Jet Propulsion Laboratory
California Institute of Technology

SysML and Beyond: Applications of MBSE at the NASA Jet Propulsion Laboratory

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About the Presenter

- Software Systems Engineer at NASA JPL
- Education:
  - Ph.D., Mechanical Engineering (Georgia Tech)
  - B.Sc. + M.Sc., Aerospace Engineering and Computer Science (Technical University Munich)
- MBSE lead for two efforts:
  - Thirty Meter Telescope APS Subsystem
  - Planning for a Mars Sample Return effort
- MBSE infrastructure development software engineer
- Research on model-based design space exploration, and applications of Artificial Intelligence for advancing MBSE

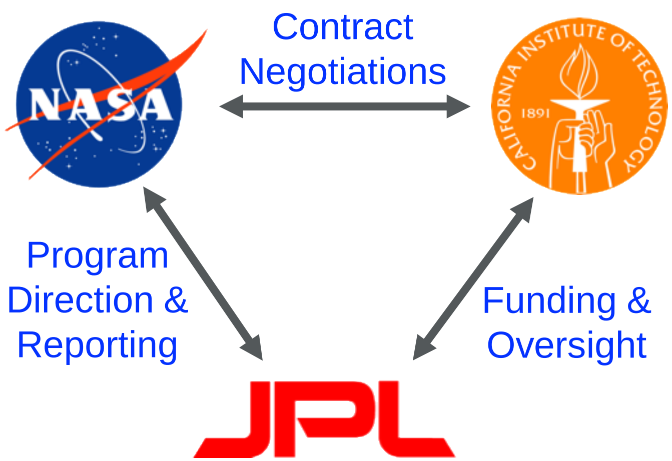
Fun fact: built my first UML model when I was 14!

Agenda

- Introduction
- Model-based Systems Engineering at JPL
- Applications of MBSE with SysML at JPL
  - Thirty Meter Telescope Project (TMT)
  - Planning for a Mars Sample Return (MSR) Effort
- Infusion & Adoption Challenges
- Vision Forward
- Summary & Conclusions

NASA Jet Propulsion Laboratory (JPL)

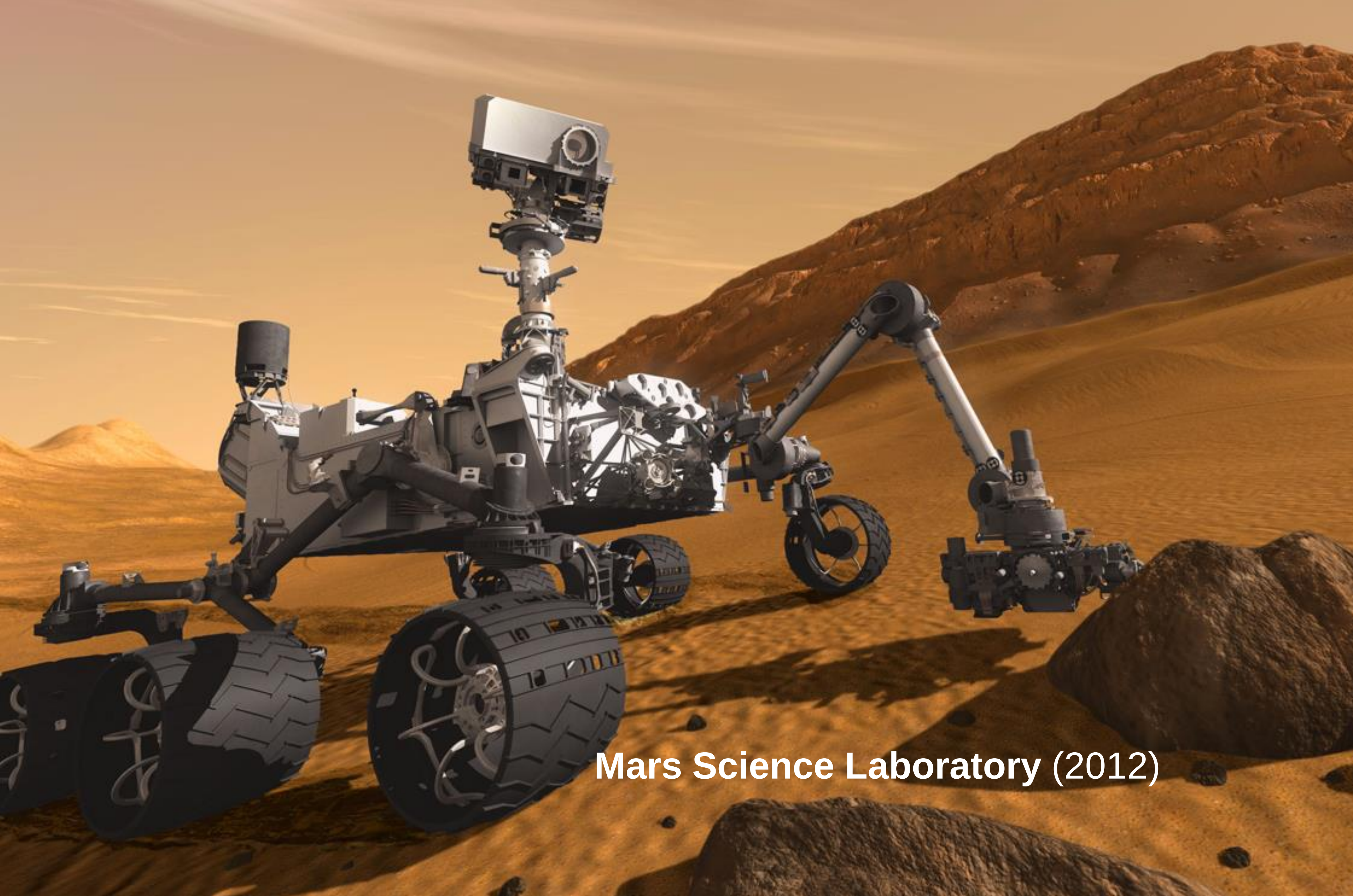
- Located in Pasadena, CA
- NASA-owned *"Federally-Funded Research and Development Center"*
- University-operated
- ~5,000 employees



Source: Lin et al., 2011


You May Know Some of Our Missions…
Voyager 1 & 2 (1977)

JPL’s Mission is Robotic Exploration



Mars Science Laboratory (2012)

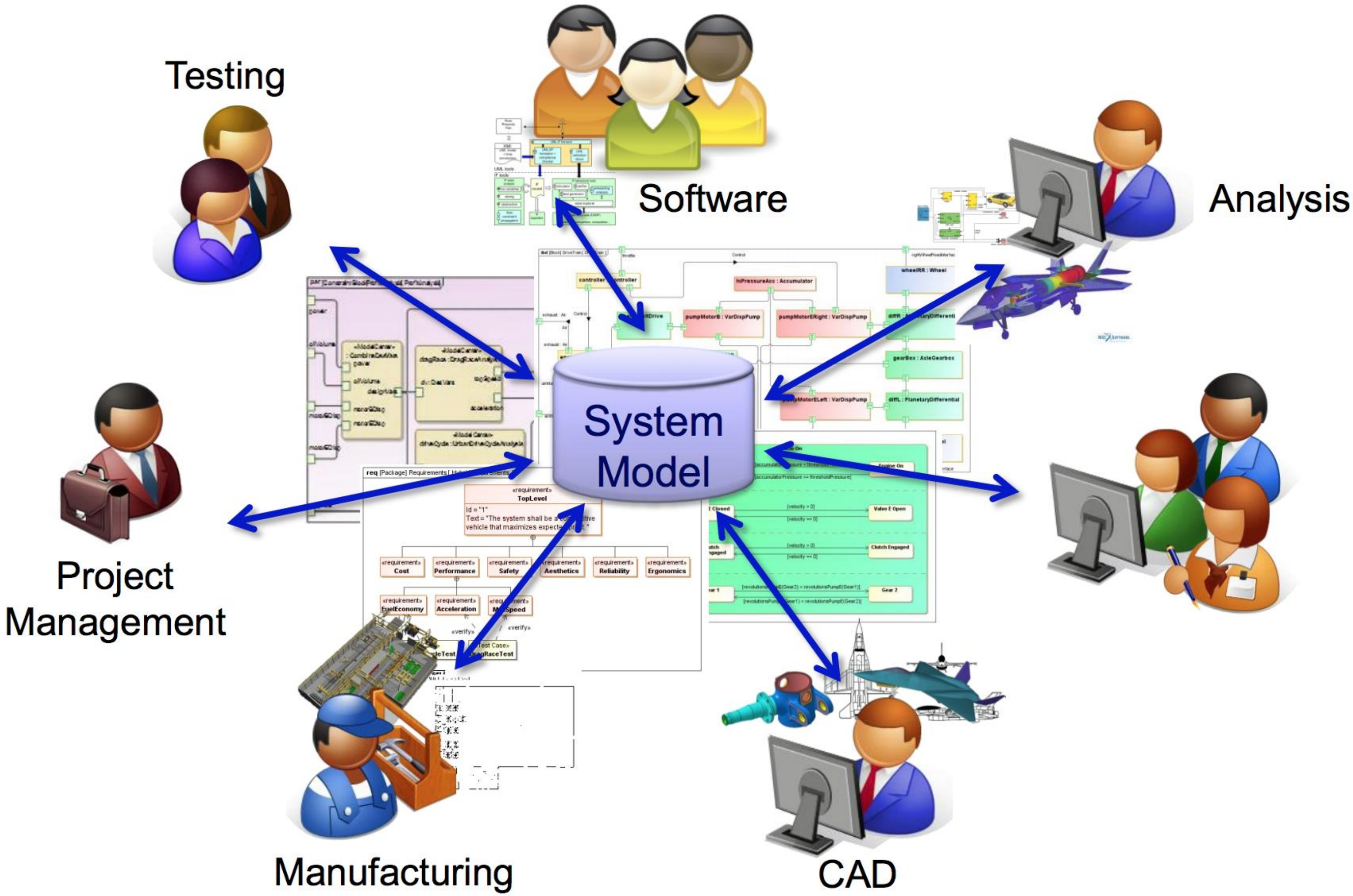
Our Motivation for Adopting MBSE

- Strengthen quality of formulation products by allowing for exploration of a more comprehensive option space
- More, and integrated engineering analysis and less paper management
- Validation of systems early and often
- Improve quality of communication and understanding among system and subsystem engineers
- Achieve greater design re-use
- Reduce number of product and mission defects in the face of growing complexity, and increase productivity, reduce cost

Source: Nichols & Lin, 2014

MBSE is Much More Than Just Applied SysML

Information Management Across All Disciplines and the Life Cycle



Source: Paredis, 2012

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Applications of MBSE with SysML at JPL

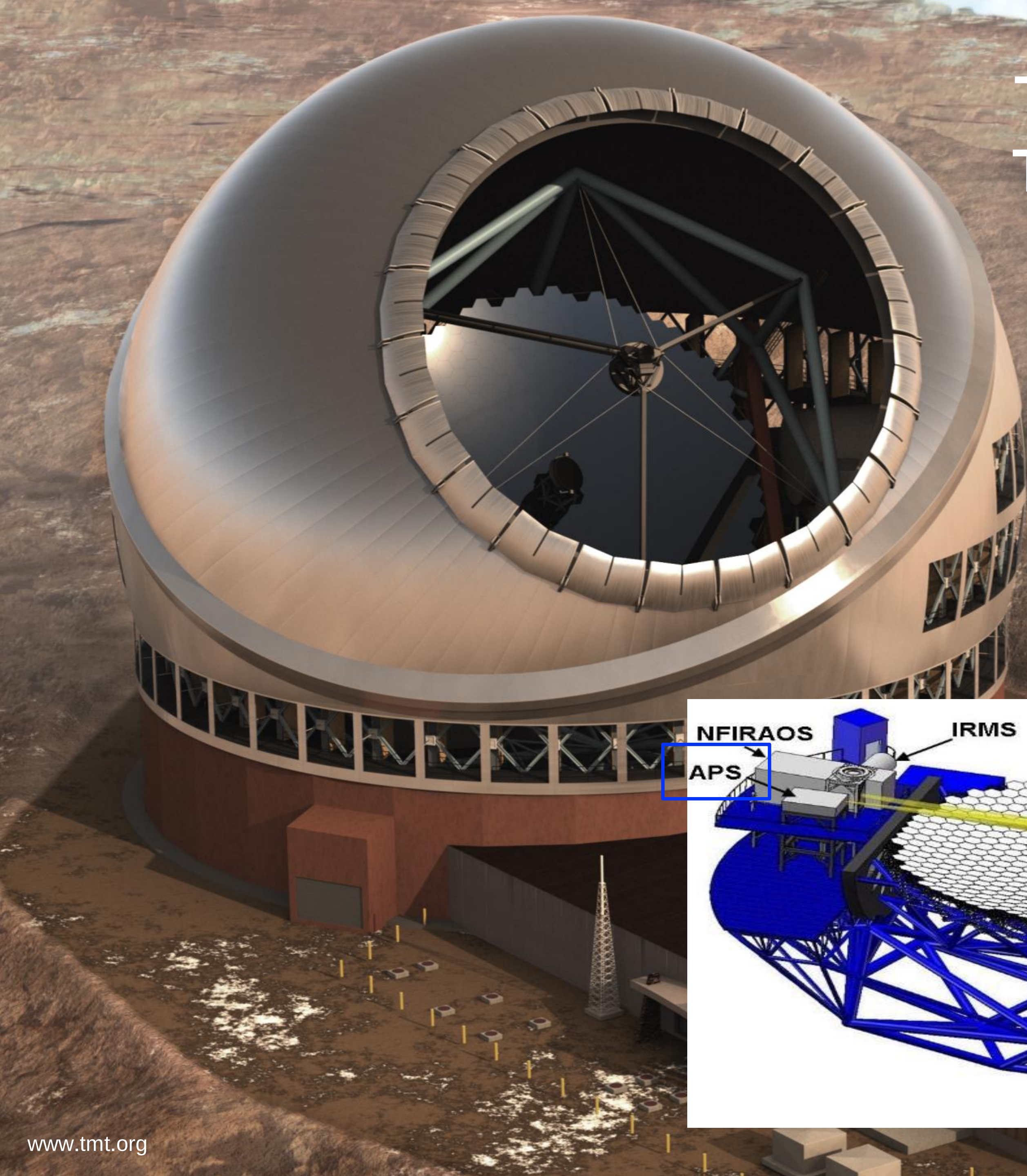
- JPL is already applying MBSE practice in a wide variety of projects, across a number of lifecycle phases
  - Planned mission to Europa / Europa Clipper
  - Mars 2020 (next Mars Rover)
  - InSight
  - Thirty Meter Telescope
  - Ground system development
  - Planning for a Mars Sample Return Effort
  - Cyber security
  - ...

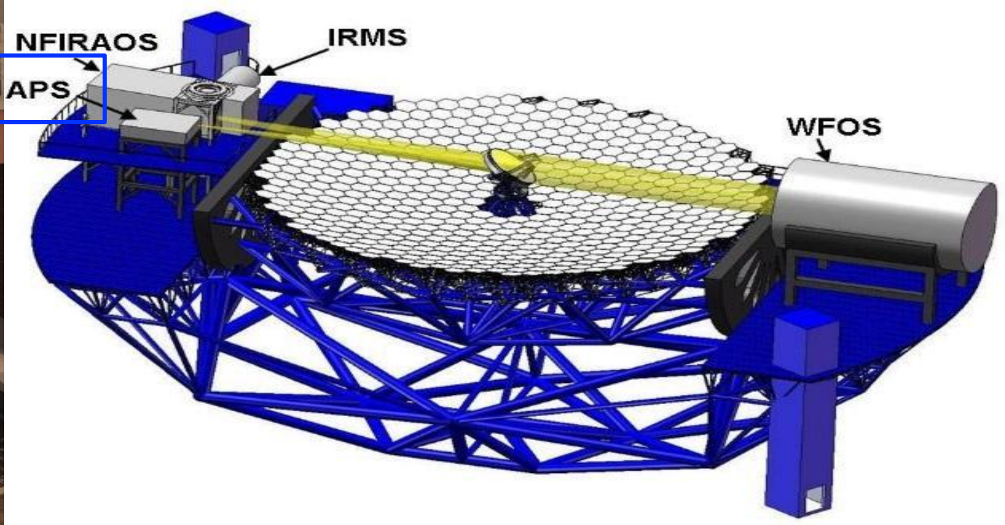
Not just spacecraft missions! Not just early phases of design!

- MELs, PELs, resource allocation and analysis, system decomposition, libraries / capturing reusable models, etc.

➔ **We use MBSE to do SE**

The Thirty Meter Telescope (TMT) Project





www.tmt.org

TMT MBSE Objectives

- Define an **executable SysML model**
- Use the model to **analyze the system design and verify requirements** on power consumption, mass, duration, pointing errors, …
- Produce **engineering documents**
  - Requirement Flow Down Document
  - Operational Scenario Document
  - Design Description Document
  - Interface Control Documents
- Use **standard languages and techniques, and COTS tools where practical** to avoid custom software development

Modeling Approach

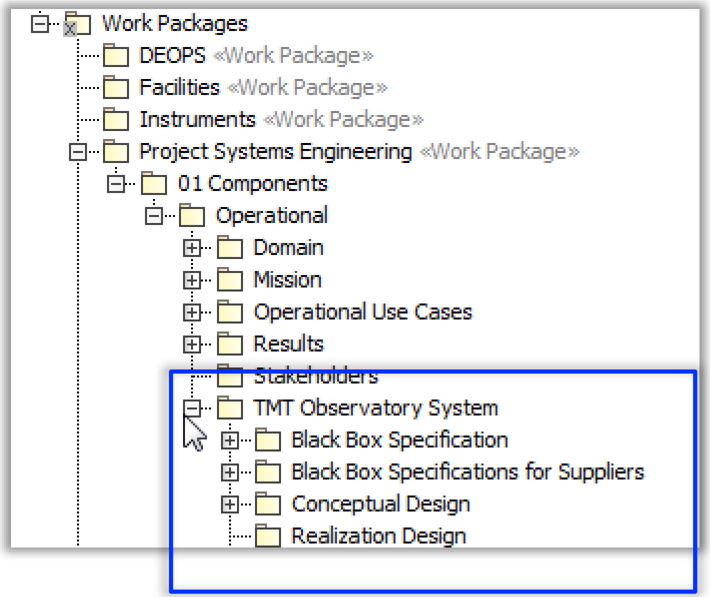
- **OOSEM**, but with additional activities focusing on building an executable model

- Use case driven model development

- Challenges:
  - JPL is a **supplier** for a number of subsystems of TMT (the **customer**)
  - Model is used by a number of teams, including TMT directly

