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

Dec 6, 2011

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Bryce Durham, Phoenix Integration

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®

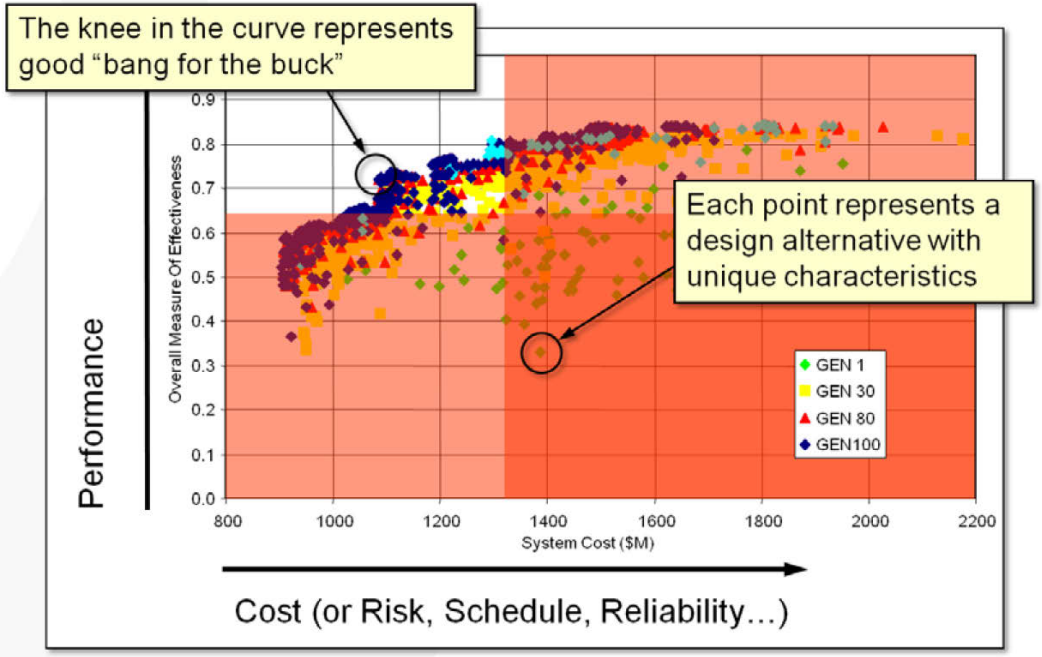
- *Analysis automation*

PHX CenterLink®

- *Load balance trade studies*

PHX AnalysisLibrary®

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



Example Application:
Analysis of Alternatives

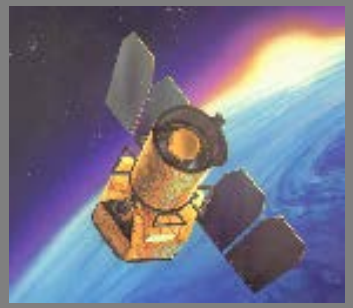
JPL is part of NASA and Caltech

- Federally-Funded (NASA-owned) Research and Development Center (FFRDC)
- University Operated (Caltech)
- $1.5B Business Base
- 5,000 Employees
- 177 Acres (includes 22 acres leased for parking)
- 139 Buildings; 36 Trailers
- 673,000 Net Square Feet of Office Space
- 906,000 Net Square Feet of Non-Office Space (e.g., Labs)

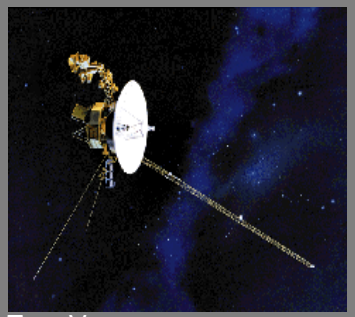
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

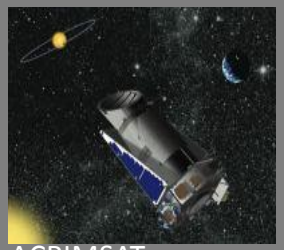
Twenty-two spacecraft, nine instruments across the solar system (and beyond)


GALEX

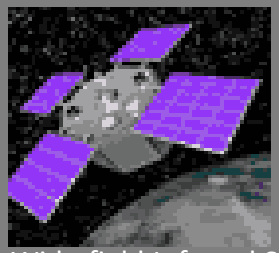

Spitzer

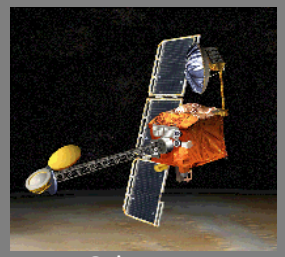

Two Voyagers

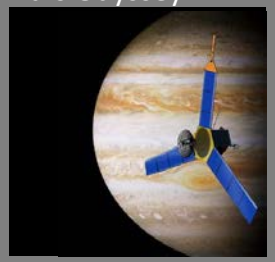

Kepler


ACRIMSAT


Dawn


Wide-field Infrared Survey Explorer (WISE)

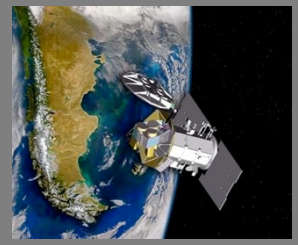

Mars Odyssey

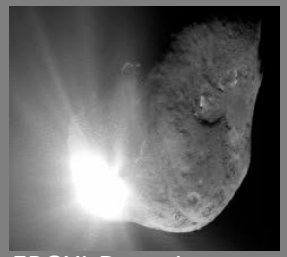

Juno


Opportunity

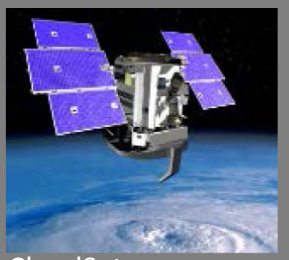

Mars Reconnaissance Orbiter


Cassini

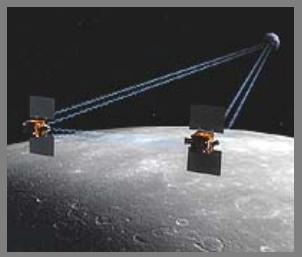

Aquarius


EPOXI-Deep Impact


Jason 1 and Jason 2


CloudSat


GRACE


GRAIL

Instruments:

