Using MBSE to Evaluate Fractionated Space Systems

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California Institute of Technology

October 10, 2013

AGENDA

- Background
- Summary of ASDA work
- Overview of the user process for modeling
- Cost Modeling
- Discrete Event Modeling
- Some Results
- Wrap-up

JPL is part of NASA and Caltech

- Federally-Funded (NASA-owned) Research and Development Center (FFRDC)
- University Operated (Caltech)
- $1.6B Business Base
  - NASA Science 72%
  - Non-NASA 12%
  - Mission Operations 12%
- 5,000 Employees
  - R&D Staff 59%
    - 32% PhD
    - 32% Masters
- Great place to work!
- www.jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

JPL Mission Statement

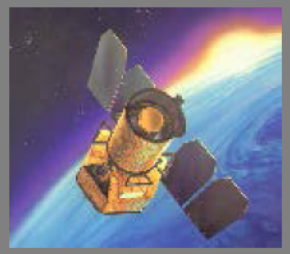
PHOENIX INTEGRATION

- To explore planetary systems -- both our own solar system and others nearby.
- To understand the origins and evolution of the universe and the laws that govern it.
- To search for life beyond Earth.
- To understand our home planet and help protect its environment by making critical measurements.
- To link scientists and the public throughout the solar system by operating the Deep Space Network.
- **To address challenge of national significance by applying unique JPL talent.**
- To support the human expansion into deep space by using JPL robotic capabilities.
- To inspire the next generation of explorers, scientists and engineers.

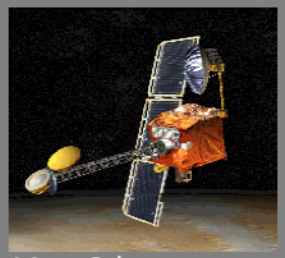
National Aeronautics and Space Administration

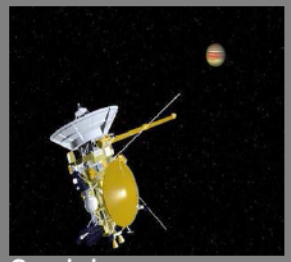
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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


GALEX


Kepler

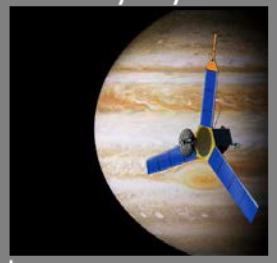

Mars Odyssey

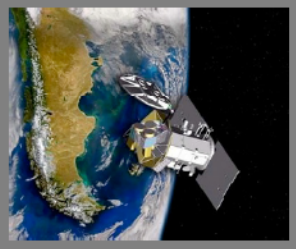

Cassini


CloudSat

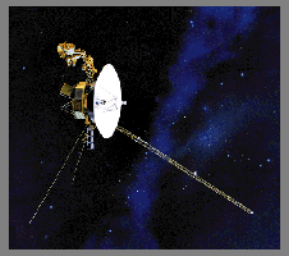

Spitzer

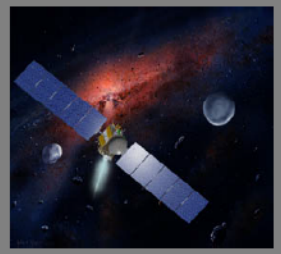

ACRIMSAT

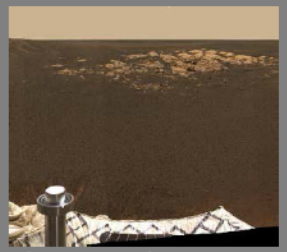

Juno


Aquarius

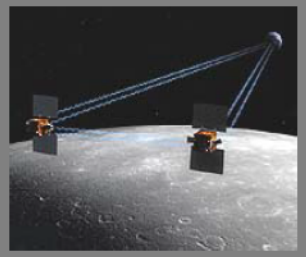

GRACE


Two Voyagers


Dawn


Opportunity


EPOXI-Deep Impact


GRAIL


MSL


Wide-field Infrared Survey Explorer (WISE)


Mars Reconnaissance Orbiter


Jason 1 and Jason 2

Instruments:

