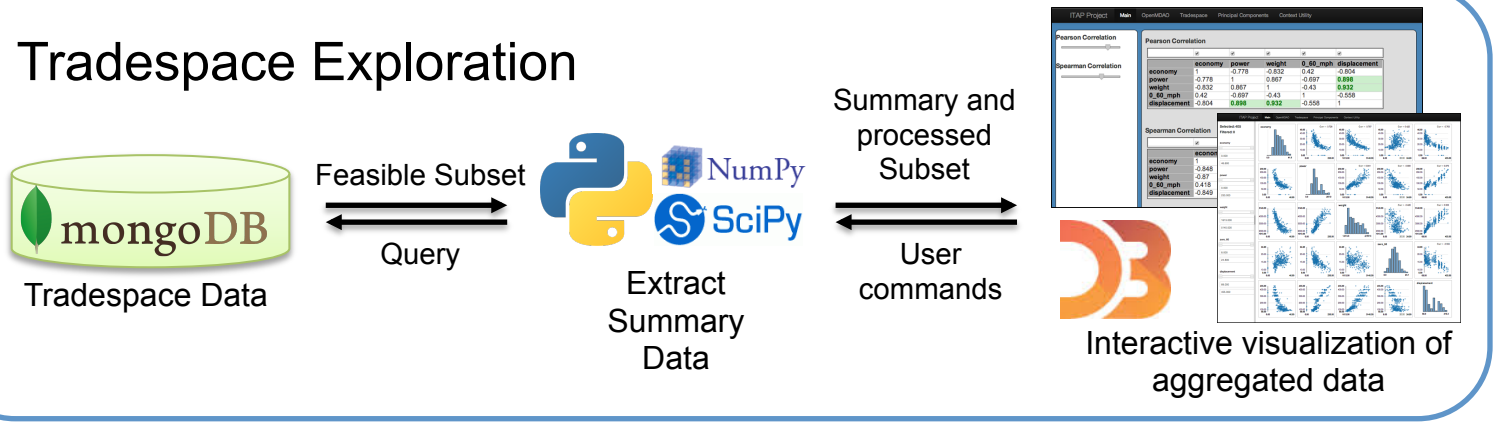






Supporting Tradespace Analytics & Visualization

Tradespace Exploration



- High-dimensional SE problems require different analyses to identify the important subspaces.
  - A variety of methods may aggregate and/or filter data and present only the salient data to the analyst
  - Additional data processing and transformation tools may identify the design variables driving the system performance
- Methods to guide tradespace exploration must be transparent, intuitive, and rational to the analyst and quantifiably traceable to promote future comparability
- Example methodology:
  - System attribute correlation properties to reduce visualization and cognitive burden using interactive scatter plot matrices
  - Correlation properties of system attributes calculated and displayed with freedom for analyst to control thresholds that highlight correlations and which system attributes to then display and interact

Needs Context Analysis:
Background & Rationale

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Challenges in requirements elicitation:
- Scope and context to reflect true user needs
- Fostering understanding among different communities affected by the development of a given system
- Requirements volatility (They change over time.)

~ Christel & Kang 1992

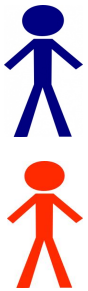
"Knowledge about evolution, and likely future requirements is critical to incorporate functional and performance options within an architecture."
~ Schultz 1999

"Robustness characterizes a system's ability to be insensitive towards changing environments. Robust systems deliver their intended functionality under varying operating conditions without being changed."
~ Fricke & Schultz 2005

"Value robustness is the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs."
~ Ross & Rhodes 2008 (IEEE SysCon)

To achieve value robustness, design systems "… using natural value-centric timescales, wherein the context and expectations define the timescales."
~ Ross & Rhodes 2008 (INCOSE)