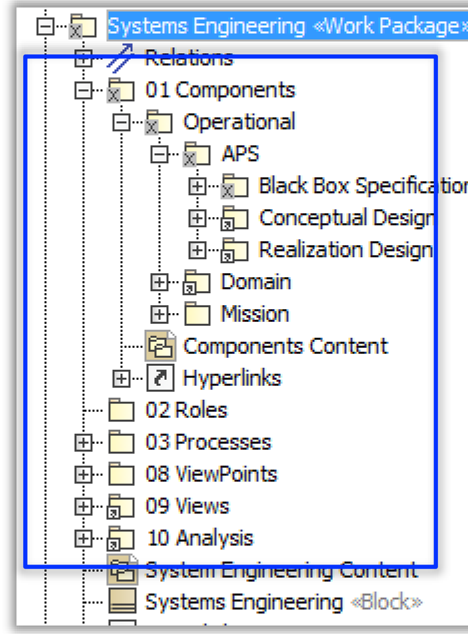
Package Organization

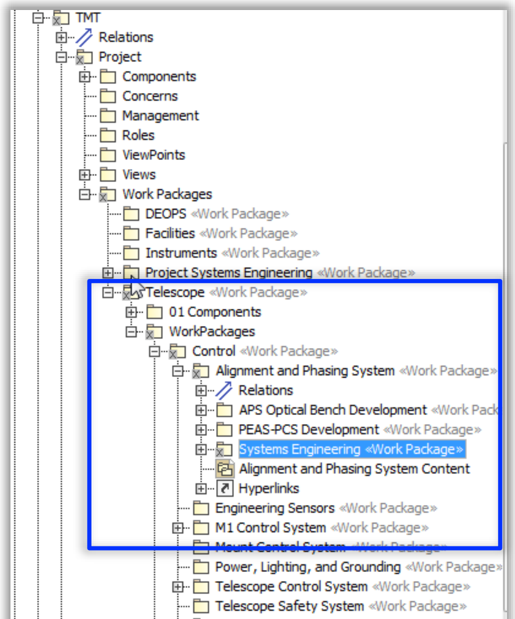
Model Organization Principles



Customer / supplier relationship

OOSEM abstraction layers

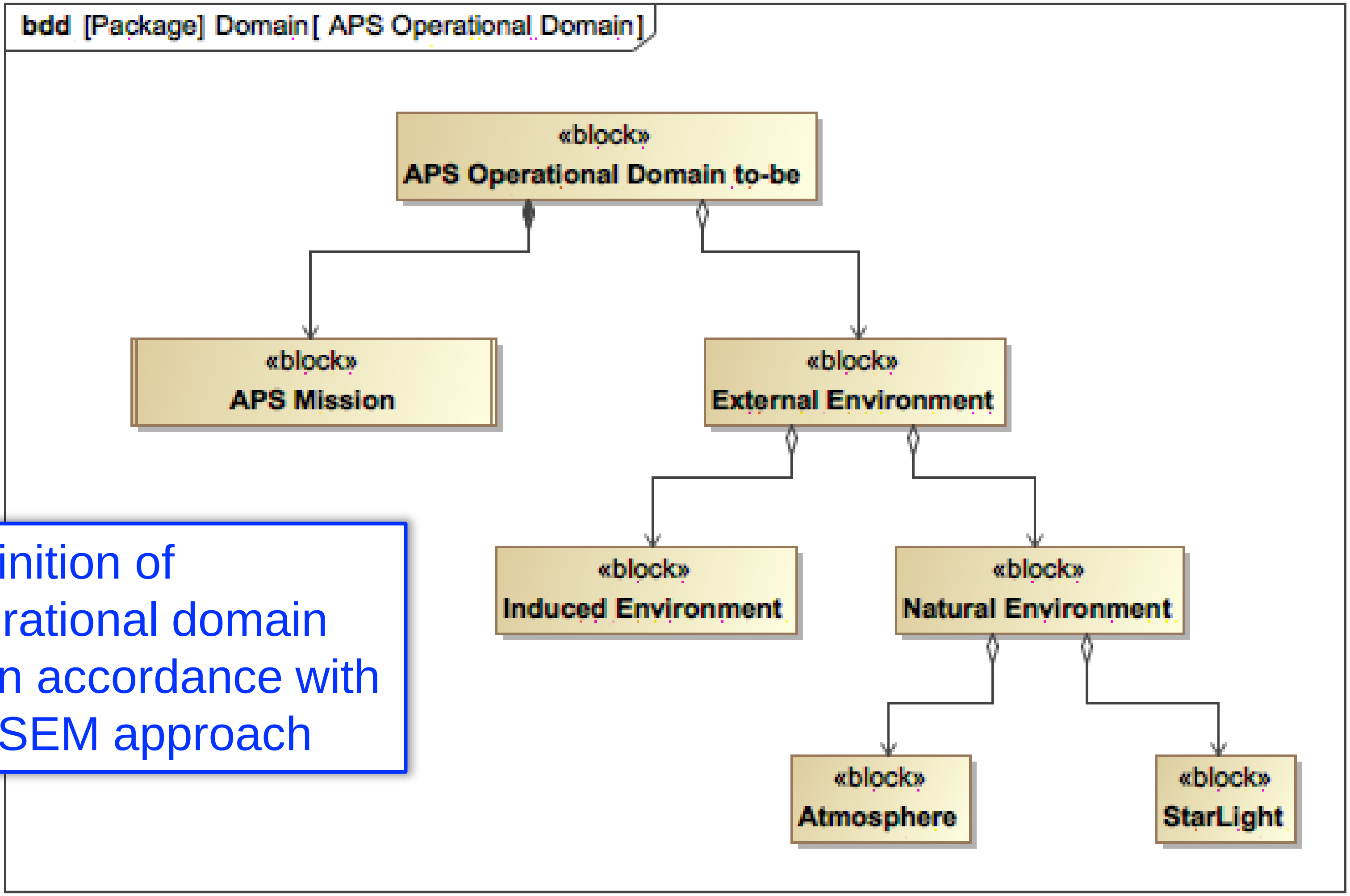




Work breakdown structure

Operational Domain

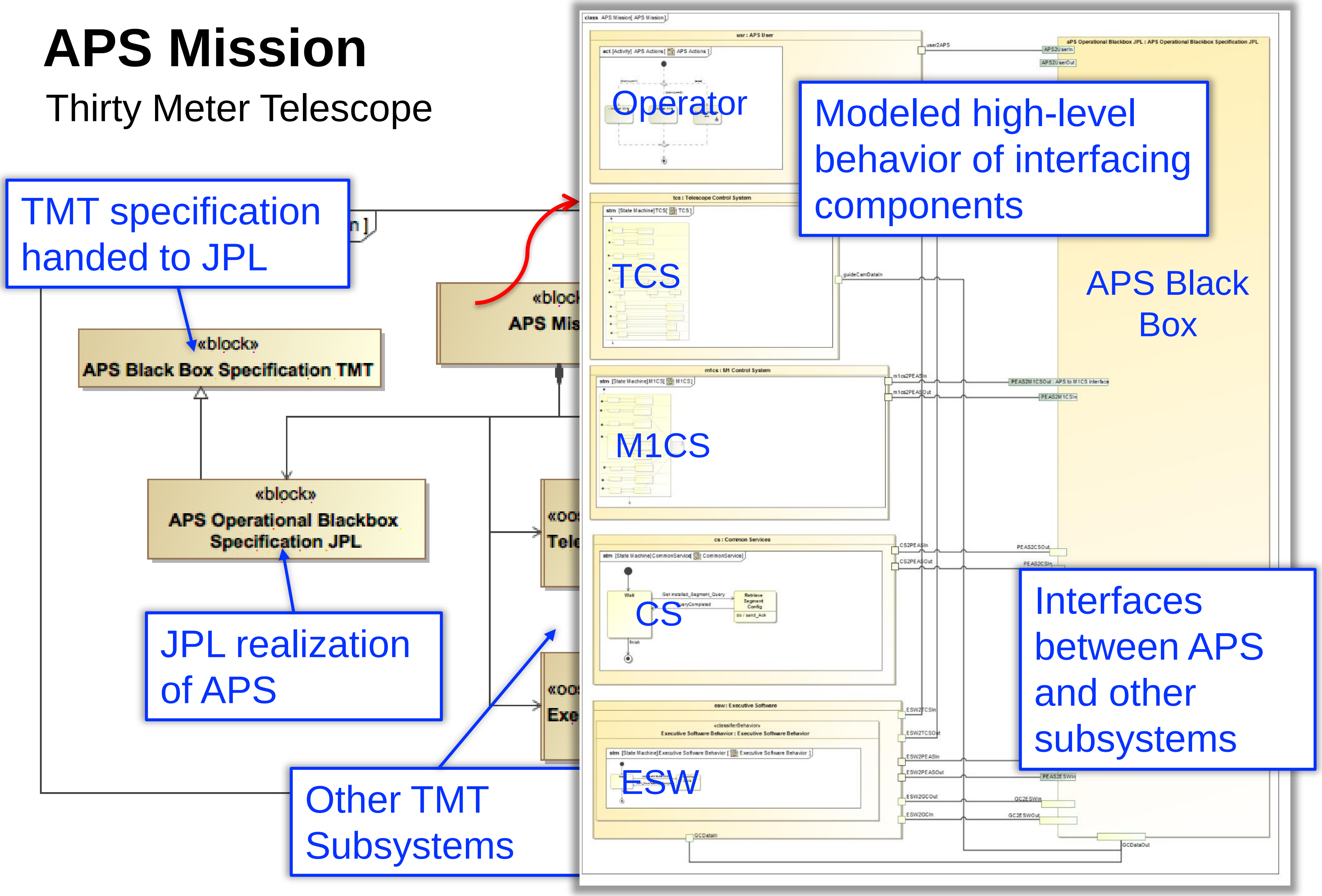
Thirty Meter Telescope



Definition of operational domain as in accordance with OOSEM approach

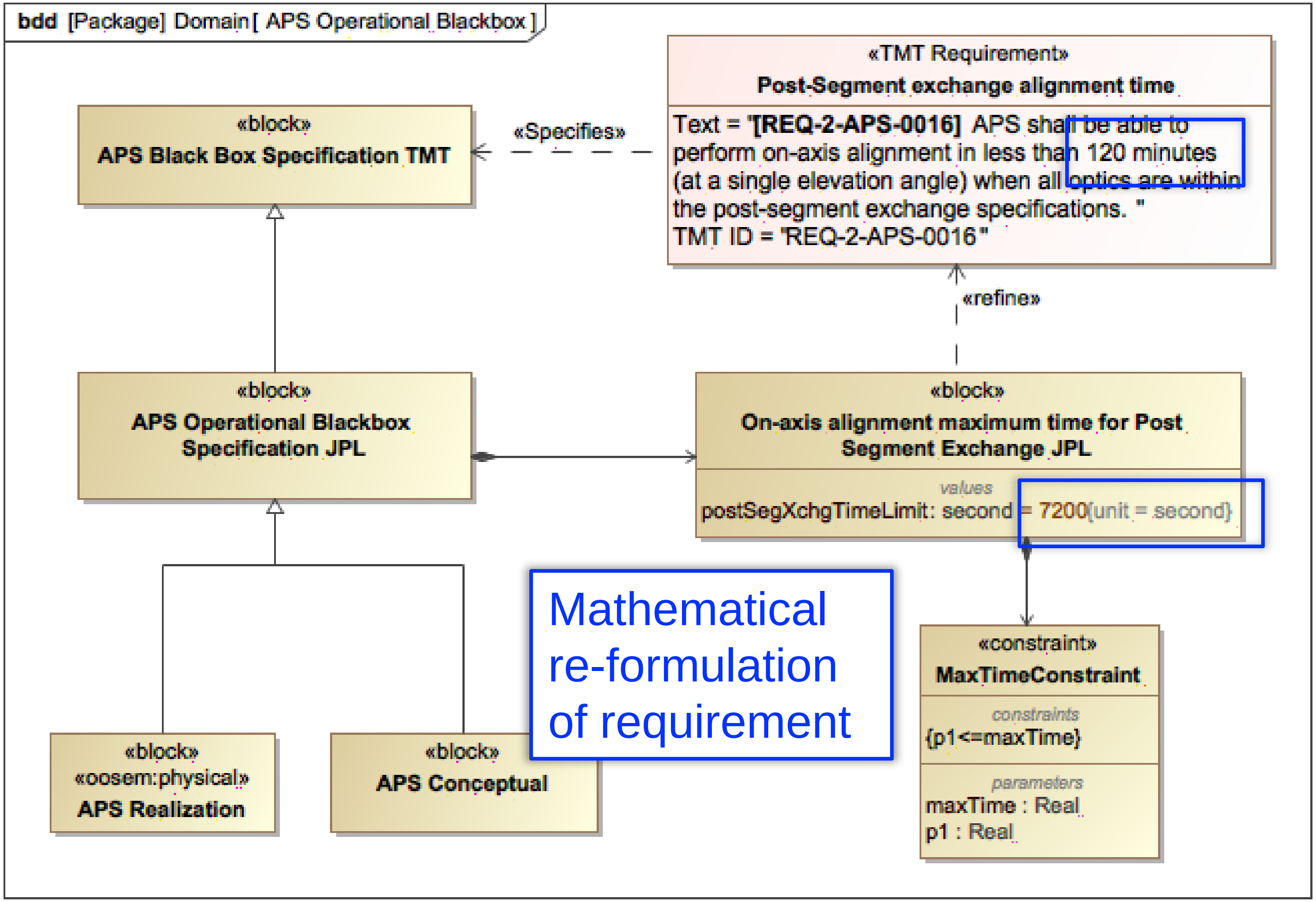
APS Mission

Thirty Meter Telescope



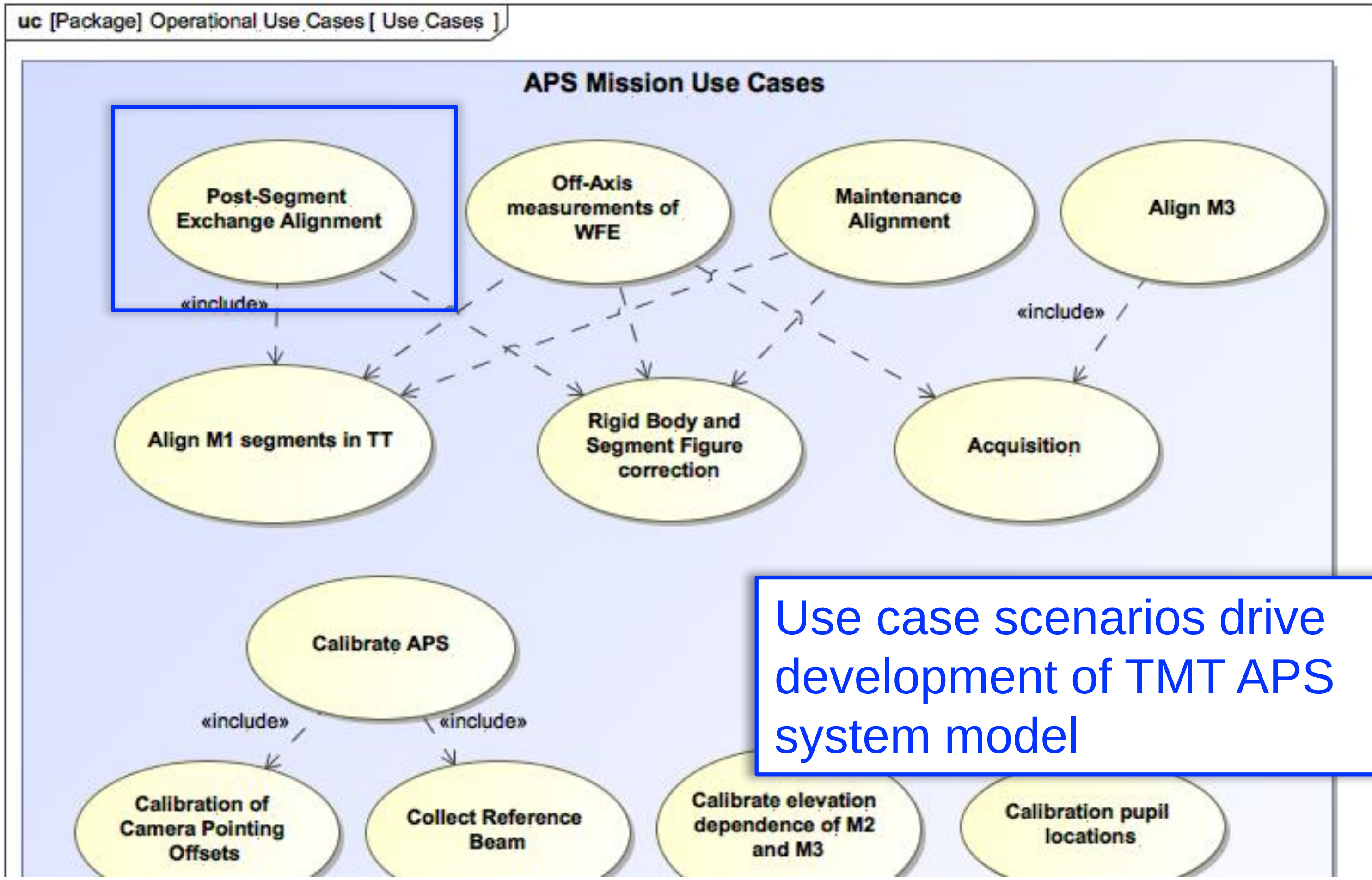
Formalizing Requirements

Thirty Meter Telescope



Use Cases

Thirty Meter Telescope

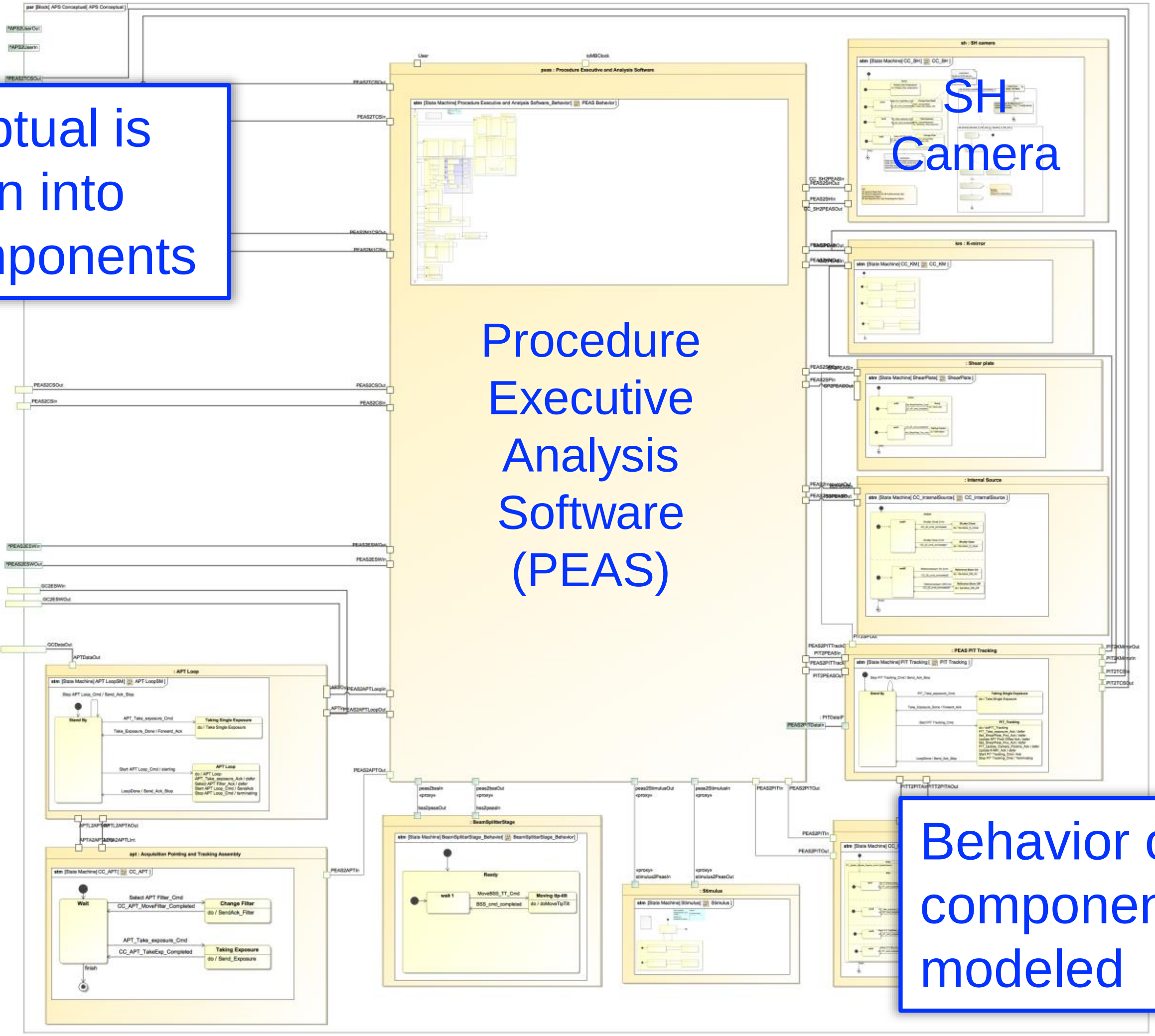


Use case scenarios drive development of TMT APS system model

Conceptual Architecture

Thirty Meter Telescope

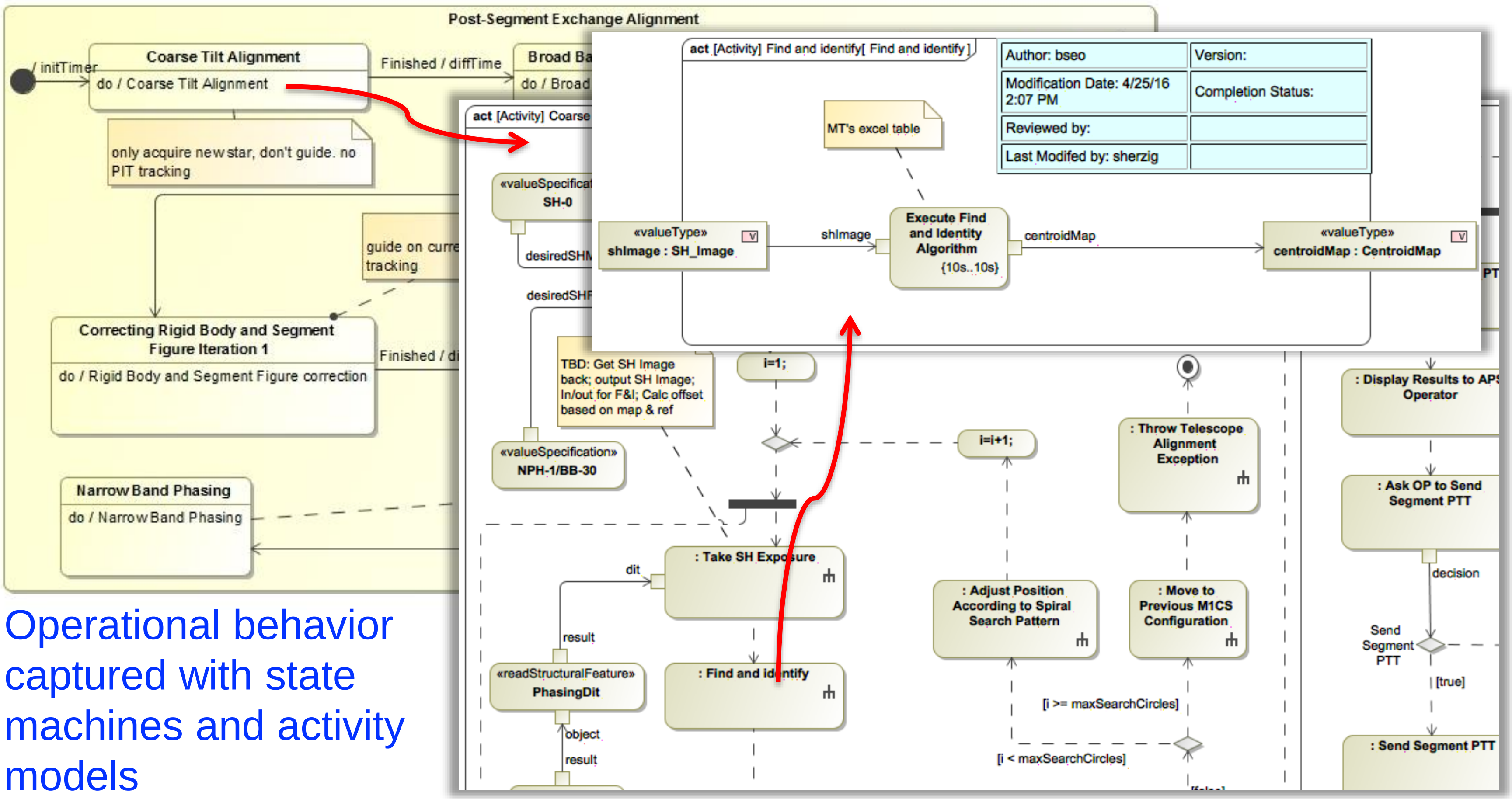
APS conceptual is broken down into several components