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

Planetary
- MIRO
- Diviner

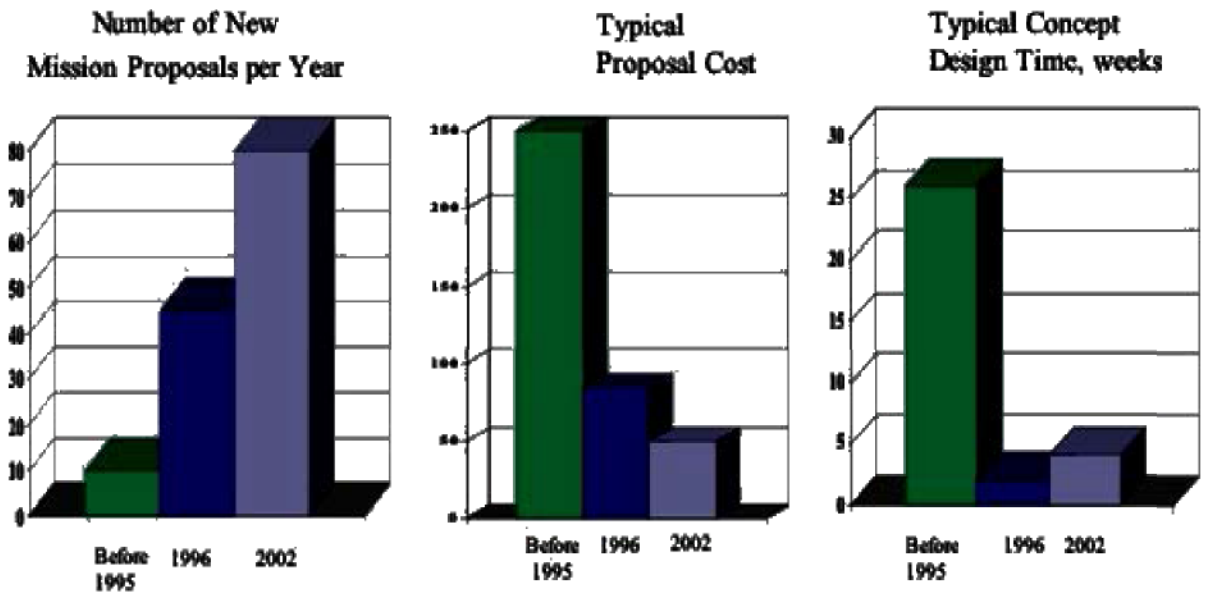
Astrophysics
- Herschel
- Planck

Jet Propulsion Laboratory
California Institute of Technology

PHOENIX INTEGRATION

JPL- Early Collaborative Engineering Metrics

CONCEPTUAL DESIGN METRICS

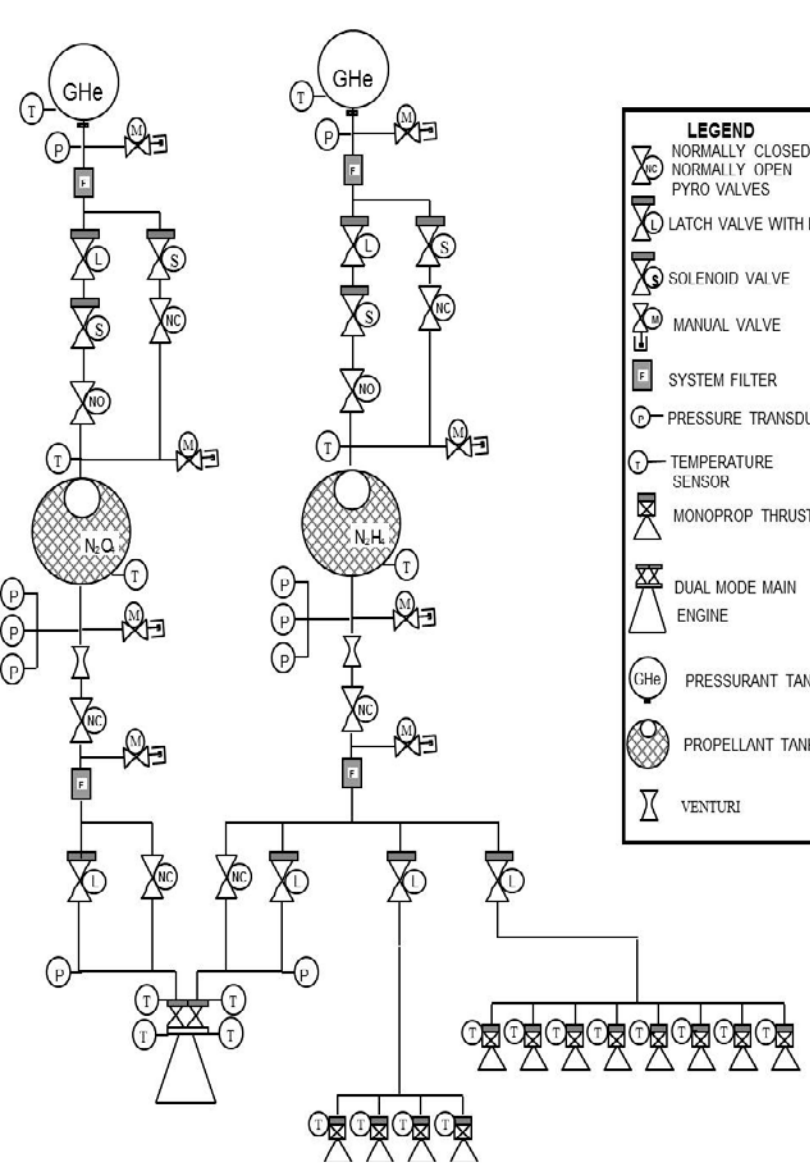


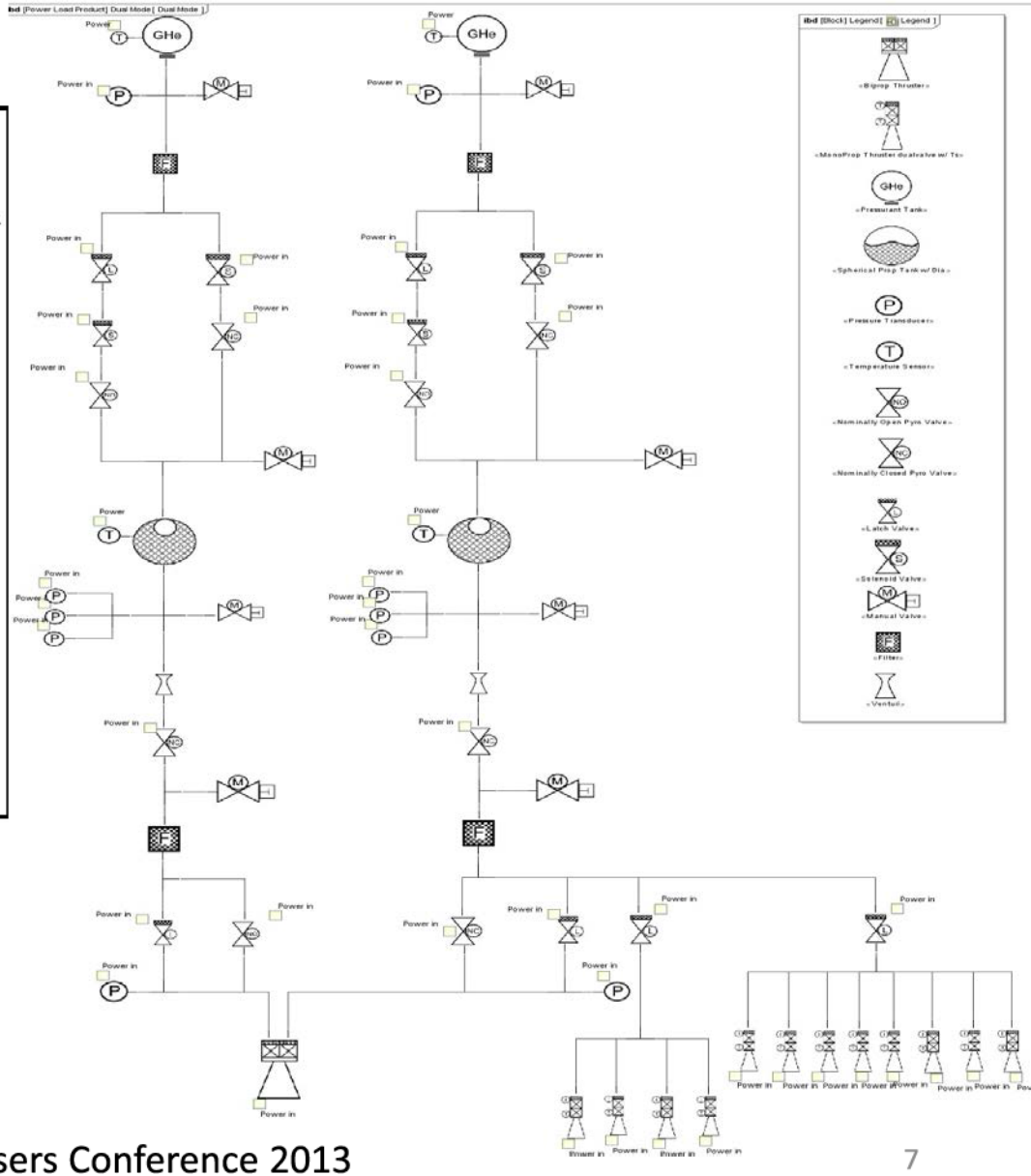
Team X can routinely synthesize and cost a design point in a few weeks

Clones now exist in many fields, several countries

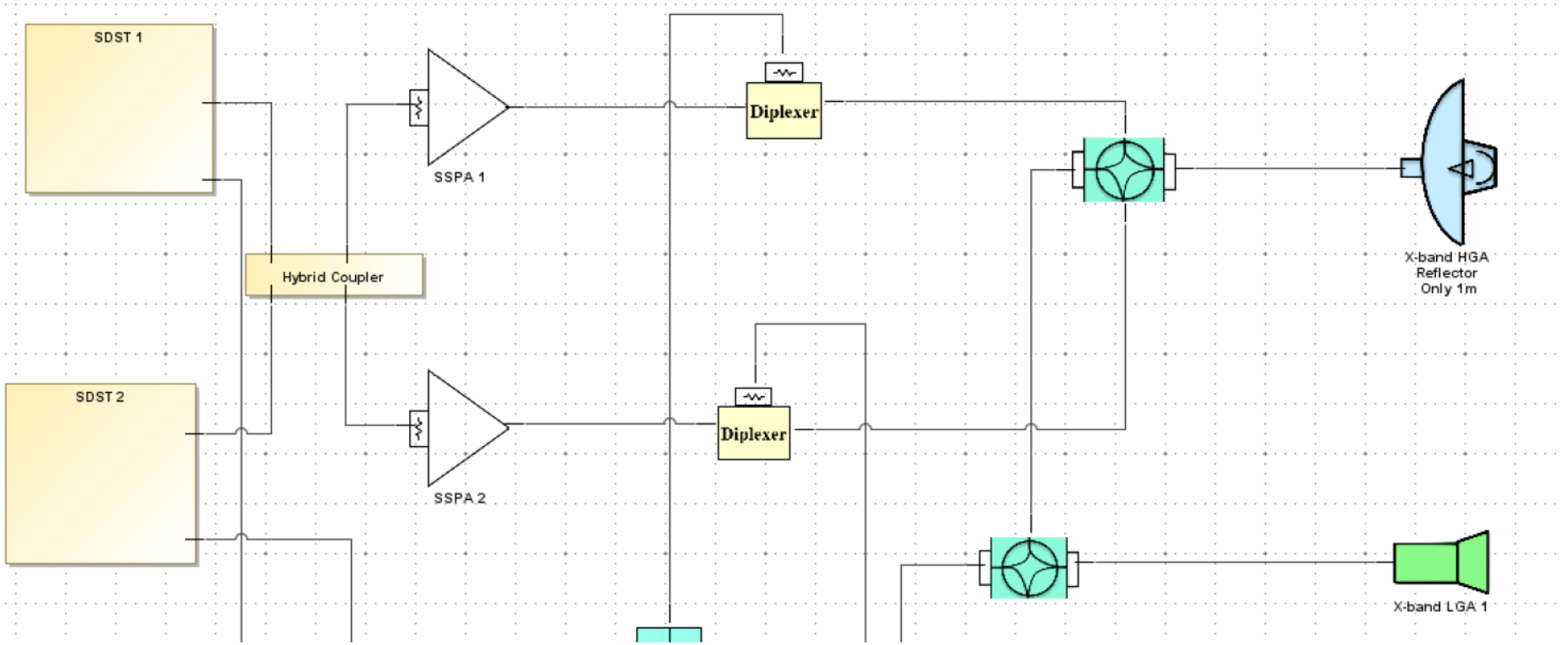
- Dedicated Teams
- Scripted Process
- Tailored Information Systems and Facilities
- Broad models
- Distributed Capability

DSL Enhanced MagicDraw – Can you tell the difference ?





And Telecom Too!



DARPA

- **D**efense **A**dvanced **R**esearch **P**rojects **A**gency
  - "Creating and preventing strategic surprise"
  - www.darpa.mil
- Brief History of Accomplishments
  - M16
  - ARPA Net (1969 had 4 nodes) → Internet (2009, $>10^9$)
  - Stealth Technology
  - GPS
  - Speech Recognition
  - … many more

DARPA System F6

- DARPA-BAA-11-01, Tactical Technology Office (TTO) released on October 20, 2010 a Program called System F6 (*Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange*). It's goal is to demonstrate the feasibility and benefits of disaggregated—or fractionated—space architectures.
- Key [most important?] feature of Technical Area 1 is *demonstration of new SE/MBE capabilities in both development and acquisition of new systems* which 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.
  - **When does a fractionated architecture make sense?**
  - **When does the business case close?**
- Question answered under *range of uncertainties* 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."*

ASDA

- ASDA=Adaptable Systems Design and Analysis
- We responded to BAA and proposed to build a tool to not only analyze a fractionated system, but also to design and architect such a system
- Our team is a partnership between JPL and Phoenix Integration
  - We proposed to use computers to automatically generate and evaluate many designs
  - We proposed to provide a GUI to allow users to design:
    - 1) futures, missions, architectures, systems, and
    - 2) their associated parameters
  - Our team "won" the down-select from the Base Period
  - We are now in the middle of the third and final phase

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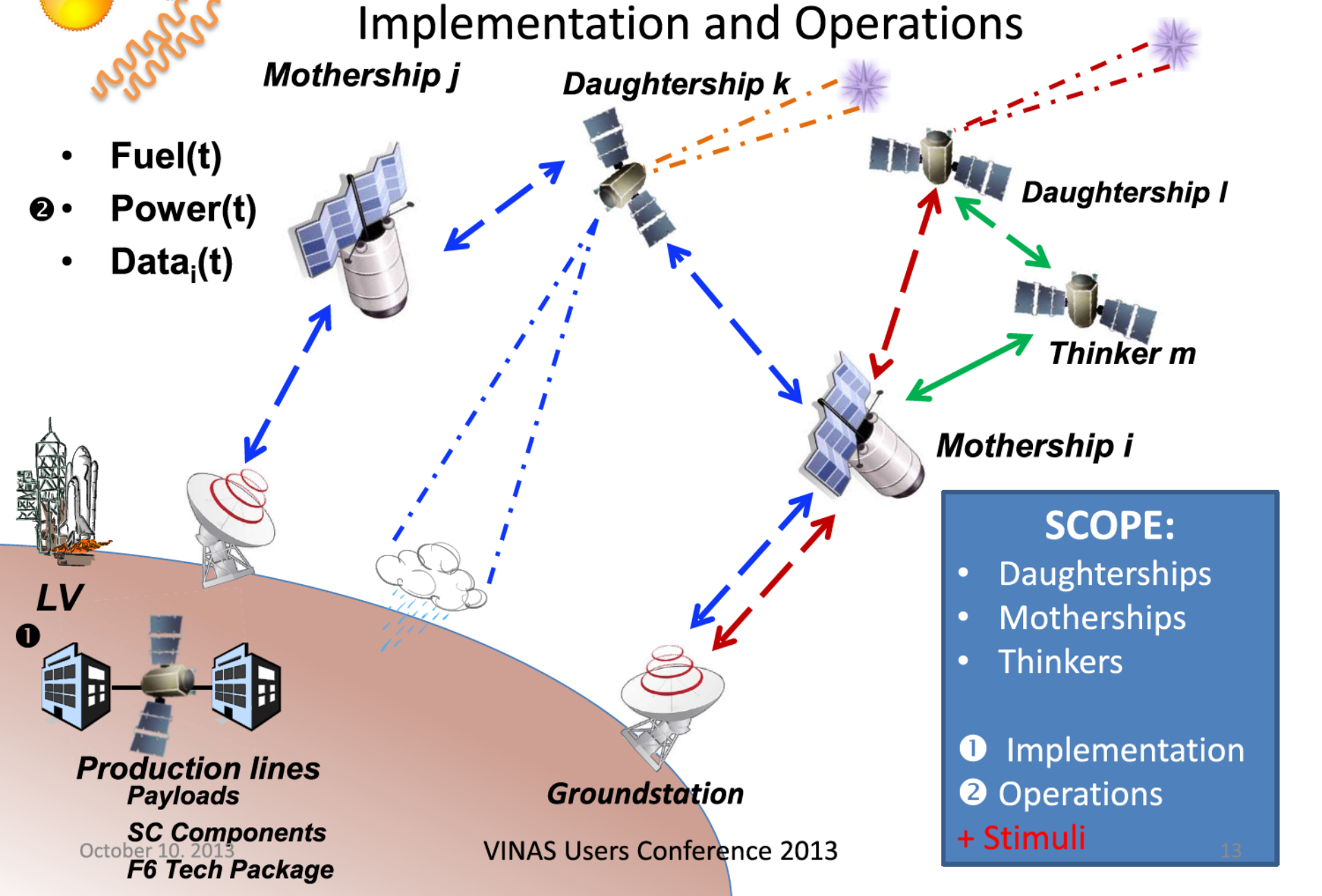
ASDA Scope Overview

