JPL Develops MBSE Tools to Perform Business Case Analysis for DARPA's F6 Program

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AGENDA

- Phoenix Overview
- JPL Overview
- DARPA F6 Overview
- Problem Description
- Solution using SysML / ModelCenter
- Demo
- Question & Answer Session

Background: Phoenix Integration

- 15 year history; Evolved out of a research program at Virginia Tech
- Provide engineering software and services to customers in aerospace, defense, and related industries
- Office locations
  - Philadelphia, PA (Corporate)
  - Blacksburg, VA (R&D)
  - California (Sales)
  - North East (Sales)
- World-wide sales in North America, Europe, and Asia

OUR VALUE PROPOSITION

Automation: Wrap simulation tasks into repeatable actions

Integration: Chain together multiple wrappers to form end to end simulation workflows

Design Exploration: Find better designs; Perform DOE, Optimization, Probabilistics

Manage your analysis capability

- Load balance trade studies
- Version control and reuse simulation workflows
- Catalog and share simulation data

Core Products

PHX ModelCenter®

- *Process integration*

Analysis Server®

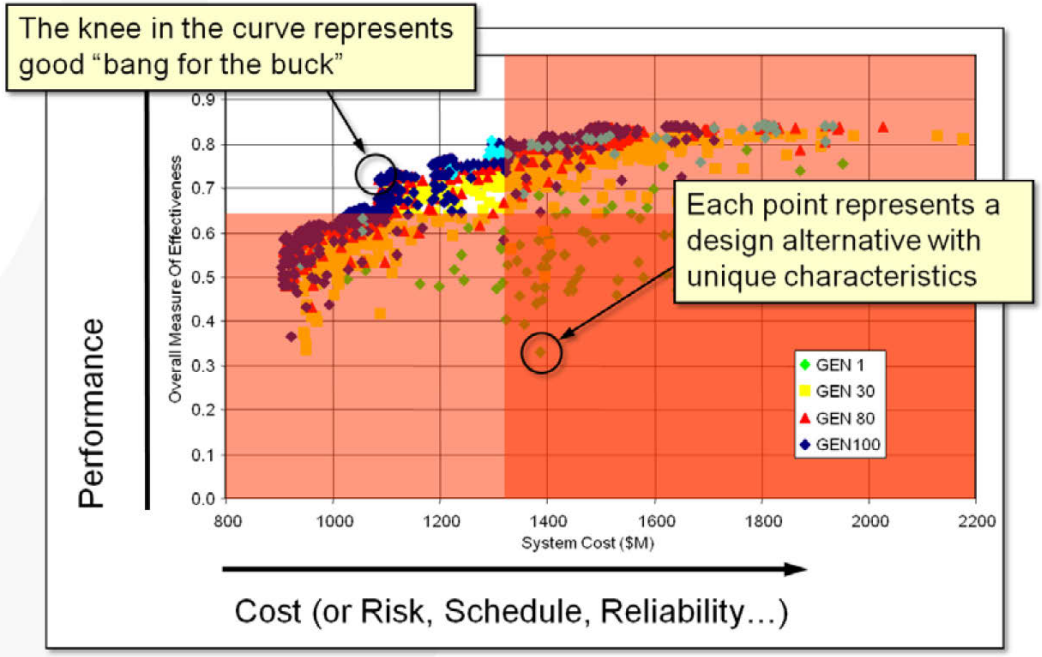
- *Analysis automation*

PHX CenterLink®

- *Load balance trade studies*

PHX AnalysisLibrary®

- *Intelligent file management*
- *Search and reuse*
- *Version control*



Example Application:
Analysis of Alternatives

JPL is part of NASA and Caltech

- Federally-Funded (NASA-owned) Research and Development Center (FFRDC)
- University Operated (Caltech)
- $1.5B Business Base
  - NASA Science 72%
  - Non-NASA 12%
  - Mission Operations 12%
- 5,000 Employees
  - R&D Staff 59%
    - 32% PhD
    - 32% Masters

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DARPA F6 BAA

- DARPA-BAA-11-01, Tactical Technology Office (TTO) released on October 20, 2010
- The goal of the System F6 (*Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange*) program is to demonstrate the feasibility and benefits of disaggregated—or fractionated—space architectures. The program will culminate with an on-orbit demonstration in 2014-2015 of the key functional attributes of fractionated architectures
- Key [most important?] feature is *demonstration of new SE/MBE capabilities in both development and acquisition of new systems*
- Four technical areas
  - 1. Design Tools for Adaptable Systems
  - 2. Wireless Inter-Module Communications
  - 3. Information Architecture
  - 4. Cluster Flight

System F6 Technical Area 1: Design Tools for Adaptable Systems

- This DARPA F6 Technical area is intended to result in "the maturation of a set of design tools that enable the explicit trade-off between system "–ilities," such as adaptability and survivability and traditional design attributes, such as size, weight, power, cost, reliability, and performance.
- This design toolset should help answer two questions. First, …
  - When does a fractionated architecture make sense?
  - When does the business case close?
- Proposed approaches should consider range of uncertainties that give rise to the need for system adaptability and survivability, including at least: technology development risks, supply chain delays, changes in user needs, program funding fluctuations, launch failures, component failures, orbital debris, and technological obsolescence."

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Research Goal Summary

Goal 1 – Generating Value

- Model the development and operations of the cluster
- Generate value by utilizing prices for different data by different users
- Explicitly model all stimuli and generate the results for the various stimuli cases

Goal 2 – Closing the Business Case/Measuring Adaptability and Survivability

- Utilizing Embedded Real Options Approach
- Metrics for Adaptability and Survivability
- Observations: The more uncertain the future the better for F6

Goal 3 – Tradespace Visualization, Exploration and Optimization

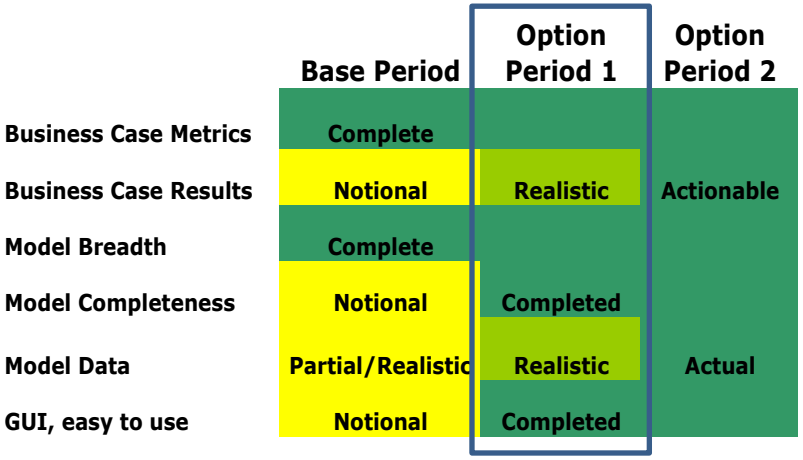
- Transparency: Able to zoom and review individual models and modify, etc.
- Explicit Models enable adding "provenance instrumentation" to the analysis
- Able to generate regression test cases
- Flexible rule-based model transformation apparatus for generating variants and filtering for analyses, can easily extend MC to automate DOEs
- Able to inspect tradespace from any perspective in various graphical forms