Behavior of all components modeled

Modeling Behavior

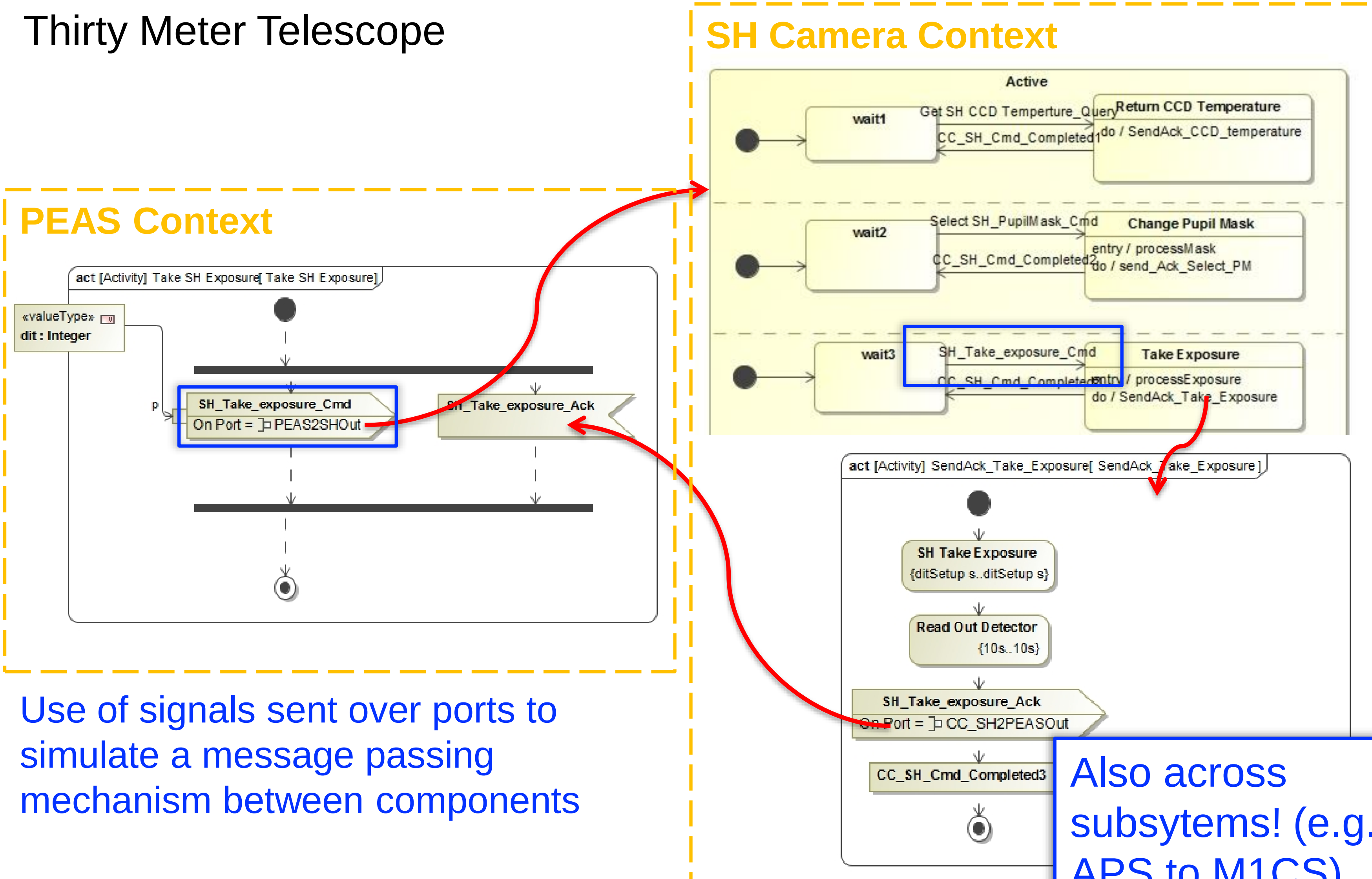
Thirty Meter Telescope



Operational behavior captured with state machines and activity models

Interactions Between Components

Thirty Meter Telescope

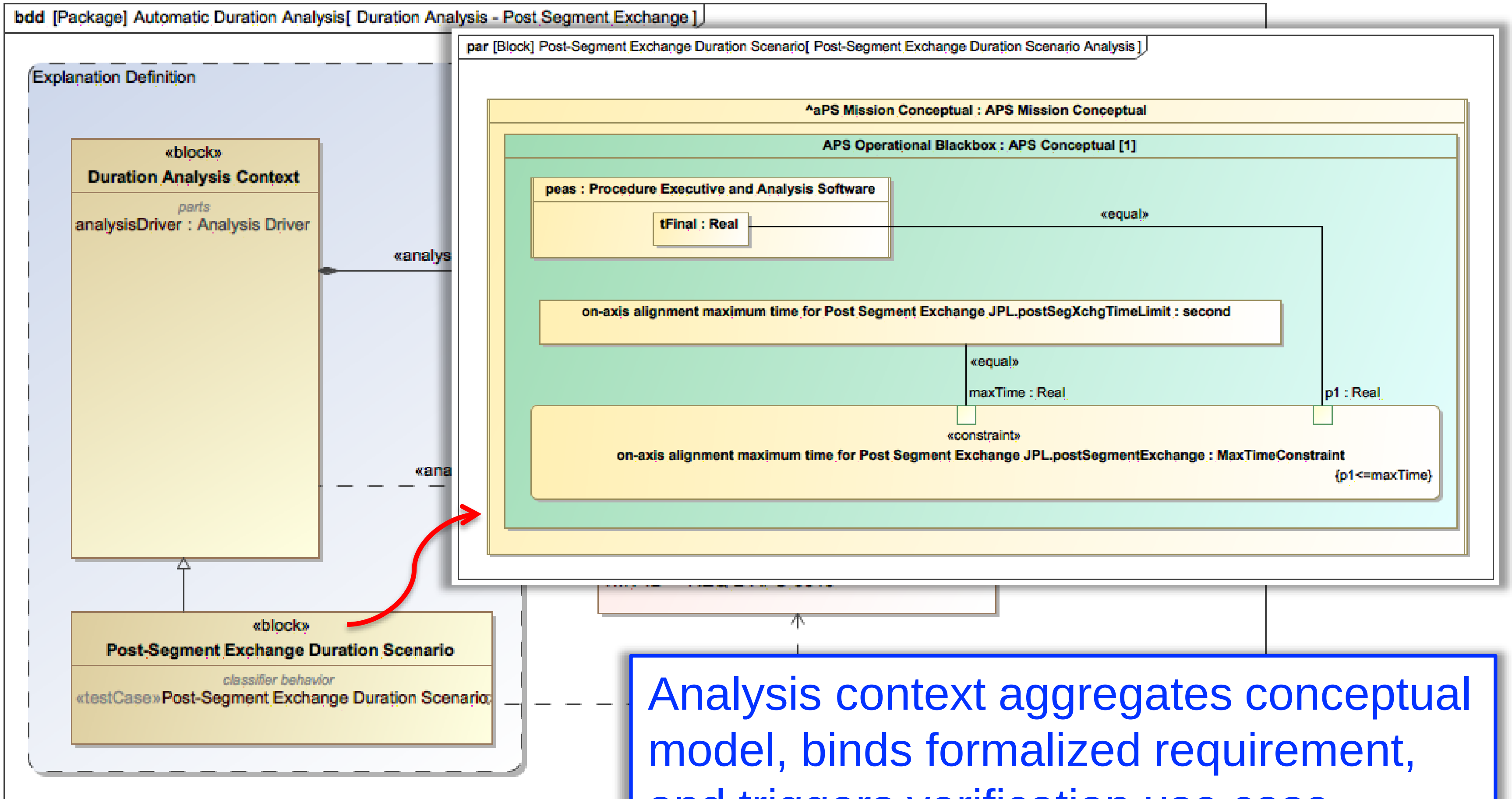


Use of signals sent over ports to simulate a message passing mechanism between components

Also across subsytems! (e.g., APS to M1CS)

Verifying Timing Requirements by Simulation

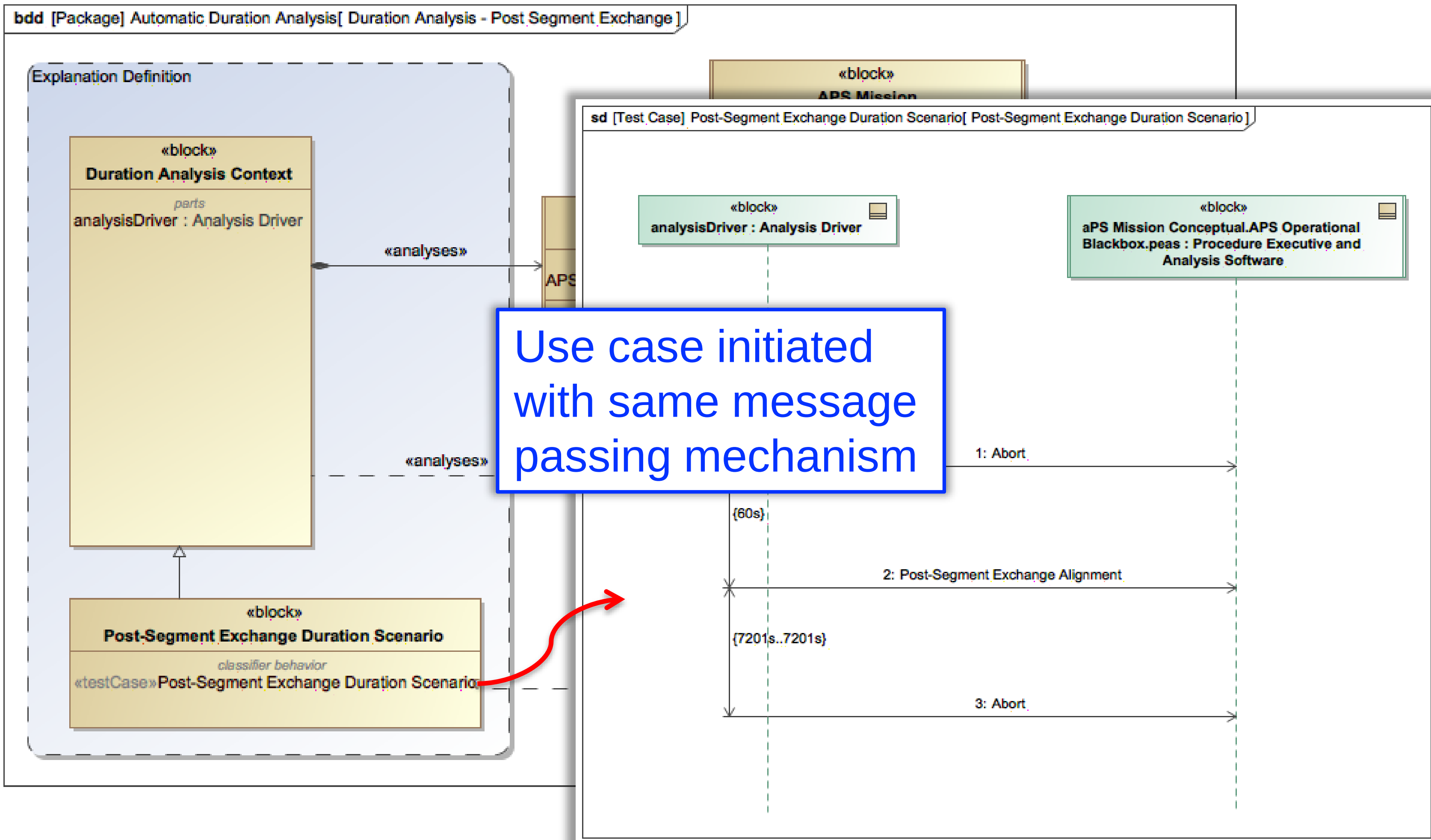
Thirty Meter Telescope



Analysis context aggregates conceptual model, binds formalized requirement, and triggers verification use case

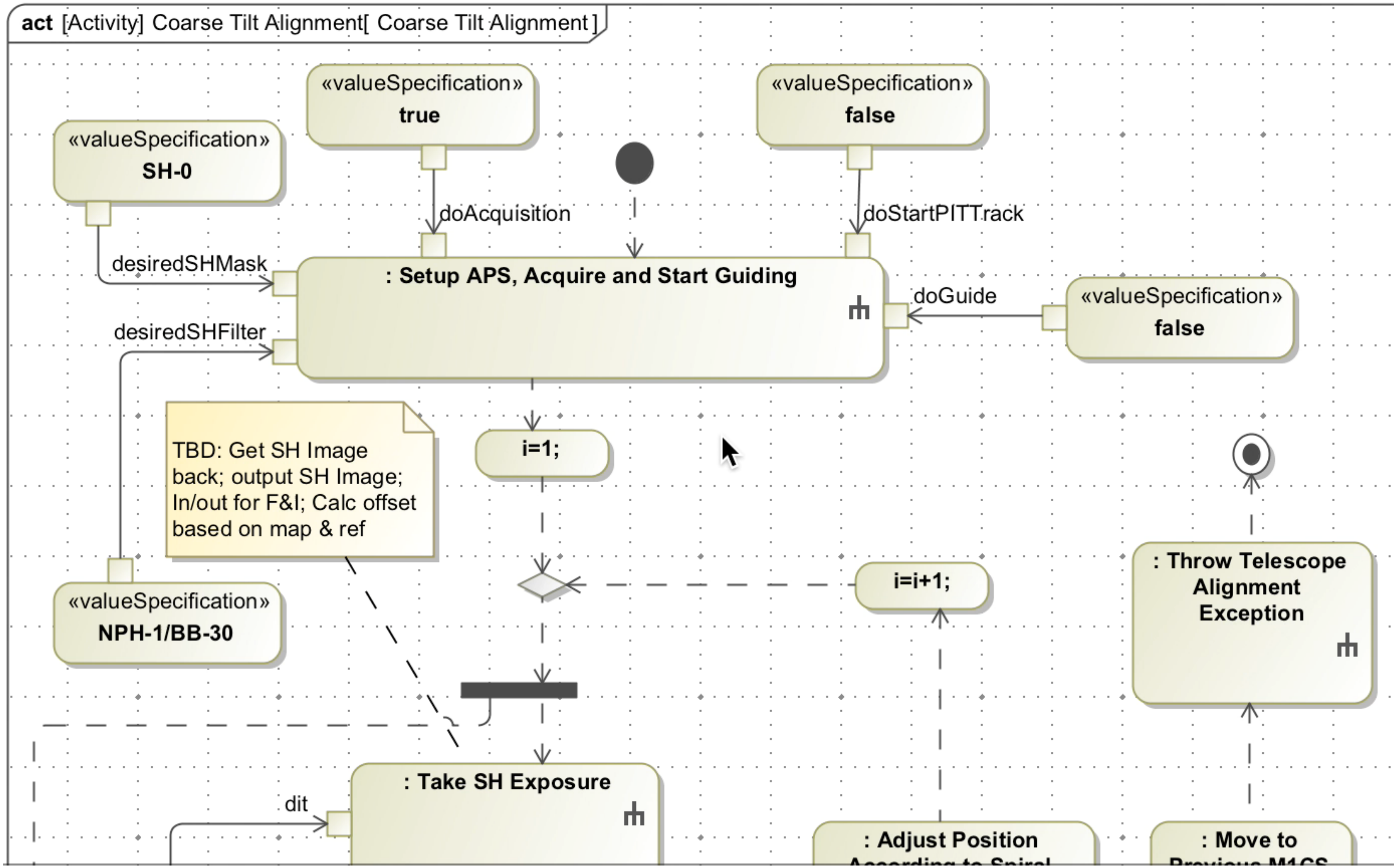
Verifying Timing Requirements by Simulation

Thirty Meter Telescope



Verifying Timing Requirements by Simulation

Thirty Meter Telescope



Verifying Timing Requirements by Simulation

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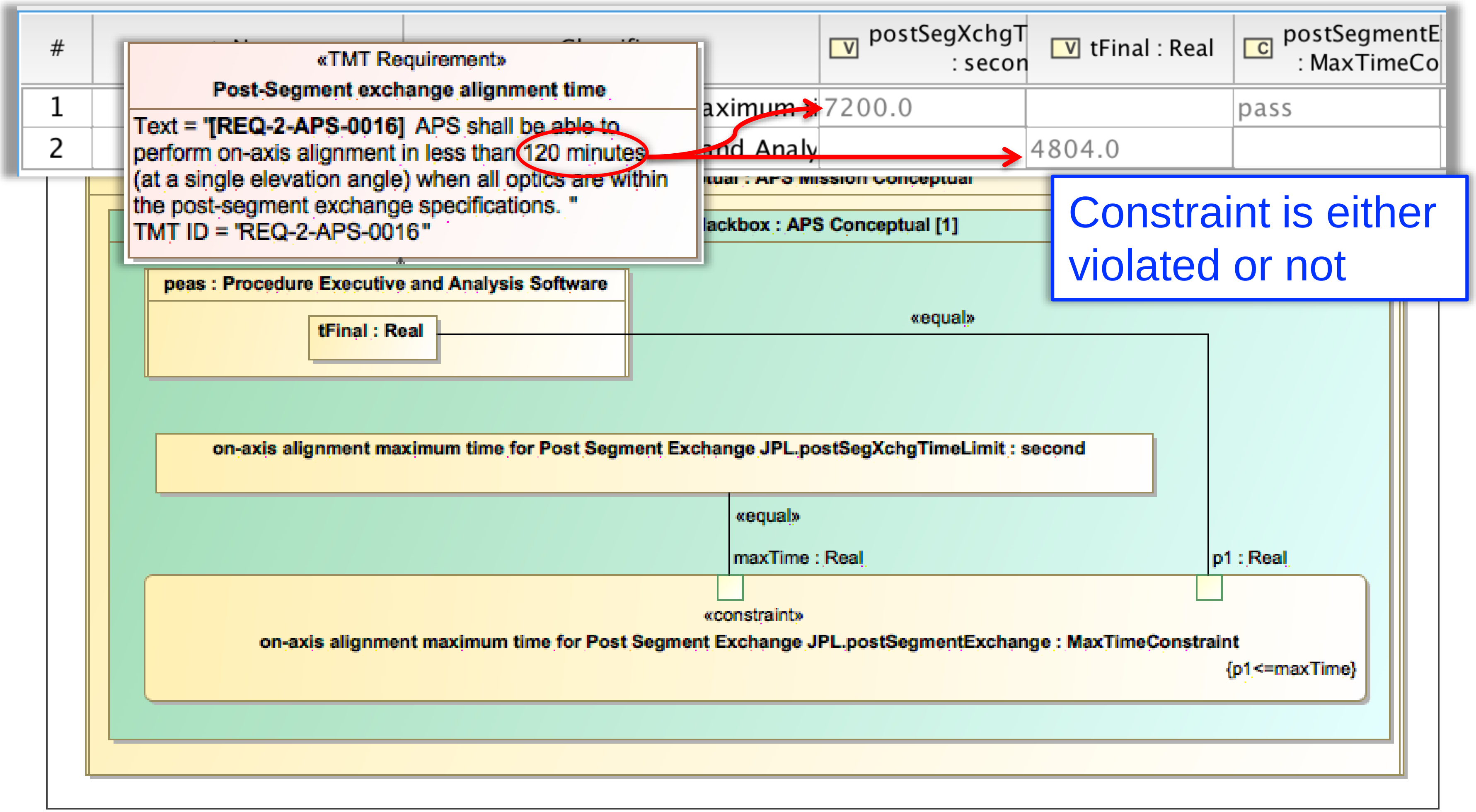
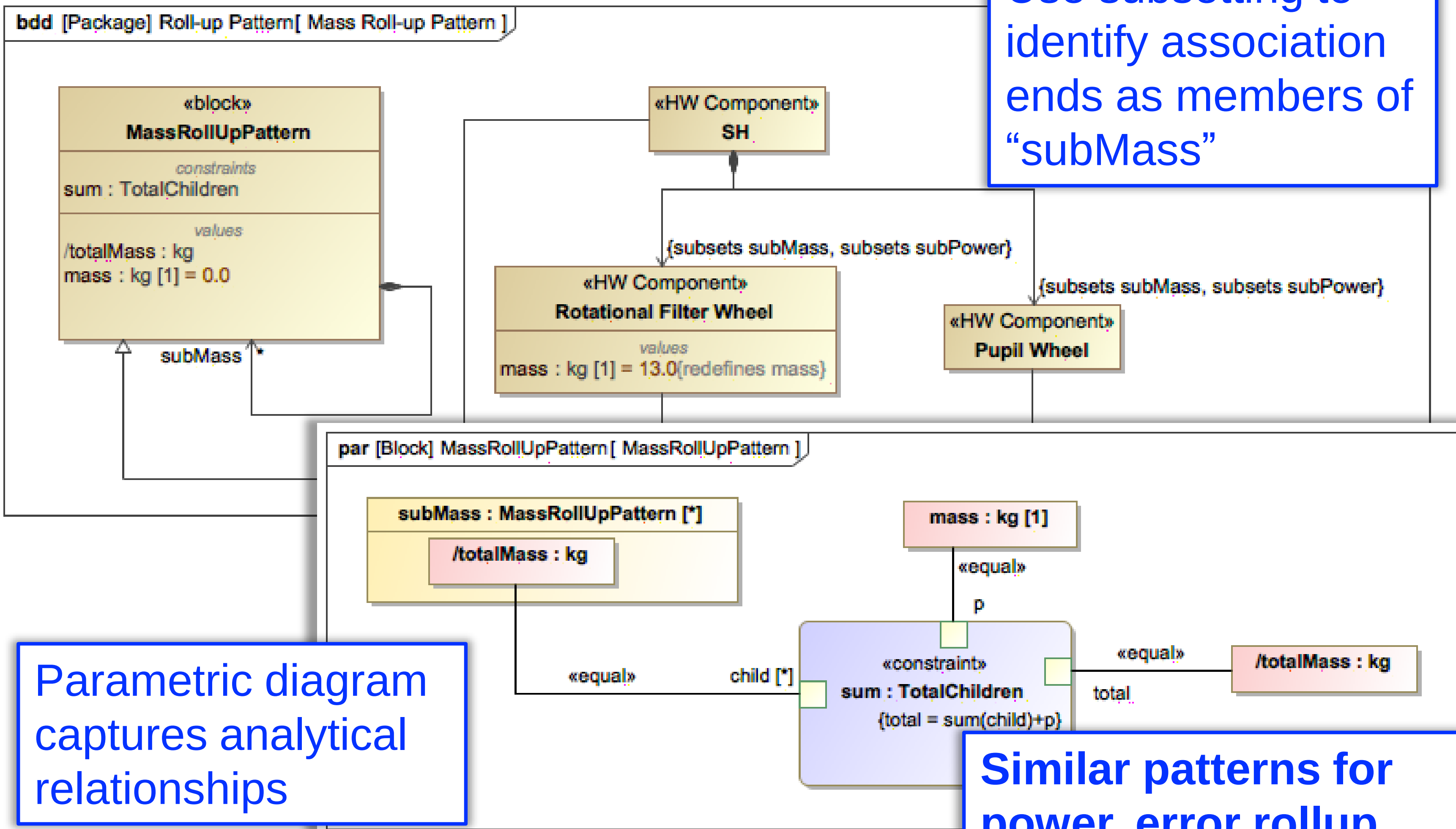


"Static" Rollup Analyses – Example: Mass

Thirty Meter Telescope

Use subsetting to identify association ends as members of "subMass"



Parametric diagram captures analytical relationships

Similar patterns for power, error rollup, …

Lessons Learned

Thirty Meter Telescope

- Possible to use only “vanilla” SysML and COTS tools, but requires **use of advanced UML features**
  - Deep knowledge of UML / SysML required
  - Makes model less accessible, and sometimes cluttered and brittle
  - Sometimes no visual representation of advanced concepts

- Approach can require **human interpretation of model**, e.g., based on names of elements (“everything is a block”)
  - Some typical SE concepts not natively supported: e.g., function
  - Some relationships semantically weak (sometimes on purpose): e.g., allocate, dependency

- Some open questions: modeling variants, relating conceptual and physical architectures, …

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MBSE with SysML for Potential Mars Sample Return

Predecisional information, for planning and discussion only

Artist's Concept

MSR MBSE Objectives

Mars Sample Return Effort

- Build a model of the **concept of operations** of a Mars Sample Return effort
  - Goals and objectives
  - Policies, and constraints affecting the system
  - Organizations, activities, and interactions among participants and stakeholders
  - Clear statement of responsibilities and authorities delegated
  - Specific operational processes for fielding the system
  - Processes for initiating, developing, maintaining, and retiring the system
- Have a **verifiably consistent** model
- Focus is on **analyzability** of systems engineering information
- Automated generation of **reports & engineering documents**