Implementation and Operations

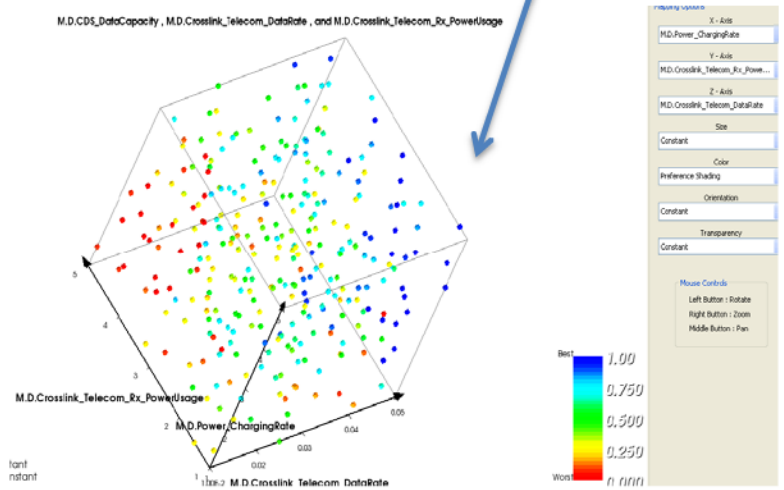


ASDA Results : Brief Summary

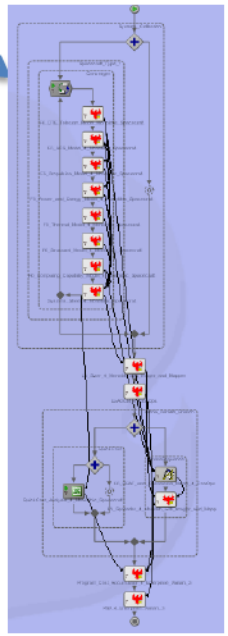
- Produced realistic model
  - Included stimuli and responses to measure adaptability and survivability
  - Automatically generated, populated and executed cluster candidates
  - Can Generate populated tradespace with Present Strategic Value as overall metric or other metrics as desired

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)

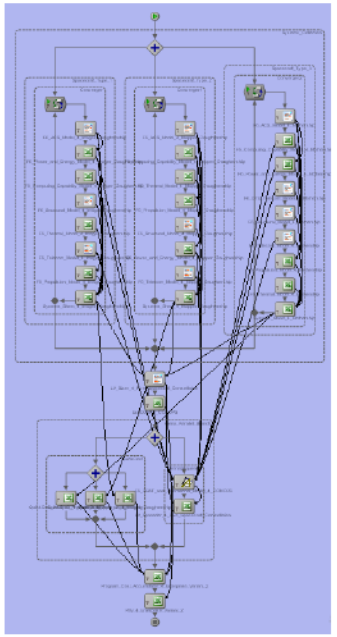
ERO Name	Units	Value
Option to Switch Payloads	$FY11M	$ 62.37
"In-the-Money" Probability		0.16



Multi-dimensional plot of tradespace for N=3 configuration

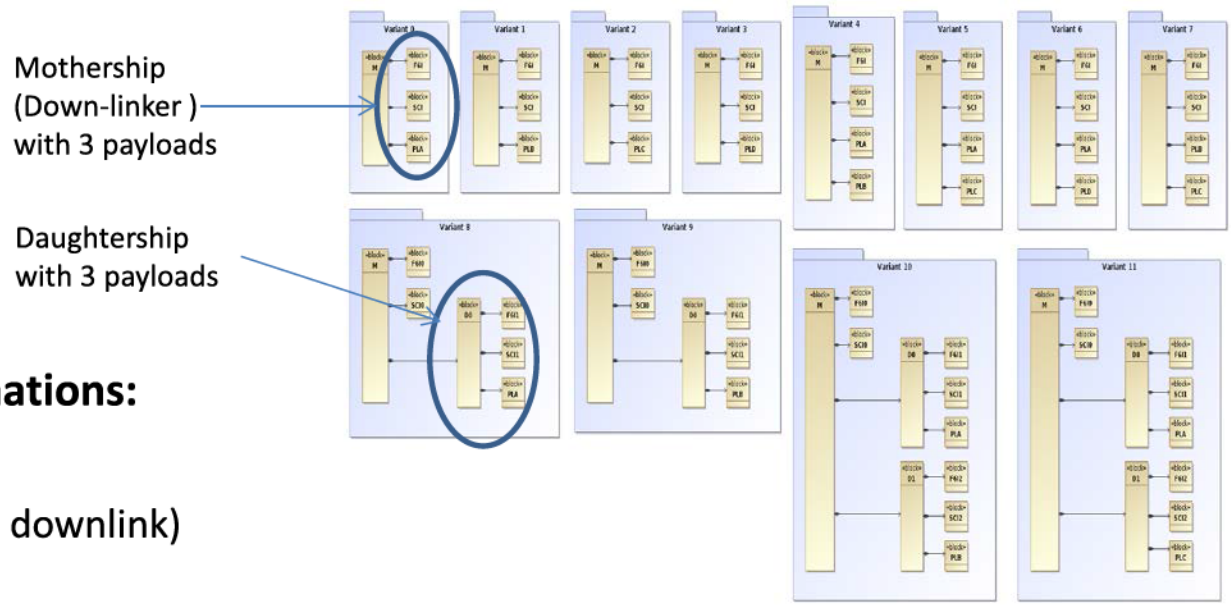


N=1



N=3

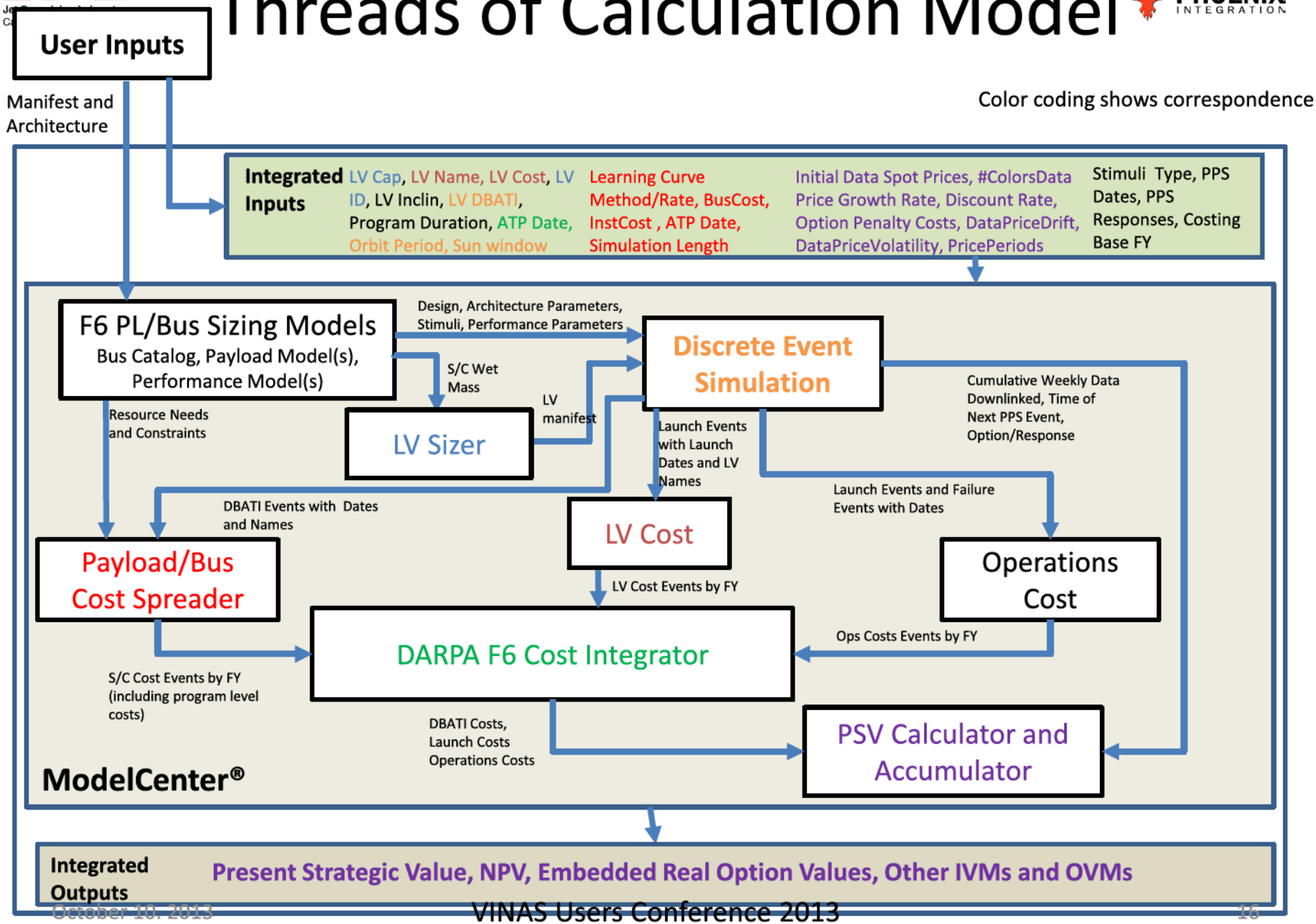
Architectural Variations



Many architectural combinations:

- # of Spacecraft
  - # of motherships (can downlink)
  - # of daughterships
  - # of thinkers (can process data)
  - **→Together they form a network**
- # of Payloads
  - Distribution of those payloads across spacecraft
- # of 'legal' architectures
  - >19,000 combinations of 3 spacecraft and 6 payloads
  - Gets much, much bigger as the number of spacecraft and payloads increase