Goal 4 – Demonstrate

- Automatic model generation and transformation for any case(s), scalable and extensible.
- Robust methodology
- Produce notional model

High Level Goals

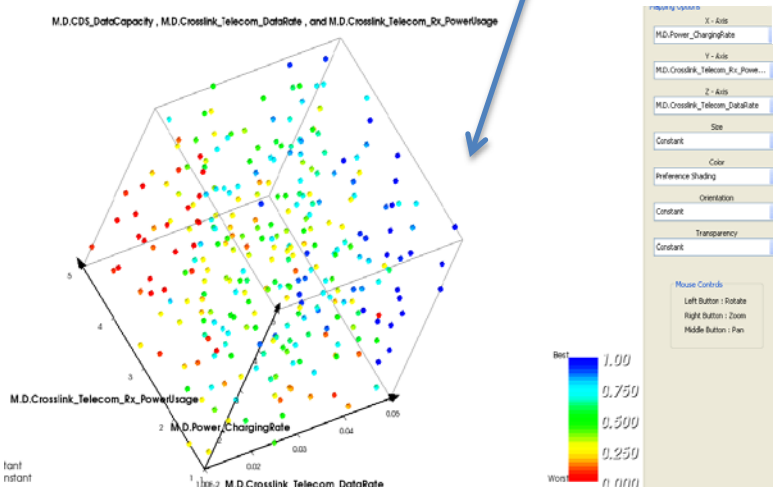
- **Option 1**
  - Expand the Base Period product into a realistic, fully-functional model
  - Complete tools for generating the tradespace for business closure and allow exploration of various subsets of it
  - Develop initial GUI
- **Option 2**
  - Pilot model on variety of use cases
  - Refine GUI, models based on feedback
  - Deliver tool as open-source product



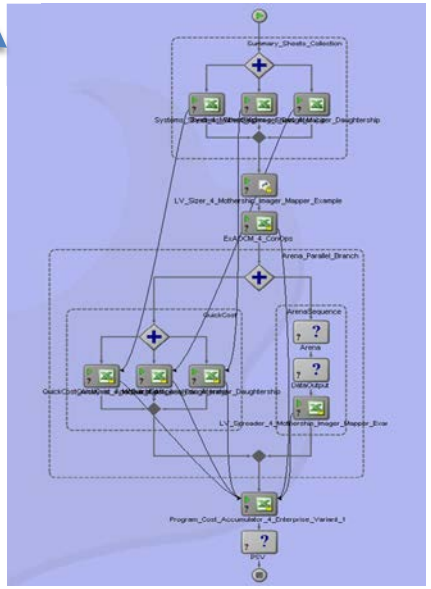
Results of Option Period 1 Recap

- Produced realistic model
  - Included stimuli and responses to measure adaptability and survivability
  - Automatically generated, populated and executed cluster candidates
  - Generated populated tradespace with Present Strategic Value as overall metric

Scenario Parameter Name	Units	Value
Scenario ID		1
Option Penalty	$FY11M	$ 10.00
Ops Cost Multiplier		1.25
Derived Parameter Name	**Units**	**Value**
ATP Date		10/1/2012
Payload launch occured here		7/6/2015
Mothership launch occured here		1/4/2016
Payload launch occured here		7/4/2016
Option Purchase Date		6/2/2014
Option Strike Date		7/6/2015
Simulation End Date		9/6/2032
Operating Breakeven Week		619
Discount (Purchase-ATP)		0.948008528
PV_Option (Operating Profit)	$FY11M	$ (110.79)
PV_Payload_Delta (DBATI)	$FY11M	$ (25.00)
Option Breakeven Draw	$FY11M	$ (164.24)
ERO Name	**Units**	**Value**
Option to Switch Payloads	$FY11M	$ 62.37
"In-the-Money" Probability		0.16



Multi-dimensional plot of tradespace for N=3 configuration



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BUSINESS CASE

Present Strategic Value (PSV) of an Investment (ala Schwartz and Trigeorgis, et al.*)

$$PSV = E_P[NPV] + \text{Value of Embedded Real Options}$$

- **General Nature of Embedded Real Options (EROs)**
  - **Expand, Contract**
  - **Defer, Accelerate**
  - **Switch (Repurpose, Abandon)**
- **Practical Implementation Issues**
  - **Consistently calculating each real option value**
  - **Embedding them in a lengthy, complex project**
    - **PSV depends on the assumed PPS and parameters of each ERO**
  - **Creating the Threads of Calculation**
    - **Inputs**
    - **Models needed/available**

*Eduardo S. Schwartz and Lenos Trigeorgis, eds., *Real Options and Investment Under Uncertainty*, 2001, MIT Press, Cambridge, MA

Uncertainties with Candidate Embedded Adaptability and Survivability Real Options

Adaptability

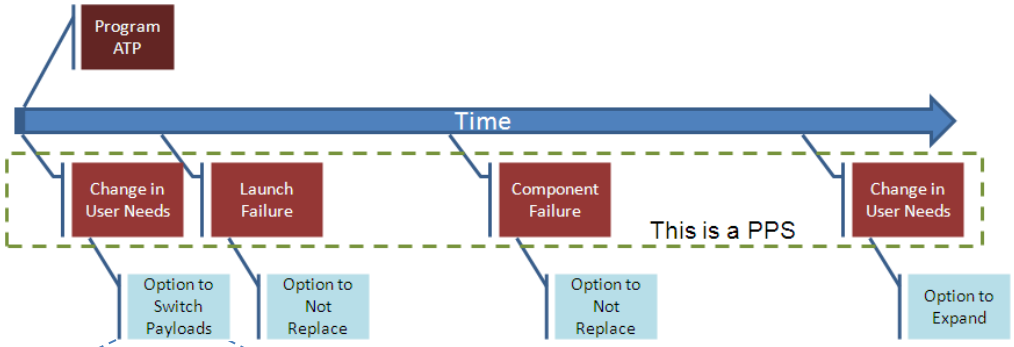
Uncertainty Type	Embedded Real Options
Technology Development Risk	Option to Switch Technologies Option to Suspend/Slow Ancillary Developments
Supply Chain Delays	Option to Switch Payloads Option to Switch Technologies Option to Suspend/Slow Ancillary Developments
Changes in User Needs	Option to Switch Payloads Option to Discontinue Option to Abandon Option to Expand Option to Accelerate Development Option to Switch Technologies
Program Funding Fluctuations	Option to Defer Development Option to Accelerate Development Option to Expand Option to Delay Launch Option to Suspend Ancillary Development Option to Switch Technologies Option to Switch Payloads Option to Discontinue Option to Abandon
Technology Obsolescence	Option to Abandon Option to Switch Technologies Option to Discontinue Option to Accelerate Development Option to Switch Payloads