Earth Science
- ASTER
- MISR
- TES
- MLS
- AIRS

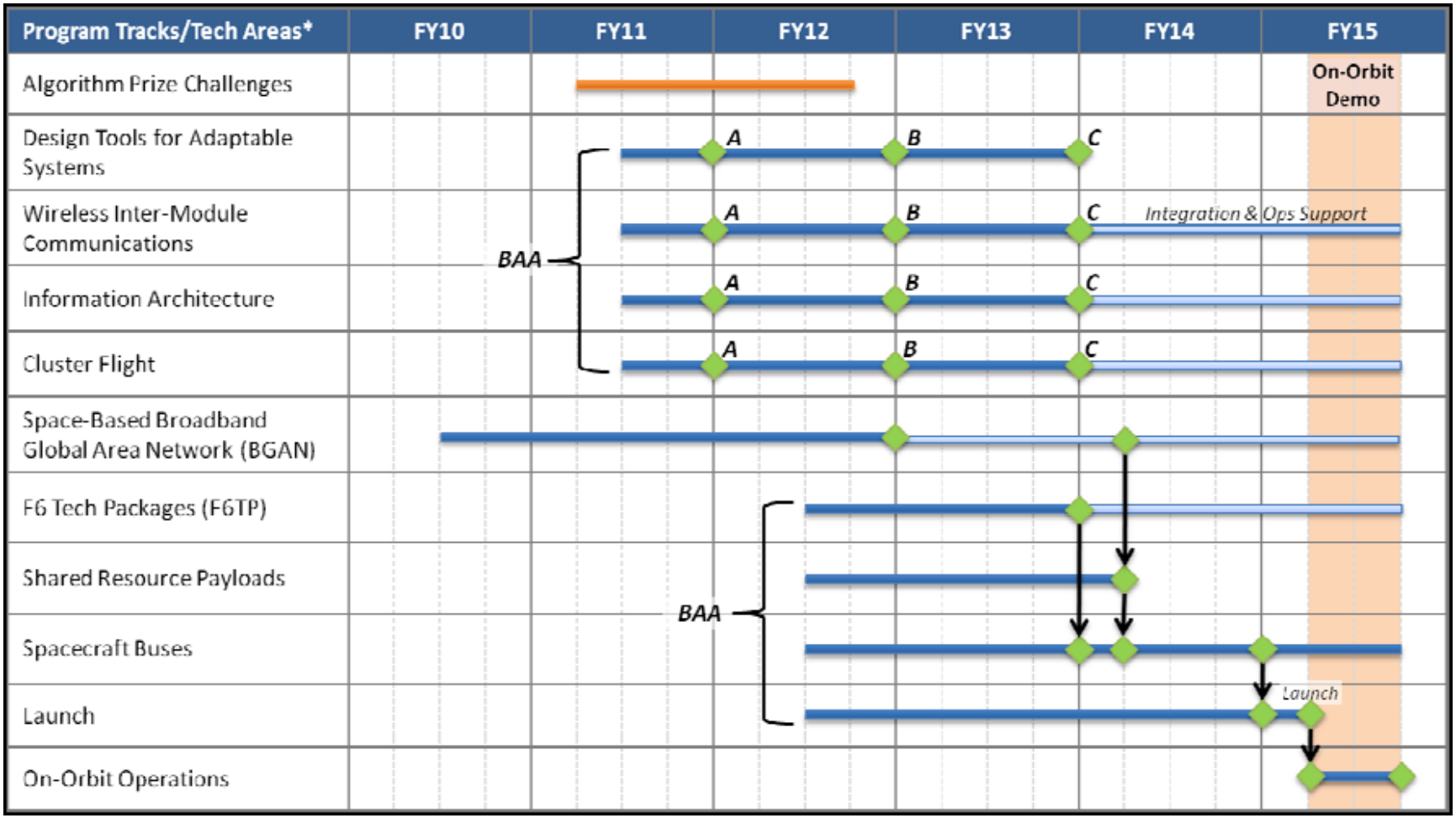
Planetary
- MIRO
- Diviner

Astrophysics
- Herschel
- Planck

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

BAA Figure 2: Notional Overall Program Timeline



TA1: 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.”

Summary of results

- We had four principal research goals to meet the objectives asked for in the BAA. These are described on the following charts.
- We produced and demonstrated a Notional Model which illustrated our approach to responding to the BAA Objectives.
  - Created and run automatically
  - Included Real Options methodology for measuring Adaptability and Survivability vs Uncertainty Events
  - Allowed mission, spacecraft, architecture, configuration and parametric variations
  - Resulted in populated trade space for these variations
- Completed in under 5 months

Summary of 4 Research Goals

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 – Getting It Done

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

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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

ASDA Threads of Calculation Model

Cluster Foundry

ModelCenter®

Integrated Inputs

Learning Curve Method/Rate, Program Duration

LifeMonths, InstComp, BusNew, InstNew

Initial Data Spot Prices, Volatilities, Discount Rate, Real Option Penalty Costs

ATP Date, Costing Base FY , PPS, PPS Responses

Manifest (vector)

Composition (matrix)

Crosslink (matrix)

Stimuli/Response (matrix)

F6 Design Model(s)
ACS, Power, Telecom, Thermal Propulsion, Structure, CDS

Design Parameters, Performance Parameters

ARENA®

S/C Wet Mass

LV Lead Time

LV Sizer

Total Dry Mass, BOL Power

Launch Schedule By Module Type

Launch Schedule By Module Type, Time of Negative PPS Event

Weekly Data Downlinked, Time of Next PPS Event,

DBATI Start Dates, Max Number of Units,

LV Selected Index (column)

LV Database/ Spreader

LV Cost by FY

QuickCost v.5.0

ExAOCM for DARPA

DDT&E and TFU Expected Cost

DARPA F6 Cost Integrator

FY Ops Costs

FY DBATI Costs, FY Launch Costs FY Ops Costs

PSV Calculator and Accumulator

Integrated Outputs

Present Strategic Value, Embedded Real Option Values, Adaptability and Survivability Metrics, Other IVMs and OVMs

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

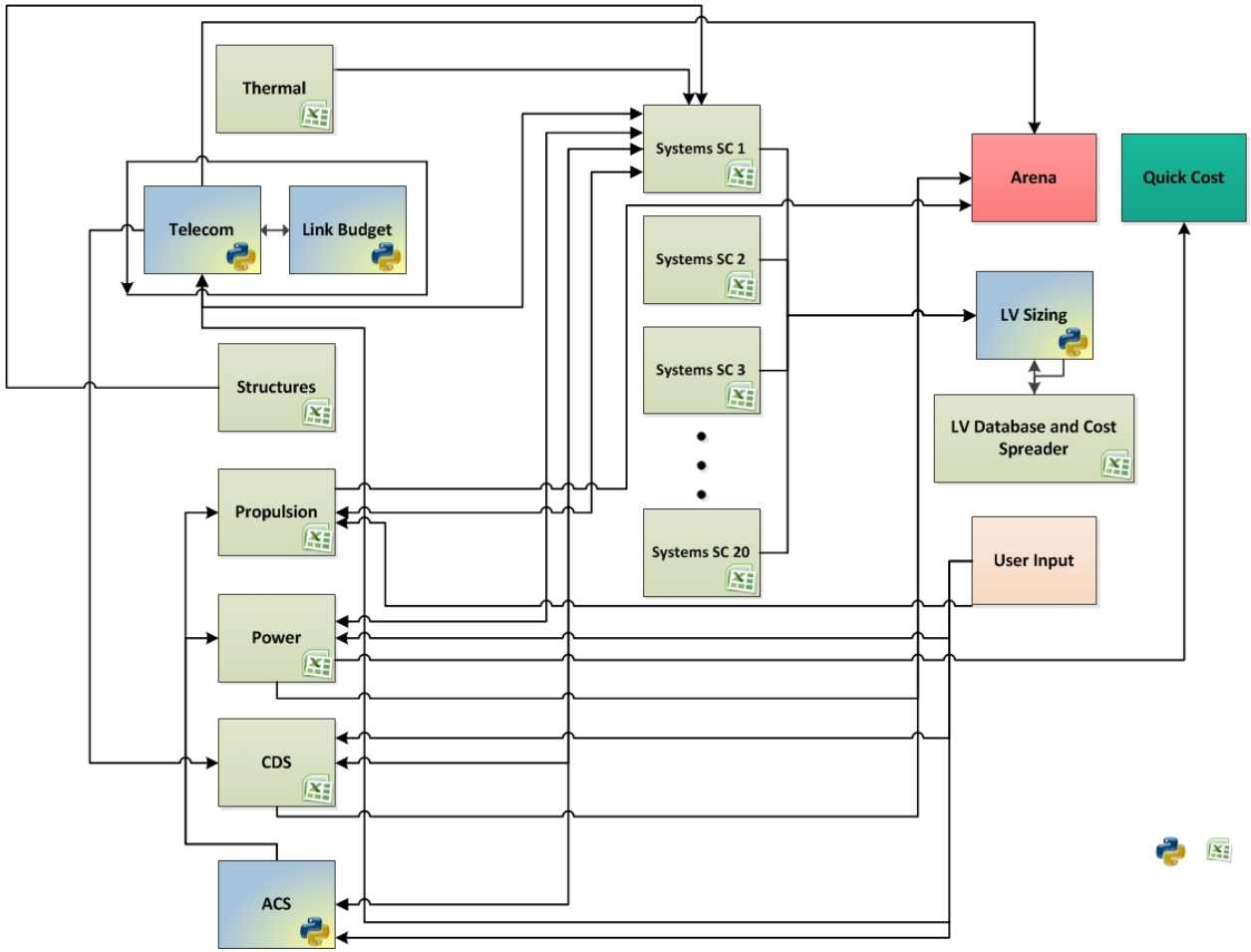
→ SysML

- **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©)