Threads of Calculation Model



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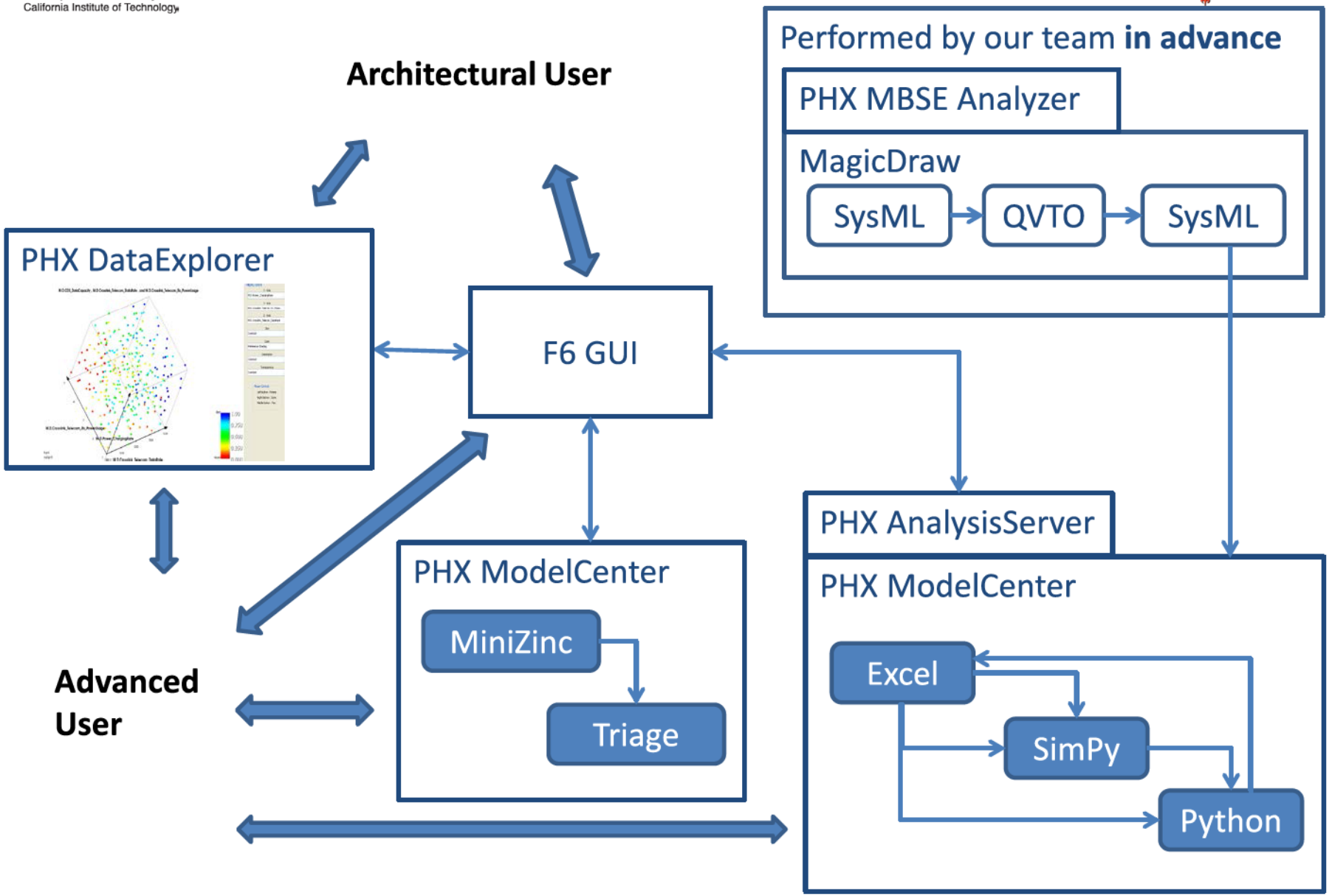
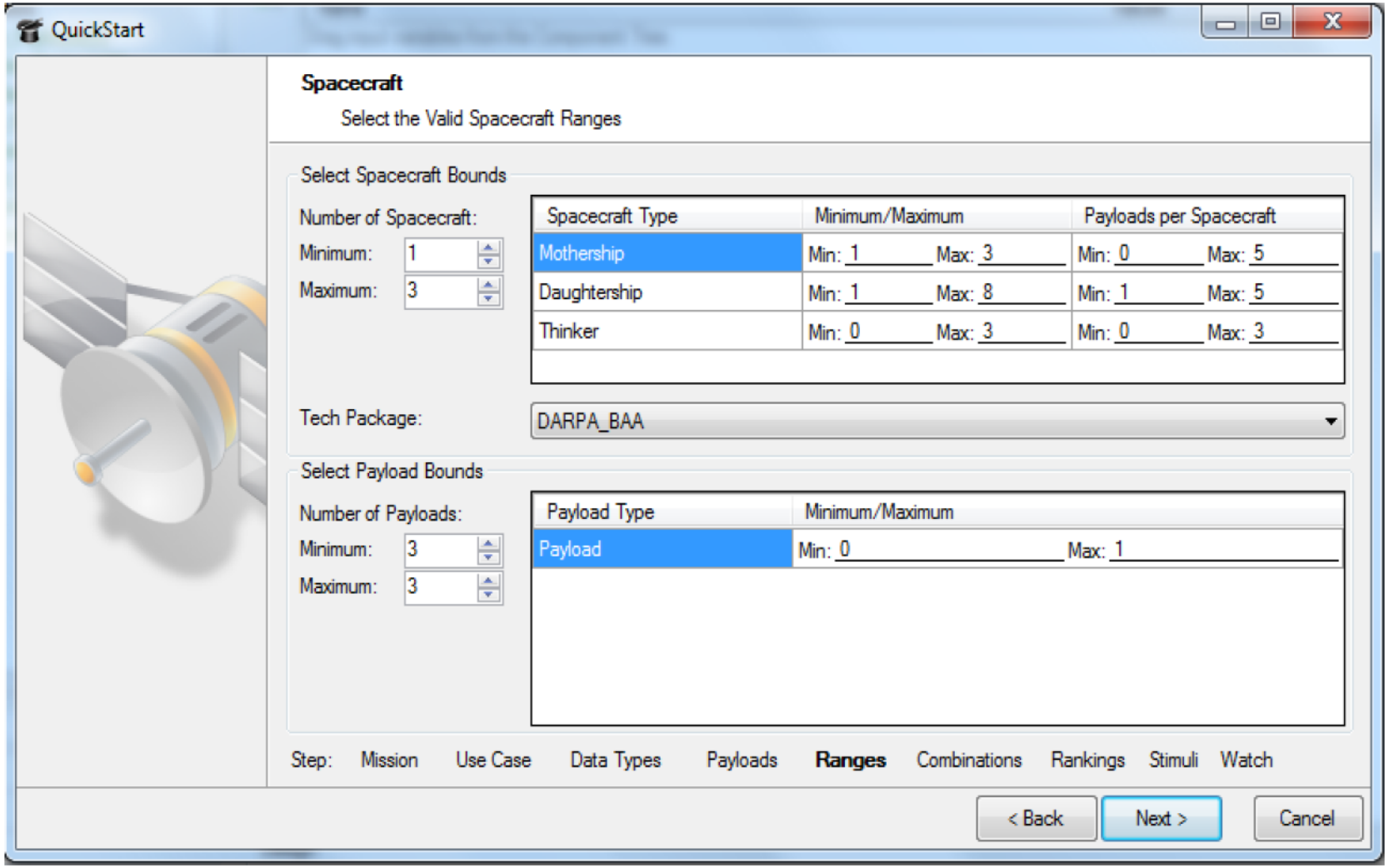
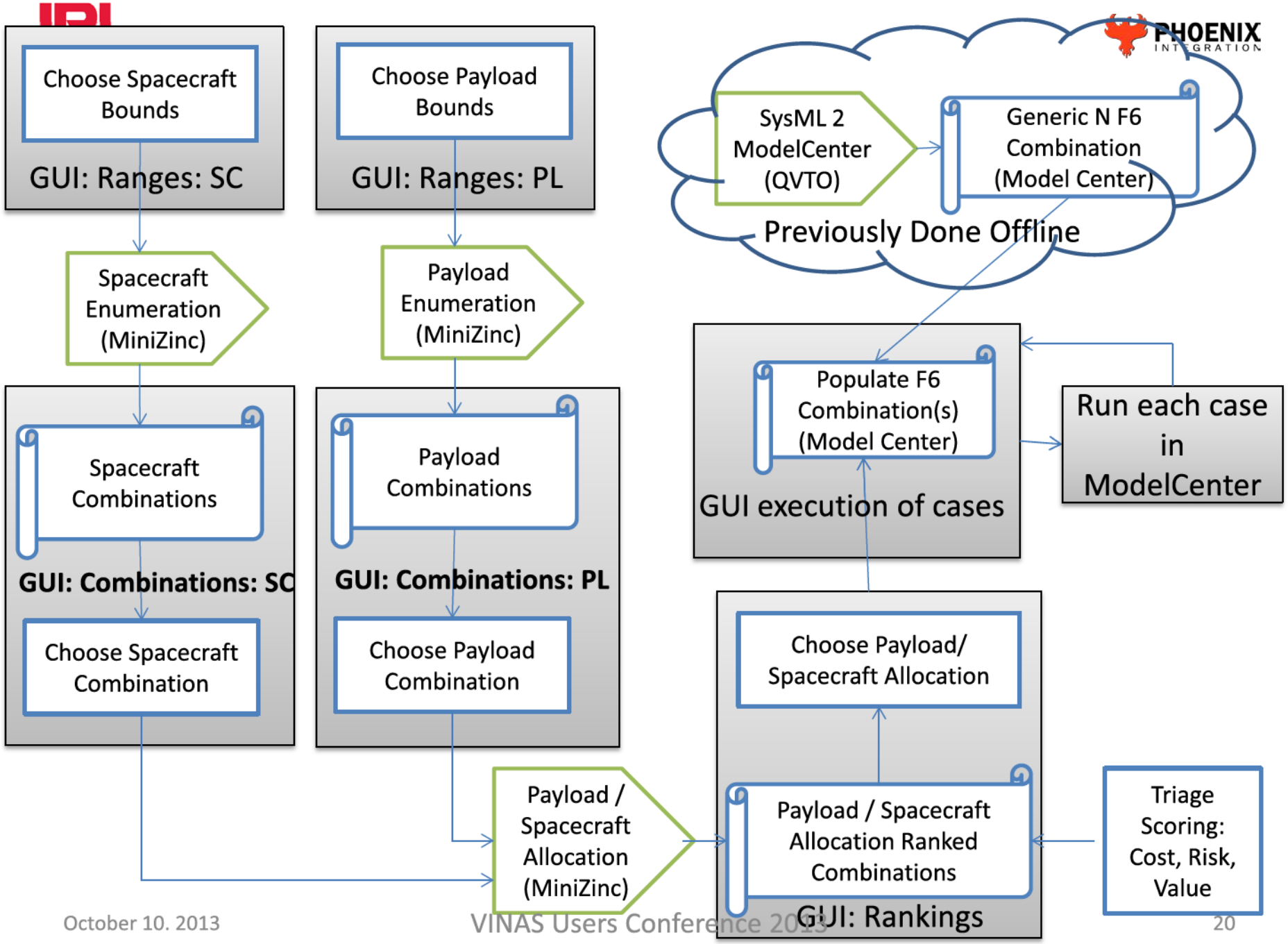

Architectural User
Performed by our team in advance
PHX MBSE Analyzer
MagicDraw
SysML
QVTO
SysML
PHX DataExplorer
F6 GUI
PHX AnalysisServer
PHX ModelCenter
PHX ModelCenter
MiniZinc
Triage
Excel
SimPy
Python
Advanced User

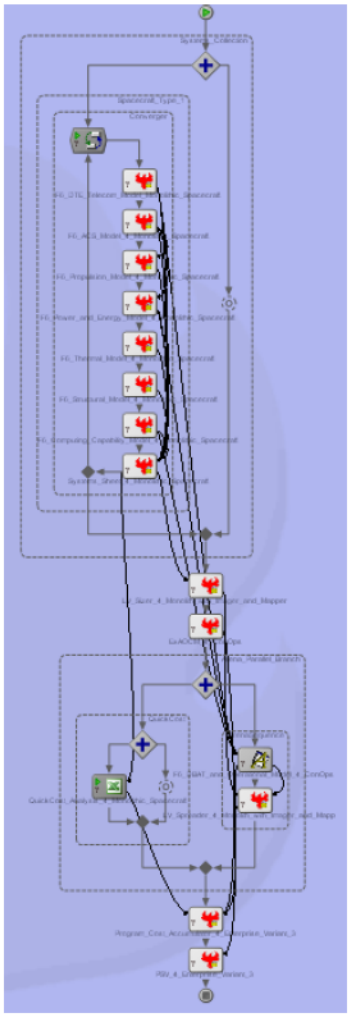
ASDA GUI: “Quickstart”

Provide means for ‘non-expert’ users to be guided thru the model setup/execution process