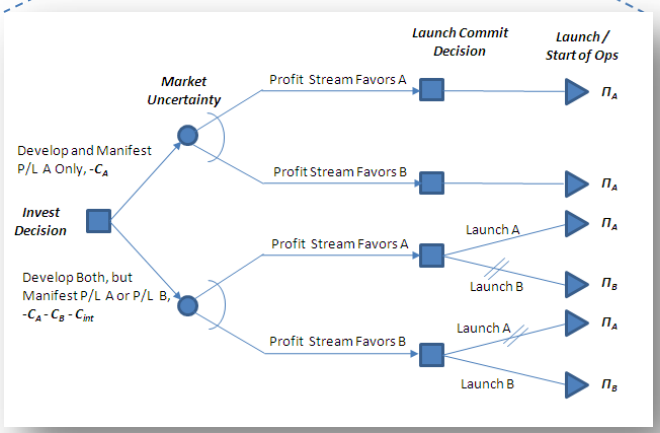
Survivability

Uncertainty Type	Embedded Real Options
Launch Failure	Option to Accelerate Development
Operator Failure	Option to Accelerate Development Option to Not Replace
Component Failure	Option to Accelerate Development Option to Not Replace
Orbital Debris	Option to Accelerate Development Option to Not Replace
Space Weather	Option to Accelerate Development Option to Not Replace
Collision	Option to Accelerate Development Option to Not Replace
Cyber Security	Option to Discontinue Option to Abandon Option to Not Replace Option to Switch Technologies Option to Accelerate Development

Currently in Base Period model

A PPS and Associated ERO Responses Together Generate a Time-Expanded Decision Network





PPS=Pre-planned Surprises
ERO=Embedded Real Option

PSV Calculation Using Monte Carlo Simulation

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Results from the PSV Model: Expected NPV for the Nominal Case

Scenario Parameter Name	Units	Value
Scenario ID		0
Simulation Duration	weeks	1040
Discount Rate	%/year	3.20%
Marginal Ops Cost (Nominal)	$FY11M/week	$ 1.45
Derived Parameter Name	**Units**	**Value**
ATP Date		10/1/2012
Payload launch occured here		7/6/2015
Mothership launch occured here		1/4/2016
Payload launch occured here		7/4/2016
Simulation End Date		9/6/2032
Operations Breakeven Week		525
PV_Nominal (Launch)	$FY11M	$ (110.59)
PV_Nominal (DBATI)	$FY11M	$ (286.16)
PV_Nominal (Operating Profit)	$FY11M	$ 18.97
NPV_Nominal	$FY11M	$ (377.78)
Expected NPV_Nominal	$FY11M	$ 107.75

Results from the PSV Model: "Switch Payload" Real Option Value

Scenario Parameter Name	Units	Value
Scenario ID		1
Option Penalty	$FY11M	$ 10.00
Ops Cost Multiplier		1.25
Derived Parameter Name	**Units**	**Value**
ATP Date		10/1/2012
Payload launch occured here		7/6/2015
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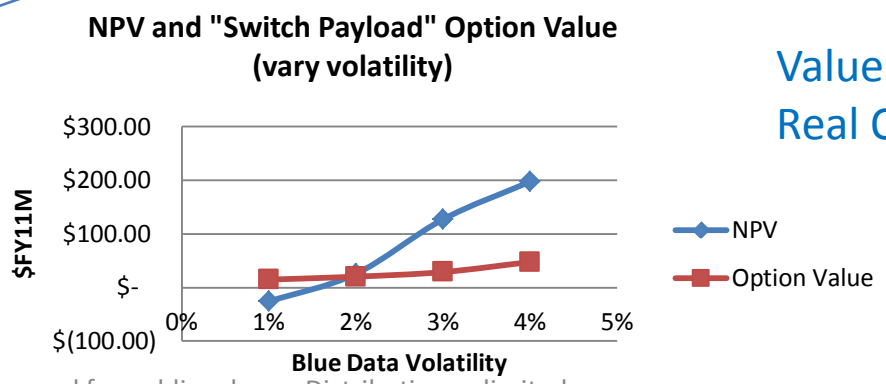
Option Breakeven Draw	$FY11M	$ (164.24)
ERO Name	**Units**	**Value**
Option to Switch Payloads	$FY11M	$ 62.37
"In-the-Money" Probability		0.18

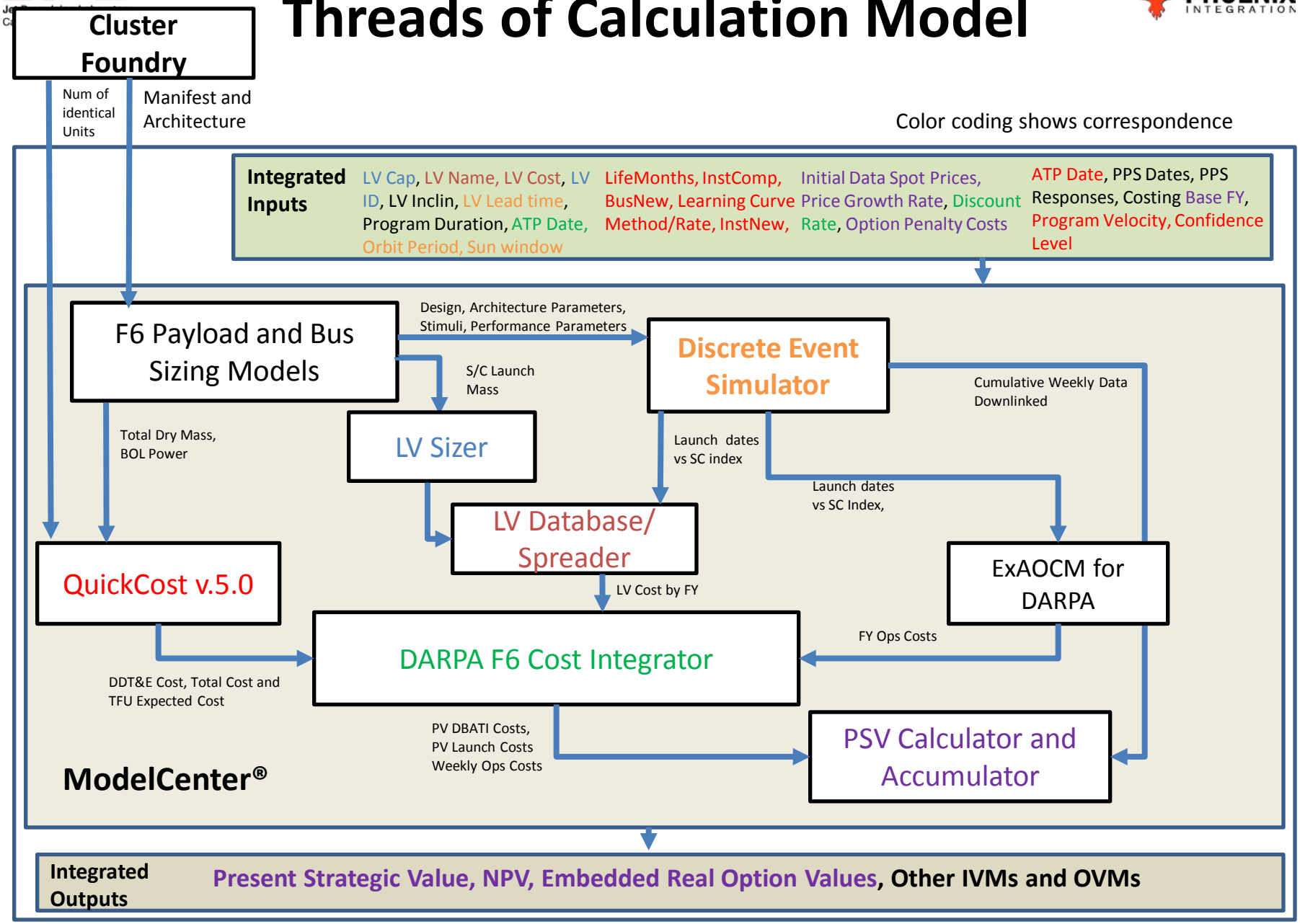
Net Present Value of Current Architecture