MSR MBSE Approach

Mars Sample Return Effort

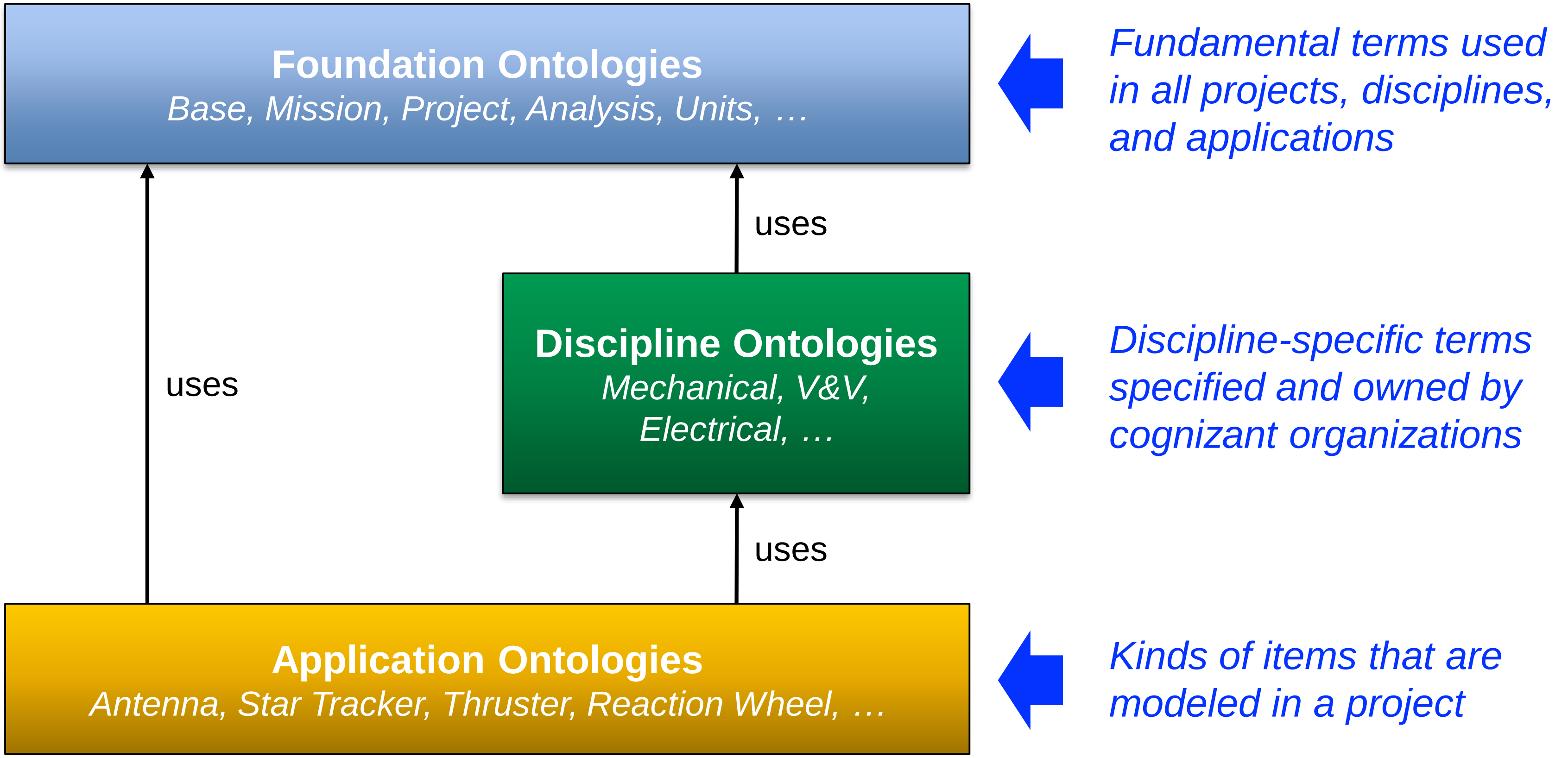
- Leverage **OOSEM** where meaningful

- **Apply best practices & lessons learned** from past projects
  - Make use of UML / SysML standards to exploit benefits of different visual syntaxes, executability
  - Use an extended systems engineering vocabulary produced by the Integrated Model-Centric Engineering (IMCE) effort over past decade

- Build an **integrated model** of the concept of operations:
  - Functional decomposition
  - Operational scenarios
  - Structural decomposition
  - Requirements and traces to other model elements
  - Authority delegation

Leveraging the IMCE SE Ontologies

Mars Sample Return Effort

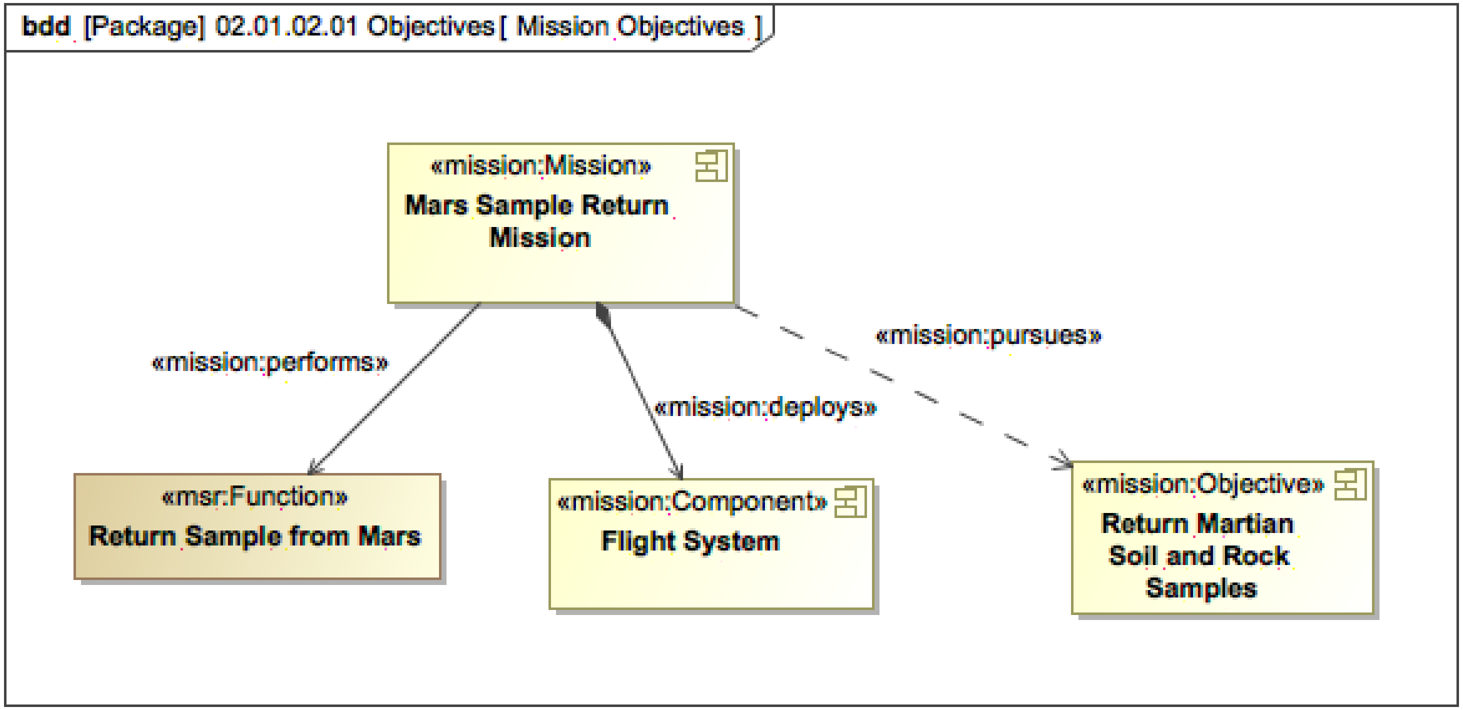


An ontology describes concepts and relationships for a domain of interest

Source: Bayer et al., 2012

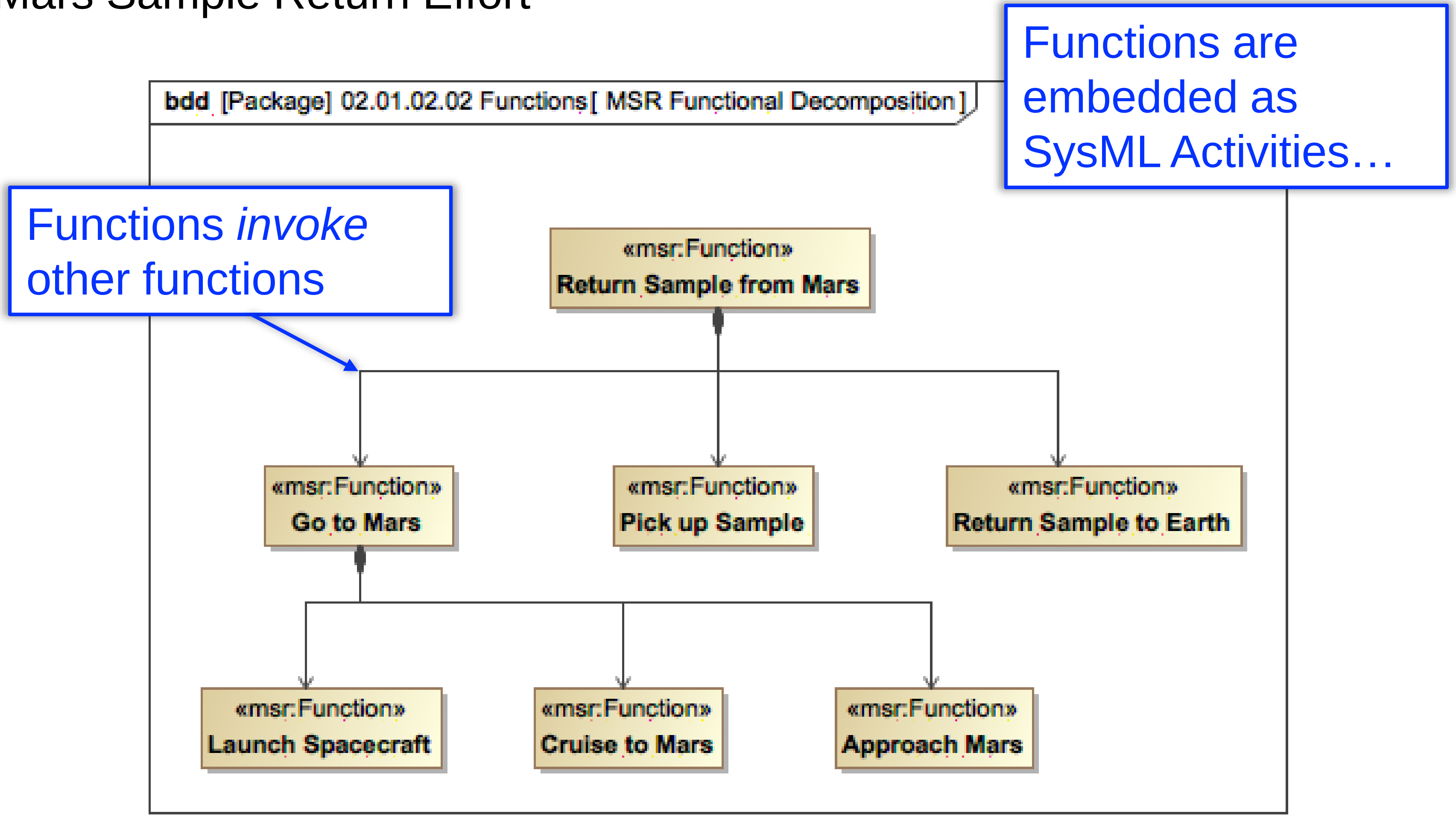
Capturing Goals & Objectives

Mars Sample Return Effort



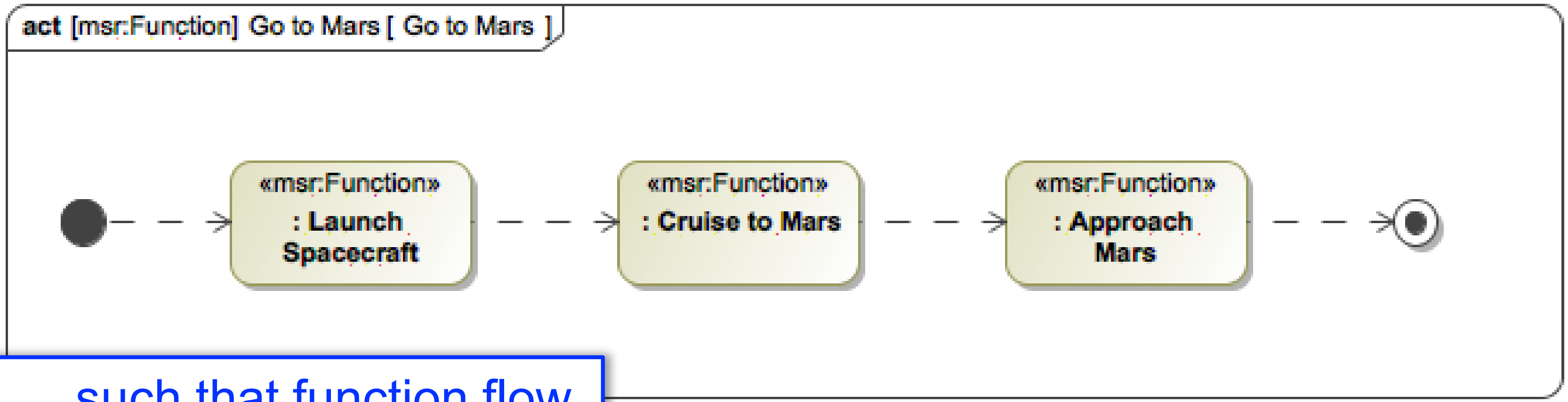
Functional Decomposition

Mars Sample Return Effort



Function Flow & Operational Scenarios

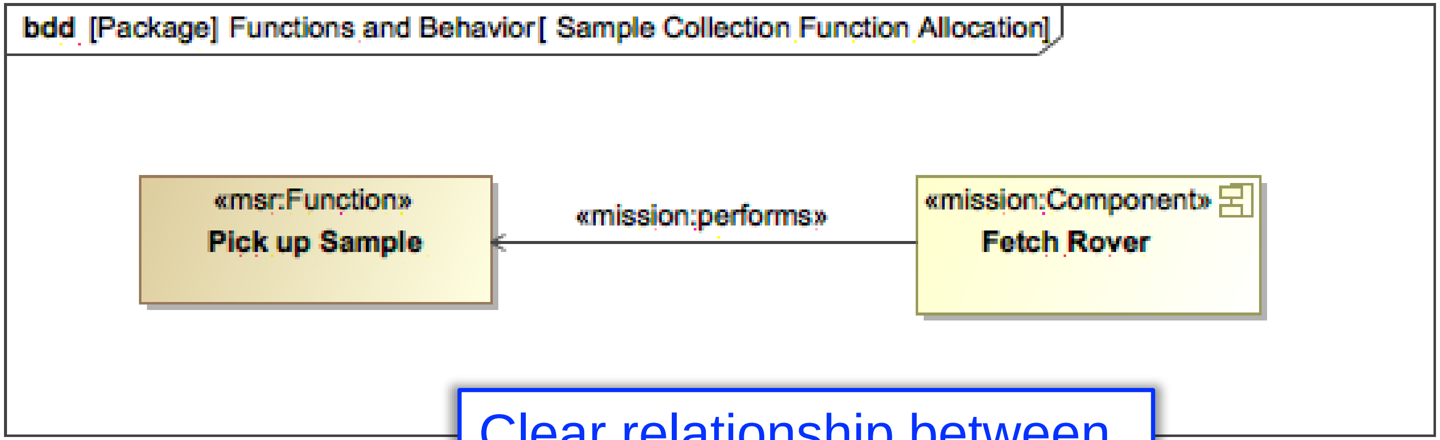
Mars Sample Return Effort



… such that function flow can be captured cleanly

Function Allocation

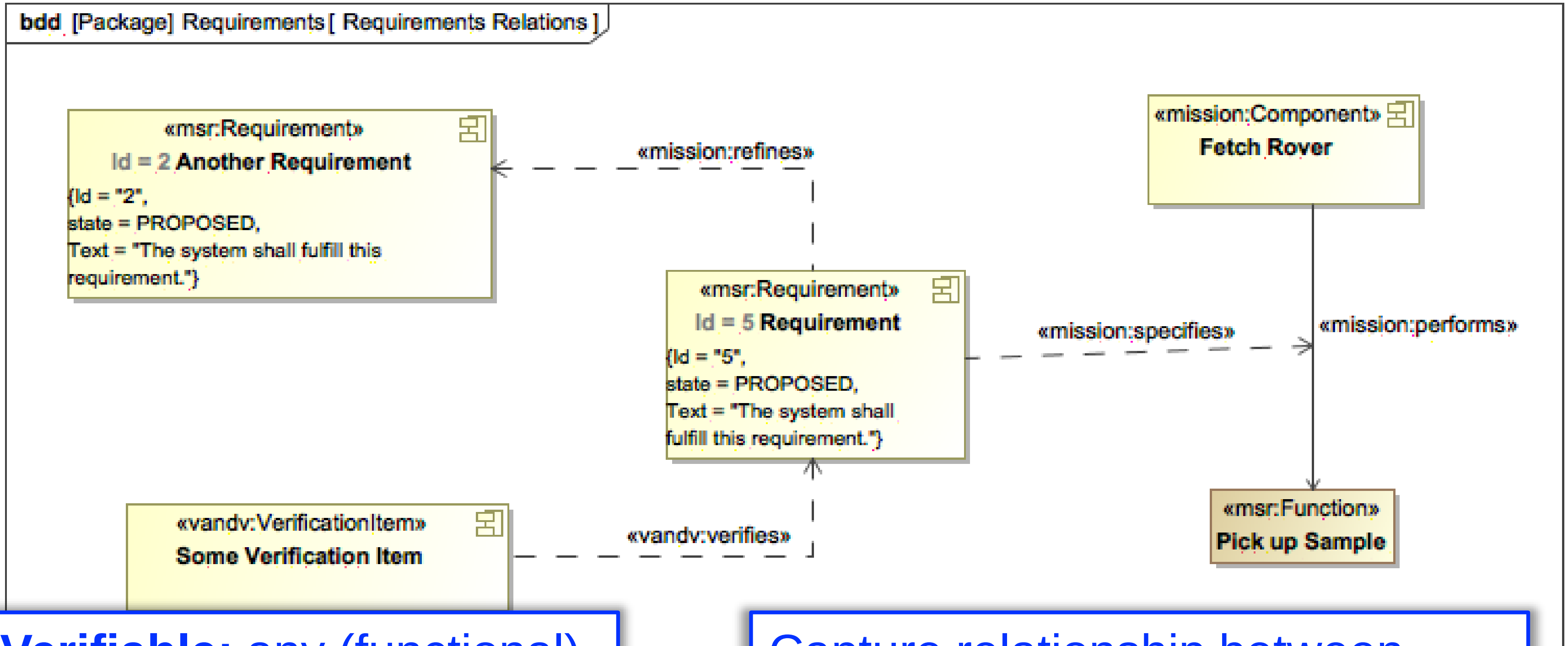
Mars Sample Return Effort



Clear relationship between functions and components
→ **Result of design synthesis activity**

Requirements Tracing

Mars Sample Return Effort

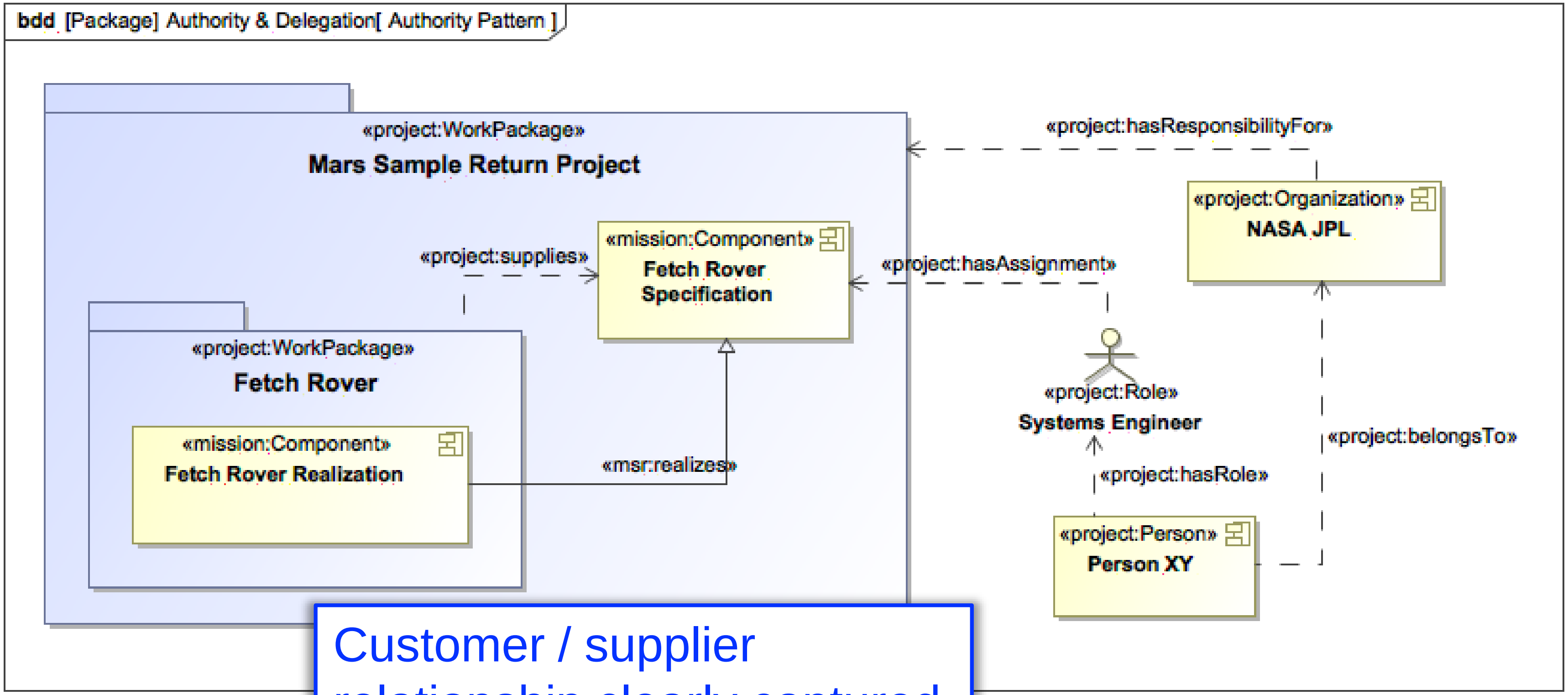


Verifiable: any (functional) requirements that do not specify a function? Any requirements that have no verification method?

Capture relationship between requirements and other system elements, and methods for how requirements are verified

Responsibilities & Authority Delegation

Mars Sample Return Effort



Customer / supplier relationship clearly captured using dedicated vocabulary

What do we do with the Modeled Information?

Mars Sample Return Effort

- Produce **reports and documents** through the use of model transformations
- Formally **reason** about design
  - Completeness checks & model audits
  - Correctness checks / checking compliance with business rules
- Verify requirements through **simulation**
- Detecting **logical fallacies**
  - Use of a *formal ontology* that carries description logic semantics
  - Formally prove consistency and satisfiability
    ➔ Applied formal methods for Systems Engineering!