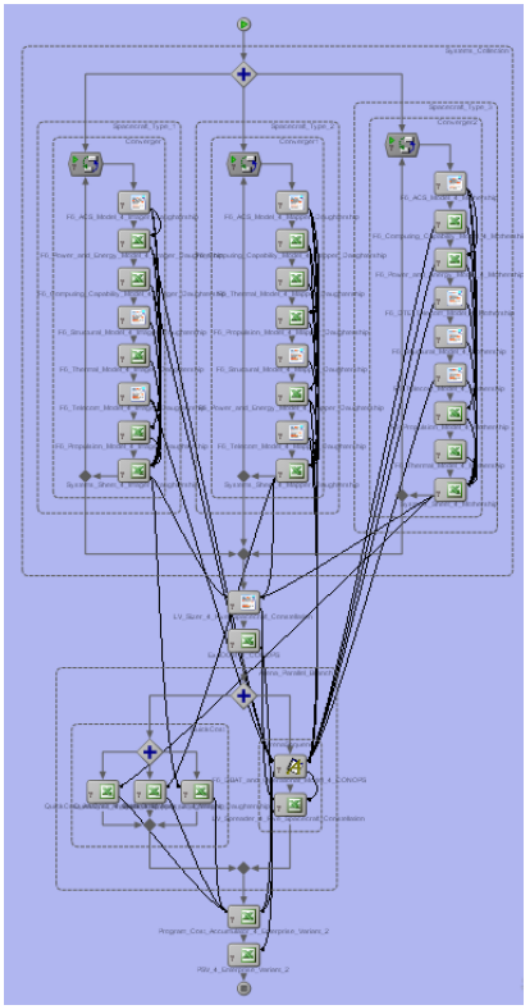



Choose Spacecraft Bounds
GUI: Ranges: SC
Choose Payload Bounds
GUI: Ranges: PL
SysML 2 ModelCenter (QVTO)
Generic N F6 Combination (Model Center)
Previously Done Offline
Spacecraft Enumeration (MiniZinc)
Payload Enumeration (MiniZinc)
Populate F6 Combination(s) (Model Center)
Run each case in ModelCenter
GUI execution of cases
Spacecraft Combinations
GUI: Combinations: SC
Payload Combinations
GUI: Combinations: PL
Choose Spacecraft Combination
Choose Payload Combination
Choose Payload/ Spacecraft Allocation
Payload / Spacecraft Allocation (MiniZinc)
Payload / Spacecraft Allocation Ranked Combinations
GUI: Rankings
Triage Scoring: Cost, Risk, Value

Examples of automatically generated Executable Model(s) in ModelCenter



Monolith



3 Module Cluster

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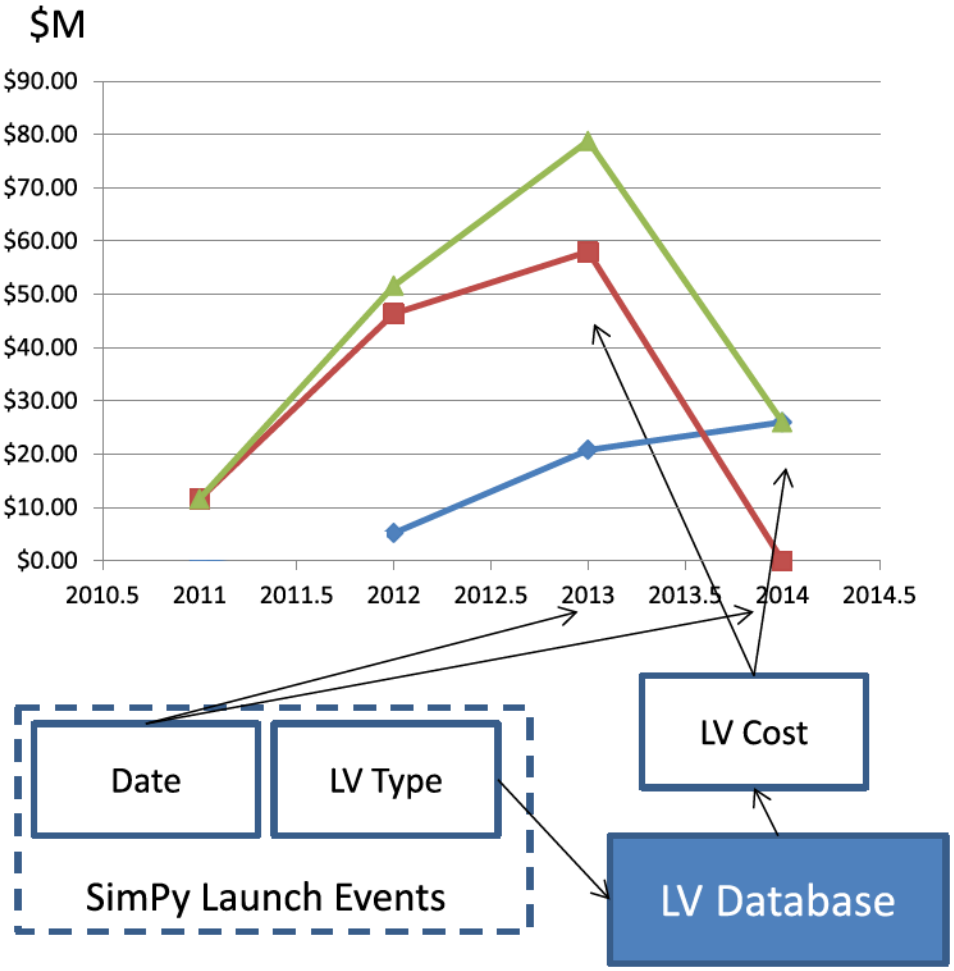
SC, LV and PL Catalogs

- Started with Design Models
  - From standard Spacecraft Engineering information
    - Populated with open-source, generic data
    - Loops for sizing propulsion, thermal, etc.
  - Used various available public cost models
  - Was realistic but…
    - run times were longer,
    - costs were tougher to estimate,
    - and results meant everything would be 'custom'
- Switched to Catalog approach
  - Spacecraft (SC) from JPL internal data (58 parameters)
  - Launch Vehicles (LV) for open source data (7 parameters)
  - Payloads (PL) from NASA Instrument Cost Model (NICM) (6 parameters)

Catalogs and costing

Example: LV Cost Model



Launch costs are spread over phases of production process.

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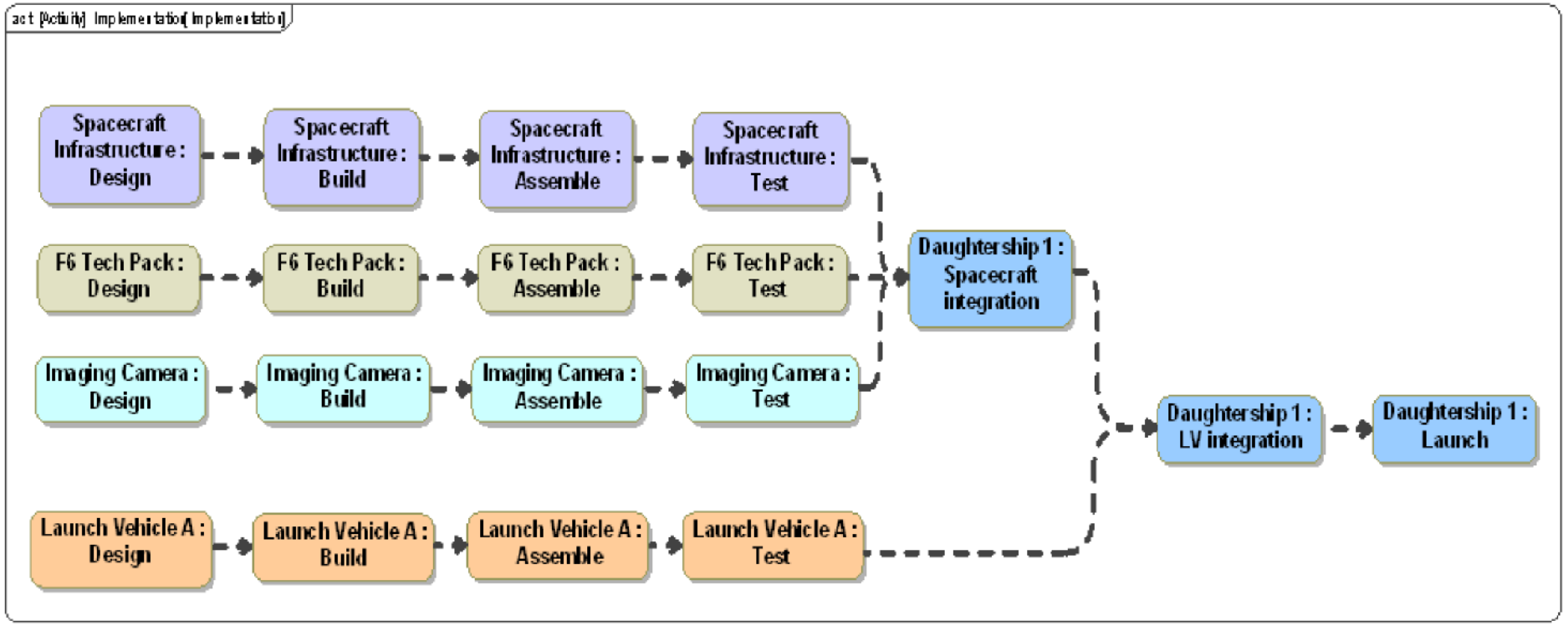
F6 DES Model overview
Implementation Phase

- Spacecraft subassemblies developed in parallel on distinct production lines, following “Design, Build, Assembly, Test and Integration” (DBATI) sequence