Value of Embedded Real Option

Results Depend on Assumptions:



Threads of Calculation Model



Generating IVMs/OVMs

- **Implementation Value Metrics (IVMs)**
  - DDT&E Costs
  - TFU (Theoretical First Unit) Costs
  - FY DBATI Costs
  - FY Launch Costs
  - FY Ops Costs
  - Max Number of Each Unit (Subsystem/Payload)

→ **DBATI Cost Model with QuickCost v5.0**

→ Launch Vehicle Database and Cost Spreader

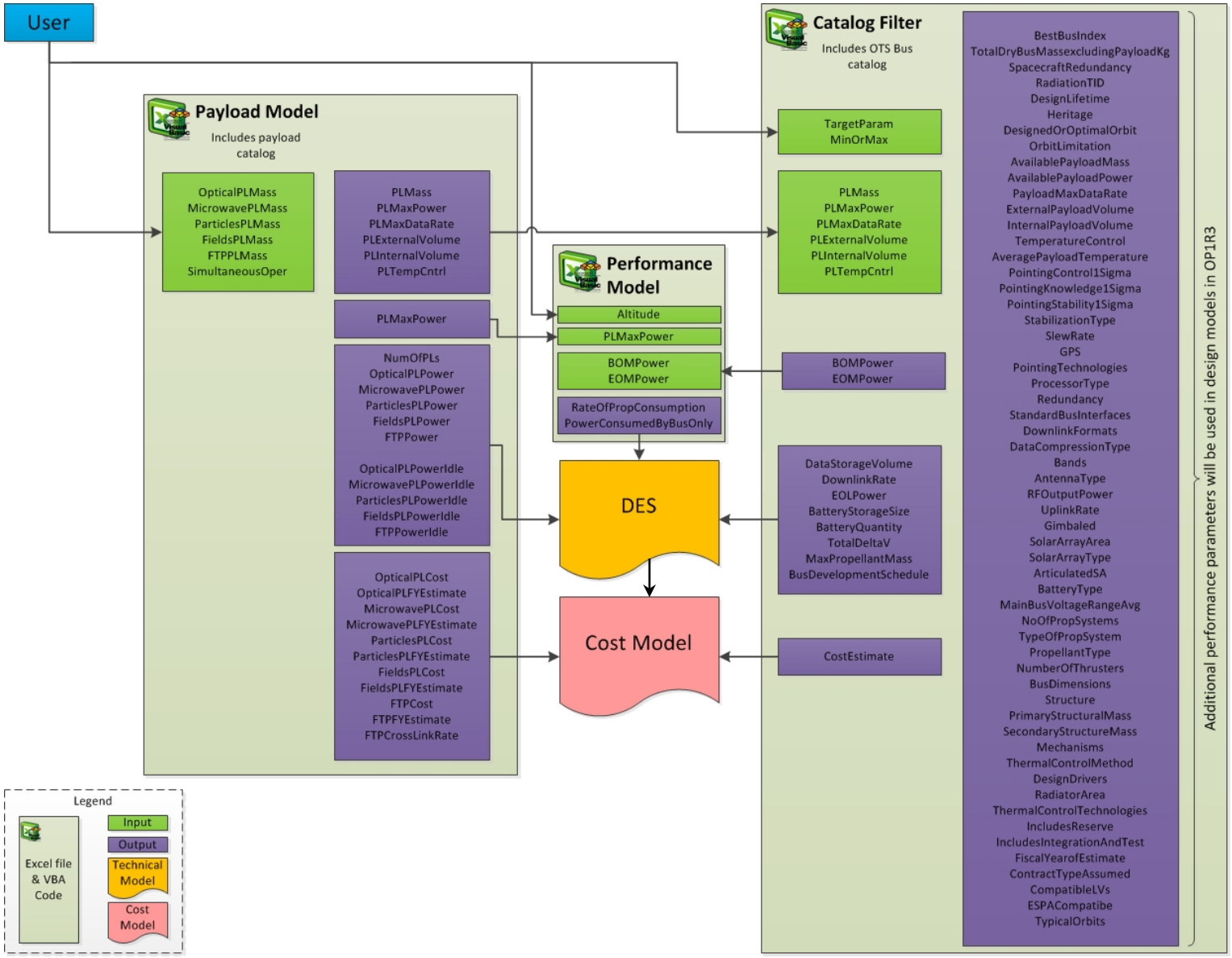
→ Exploration Architectures Operations Cost Model

→ SysML

- **Operational Value Metrics (OVMs)**
  - Weekly Data Downlinked (Red Data ("Imager Data"), Blue Data ("Mapper Data") now, Green Data next period)
  - Data Taken by Spacecraft
  - Up Time/Time in Safe Mode (not used as OVM directly in Base Period)

→ Discrete Event Simulator (currently ARENA©)