Early Lessons Learned

Mars Sample Return Effort

- Extended vocabulary leads to **significantly less ambiguity** in model, but **can be overwhelming** due to the large scope
  - Significantly easier to process (especially computationally), allowing for extensive automated verification
  - More understandable by a human, but potentially vast amount of information

- Effective use **requires tool customizations**

- Requires **training, evangelism** ("does not look like the SysML I'm used to from books")

- Some **pushback**, since focus is *not* on ease of use and accessibility, but rather on completeness, precision and rigor
  → Requires investment and commitment

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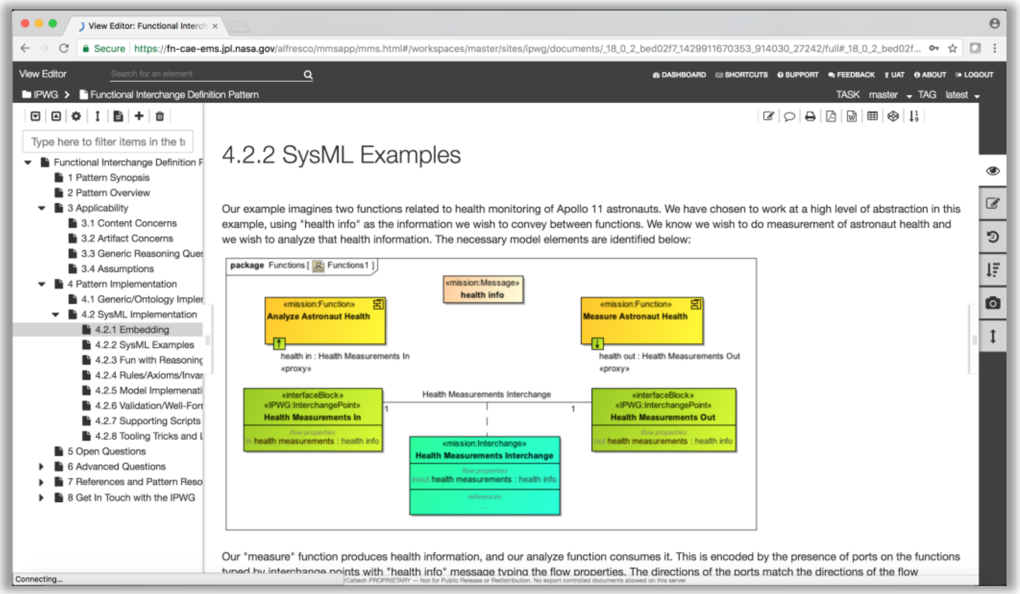
Infusion & Adoption Challenges

- MBSE with SysML still quite a jump for most SE’s that are used to Visio, Excel, …
  - Perceived complexity can be overwhelming, benefits may not be immediately clear (“it worked before”)
  - Mistrust in new technology, since not sufficiently proven
- Oftentimes little resources available for training
  - Is <u>not</u> intuitive, and methods / tools still maturing
  - Search for “easier solution” often leads to formality shortcuts
- Still early in its development
  - Tool support lacking
  - Lack of tried & tested methodologies, standards

How We Are Addressing These Challenges

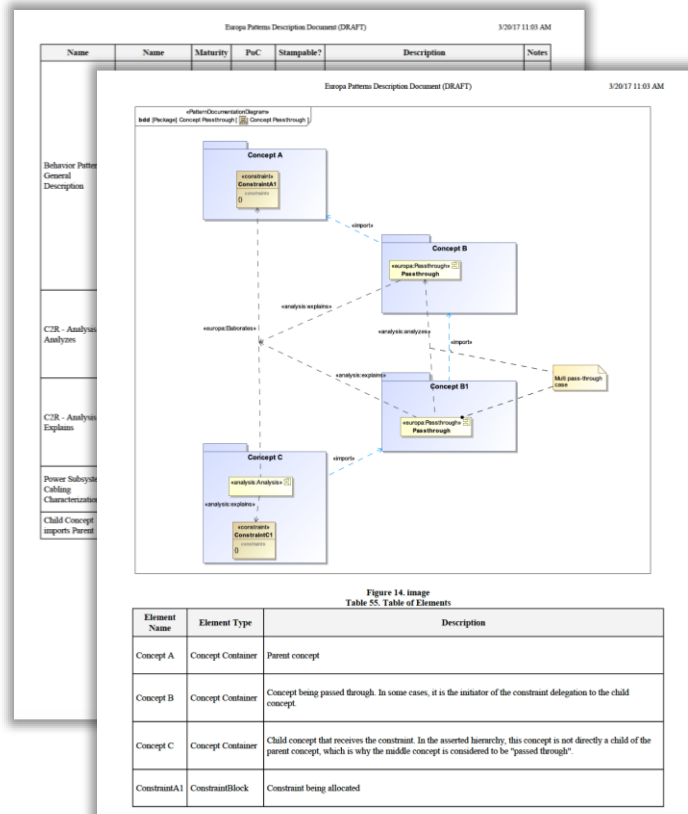
- Clear, consistent message from leadership / line organization
- Dedicated modeling teams composed of modeling experts
  - Either act as “scribes” for systems engineering team
  - Or are part of systems engineering team
- Generation of textual documents and tabular views that have familiar “look and feel”, but interface with model
  → Often required for deliverables anyway
- Provision of internal training: “MBSE bootcamp”, tutorials, ”JPL MBSE Cookbook”, modeling patterns development, …

SysML Modeling Patterns Development

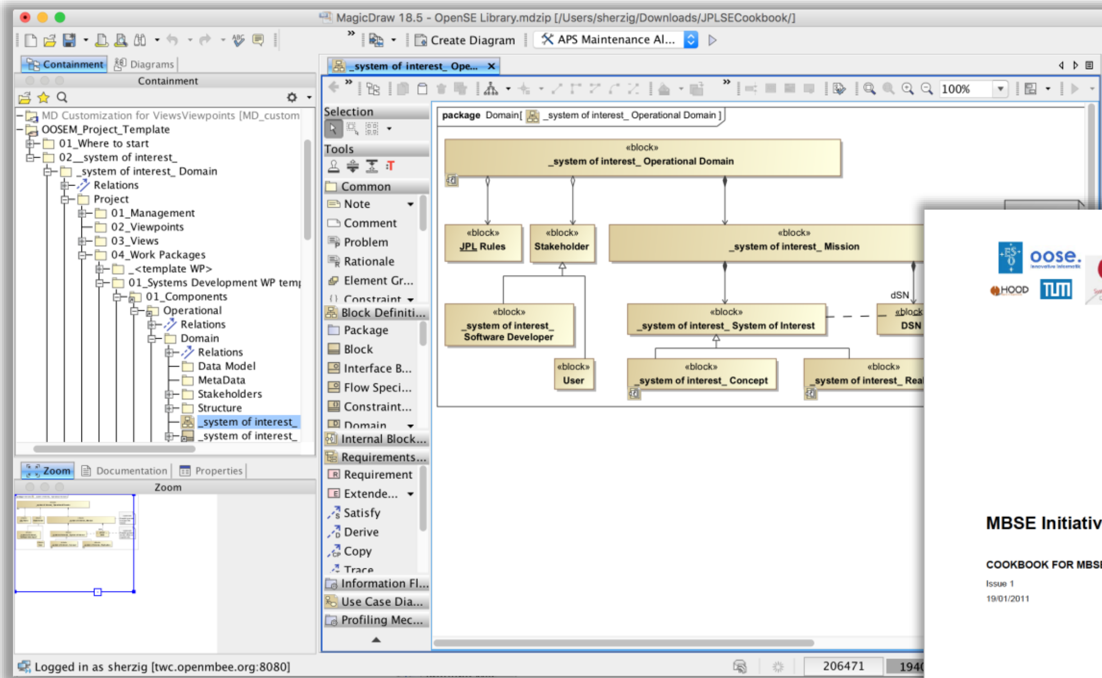


Project-independent modeling patterns as guidelines from overarching line organization

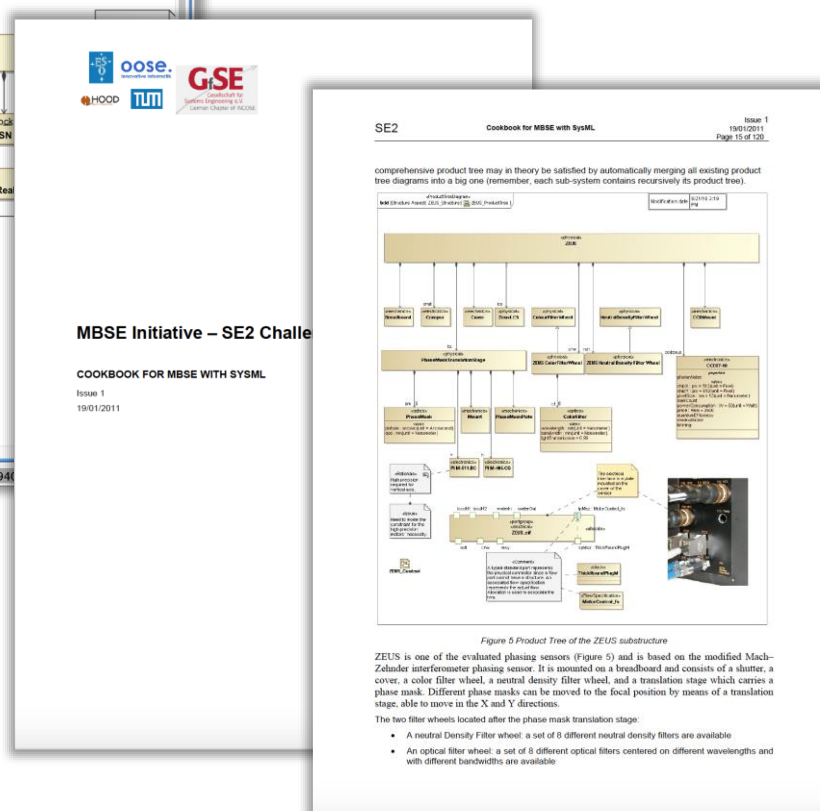
Project-specific modeling patterns for common modeling tasks



JPL SE "Cookbook" and Template Model

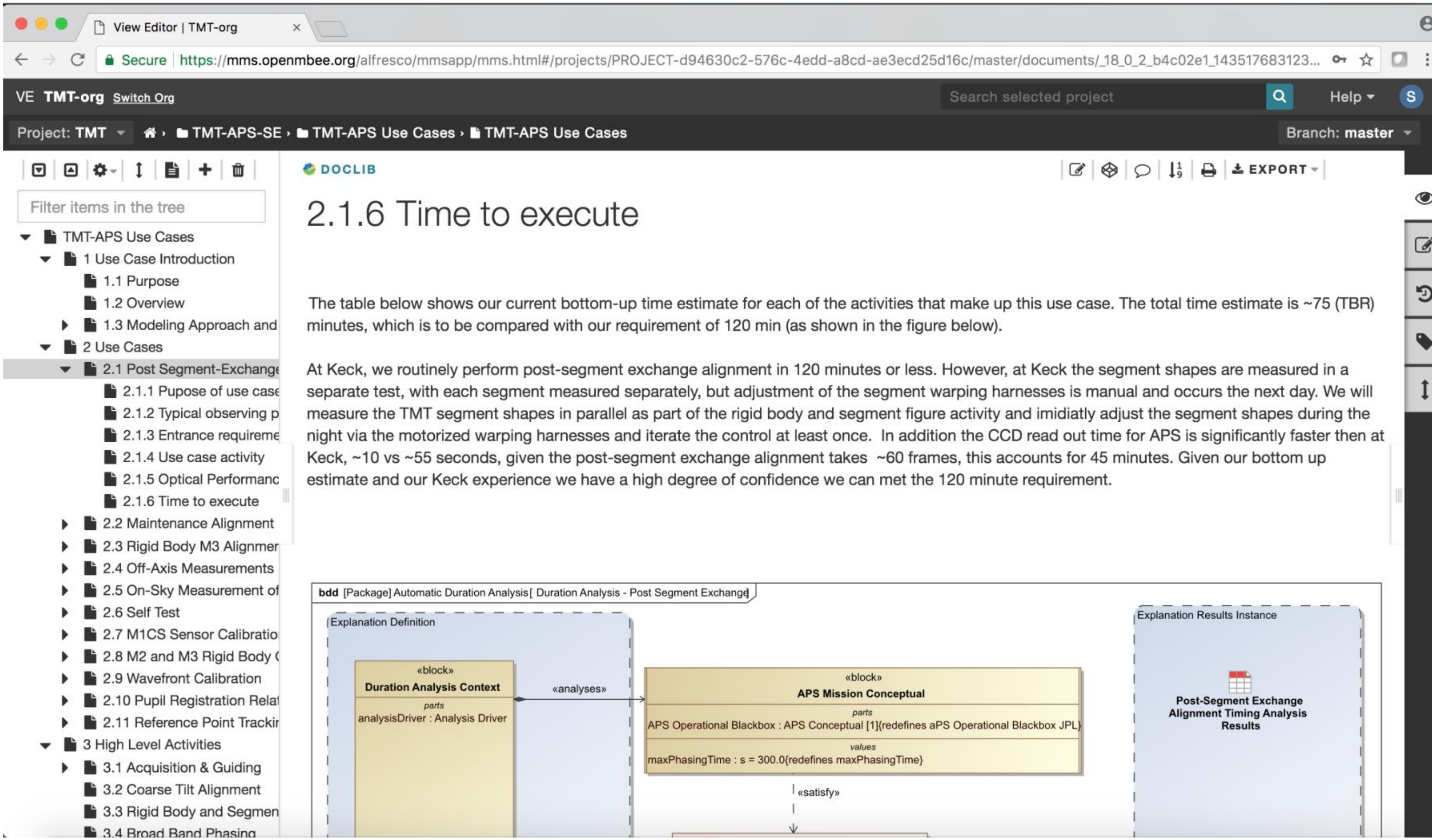


"Cookbook" for modeling methodology & patterns



Template models to be used by projects as a starting point, with recommended organization, model libraries, etc.

Document & Report Generation via View Editor



* OpenMBEE / ViewEditor is open source, and available at http://github.com/Open-MBEE

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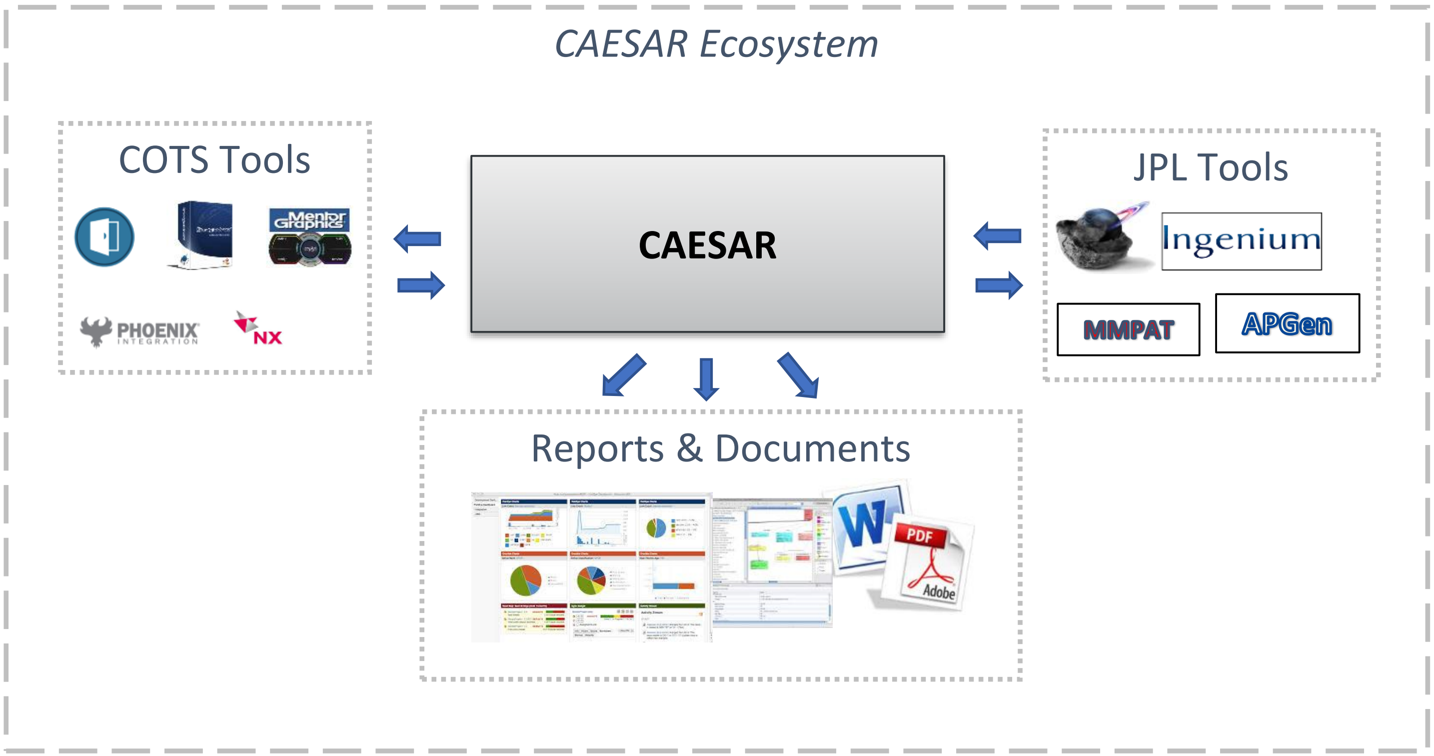
Next-Generation Infrastructure Development

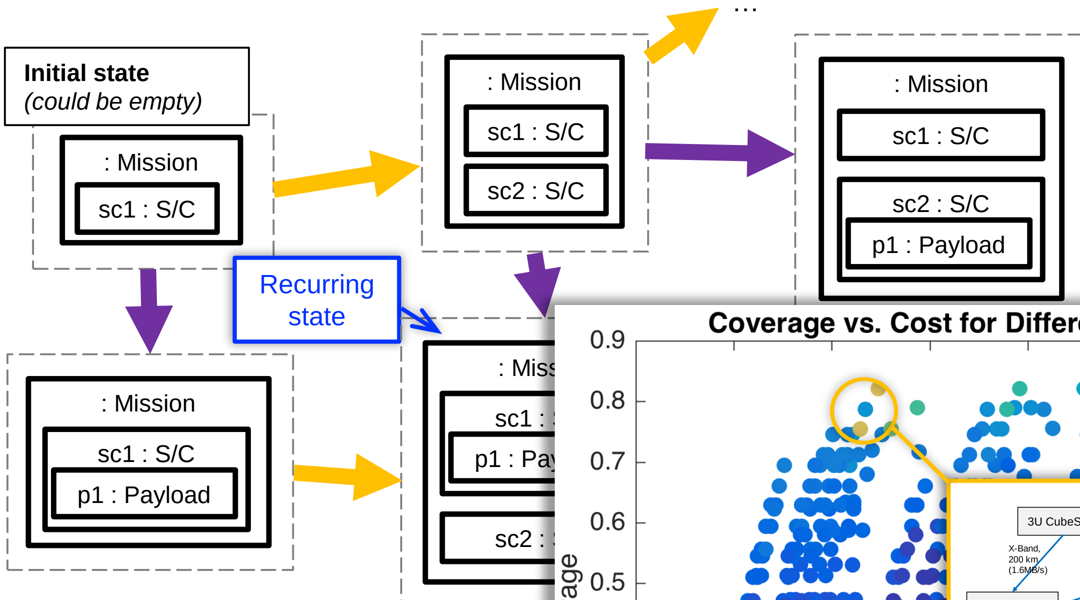
Ontology-based Systems Engineering Information Management



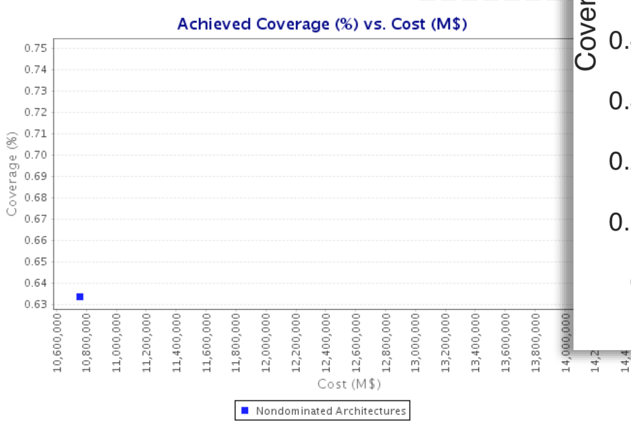
Focus is on integration of information rather than tool or model integration!

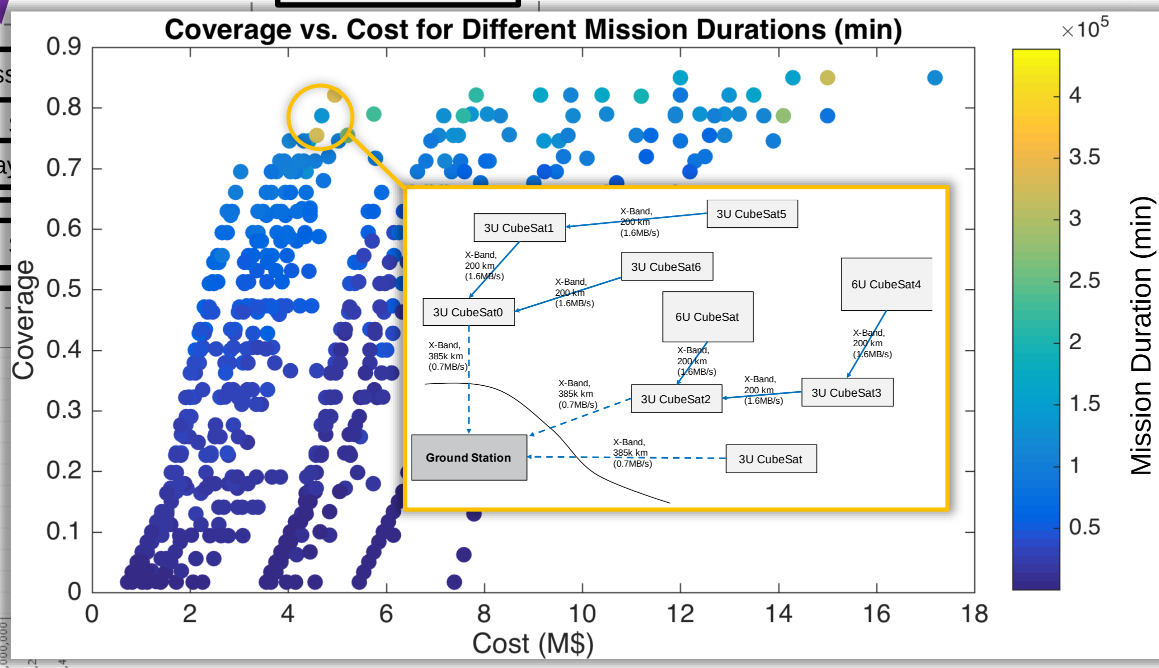
Model-based Design Space Exploration

Cutting Edge MBSE Research at JPL



Model-transformation-based design space exploration





Just one of many ongoing projects…

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Summary & Conclusions

- JPL is successfully applying MBSE with SysML to numerous projects - large and small – over different life cycle phases
- Clear benefits: early verification, consistency, less ambiguity
- There has been tremendous progress in tools and methods in the past decade – and we're only just starting
  - Many lessons learned, tools, techniques integrated from MBSE practice
  - Strong developments in methodology and theory
- Magnitude of paradigm shift still leads to skepticism and adoption challenges ➔ transition inevitable, but slow

MBSE is the future of SE - and all of you will take part in shaping it!

Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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References

[1] C. Lin, D. Nichols, H. Stone, S. Jenkins, T. Bayer, D. Dvorak: *Experiences Deploying MBSE at NASA JPL*. Frontiers in Model-based Systems Engineering Workshop, Georgia Institute of Technology, Atlanta, Georgia, USA, April 2011.

[2] Dave Nichols and Chi Lin: *The Application of MBSE at JPL Through the Life Cycle*. INCOSE International Workshop, January 2014.

[3] S.J.I. Herzig, S. Mandutianu, H. Kim, S. Hernandez, T. Imken: *Model-Transformation-Based Computational Design Synthesis for Mission Architecture Optimization*. AIAA / IEEE Aerospace, March 2017.

[4] Open-MBEE, available online at http://github.com/Open-MBEE.

[5] TMT SysML Model, available online at http://github.com/Open-MBEE/TMT-SysML-Model.

[6] C. Paredis: *Model Transformations in Model-based Systems Engineering*.