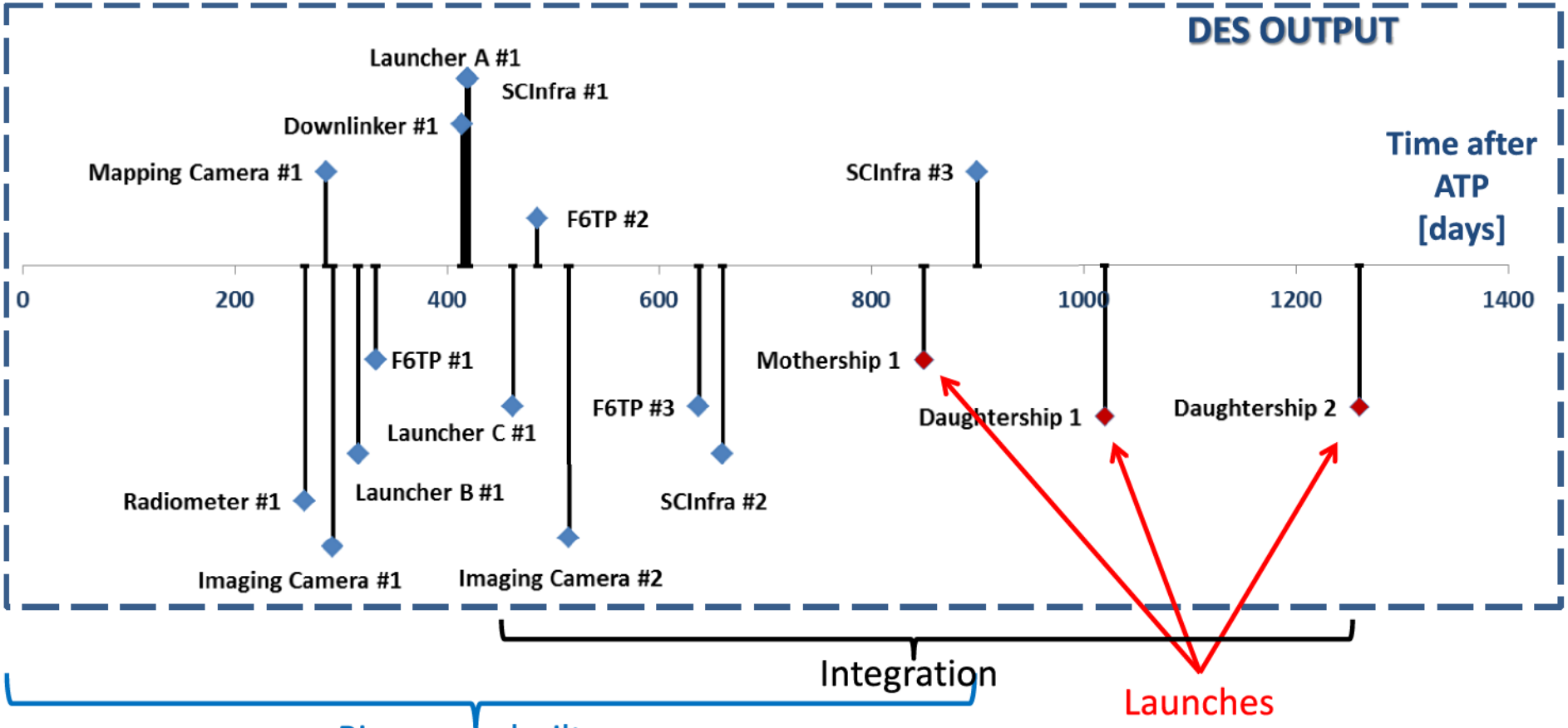


Discrete Event Simulator Example

Mothership [1]: F6TP, Downlinker, Spacecraft

Daughtership [1]: F6TP, Imaging Camera, Mapping Camera, Spacecraft

Daughtership [2]: F6TP, Imaging Camera, Radiometer, Spacecraft

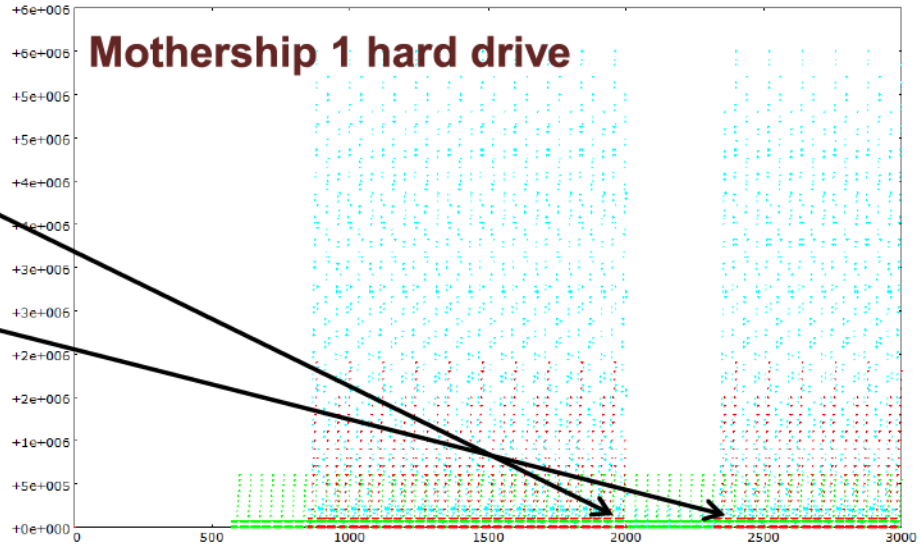


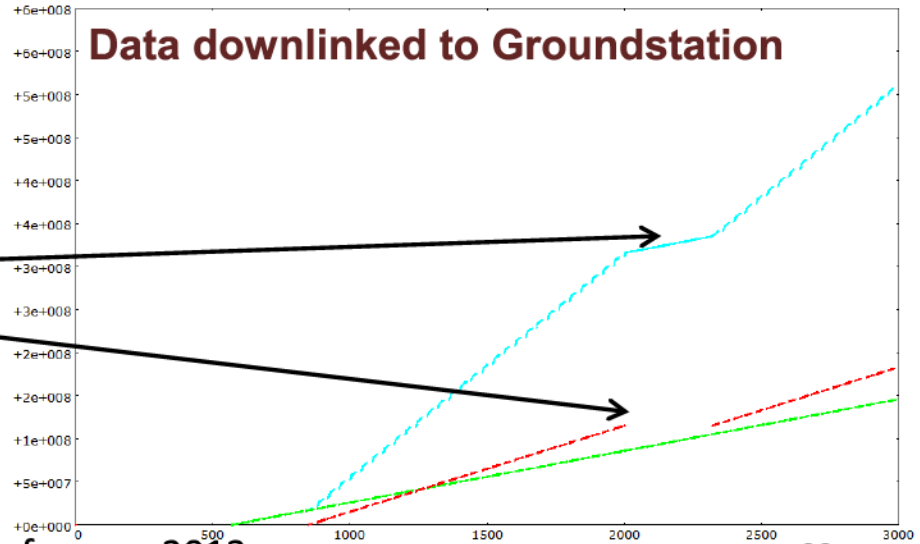
DES Example (cont.)

Scenario: On-Orbit Failure

Daughtership 1 Total Failure,
"*Replace spacecraft*" option exercised

Replacement Daughtership launched





Consequences:

Reduction in incoming data

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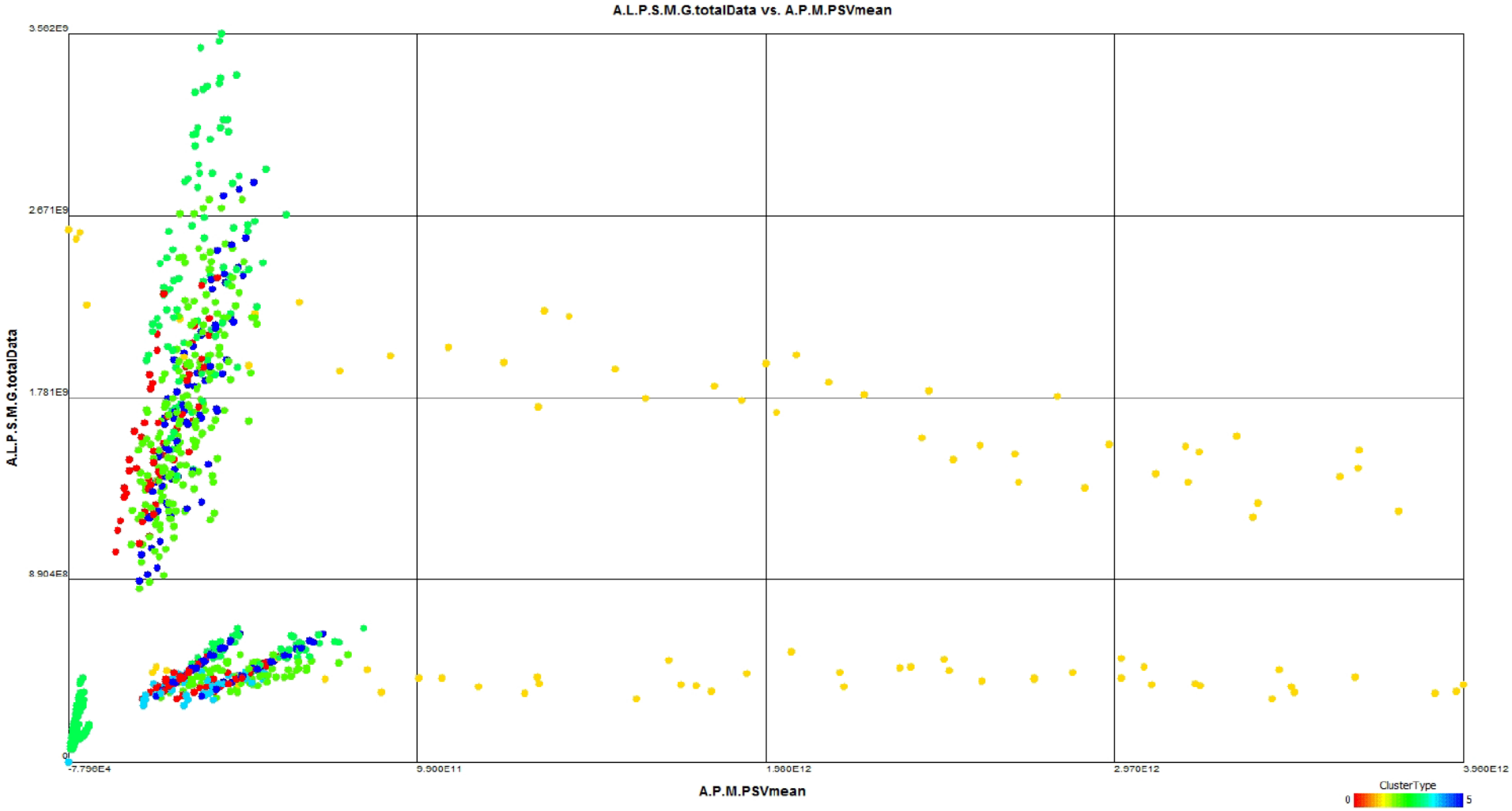
Preliminary Case Study

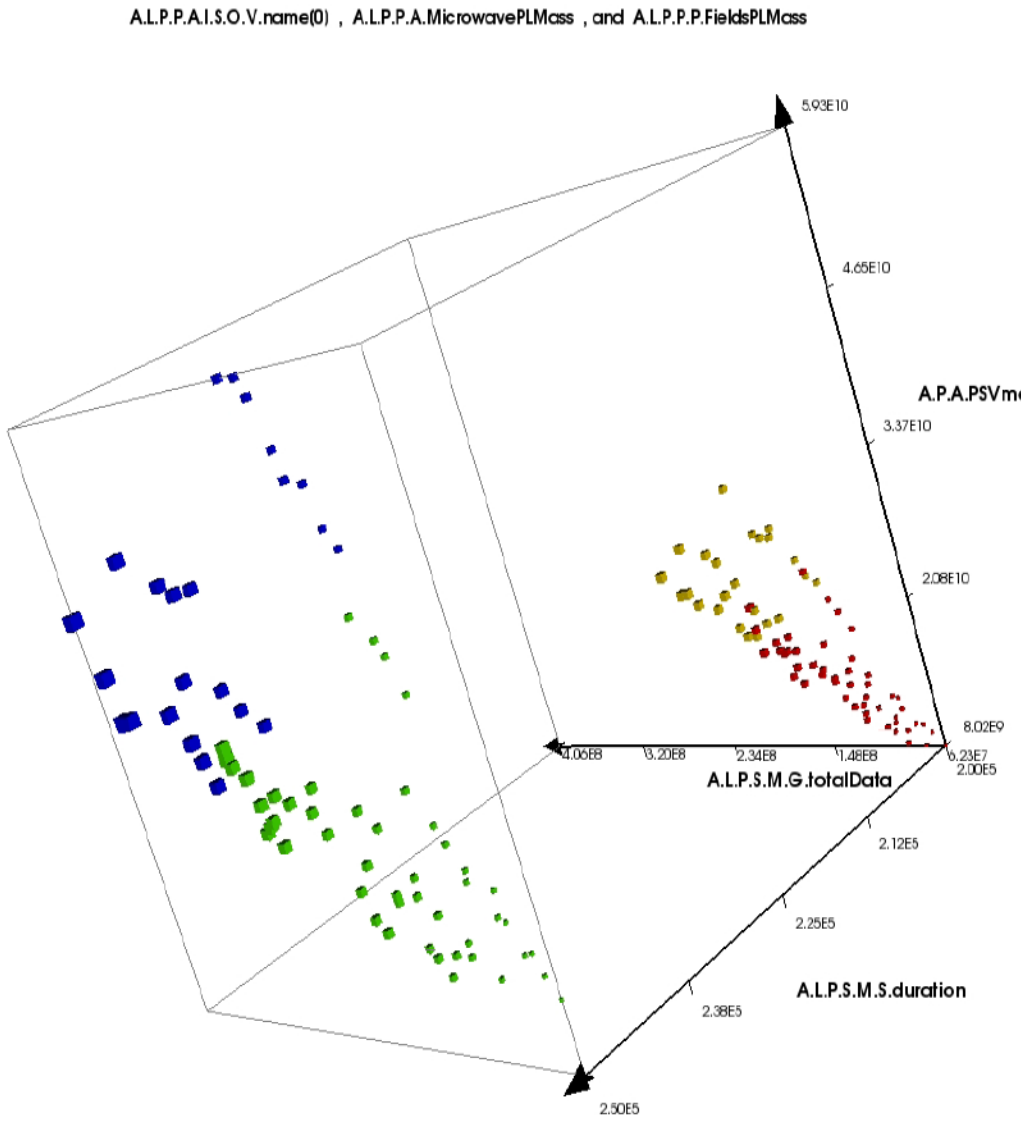
- Orbital Debris
  - Debris event at around halfway point of mission
  - Vary the size and type of payloads
  - Vary the constellation (e.g. # MS, #DS)
    - Vary the assumed victim
    - Vary the distribution of payloads
  - Note 1 MS means only one way to downlink