EXPANDED THREADS OF CALCULATION



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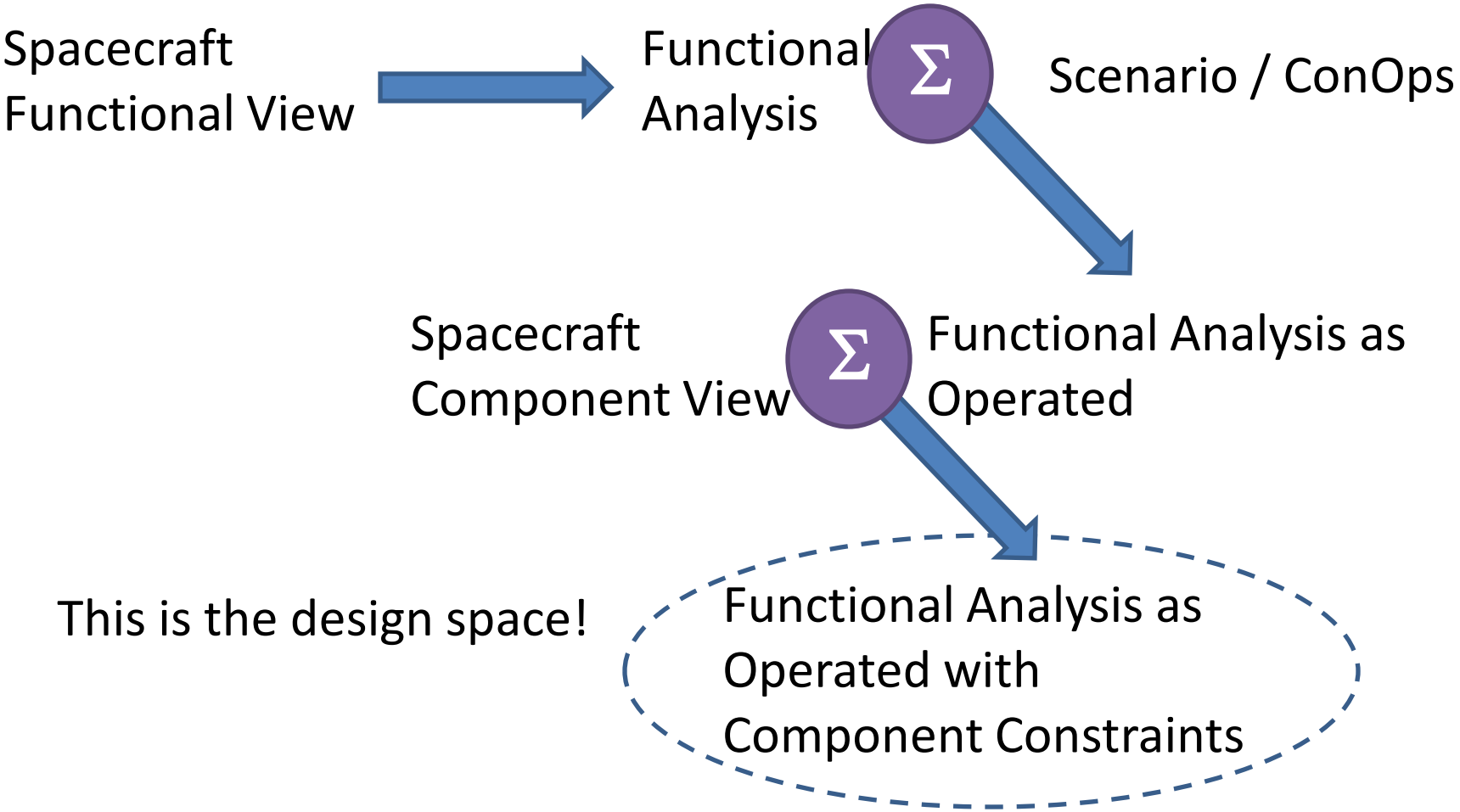
MODEL BUILDING AND TRANSFORMATIONS

We want to vary …

- The number and types of spacecraft in the cluster
- Order of deployment
- Possible responses to unforeseen circumstances, including various ways to change the cluster
- The cluster architecture and formation to fly
- Different operating strategies
- And so on

- Too many combinations to deal with by hand!

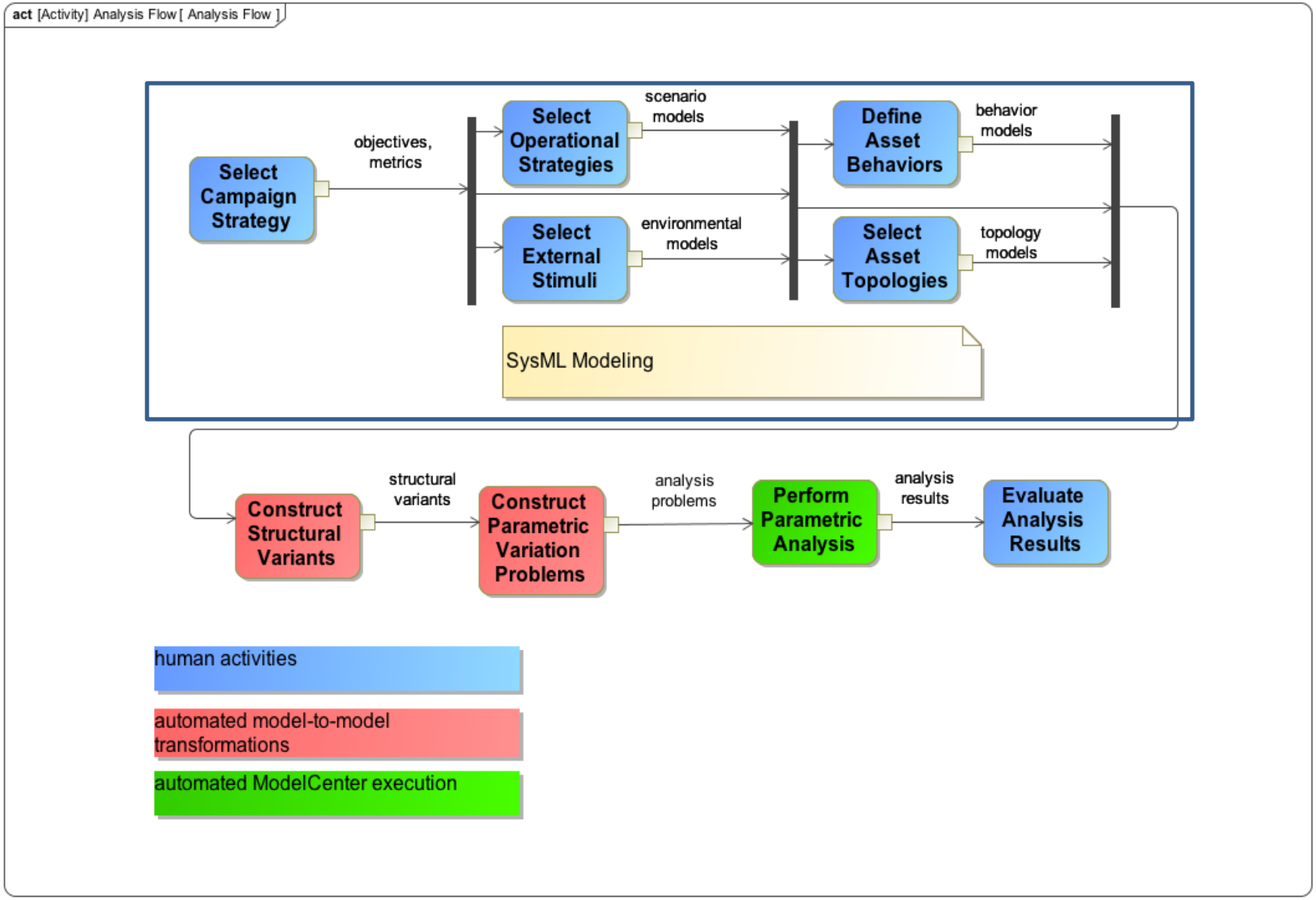
The Power Of Model Transformation



Model Building and Transformation Summary

- Separated tractable and non-tractable parts
  - Have design models up front (can do feedforward or iterative convergence)
  - Operations models (operate completed design in real world) generate results. They are non closed-form tractable because can't represent the real world with closed form sizing equations! They require simulation especially with stimuli, responses, and stochastic elements
  - Have cost models use output of design models and simulation
  - Apply economic value function (costs, benefits)
- Scalability, Flexibility and Transparency
  - Utilized standards: SysML and OWL underpinnings
  - Utilized ModelCenter and other COTS software
    - ModelCenter can wrap almost anything
    - ModelCenter open and explore "guts" of any model
    - COTS tools have proven track record: No need to reinvent, have GUIs, available help desks/maintenance/support/training/customization