Threads of Calculation Model
Expanded To Highlight the F6 Design Models

F6 Design Model Flow Diagram



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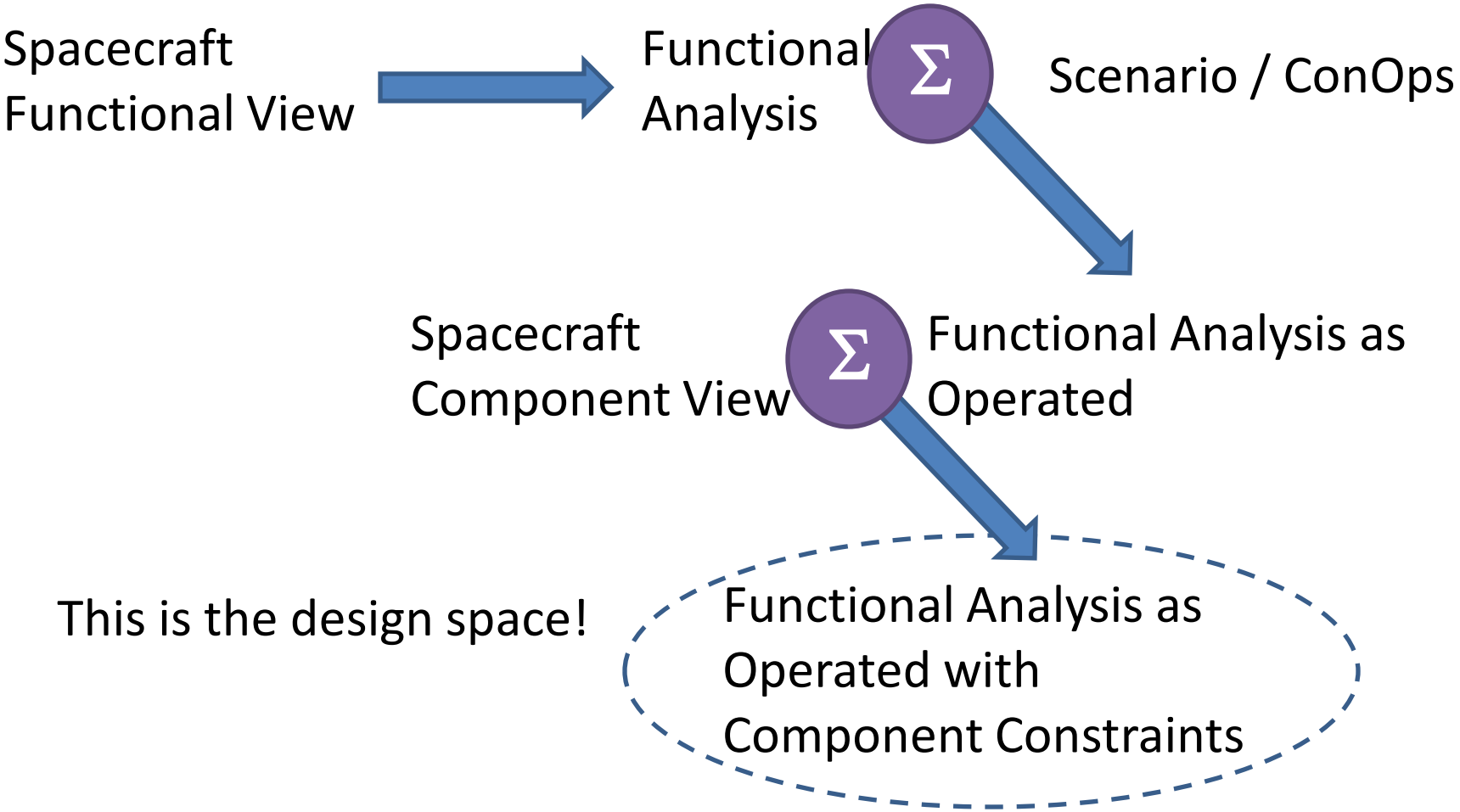
MODEL BUILDING AND TRANSFORMATIONS

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

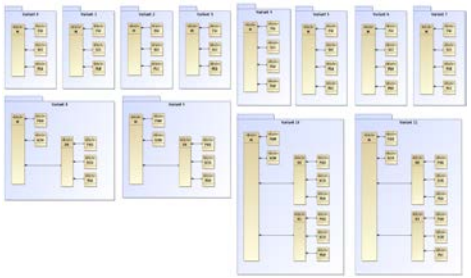
- Separated tractable and non-tractable parts
  - Have design models up front (can do feedforward or iterative convergence)
  - Operations models (operate completed design in real world) generate results. The are non closed-form tractable because can't represent the real world with closed form sizing 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

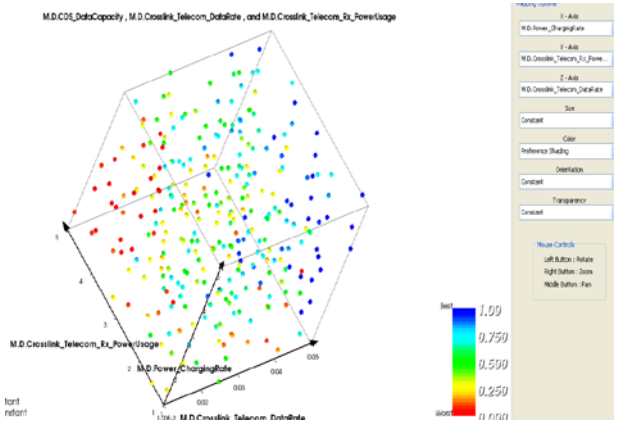
Simplified version of Model Transformations

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

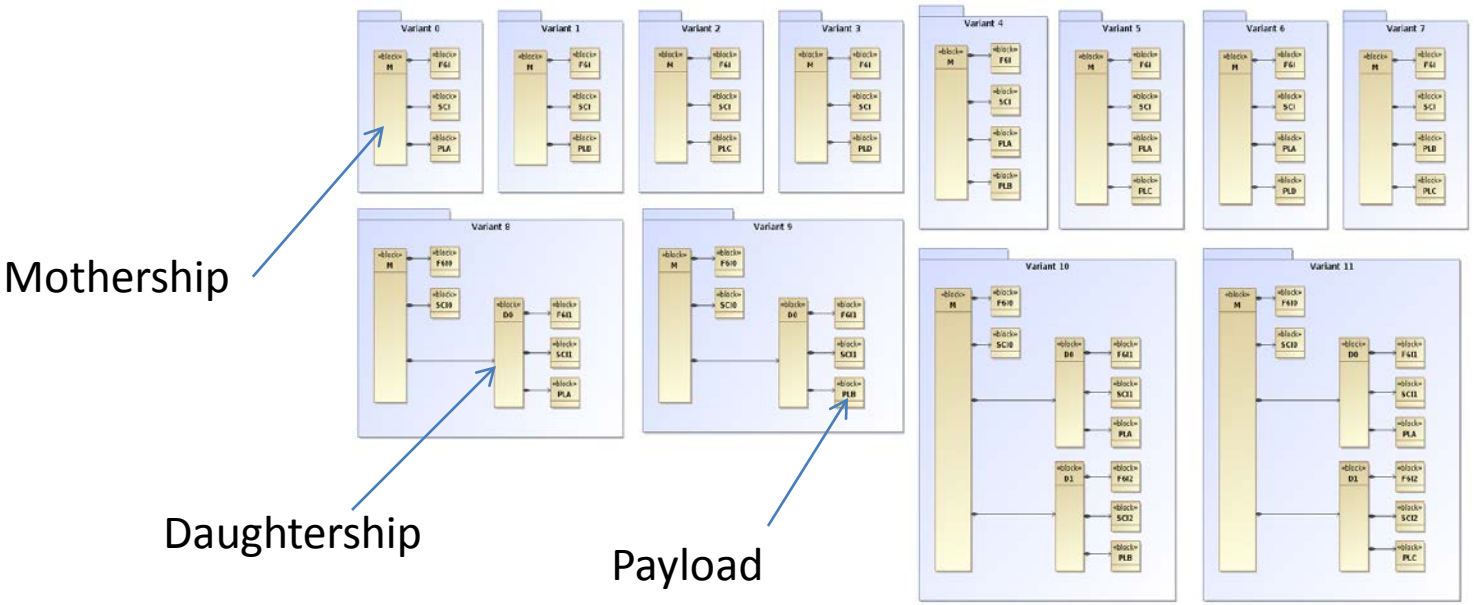




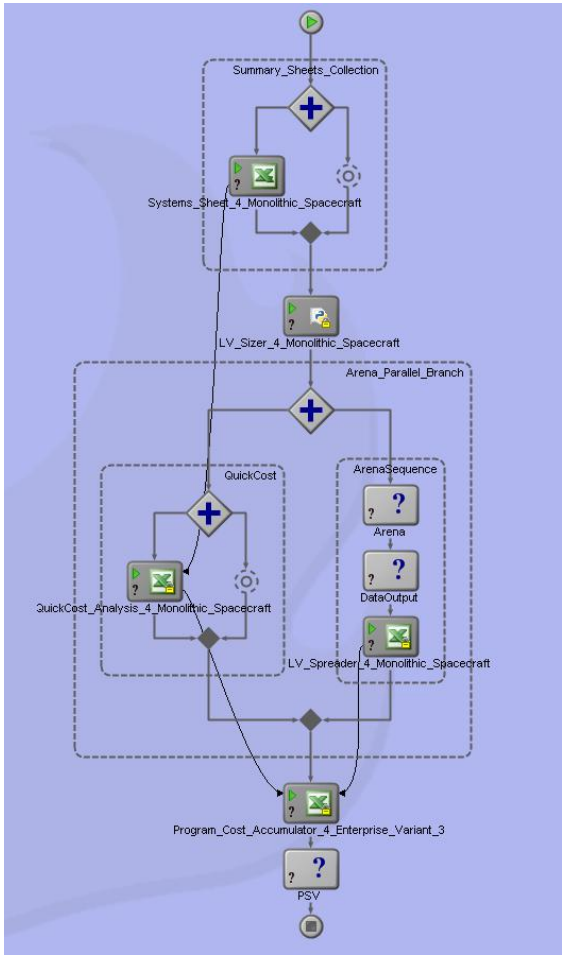
What is SysML and why did we use it?