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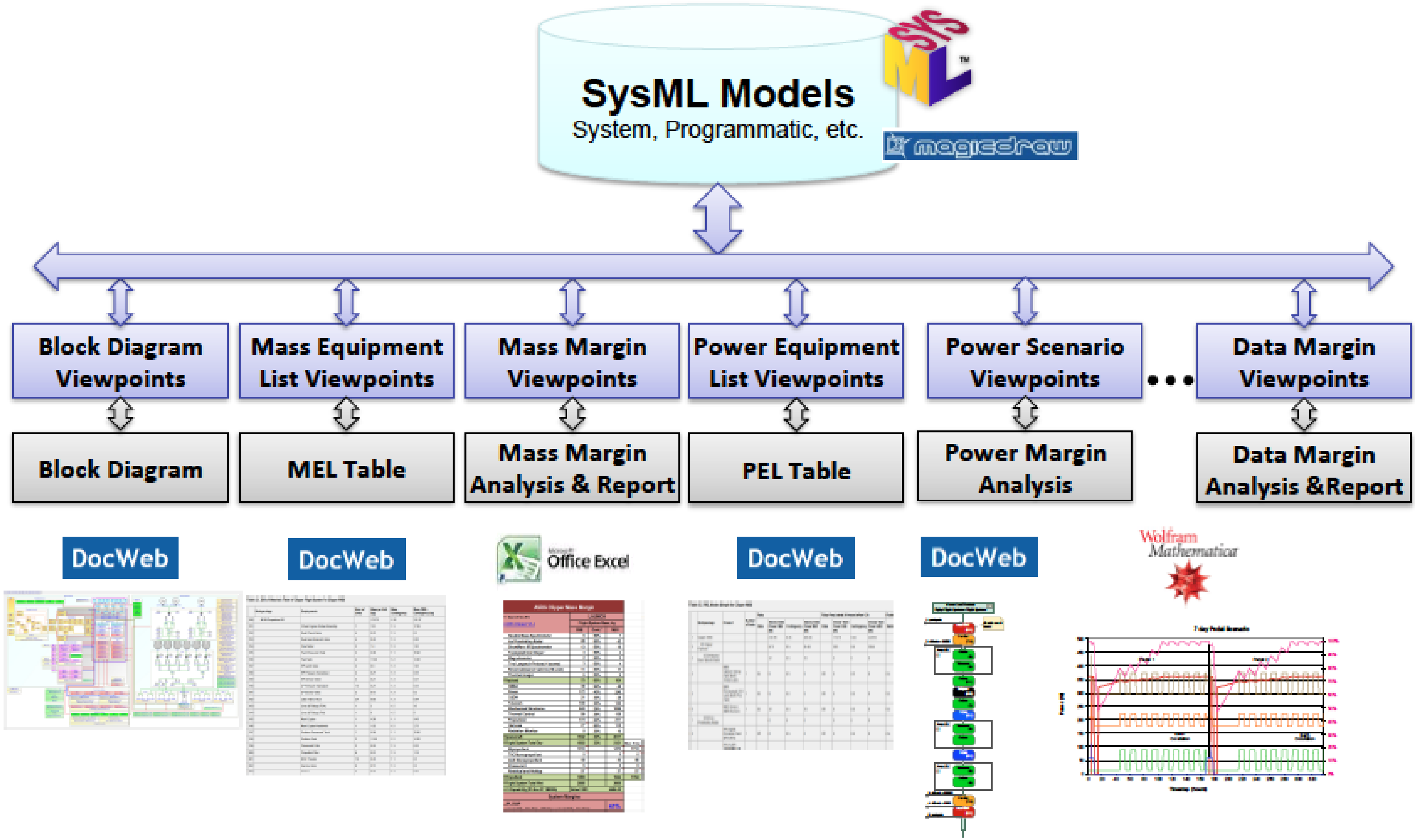
BACKUP SLIDES

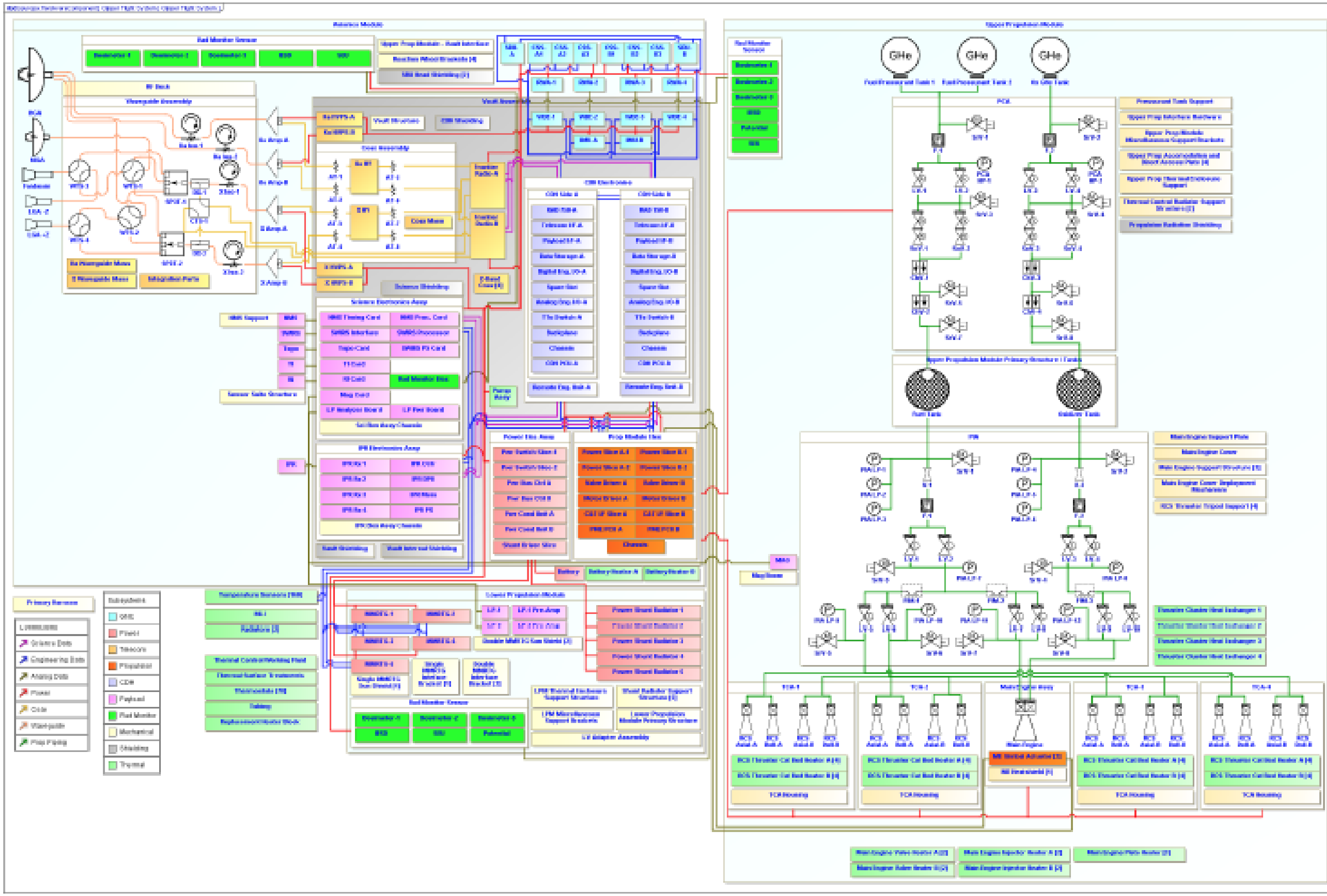
Europa System Model Framework



Pre-Decisional Information -- For Planning and Discussion Purposes Only

Source: Nichols & Lin, 2014

More Meaningful System Diagrams



Pre-Decisional Information -- For Planning and Discussion Purposes Only

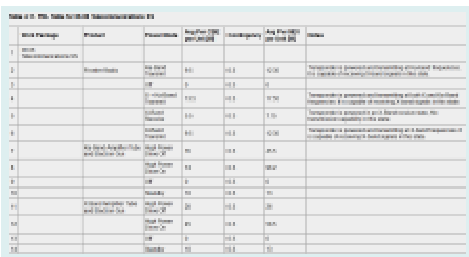
Source: Nichols & Lin, 2014

Integrated Power / Energy Analysis

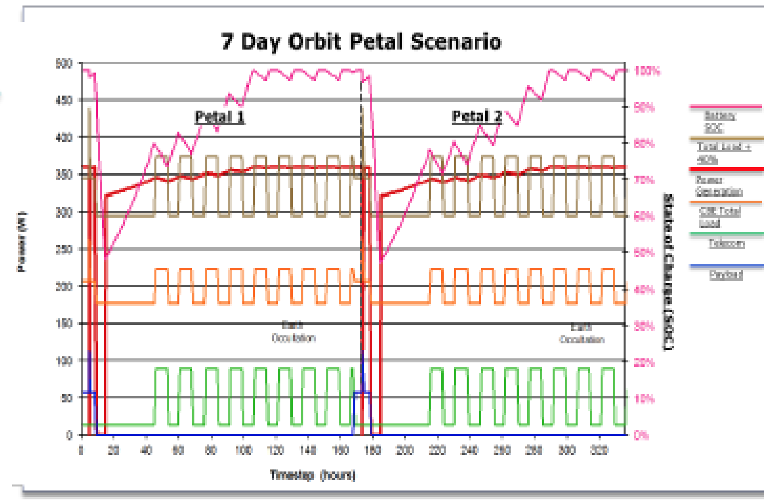
System Model:
- Equipment List
- Demand vs Mode
- Scenario Definitions

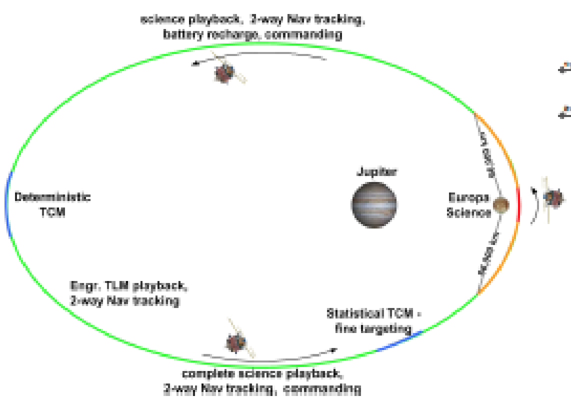
Subsystem Power Models
- Power Source Models
- Battery Models
- Load Profile Simulation

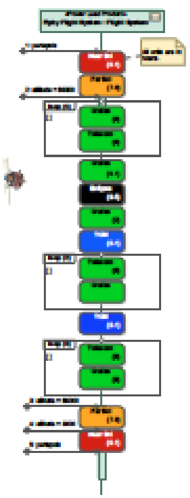
Integrated Power/Energy Analysis



Power Profile Analysis



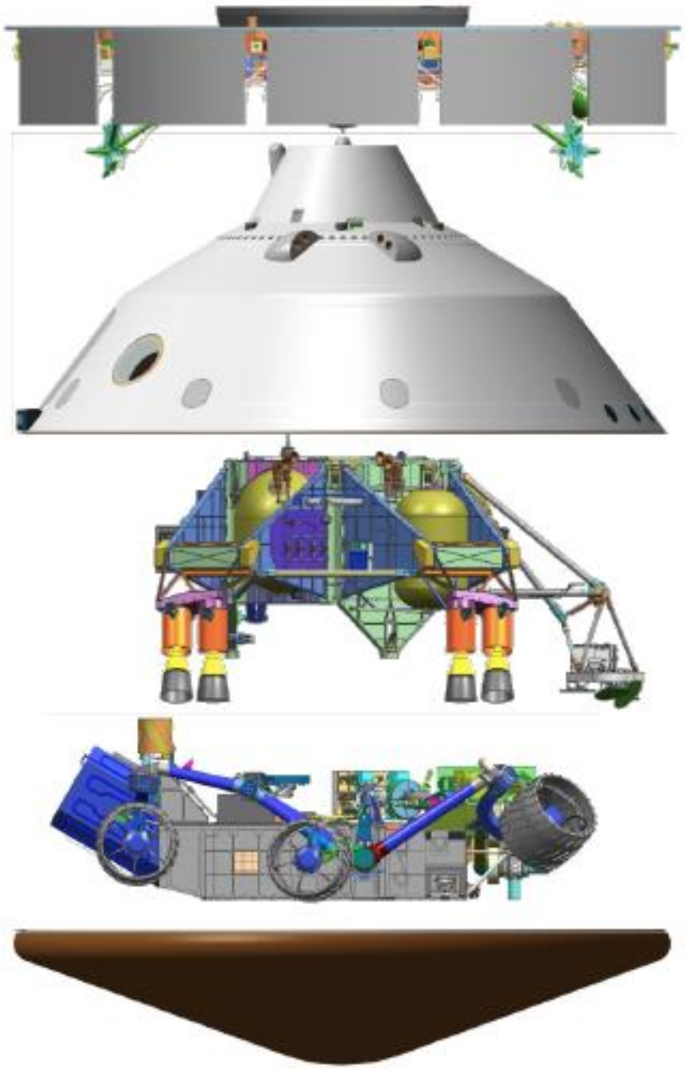




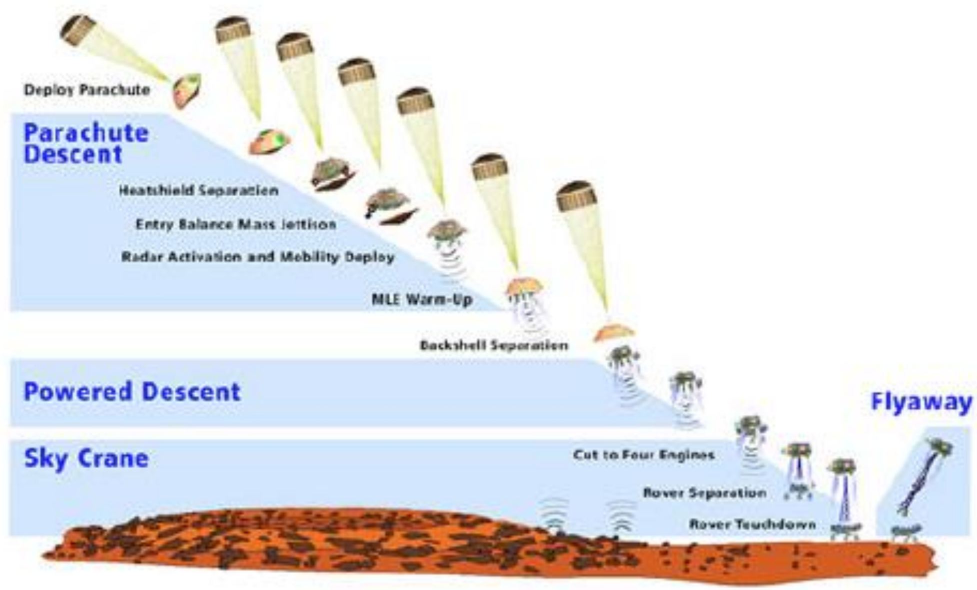
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Source: Nichols & Lin, 2014

Mars 2020 - Coping with Complexity



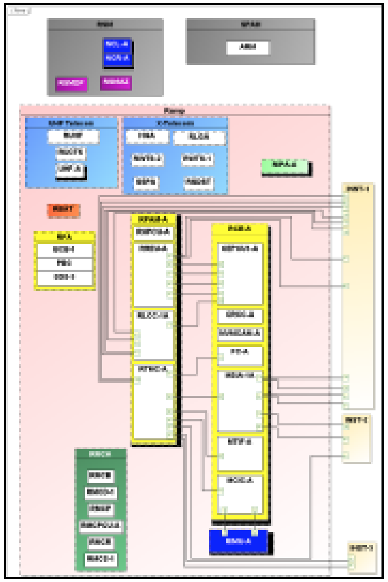
- Mars 2020: follow-on to MSL
- Challenge: engineer inherently complex mission and system at lower cost, and changes to payload instruments



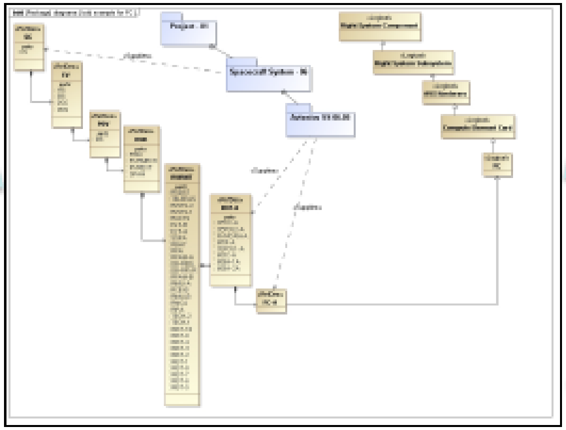
Source: Nichols & Lin, 2014

Example System Modeling (Derived) Products

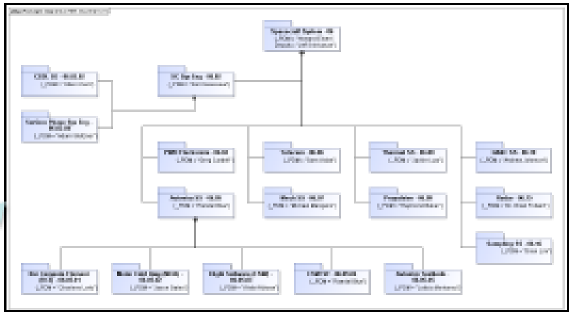
System Block Diagrams and Interfaces



Physical Decomposition, Logical Decomposition, and WBS



Org Chart



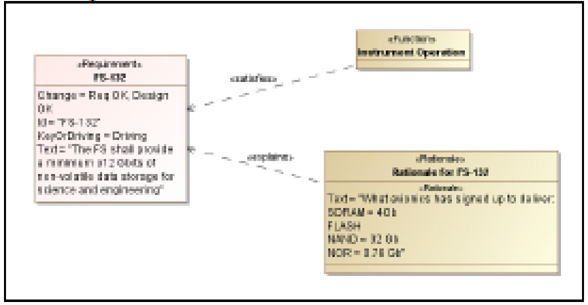
Linking information to core components (Reference Designators)

Resource Tracking (e.g., subset of web-accessible MEL)

Flight System	Flight Quantity	CBE (kg)	MEV (kg)	Contingency (Percent)	Contingency Level	CBE All Count (kg)	MEV All Count (kg)
Flight System	1	915.06	942.27	2.97	N/A	915.06	942.27
RPS	1	44.79	45.68	2.00	N/A	44.79	45.68
RTG	1	44.79	45.68	2.00	N/A	44.79	45.68
_PAYLOAD	1	72.23	73.73	2.04	N/A	72.23	73.73
Thermal	1	41.14	41.96	2.00	N/A	41.14	41.96
RVRTSTAT	12	0.01	0.01	2.00	N/A	0.16	0.16
RIPA	1	14.58	14.87	2.00	N/A	14.58	14.87
RVRTHRM	1	17.28	17.63	2.00	N/A	17.28	17.63
CHRSFL	1	0.90	0.91	2.00	N/A	0.90	0.91
RVRPRT	192	0.00	0.00	2.00	N/A	0.28	0.29

Subset of patterns are extended from institutionally-and Europa derived patterns

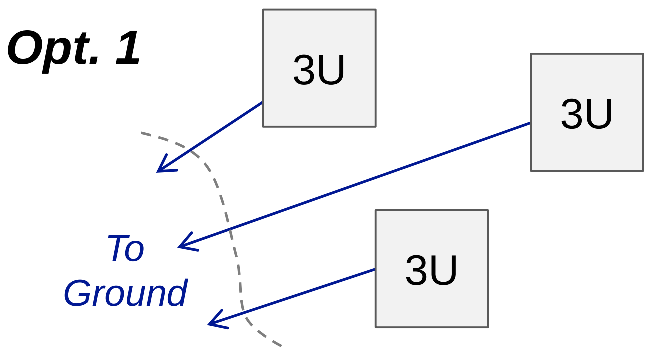
Assessment of Key & Driving Requirements

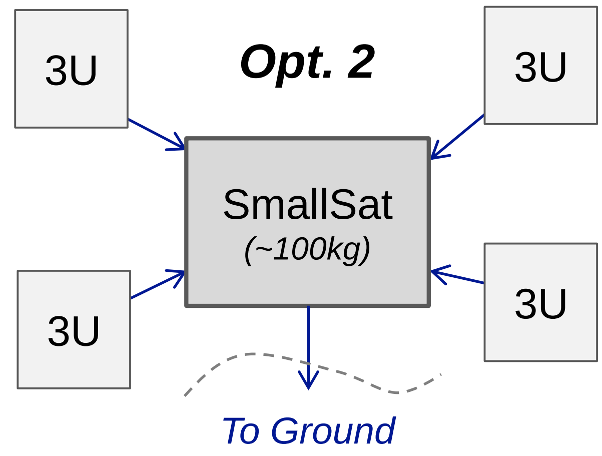


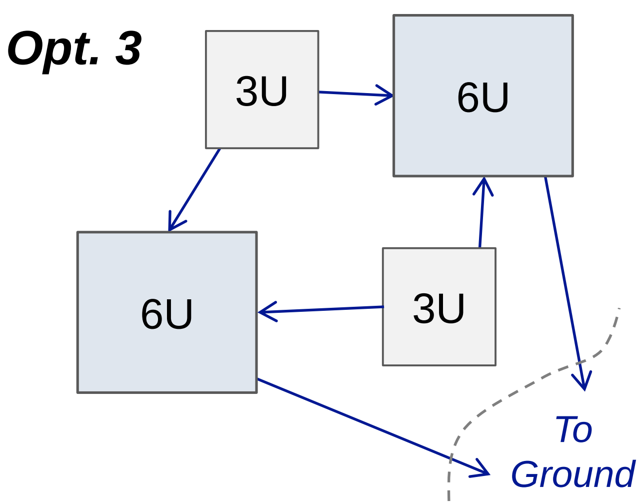
System model provides integrated, consistent, and broadly-accessible design information and change assessment

Source: Nichols & Lin, 2014

Which Architecture is Optimal?



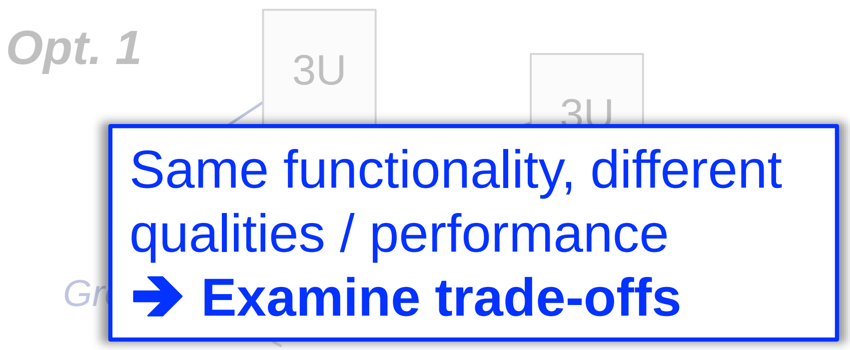




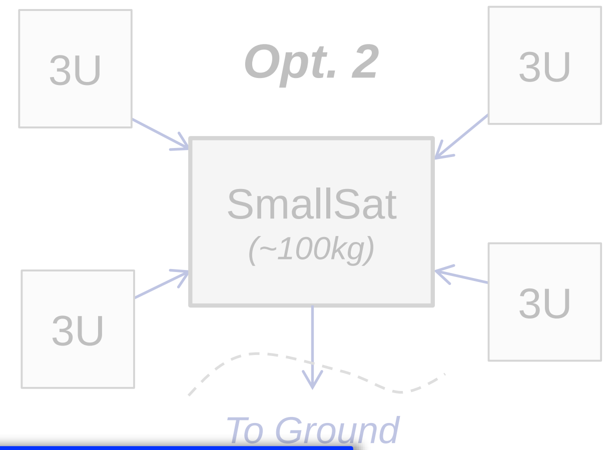
Challenge: transmit very large data volume from LLO to Earth

- How many spacecraft?
- Are all equipped with interferometry payload? Are some just relays?
- Who communicates with Earth?
- What frequency bands? Multi-hop?
- …
- Optimal w.r.t. cost? Science value?