Summary of Model Transformation flow

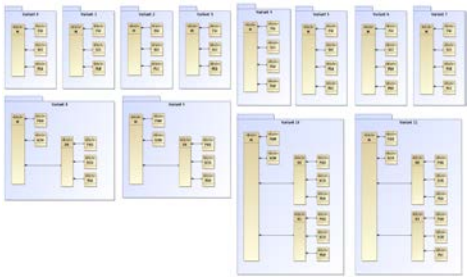


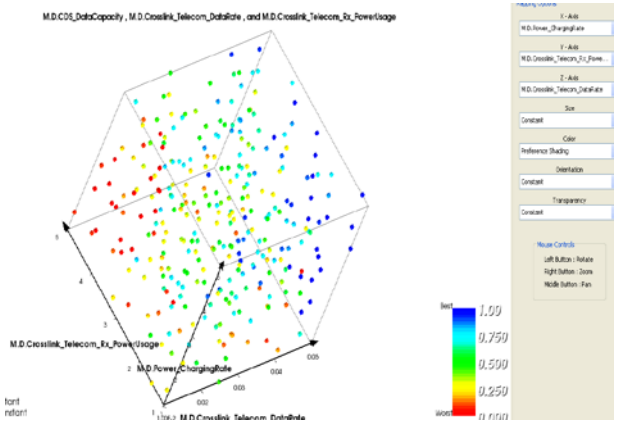
Simplified version of Model Transformations

Analysis Needs

Rules to Apply

Done in advance (human setup)	Done at build time (automatic)	Done at run time (automatic)
Produces: Analysis Specs	Produces: Variants	Produces: Populated Tradespace

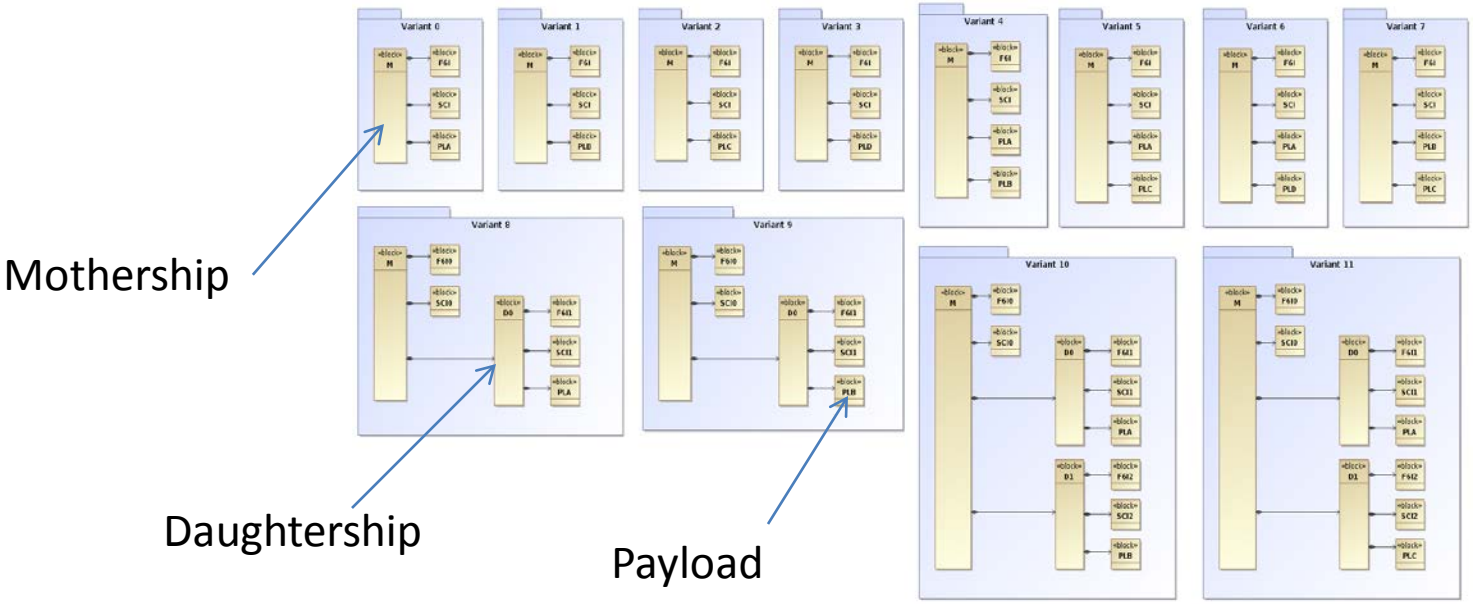




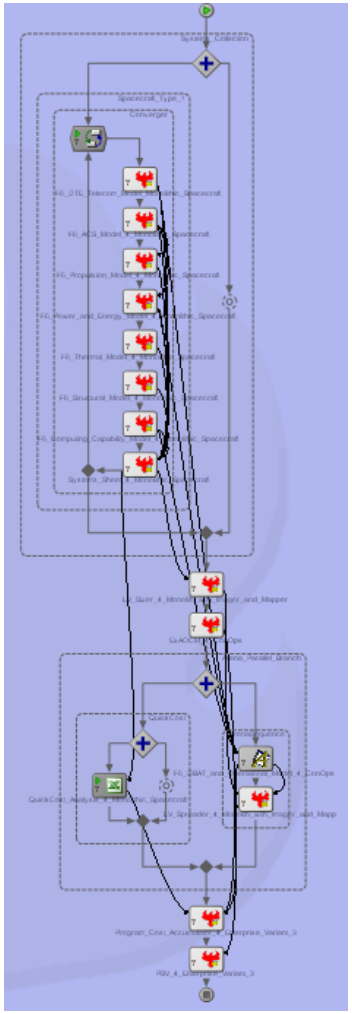
What is SysML and why did we use it?