- Powerful Standard
  - Ability to model the needed aspects of a “system”
  - Correct by construction
  - Can create, select and implement Rules and Constraints
  - Have traceability back to constraints
  - Can iteratively refine (elaborate) models

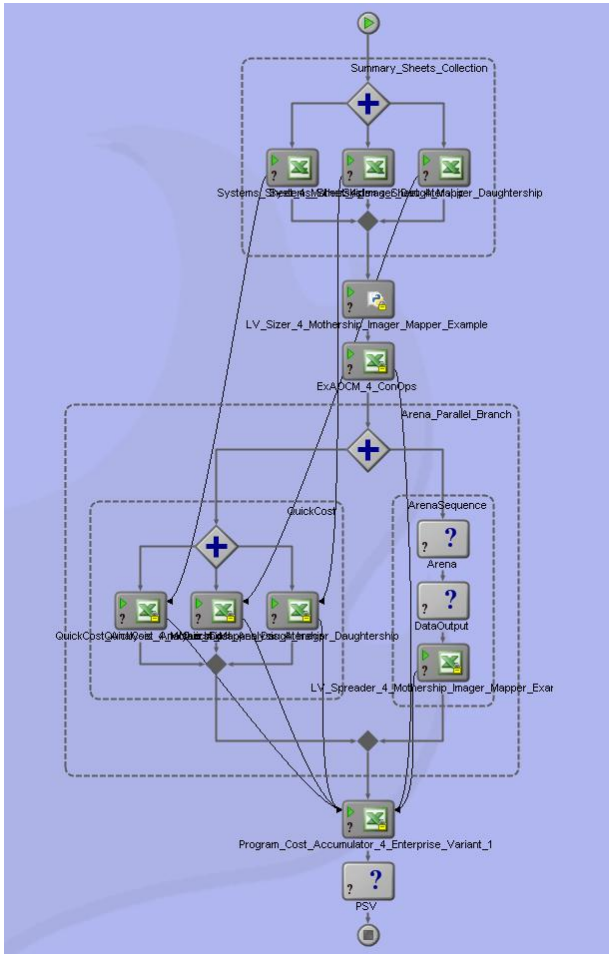
Sample “valid” variants generated automatically



Examples of automatically generated Executable Model(s) in ModelCenter



Monolith



3 Module Cluster

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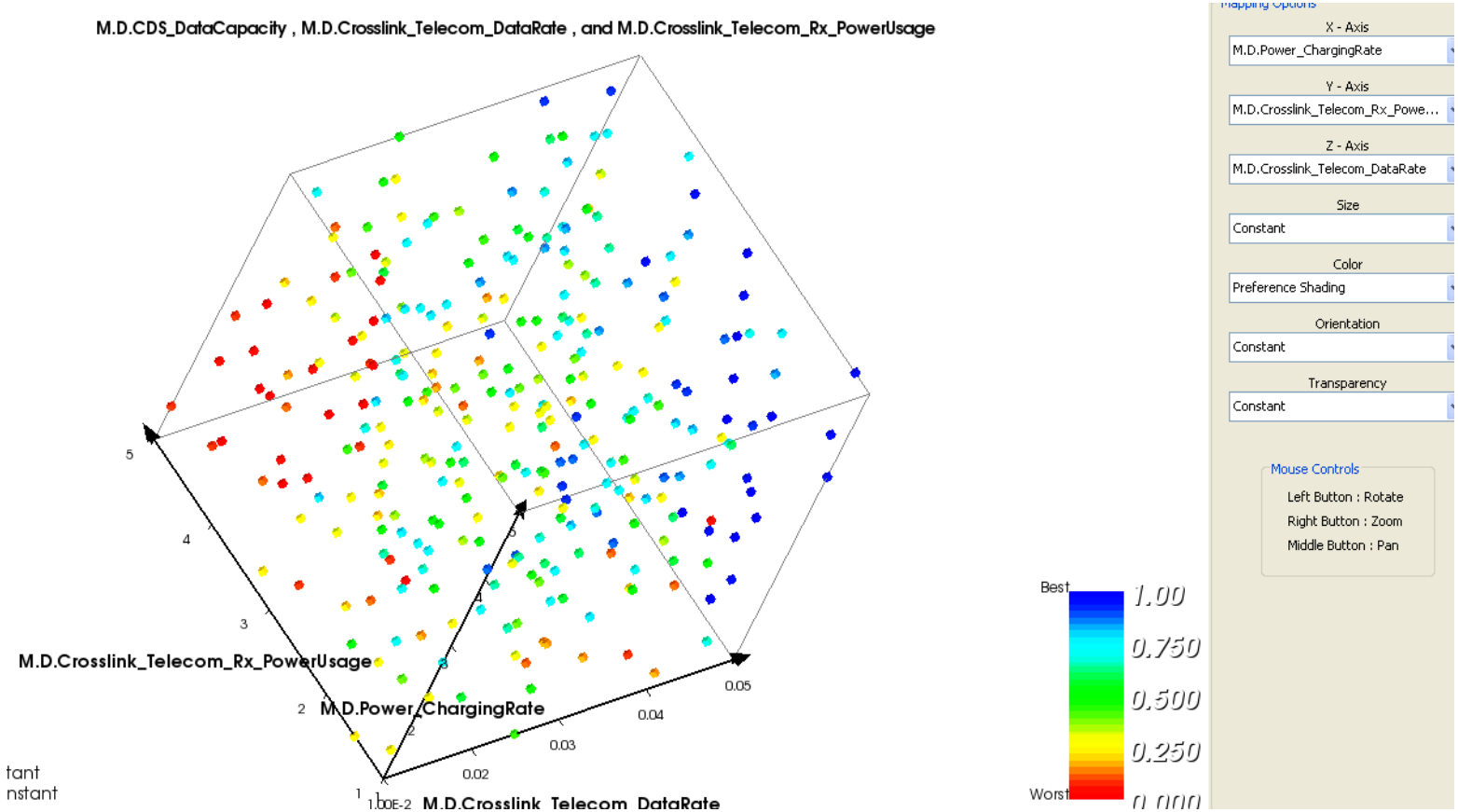
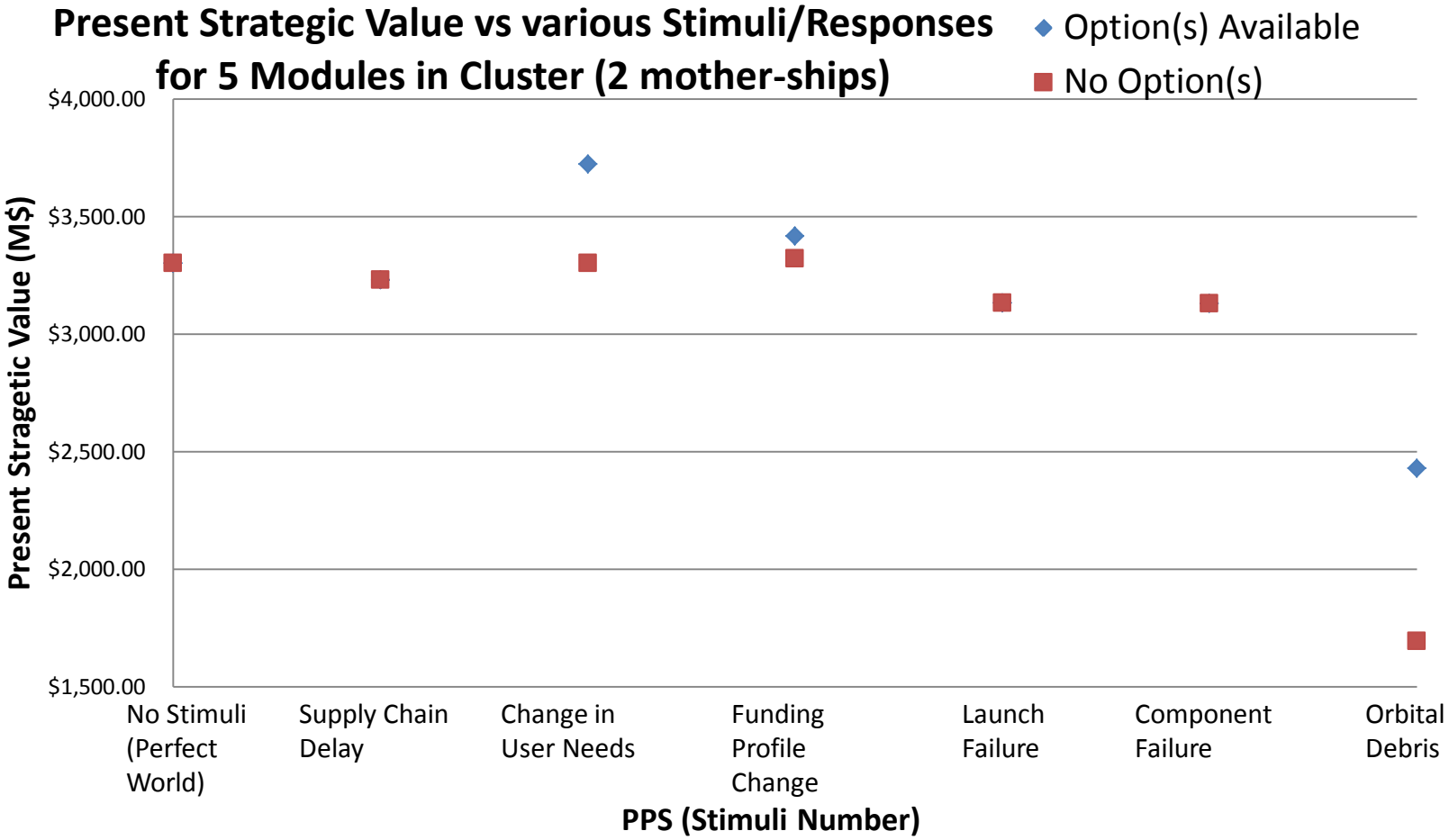
Model Center Demo