Preliminary Debris Study: Results



Yellow,Red=1MS1DS, Green,Blue=1MS2DS, lightBlue=1MS

Preliminary Debris Study: Results



PSV
Blue=best
Red=worst

Cost
Bigger
size=more

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Wrap-up

- Provided brief summary of the JPL/Phoenix Integration team product for the DARPA System F6 Program
- Tool is available for others to uses
  - Still working one remaining Export Control issue before general release
- Utilizing the some of the power of MBSE
  - Single source of data
  - Transformations of base model to specific models
  - Framework in place, allow users to customize data contents
  - Domain experts can visualize of relevant subsets
  - Strong enabling of collaborative design in architectural phase
  - Can (easily) modify for other applications

Plans for this last Option Period

- Get the tool deployed
  - Improve the GUI
  - Verify and Validate
    - Perform case studies
    - Perform Pilot applications
  - Get the word out
  - Develop and Implement training sessions and materials
  - Provide insight into to how to customize
- Upgrade F6 Trade tool as needed
  - Features that are necessary for infusion
    - For design/trades
    - For ease of use
  - Bugs as discovered

Obtaining the F6 Design Tool

- 1) Interested party is sent a link to the F6 Design Tool submission form; http://www.phoenix-int.com/f6dk_request.php.
- 2) After submitting, F6 ASDA team leadership (Steve Cornford and Peter Menegay) will receive the request via an automated email.
- 3) The requester is sent a reply, either a rejection, or a request for the necessary information to Phoenix Integration to respond with appropriate licenses and download account information.
- 4) When the requested information is received, Phoenix Integration will create the needed ModelCenter and Analysis Server license files, and provide a download link with a download account that has all necessary files, including a word document.
  - Downloads link: https://analysislibrary.phoenix-int.com/content/files/Groups/F6DK/Downloads/
  - Instructions file: F6DK Installation Instructions.docx
- 5) Support is provided as needed.

BACKUP

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 ASDA model

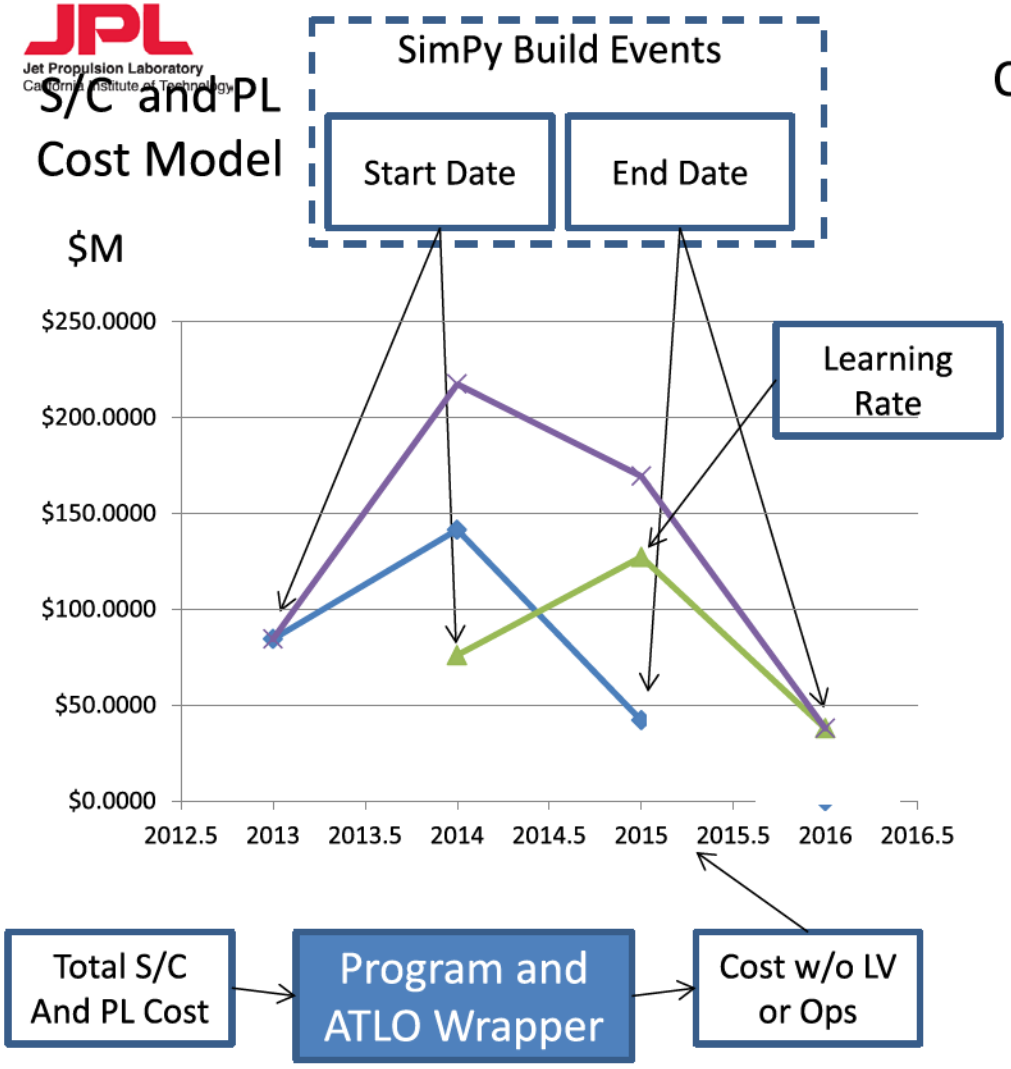
Present Strategic Value (PSV) of an Investment (ala Schwartz and Trigeorgis, et al.*)

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

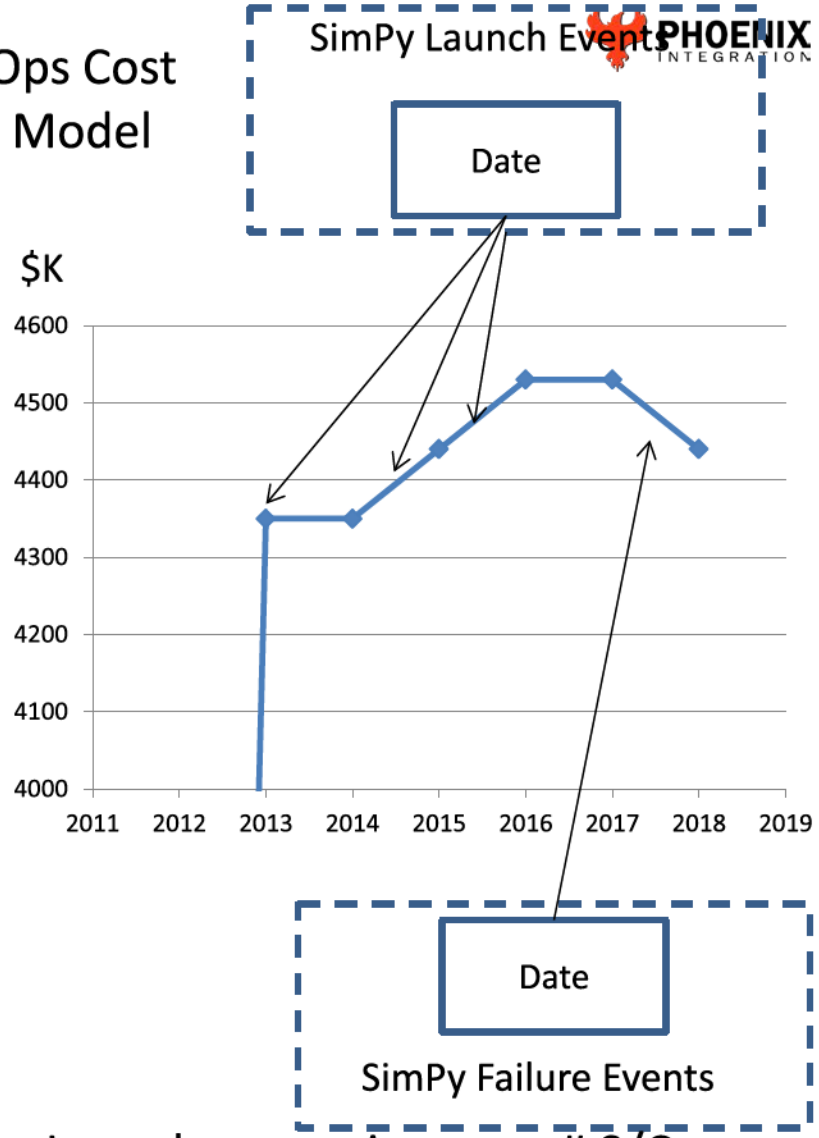
- **General Nature of Embedded Real Options (EROs)**
  - **Expand, Contract**
  - **Defer, Accelerate**
  - **Switch (Repurpose, Abandon)**
- **Practical Implementation Issues**
  - **Consistently calculating each real option value**
  - **Embedding them in a lengthy, complex project**
    - **PSV depends 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