- Powerful Standard
  - Ability to model the needed aspects of a “system,” both structure and behavior
  - Active community working to reduce issues with pragmatic focus
  - Tree-based structure, can be queried by tools with API
  - Can create, select and implement Rules and Constraints
  - Have traceability back to constraints
  - Can iteratively refine (elaborate) models

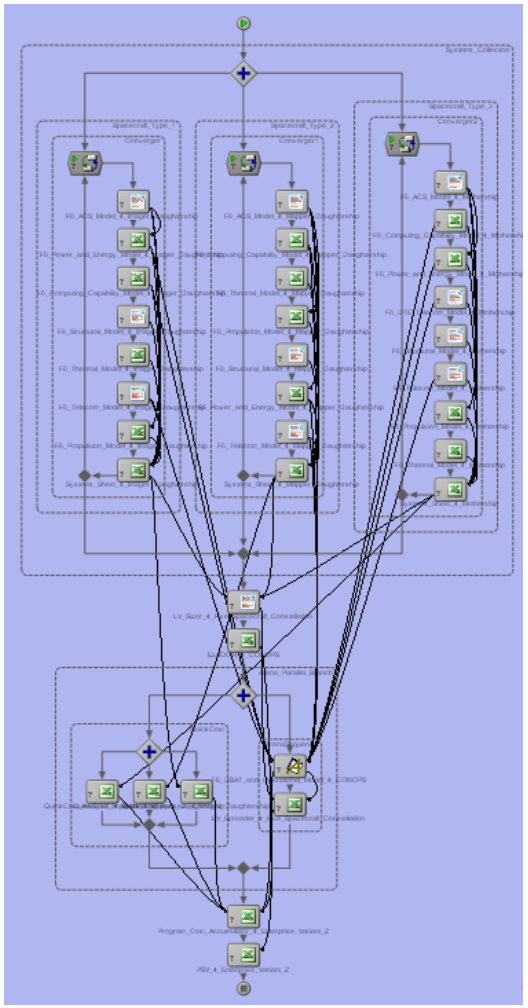
Sample “valid” variants generated automatically



Examples of automatically generated Executable Model(s) in ModelCenter



Monolith



3 Module Cluster

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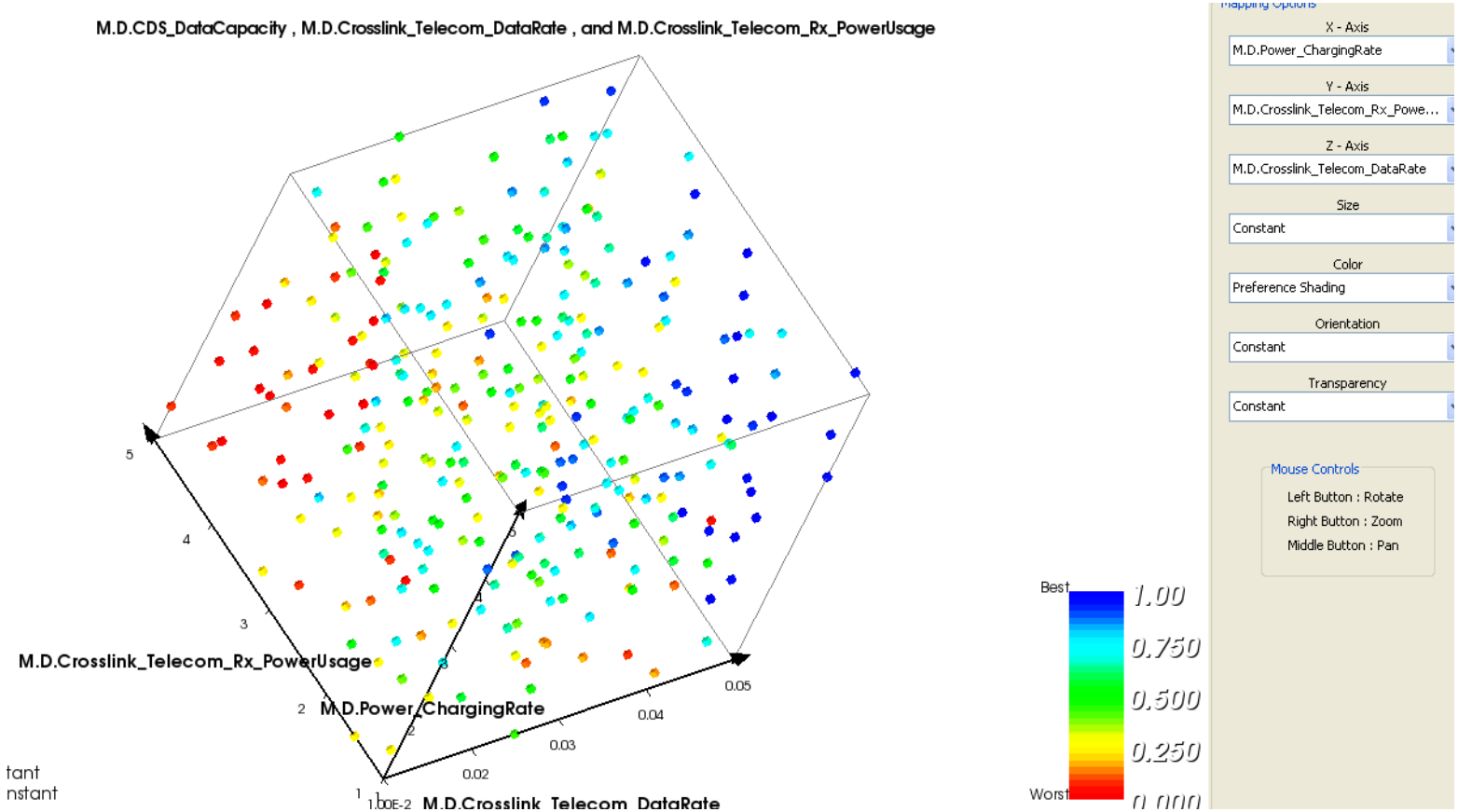
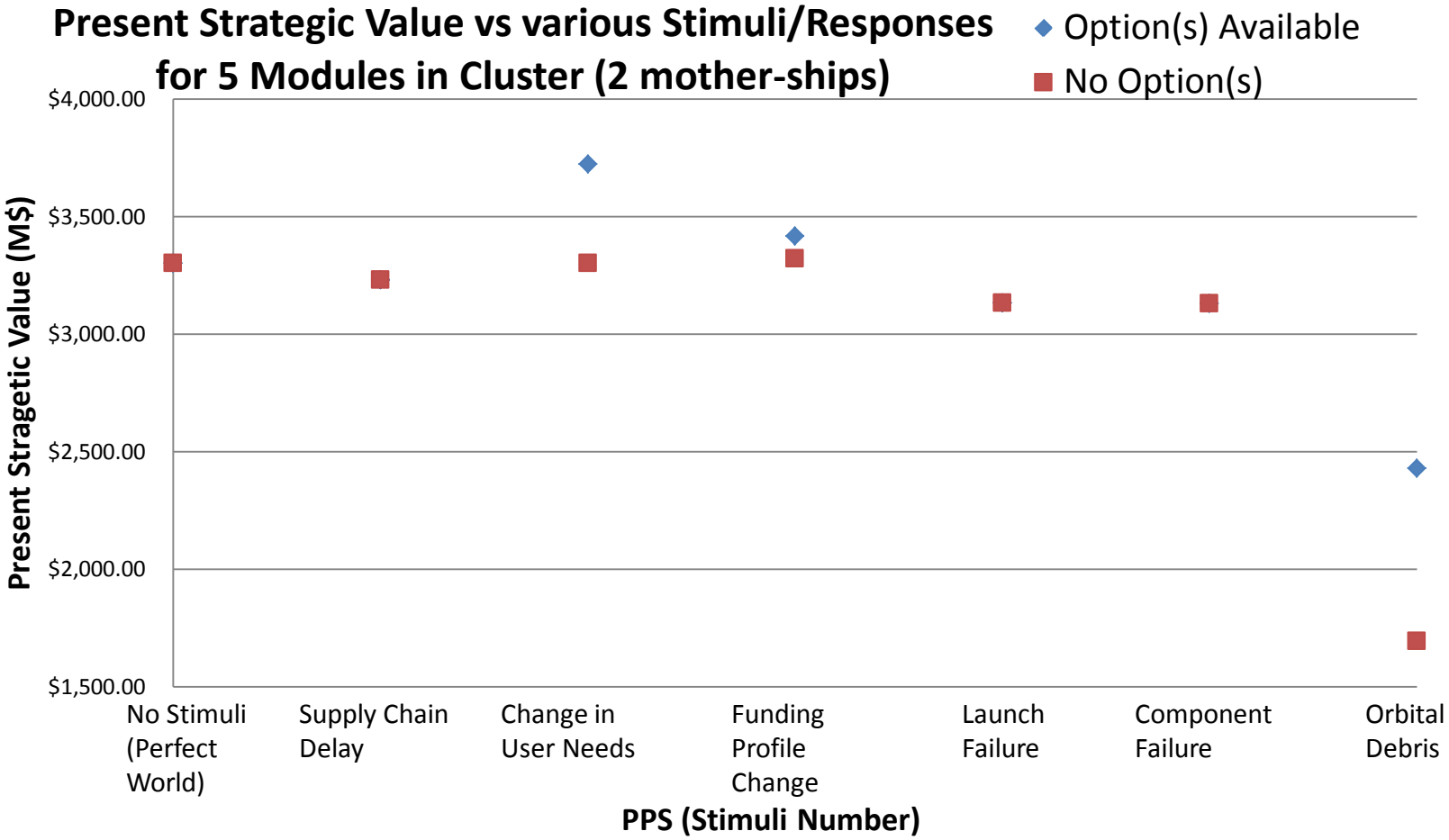
Model Center Demo