Sample Output

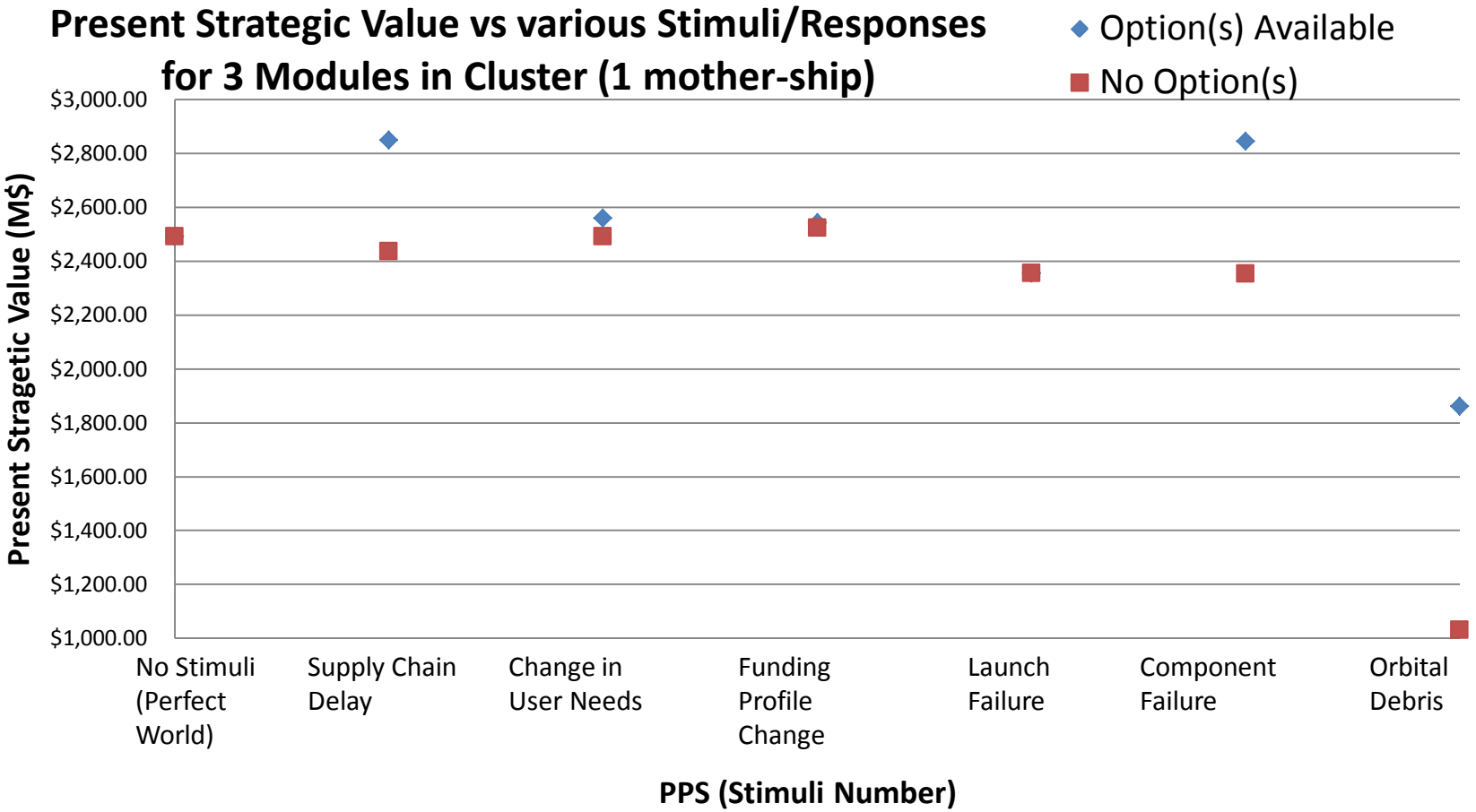


Zooming in to one Tradespace point



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.

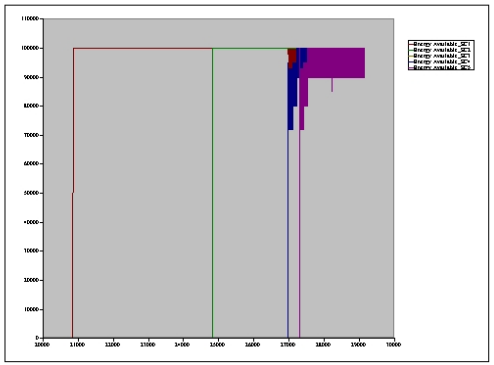
Zooming in to another Tradespace point

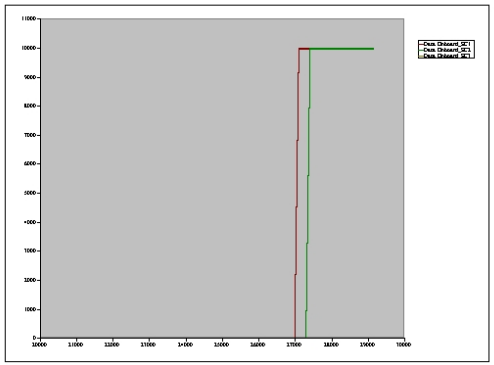


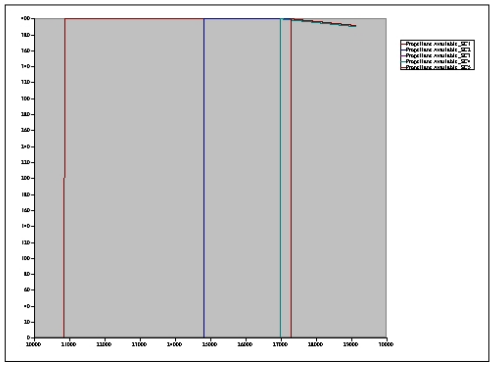
Note for this particular (random) case, not all options were worth exercising. For example, cost of replacing a failed launch near the end of the 20 year operational time span was not worth the additional data to be obtained.