S/C and PL Cost Model



Ops Cost Model



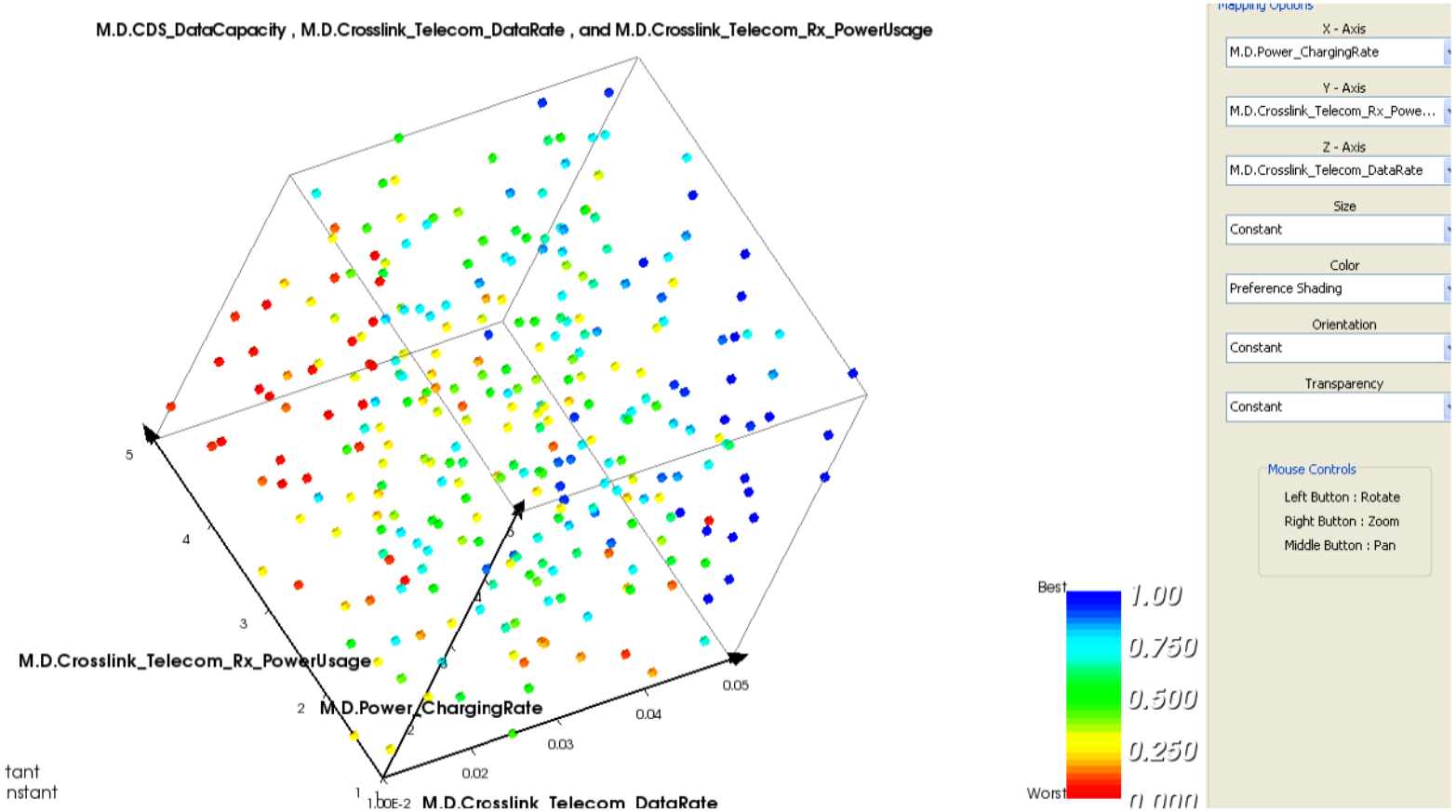
Bus and payload catalog costs are wrapped and spread over phases, and learning rates are applied.

Launch events increase # S/C to operate, failure events decrease # S/C to operate. # S/C -> # FTE -> Cost

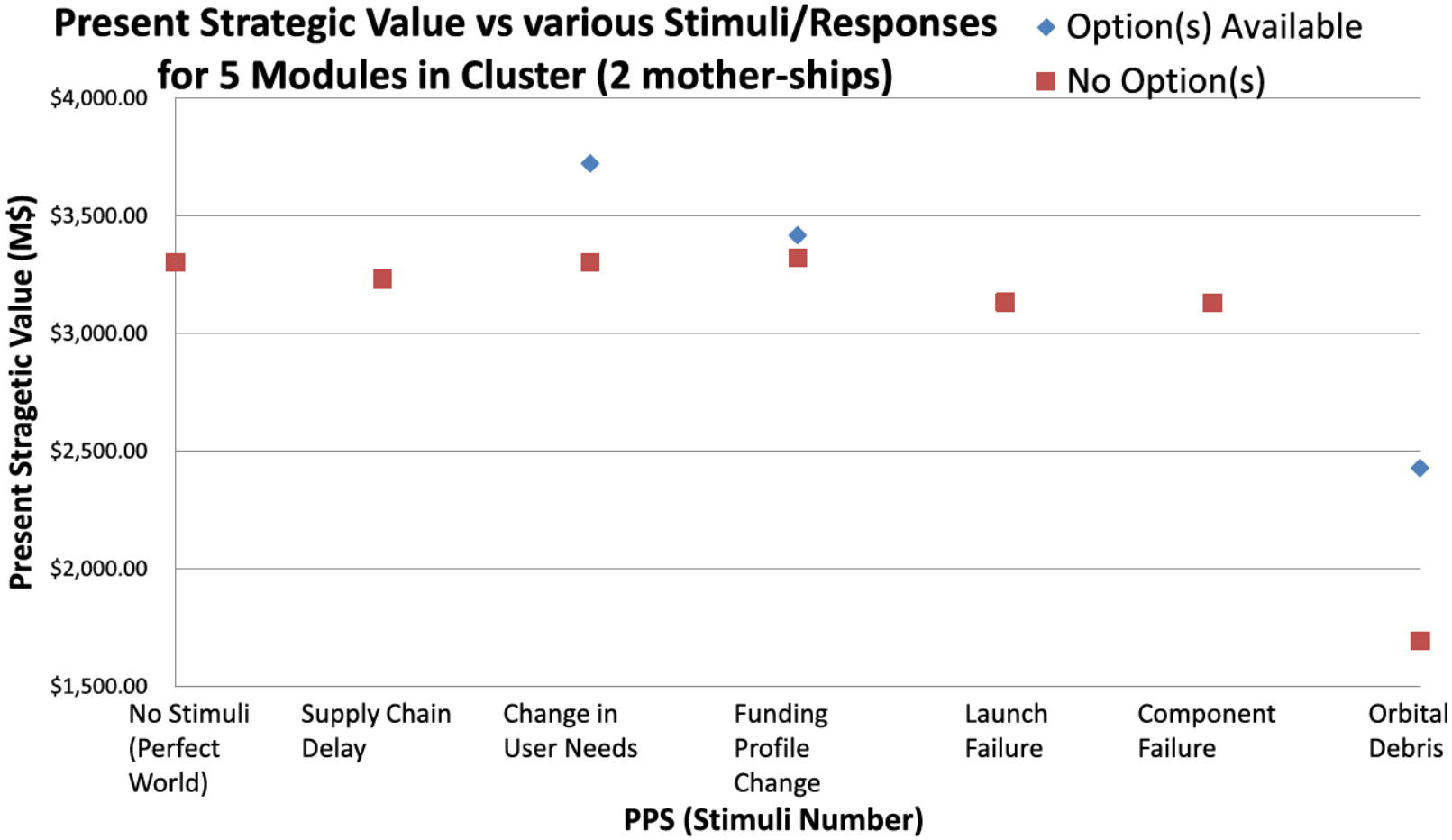
Preliminary Case Study

- Orbital Debris
  - Debris event at around halfway point of mission
  - Vary the size and type of payloads
  - Vary the constellation (e.g. # MS, #DS)
    - Vary the assumed victim
    - Vary the distribution of payloads
  - Note 1 MS means only one way to downlink

Sample Output

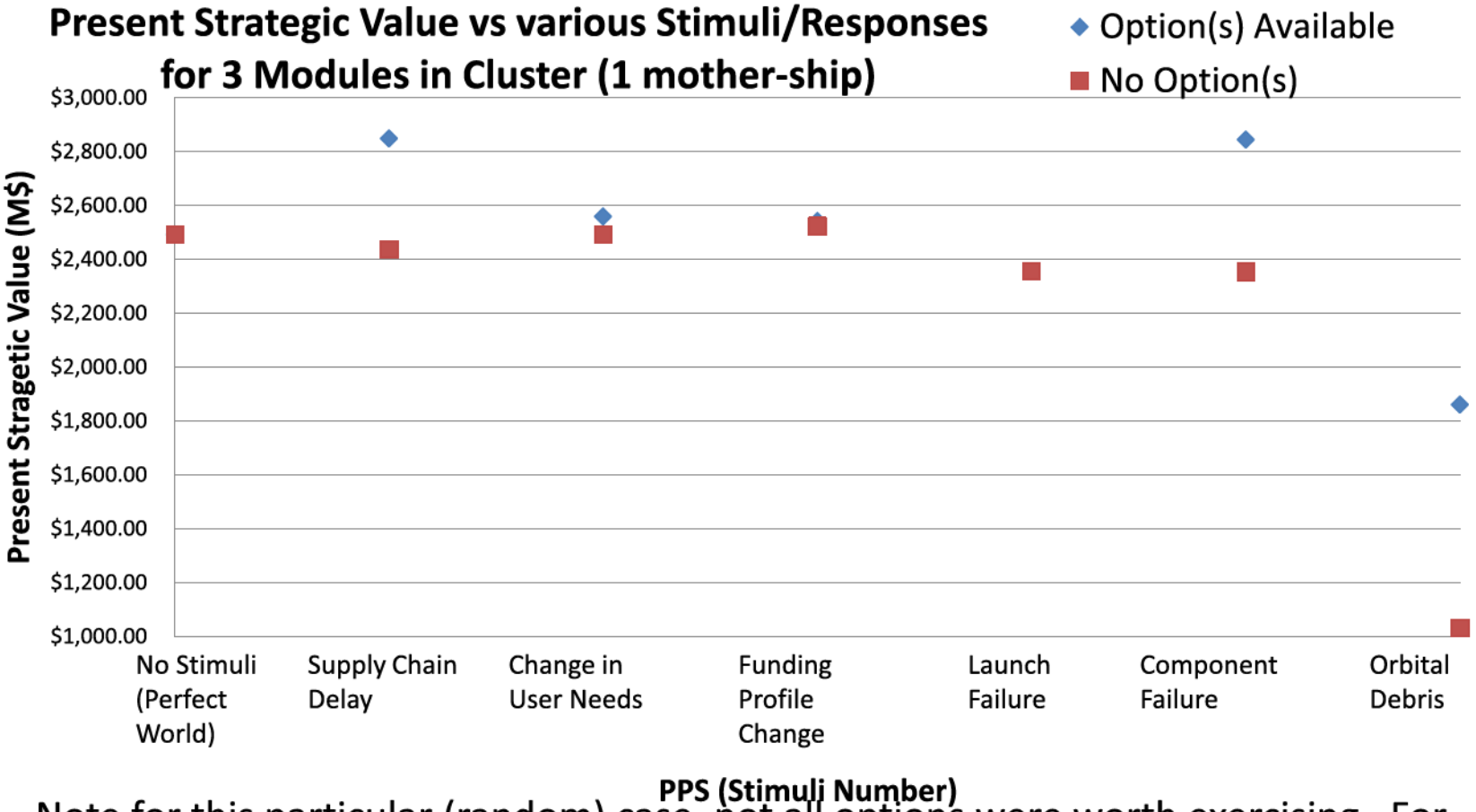


Zooming in to one Tradespace point



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



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