Competing Objectives in Parallel



Stakeholder 1: Prioritizes capabilities {A, B, C}

Stakeholder 2: Prioritizes capabilities {C, D, E}

Competing Objectives in Series

Prioritize capabilities {A, B, C}
At levels $\{A_{R1}, B_{R1}, C_{R1}\}$

Prioritize capabilities {C, D, E}
At levels $\{C_{R2}, D_{R2}, E_{R2}\}$

System Service Life

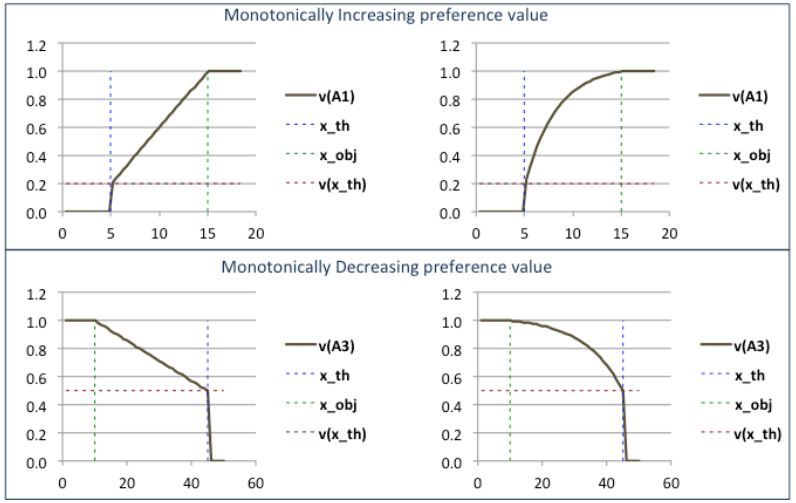
Requirements or Mission Profile at Time 1

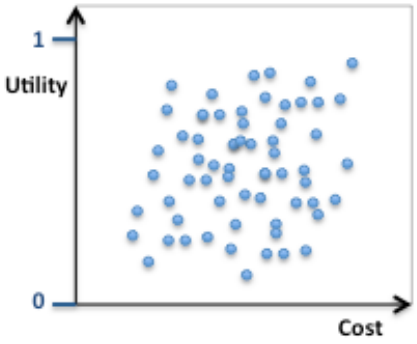
Requirements or Mission Profile at Time 2

Operationalizing a Needs Context: Method

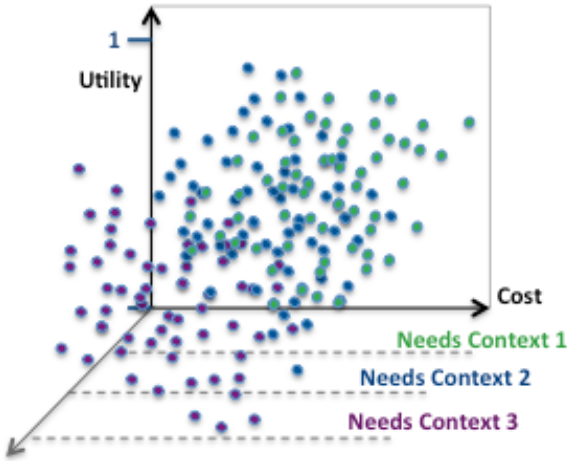
Method

- User selected and ranked performance attributes contribute to ***a weighted, additive value function*** (i.e., a utility)
- Scaled against ***Objective and Threshold*** requirements
- Provides ***comparability*** from one tradespace to the next regardless of attribute value range
- In line with ***Key Performance Parameter*** (KPP) concept
- ***Flexible*** attribute selection, ranking, and value scaling

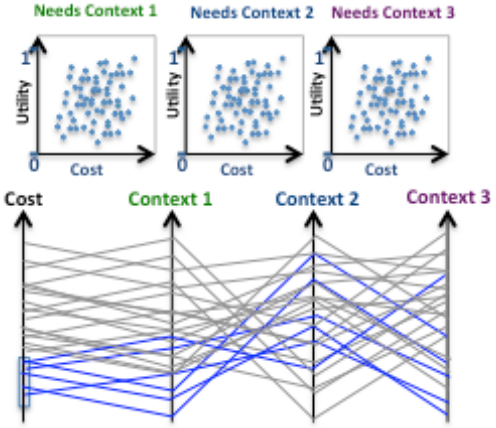




Classical Utility (2D)



Multi-Utility or Needs Context (3D)



Parallel Coordinate Representation

Needs Context Analysis:
Workflow and Application

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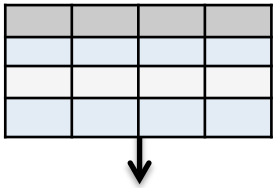


Tradespace Data (Data $_O$)

Each contiguous line represents a candidate system design.