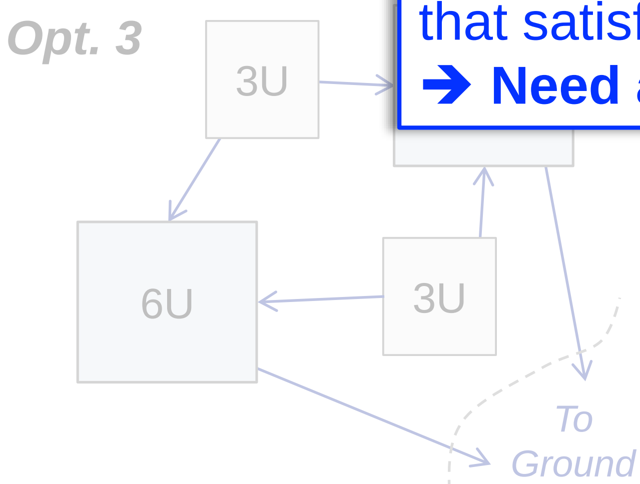
Which Architecture is Optimal?



Same functionality, different qualities / performance
➔ **Examine trade-offs**



Very large number of architectures that satisfy mission objectives
➔ **Need automation**



…ery large data
…Earth

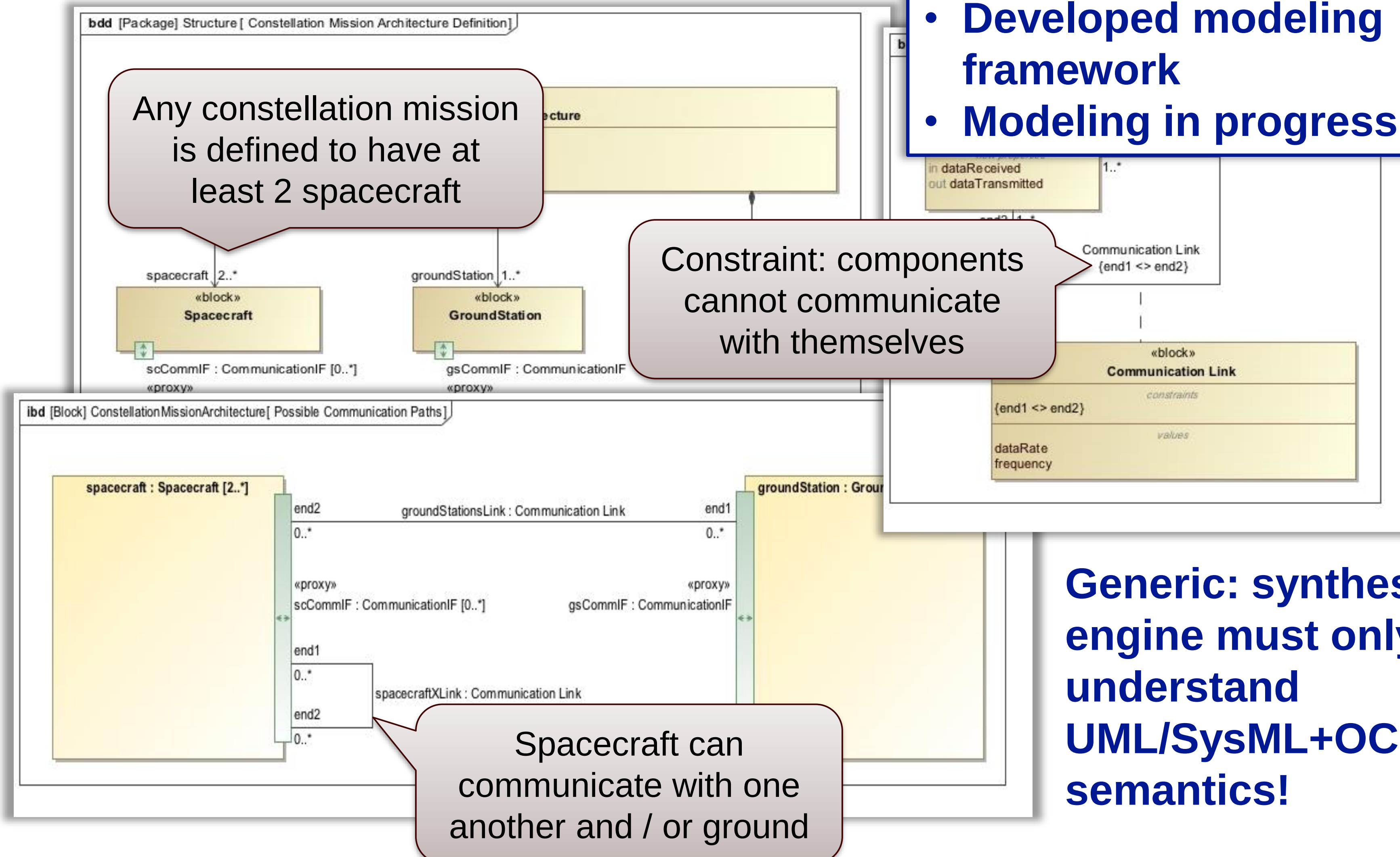
- …ft?
- Are all equipped with interferometry payloa…
- Who c…
- What frequency bands? Multi-hop?
- …
- Optimal w.r.t. cost? Science value?

Functional allocation is key
➔ **Synthesis problem**

Model Library Development

Capturing Domain Elements

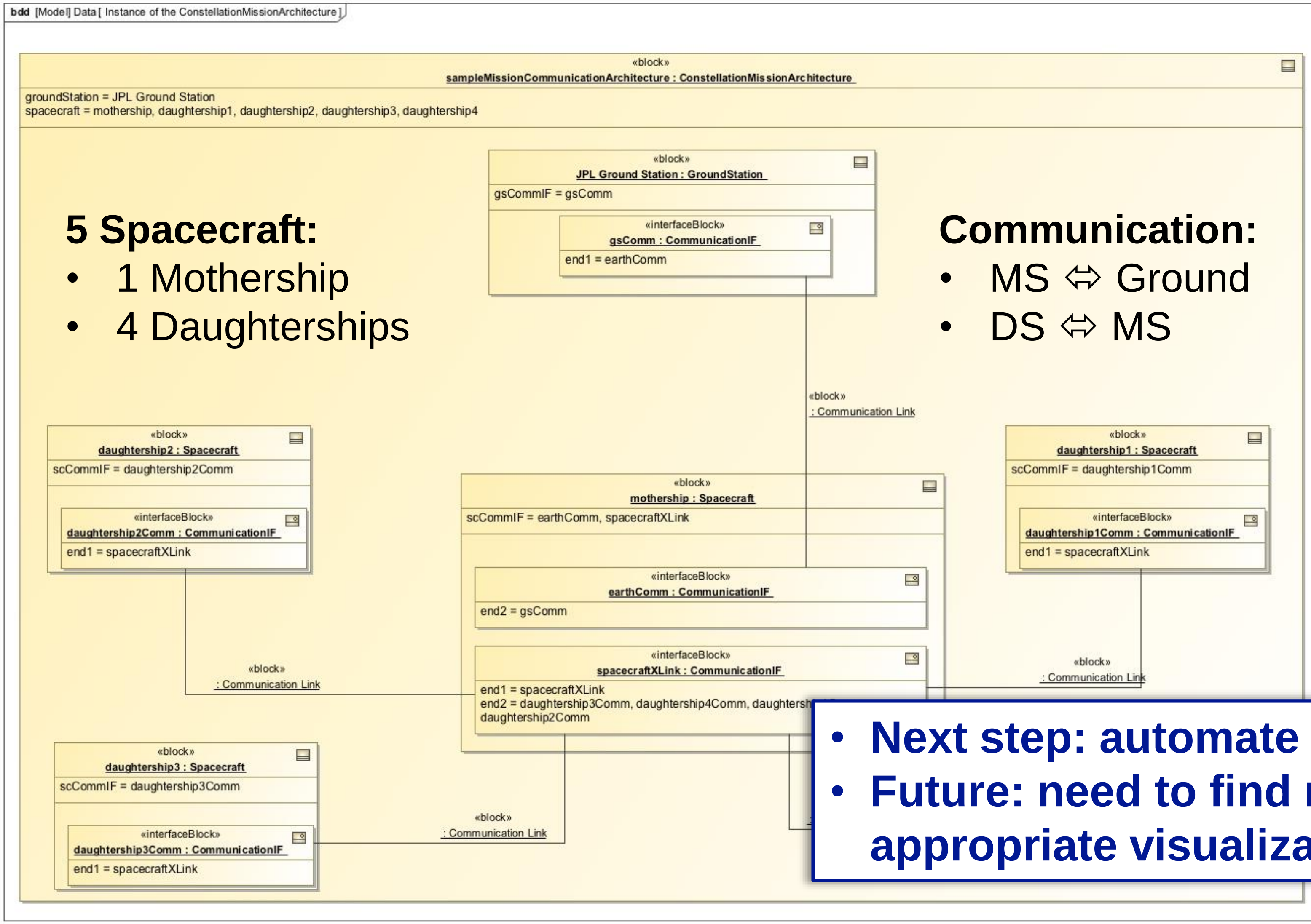
- **Developed modeling framework**
- **Modeling in progress**



Generic: synthesis engine must only understand UML/SysML+OCL semantics!

Instance Creation: Example Partial Instance

Optimized Integrated Network Constellation Design



5 Spacecraft:
- 1 Mothership
- 4 Daughterships

Communication:
- MS ⇔ Ground
- DS ⇔ MS

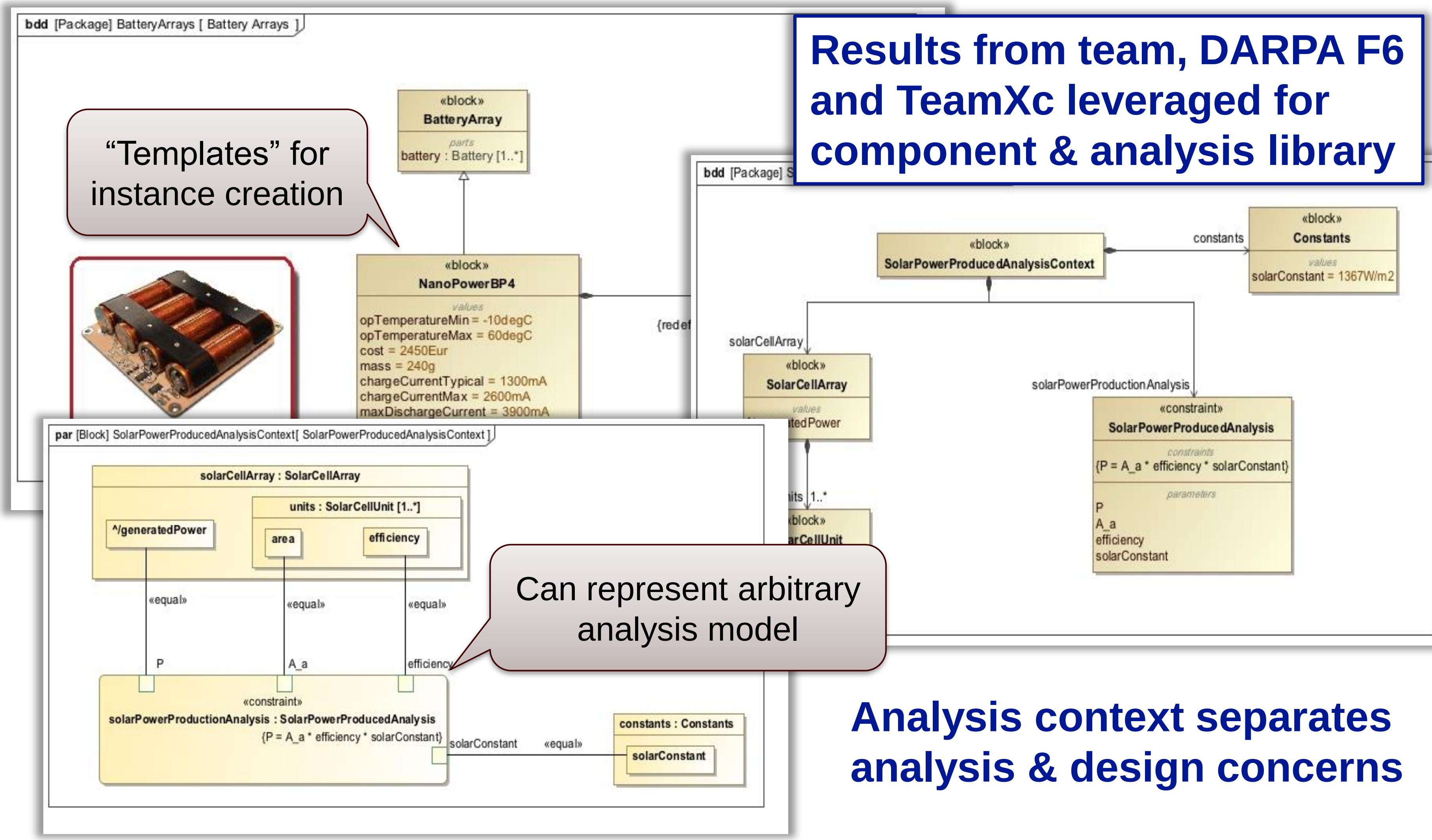
- **Next step: automate**
- **Future: need to find more appropriate visualization**

Model Library Development

Capturing Physical Components & Parametric Relationships

Results from team, DARPA F6 and TeamXc leveraged for component & analysis library

"Templates" for instance creation

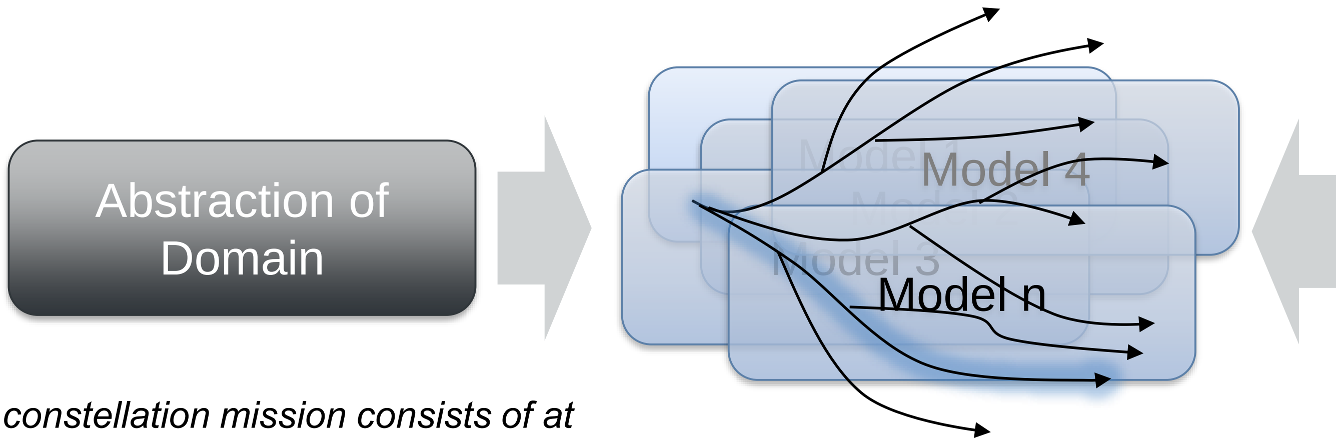


Can represent arbitrary analysis model

Analysis context separates analysis & design concerns

Mission Architecture Trade Space Exploration

Mechanized Exploration



Which interferometry missions are optimal with respect to cost & scientific benefit?

"A constellation mission consists of at least 2 spacecraft and at most 100"

"A spacecraft can, but does not have to contain the interferometry payload"

"Operation of the interferometry payload operation requires power"

Solution Generation
Search
Models in domain

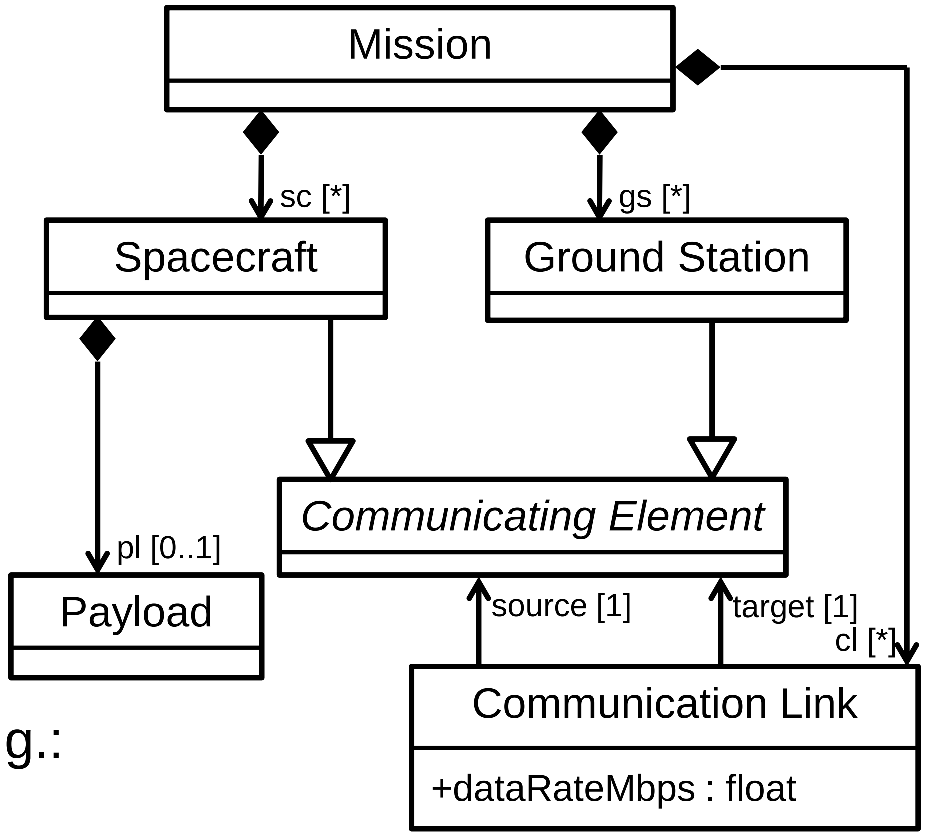
"Constellation mission A with 3 spacecraft, one of which has a

Problem Description
Which models in the domain are we looking for?

In practice, too many possible solutions to generate & compare all
➔ **View as a search problem**

Domain Model & Well-Formedness Constraints

- Domain model
  - Concepts
  - Associations / relations
  - Attributes
  - ➔ Describes a **universe of discourse**: many models in domain
  - ➔ Describes structural part of the problem



- Typically annotated with addl. well-formedness constraints, e.g.:

  "No communication loops may exist"

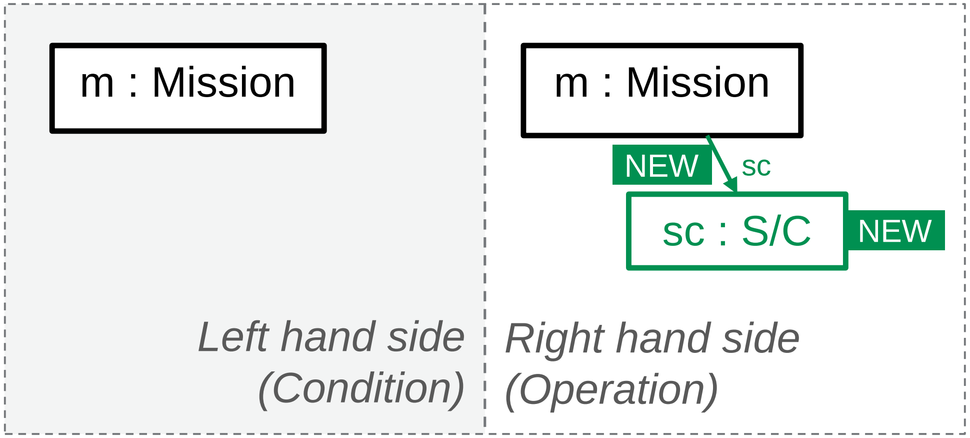
  "All spacecraft must (transitively) be connected to at least one ground station through a communication link"

Any model in the domain is a (structurally) valid solution

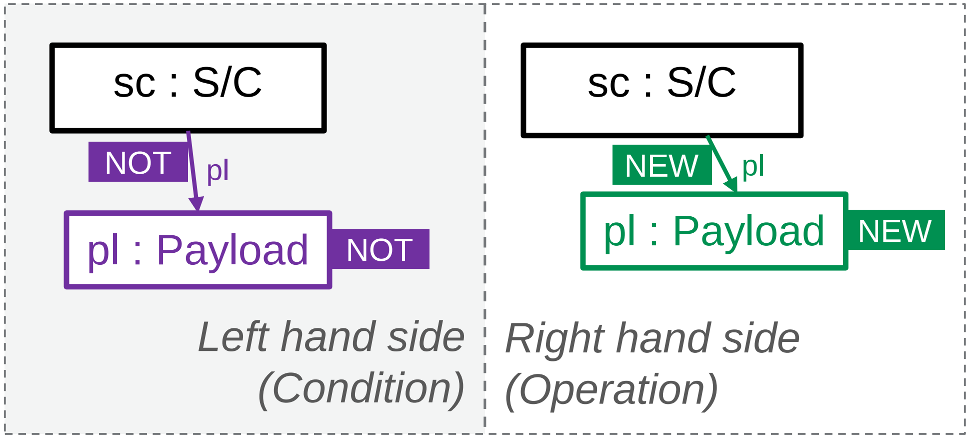
Model-Transformation-Based Exploration

Model Transformation Rules as Enablers for Evolving Solutions

- Transformation Rules
  - **LHS**: Condition for match in input model (e.g., *"find an element of type Mission"*)
  - **RHS**: Operation to be performed (e.g., *"create a new element of type S/C (Spacecraft) and attach it to the matched mission"*)
- Here: *endogenous* transformations
  - Source and target meta-models are the same
- Used for generating models in domain (~design rules)