Sample Output

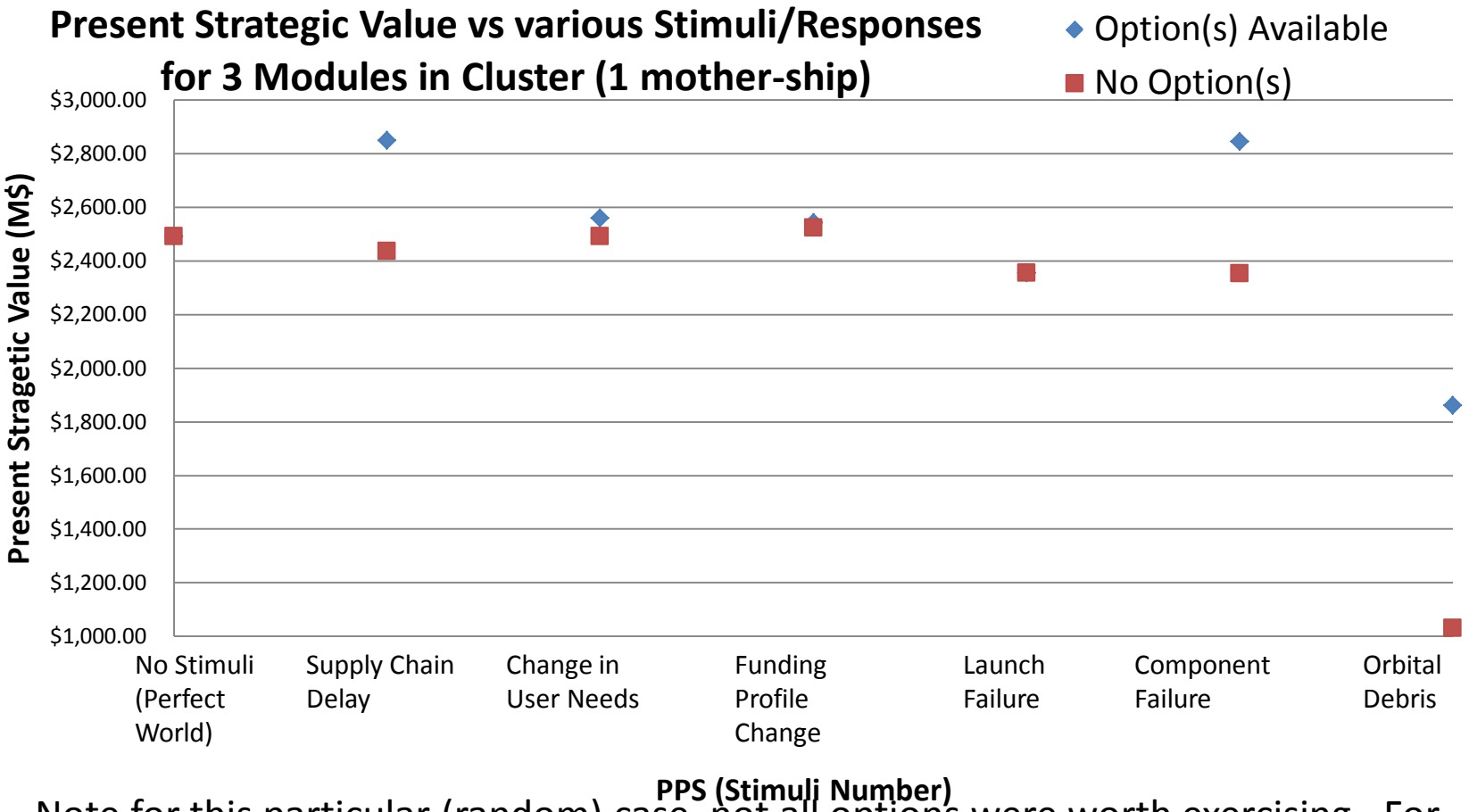


Zooming in to one Tradespace point



Note for this particular (random) case, not all options were worth exercising. For example, cost of replacing a failed component near the end of the 20 year operational time span was not worth the additional data to be obtained.

Zooming in to another Tradespace point



Note for this particular (random) case, not all options were worth exercising. For example, cost of replacing a failed launch near the end of the 20 year operational time span was not worth the additional data to be obtained.

Conclusions

- Produced ‘realistic’ model
- Rapidly generates tradespace
- Variety of users
  - High-level Models\GUI for “normal users”
  - Details of Models for “power users”
- Early insights:
  - Greater uncertainty in future leads to more fractionation
  - This methodology is more broadly applicable
  - Answers depend strongly on envisioned futures (e.g. pessimists vs optimists)

Future Work

- DARPA System F6
  - Option Period 1
    - Complete documentation of model
  - Option Period 2
    - Allow users to incorporate their own models
      - Proprietary data, IP
    - Evaluate the tradespace
    - Complete implementation of methodology for iterative model refinement
    - Working with customers/users to find opportunities to fractionate (use cases)
- Other
  - Deploy methodology in other domains

Questions?

- For more information, contact:
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  - steven.cornford@jpl.nasa.gov,