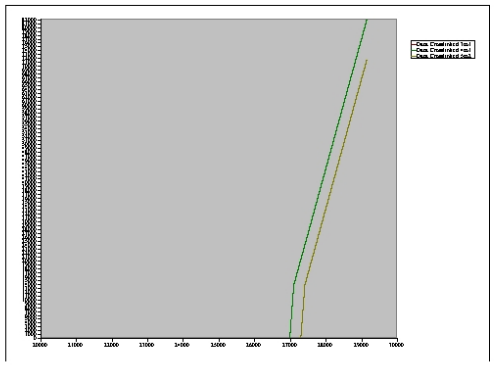
Example Output from Discrete Event Simulation

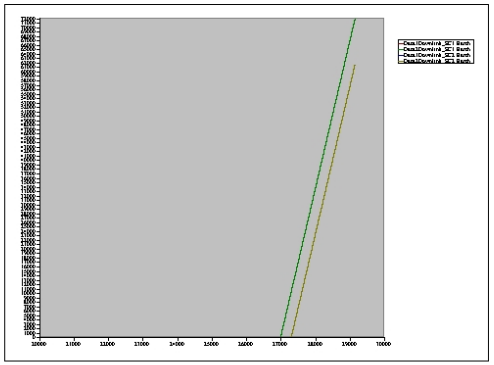
5 Module Summary: All Resources











Conclusions

- Produced notional model
- Rapidly explores tradespace
- Early insights:
  - Greater uncertainty in future leads to more fractionation
  - This methodology is more broadly applicable

Future Work

- DARPA F6
  - Complete the model
  - Allow users to incorporate their own models
    - Proprietary data, IP
  - Evaluate the tradespace
  - Focus on implementing methodology for iterative model refinement
  - Working with customers/users to find opportunities to fractionate (use cases)
  - Automated Design of Experiment population and execution
- Other
  - Deploy methodology in other domains

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For more information

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  - Dr. Scott Ragon (sragon@phoenix-int.com)

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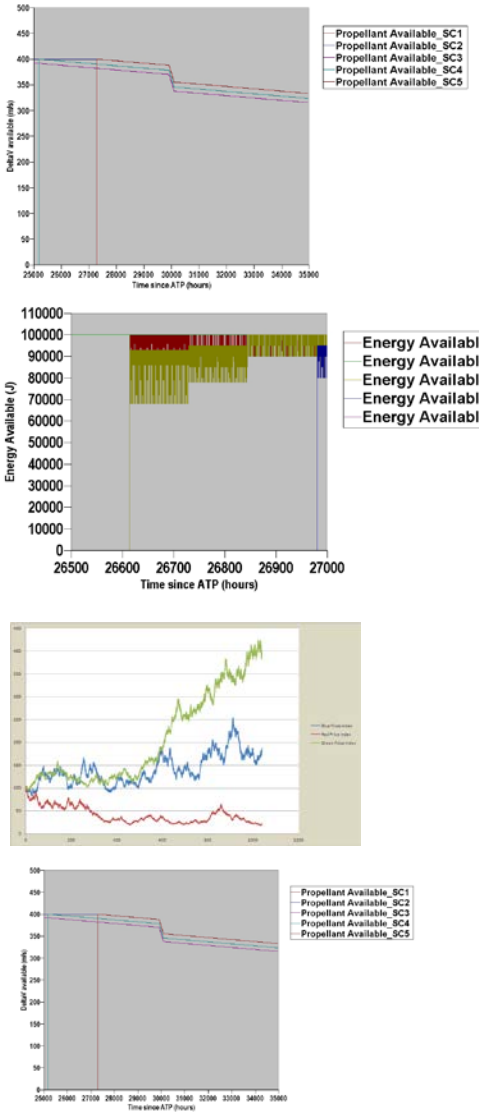
Backup

Four Research Goals (1 of 4)

Goal 1 – Generating Value

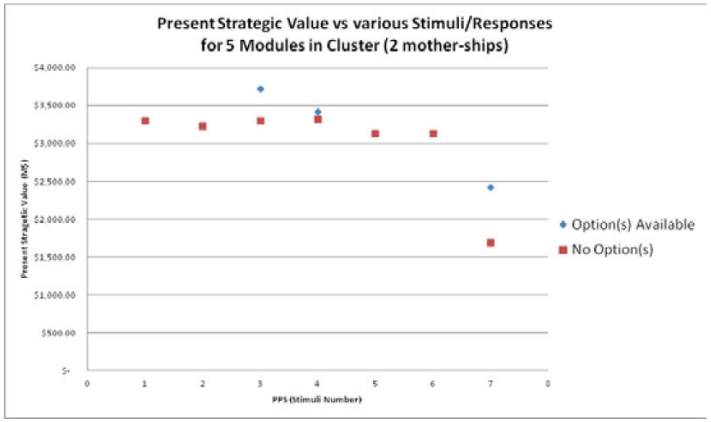
- Model the development and operations of the cluster
  - Use time-based simulation to capture the data down-linked (data vs time to Earth from mother-ships which in turn received cross-linked data from daughter-ships NO data when module in safe mode, scattering or failed.
  - Simulate the consecutive developmental phases (DBAT) of a cluster and the impact of their schedule on the cumulative value generated over time horizon of interest
  - Have different "colors " of data and have features in place to account for data latency, "up-time" of cluster elements, lost data (e.g. hard disk full, missed downlink window, degree of utilization
- Generate value by utilizing prices for different data by different users
  - Have initial value and biased random walk in those values
  - Can model changes in user needs as change in value of data at specific dates
- Explicitly model all stimuli and generate the results for the various stimuli cases
  - Model explores various Stimuli/Response pairings and computes value of exercising the Option(s) available



Four Research Goals (2 of 4)

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

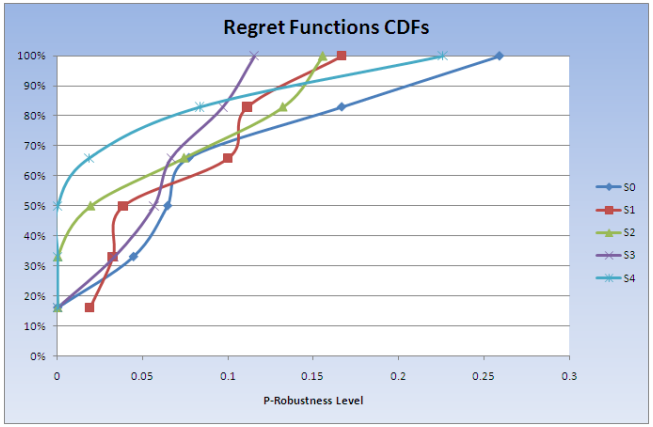
- Utilizing Embedded Real Options Approach
  - Have incorporated BAA stimuli and have building blocks for each
  - Have multiple options for each stimulus
  - Have completed mathematics for evaluating Real Options
- Adaptability
  - Measured as value of Embedded Real Options for Adaptability stimuli versus the case of Do Nothing
- Survivability
  - Measured as value of Embedded Real Options for Survivability stimuli versus the case of Do Nothing
- Observations
  - The more uncertain the future the better for F6
  - The more volatile the prices the better for F6



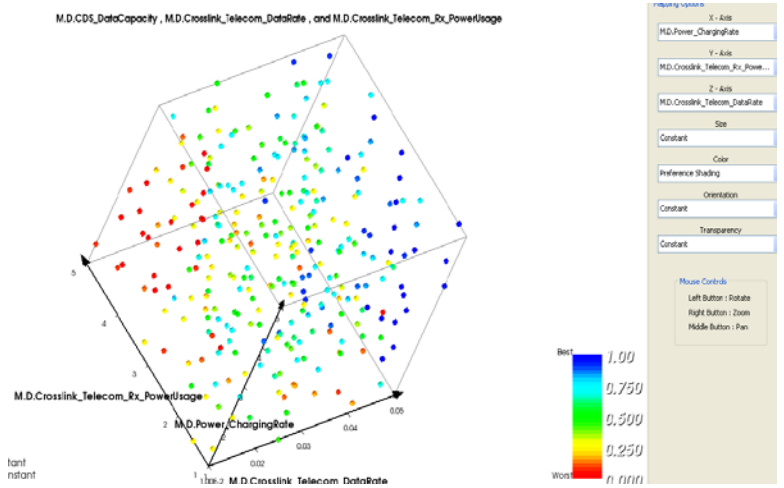
Four Research Goals (3 of 4)

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
- ATSV Plots: able to inspect tradespace from any perspective in various graphical forms (example below)



% Regret Cumulative Distribution Functions for a Set of Architectures/Strategies

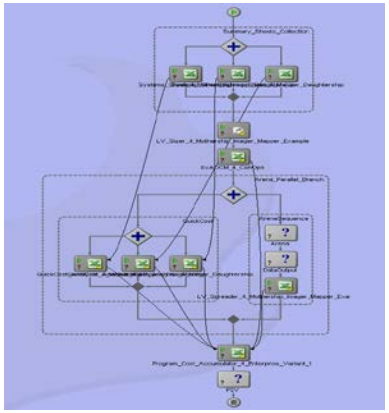


Multi-dimensional plot of tradespace for N=3 configuration

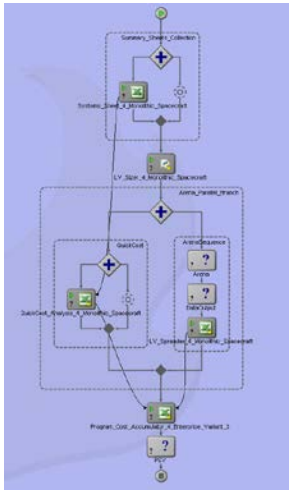
Four Research Goals (4 of 4)