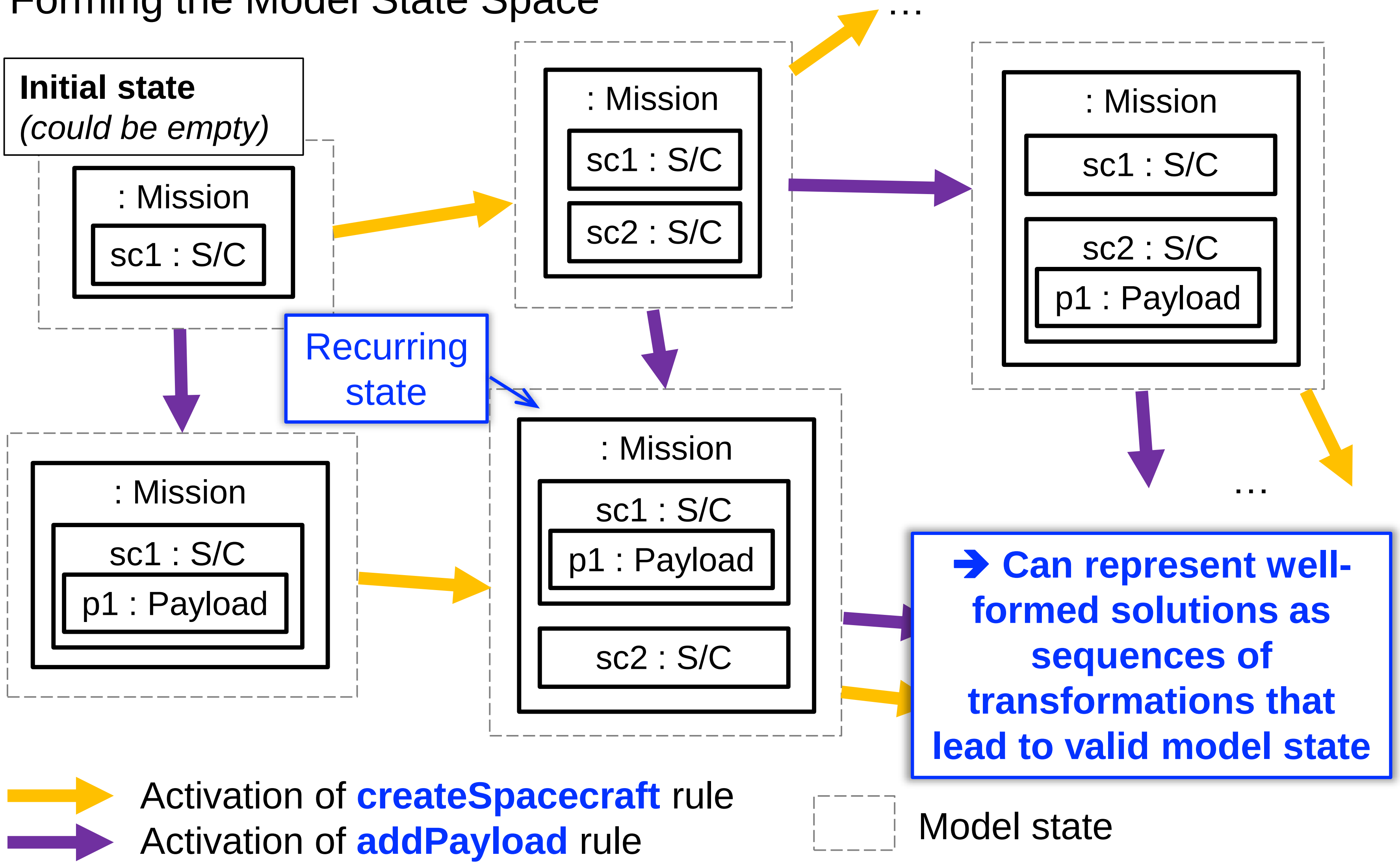
Rule "createSpacecraft"



Rule "addPayload"

Model-Transformation-Based Exploration

Forming the Model State Space



Driving Exploration Towards Optima

Using Evolutionary Algorithms to find Pareto-Optimal Solutions

Crossover

Individual x:	Add Spacecraft	Add X-Band Comm	Add Spacecraft	Add Comm Link	*fitness=0.6*
(Selection from population)					*(Obj. Fct. Values)*
Individual y:	Add Spacecraft	Add Ka-Band Comm	Add Payload	Add Spacecraft	*fitness=0.5*

Here, individuals are **sequences of transformation rule activations**
→ Each genome in population is a variable with set of trafo rules as range

New: Add Ka-Band Comm *fitness=0.8*

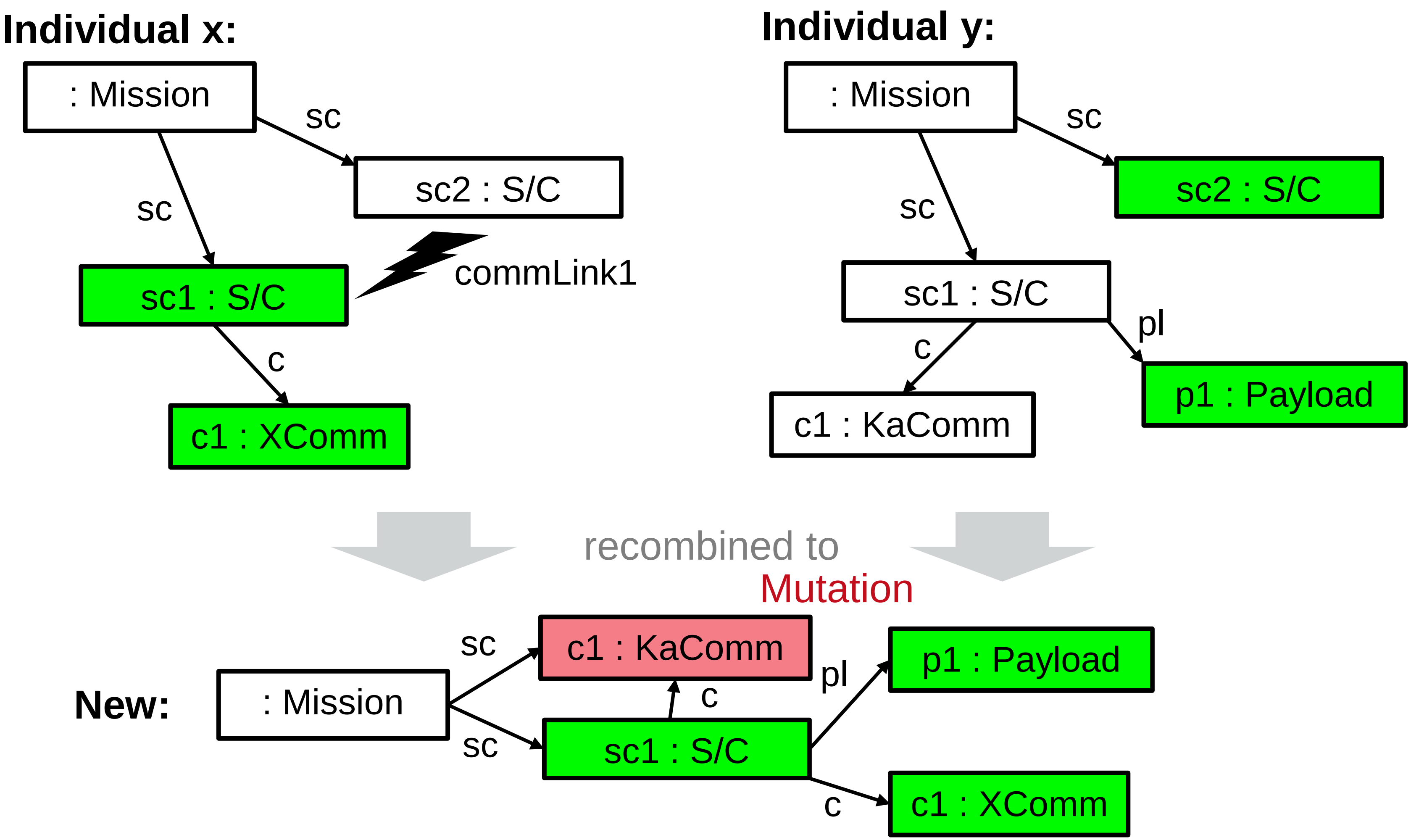
(Recombined individual in next generation)

Mutation

Could also be a "placeholder" transformation (= rule "do nothing")

Driving Exploration Towards Optima

Models Resulting from Executing Transformations



Implementation

Open Source Technologies Used in Implementation

- Representation of Domain
  ➔ Ecore / Eclipse EMF + OCL

- Exploration Rules
  ➔ Henshin (or Viatra)

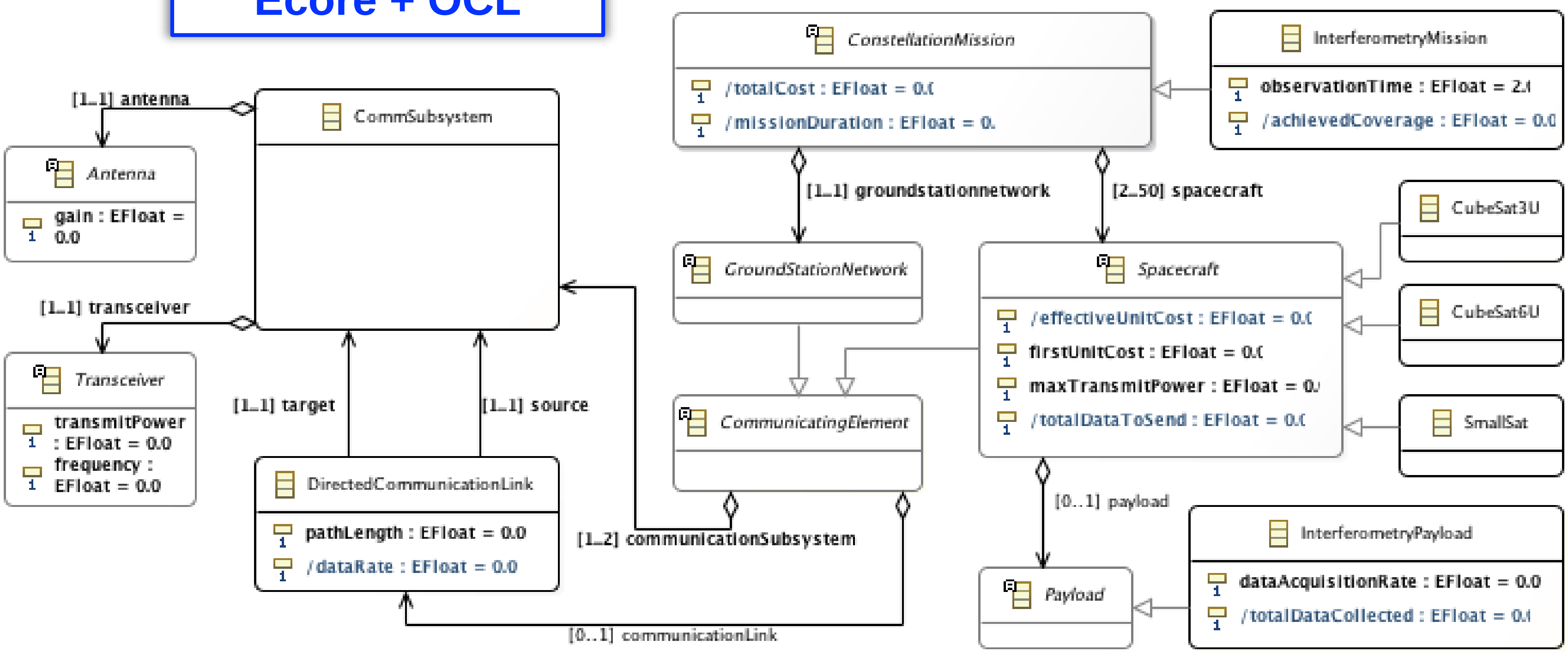
- Analyses / Fitness Functions
  ➔ Java

- Optimization Using Genetic Algorithms
  ➔ MOMoT, MOEA (or Viatra DSE)

Application to Case Study

Representation of Domain (Excerpt)

Domain model in Ecore + OCL



20 concepts, 9 associations, 15 attributes / parameters

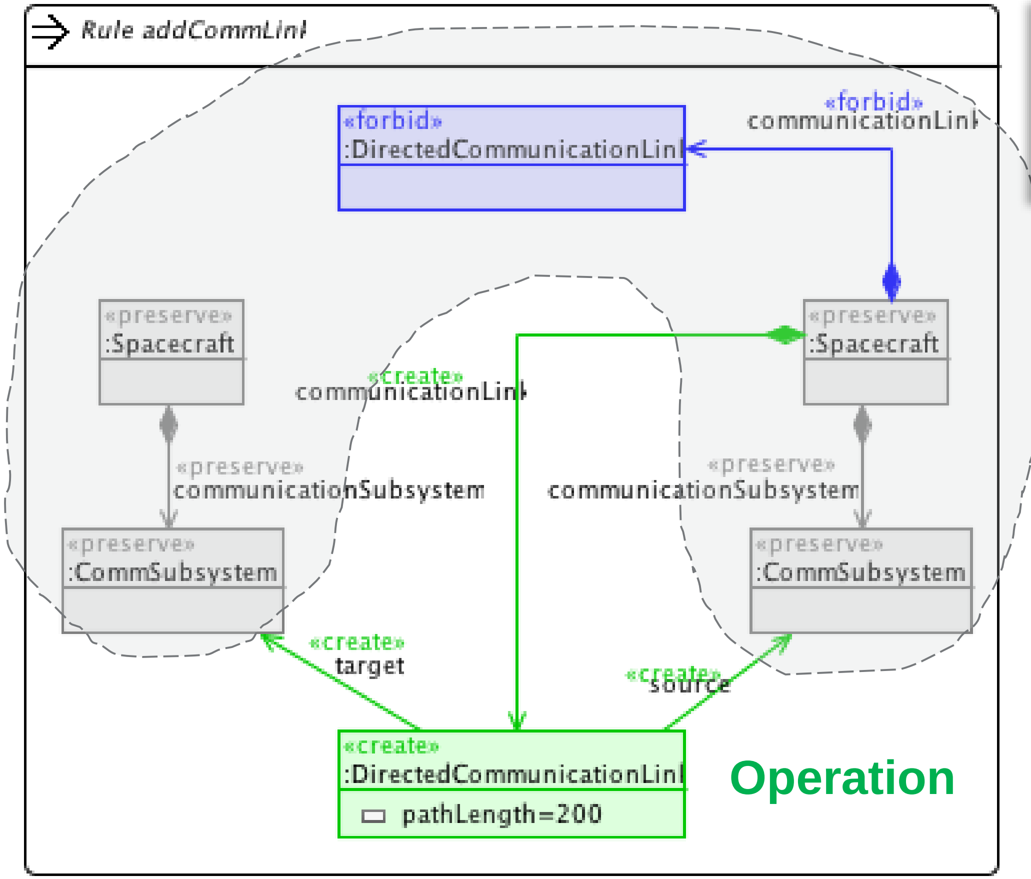
> 48^{10} possible models

Too many for exhaustive search

Application to Case Study

Transformation Rule Example (Henshin Syntax): Add Comm. Link

Condition



Operation

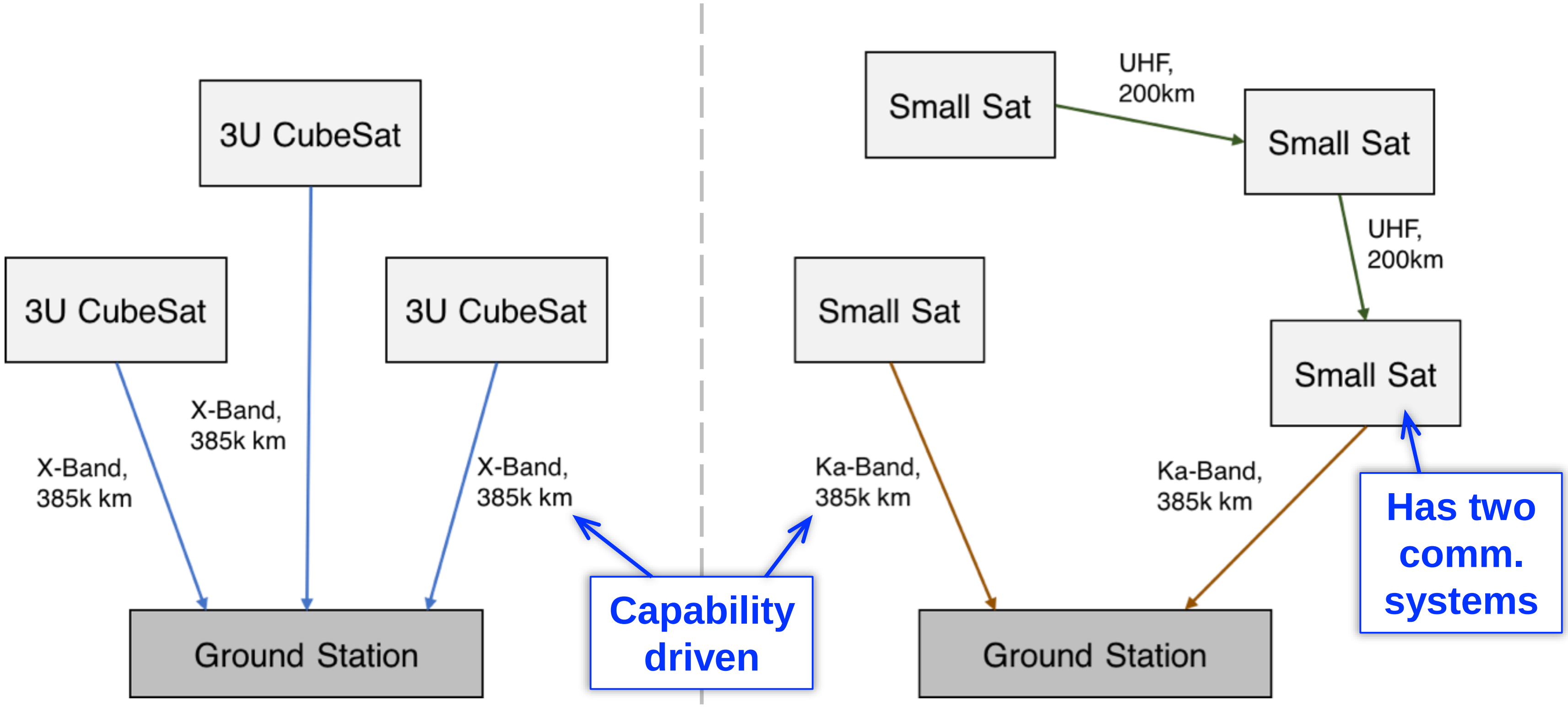
Transformation Rules in Henshin

LHS and RHS folded together

In Prose: *"Find 2 distinct spacecraft instances, and add a communication link between them"*

Results from Application to Case Study

Examples of Pareto-Optimal (Nondominated) Solutions



Candidate Solution #1
$1M, ~0.02 coverage

Candidate Solution #2
$10M, ~0.4 coverage

Similar mission duration, but #1 has much longer downlink time

Tool & Language for Integrated Optimization

Development of the ”Kigen” Optimization Environment

- Able to concisely define an optimization problem
- Similar to LP, QP languages
- Supports:
  - Variables, constants
  - Custom types 🡐 **Unique!**
  - Constraints, helper functions
  - Multiple objectives
- Can directly call Java functions
- Able to generate a set of Pareto-optimal mission concepts
- **Since Q1 also in use by 6x R&TD task “MOSAIC” for trade studies**

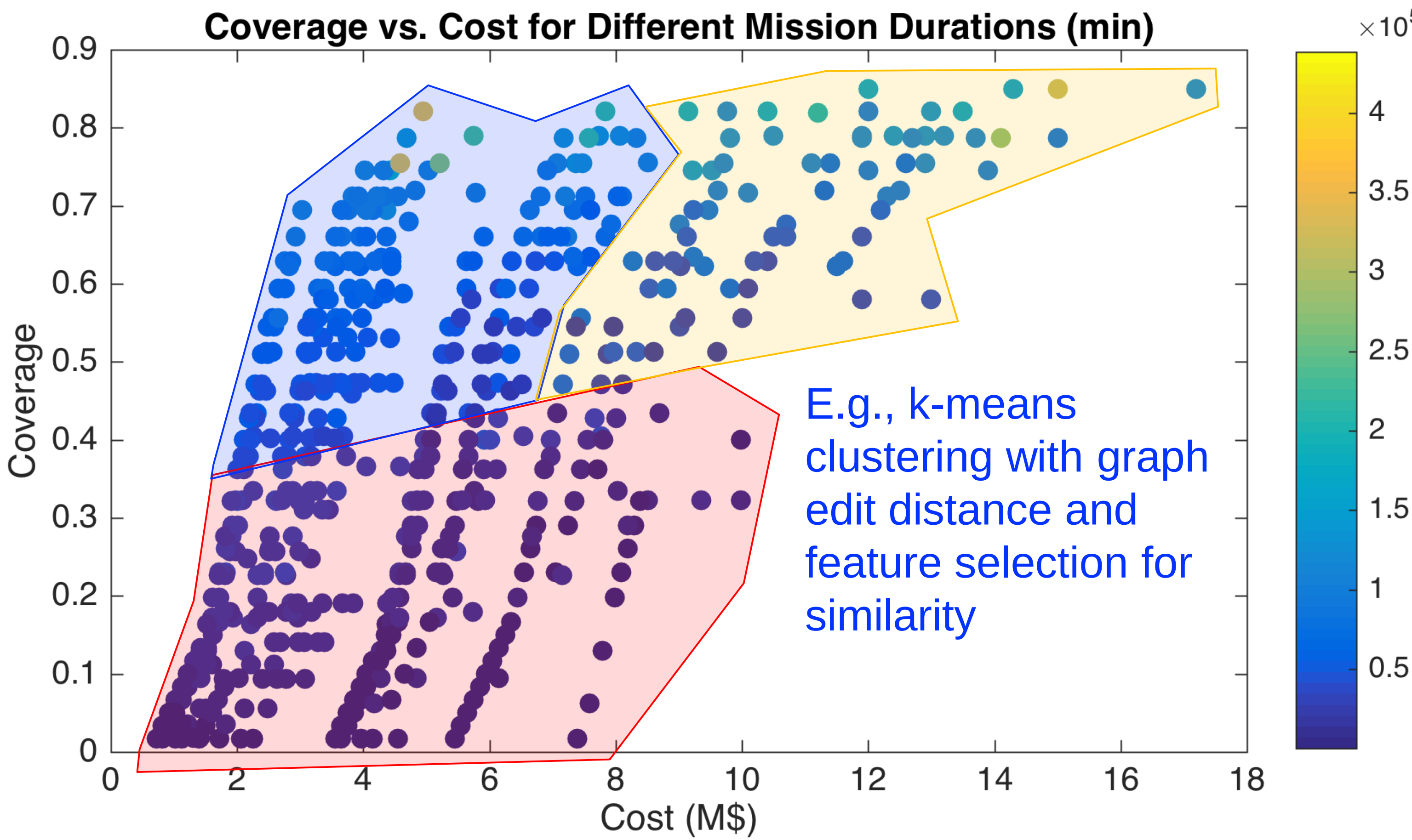
Example.kml

```
type FlightSystem {
    var spacecraft : Spacecraft [ 1 .. 100 ]

    fun cost = {..

    constraint mustBeInBudget: cost < 100 //M$
}

type Spacecraft {
    var mass = 1 .. 50 //kg

    var payload : Instrument [ 0 .. 2 ]
}

abstract type Instrument

type Camera extends Instrument
type Radar extends Instrument

minimize FlightSystem.cost
maximize FlightSystem.spacecraft.size

solve optimize using 'nsgaii' 1 times with
    populationSize 25,
    maxGenerations 10,
    maxSolutionLength 20
```

Notional Example of a KigenML program

What's Next?

Clustering of Similar Architectures



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