Analyst Defines m Needs Contexts (NCs)

Specify per NC:

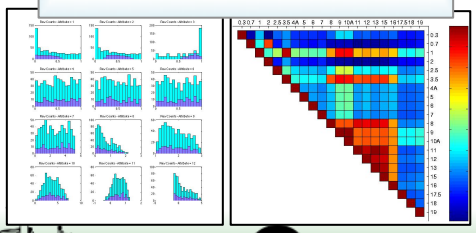
- System attributes (Y_j) of interest
- Threshold and Objective Requirement values for each attribute
- 'Value' [0,1] at Threshold
- Way each attribute is valued (linear or exponential)
- Ranking of attributes

NC $_1$ → **Utility $_1$**
NC $_2$ → **Utility $_2$**
NC $_N$ → **Utility $_N$**

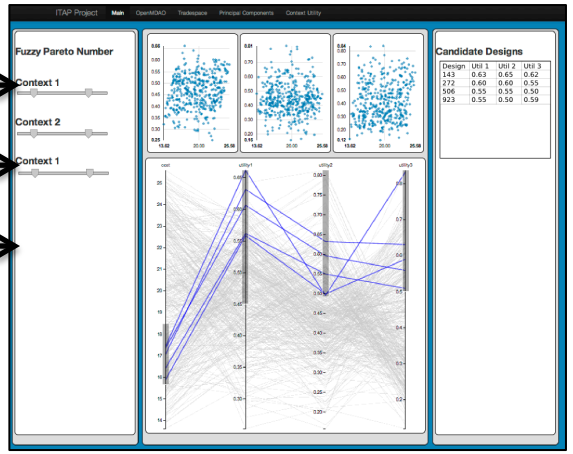
Evaluate 'Big Picture' of Results for each NC

Create raw count histograms of top X% of Needs Context utility scores and overlay with 'full' tradespace before the Needs Context filter.

Display alongside heatmap showing Spearman correlation characteristics from 'full' tradespace before the Needs Context filter.

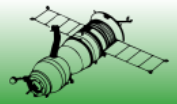


Create Parallel Coordinate Visualization



Analyst controls both:

- Fuzzy Pareto Number to highlight candidate designs on parallel coordinates
- Parallel coordinate axes to vary which designs are still highlighted based on priorities or compromises


Discussion:
Benefits & Needs Context Analysis

Benefits

- Open, flexible framework and approach promote ***qualitative and quantitative transparency*** of tradespace refinement
- Framework and workflow support ***exploration and evaluation*** of multi-dimensional analysis constructs for ***–ilities*** applicable to early-stage design
- Maturation leads to methods that enable ***more complete and robust requirements Pre-Milestone A***
- Approach allows us to provide a ***traceable, justifiable basis for reducing a set*** of options for further analysis from a broader alternative set

Needs Context Analysis

- Enables analysis across ***Stakeholders*** and ***Mission Profiles*** that necessitate different performance objectives… Whether simultaneously or across time, using a ***single construct***
- ***Value-centric but also KPP-based*** – promotes clarity in understanding and comparability across runs
- Helps capture ***resiliency*** of a system design across competing or changing requirements by investigating ***robustness*** of design alternatives under changing conditions
- Applies when there is a need to analyze ***tradespace data*** without access to full model information
- Aids refinement and ***analysis of requirements*** and to see why ***compromises may not be acceptable***
- May therefore help ***identify platform capabilities*** for further investigation as multi-design

Discussion:
Challenges & Lessons Learned

- **SysML & OpenMDAO**
  - Improvements to existing SysML parser are needed for more efficient and effective conversion to OpenMDAO.
  - Better in-browser tools for displaying SysML diagrams are needed to promote broader use and improved visual comprehension
- **Requirements & -ilities**
  - Requirements often conflate functional requirements ('what' a system should perform) and non-functional requirements ('how well' – the "-ilities")
  - -ilities are often defined according to life cycle stage or blur across several; care must be taken to operationalize appropriately

Robustness =
"the measure of how effectively a system can maintain a given set of capabilities in response to external changes after it has been fielded"

(Ryan, Jacques, and Colombi 2013)

- **Mapping design variables to system attributes**
  - The model of the system alone is insufficient to produce all quantitative system attributes important to the decision making process
- **Workflow matters**
  - Where in the tradespace exploration process an analytical filter is used can alter subsequent findings

Acknowledgements

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