Goal 4 – Getting It Done

- Automatic model generation and transformation for any case(s), scalable and extensible. Integrated from configuration, to design models, to executable models, to business case.
- Robust methodology – Static models combined with dynamic modeling (discrete-event simulation) allows realistic modeling of "surprises" that in practice always occur. Their unpredictability adds to/makes the case for fractionation.
- Representative data libraries, evidence based exploration, repeatability of our findings. Ability to extend or replace any constituent model

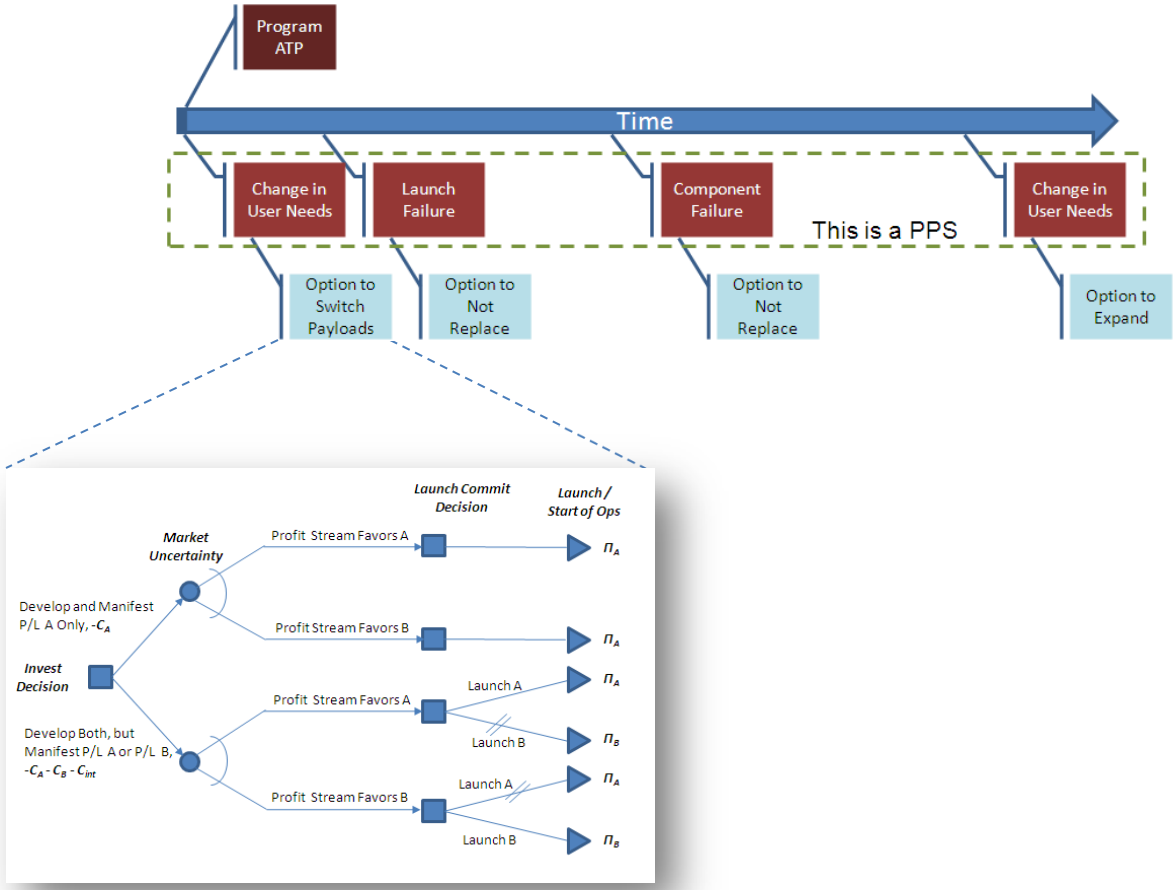


3 Module Cluster



Monolith

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



PSV Calculation Using Monte Carlo Simulation

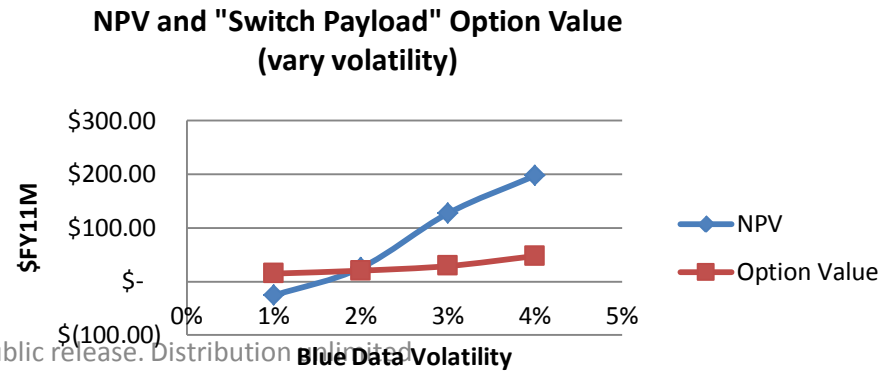
Results from the PSV Model: Expected NPV for the Nominal Case

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

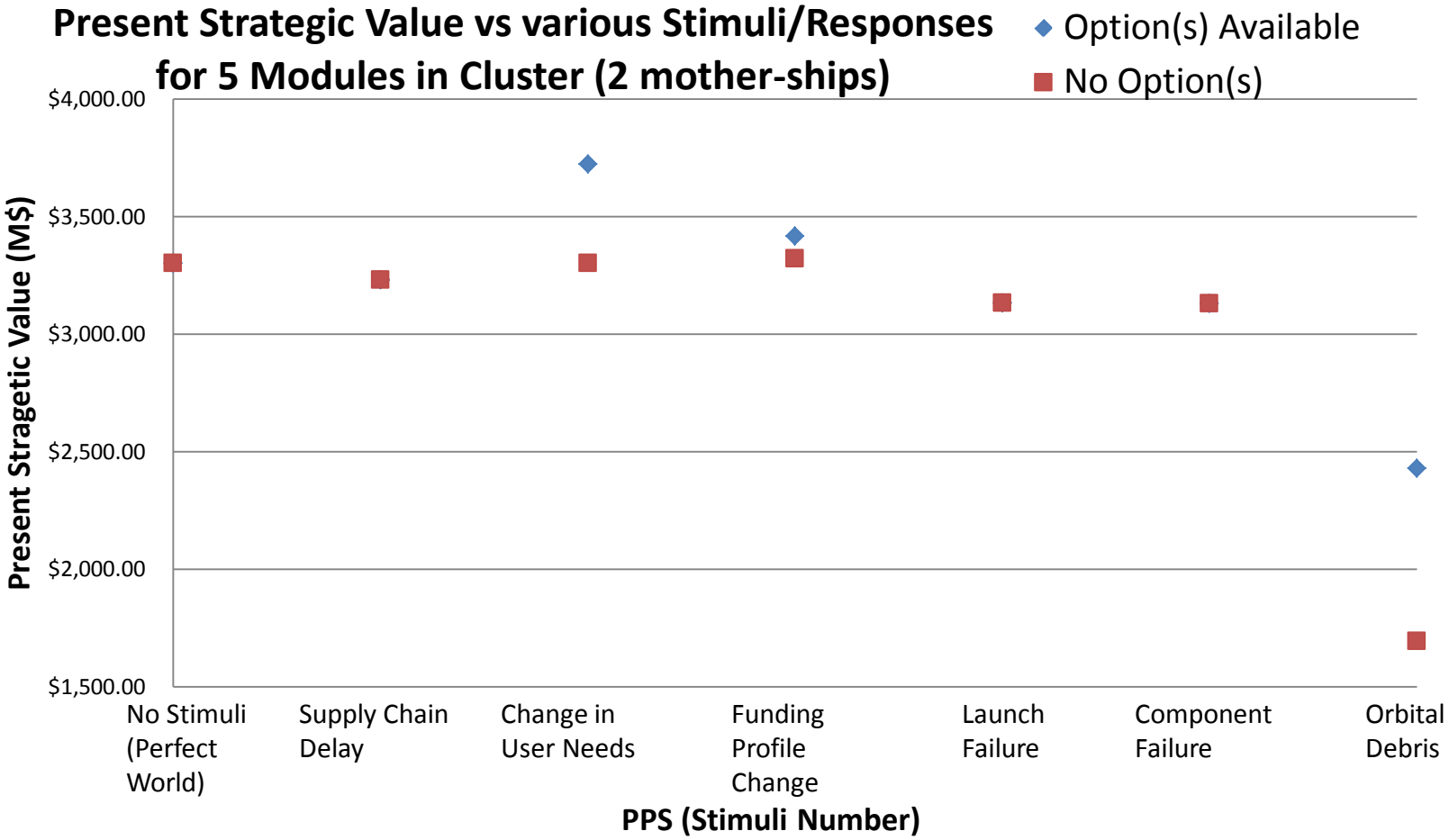
Results from the PSV Model: "Switch Payload" Real Option Value

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
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**

Results Depend on Assumptions:



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.

Innovative Usage of Model Transformation

Analysis Specification Script Wrapper Specification

Analysis Instancing (N instances)

ModelCenter

Analysis Execution

For a given N and a given topology

ModelCenter Execution

SysML Pattern Specification

SysML Variant Generation

Vary N

Vary Manifest

Vary Crosslinks/ Topology

ModelCenter Model Generation

ModelCenter Model Linking (connects arrows in TOC)

Parameter Variation (Automated in Option Period 1)

Legend

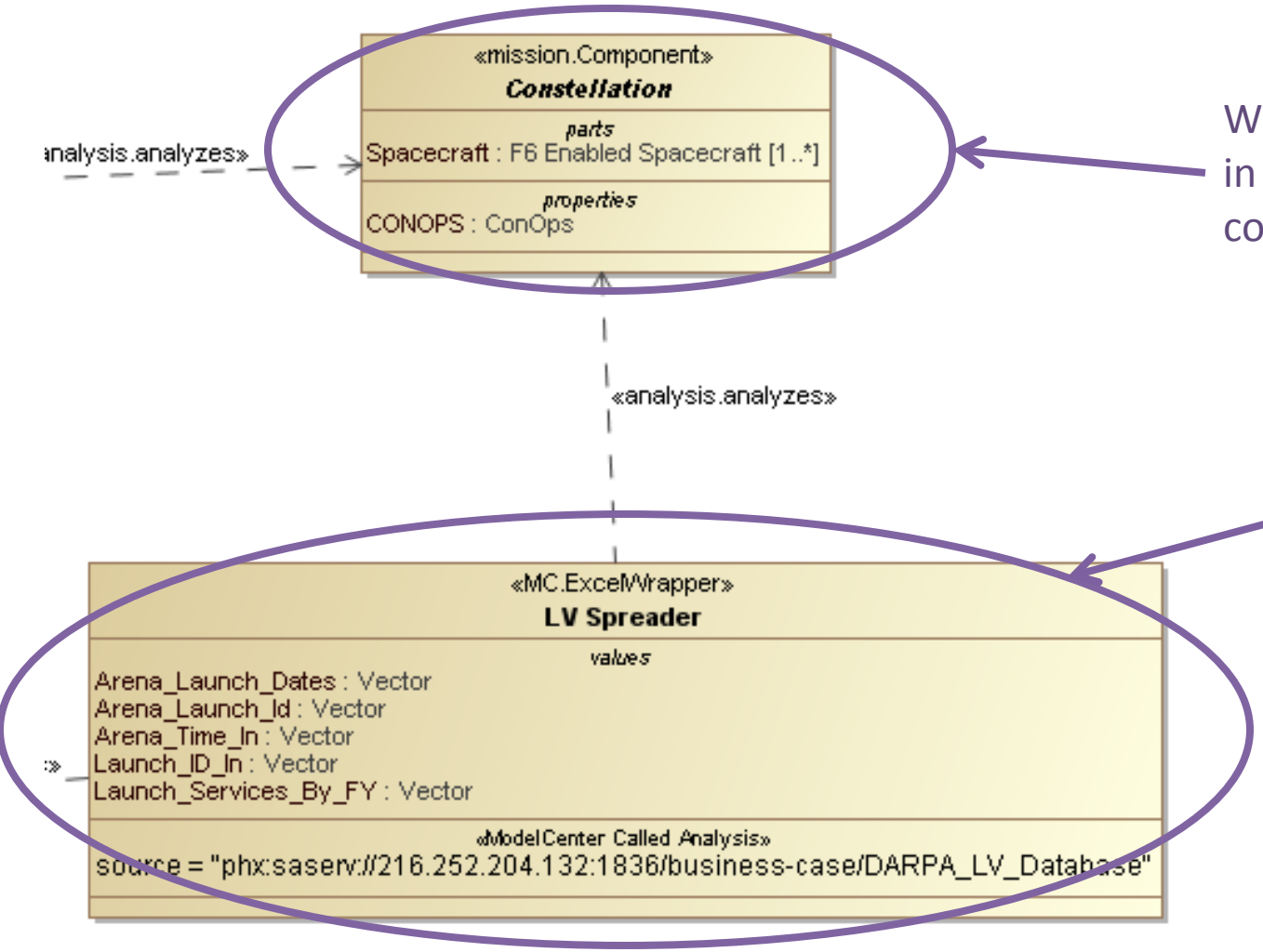
Executed in advance

Executed at build time

Executed at run time

Video of transformation process available

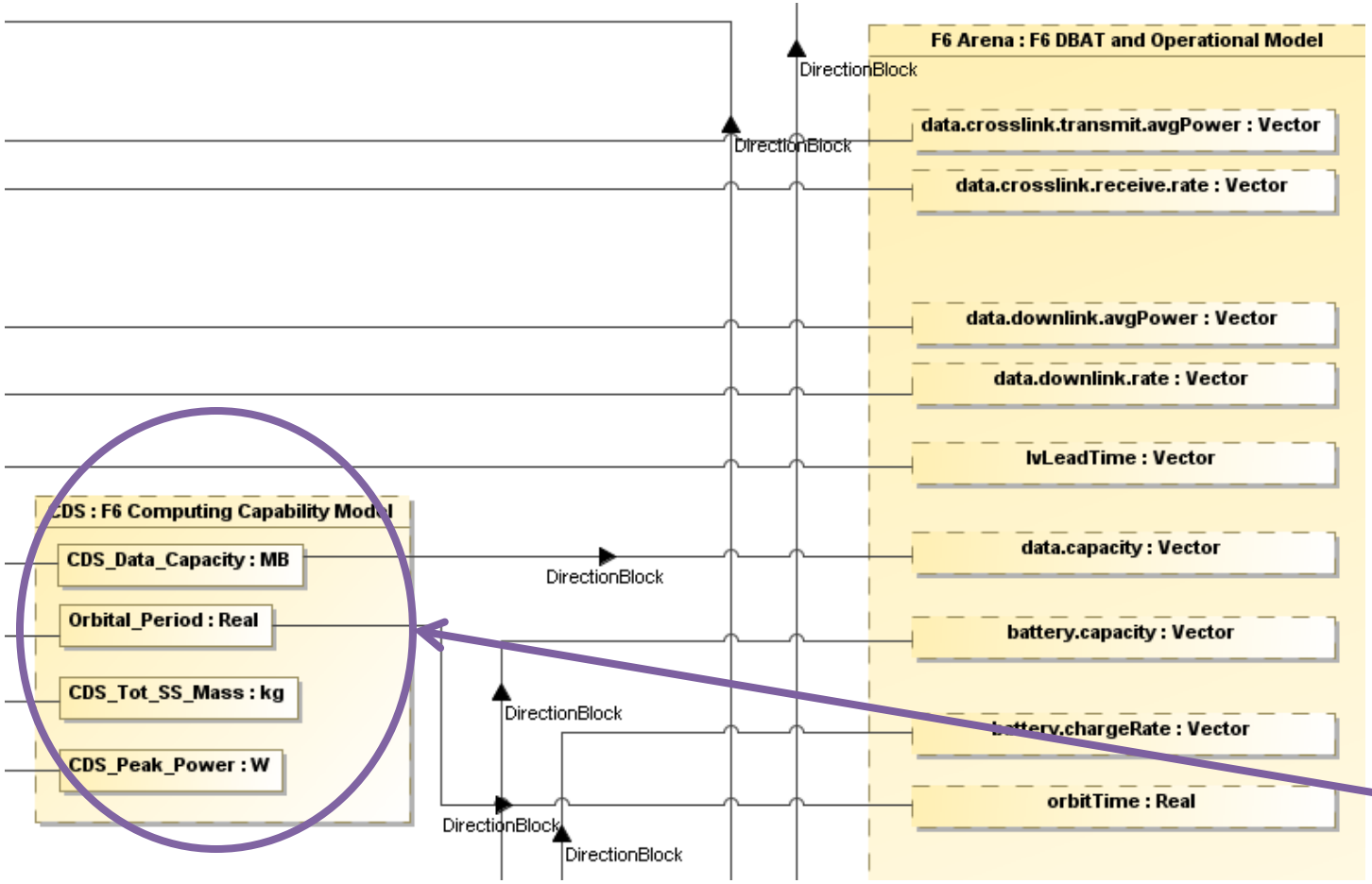
Analysis Tied to Specification



When one of these is in the problem under consideration …

… One of these is required in the analysis

Analysis Tied to Specification



Multiple copies of this analysis can be used … special rules on connections for consistency