Model-Based Systems Engineering: A Roadmap for Academic Research

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www.omg.org/ocsmp

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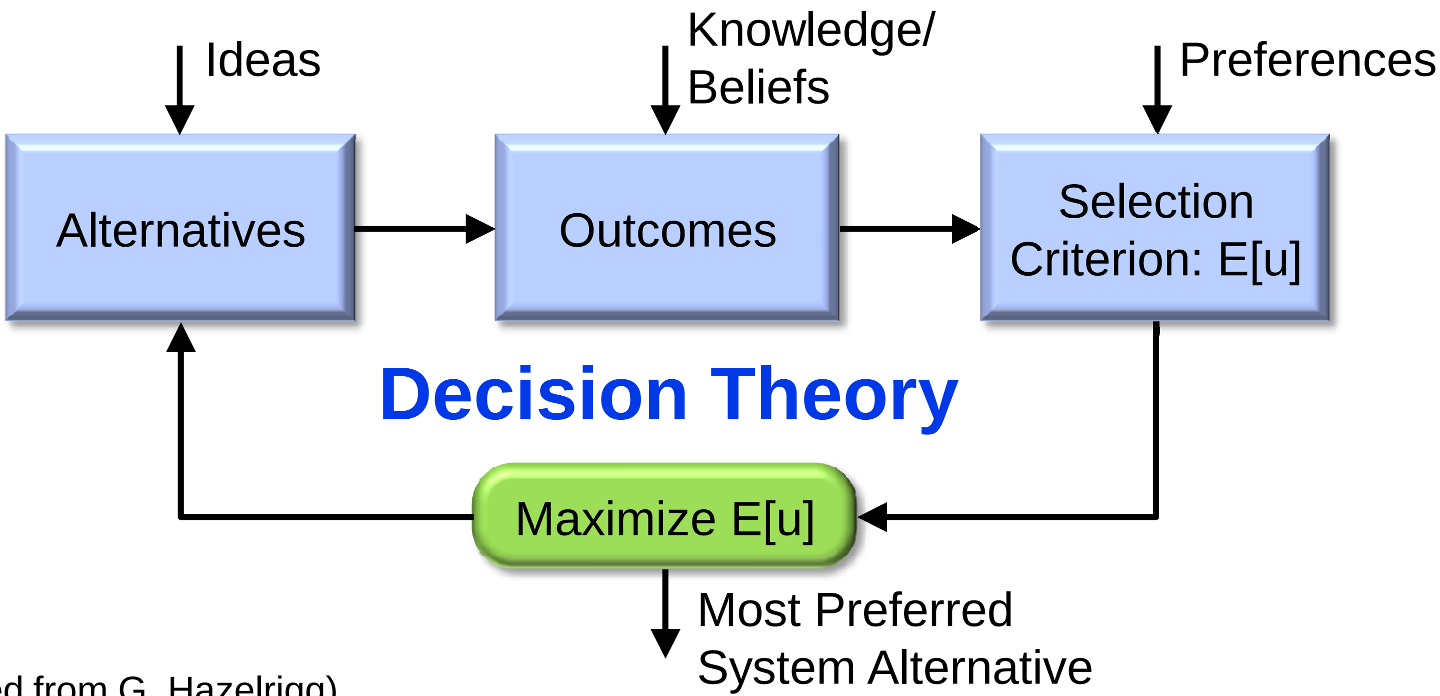
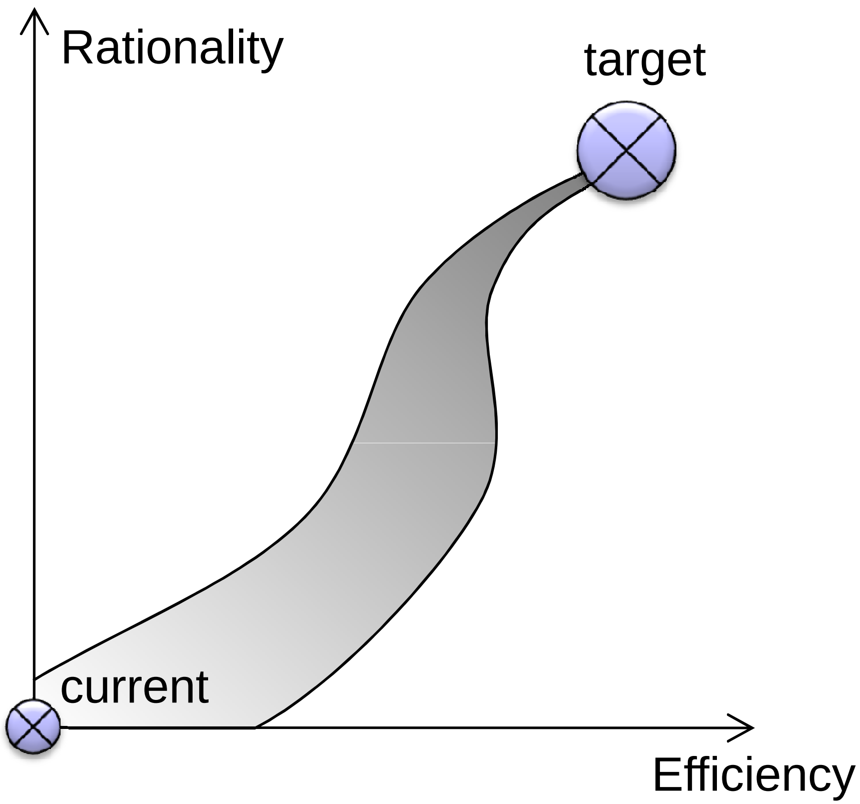
Context: MBSE and Decision Making



(Figure Adapted from G. Hazelrigg)

- Goal of MBSE: Improve Efficiency & Rationality
  - Efficient = Perform the SE process with fewer resources
  - Rational = Be consistent with designer's beliefs and preferences

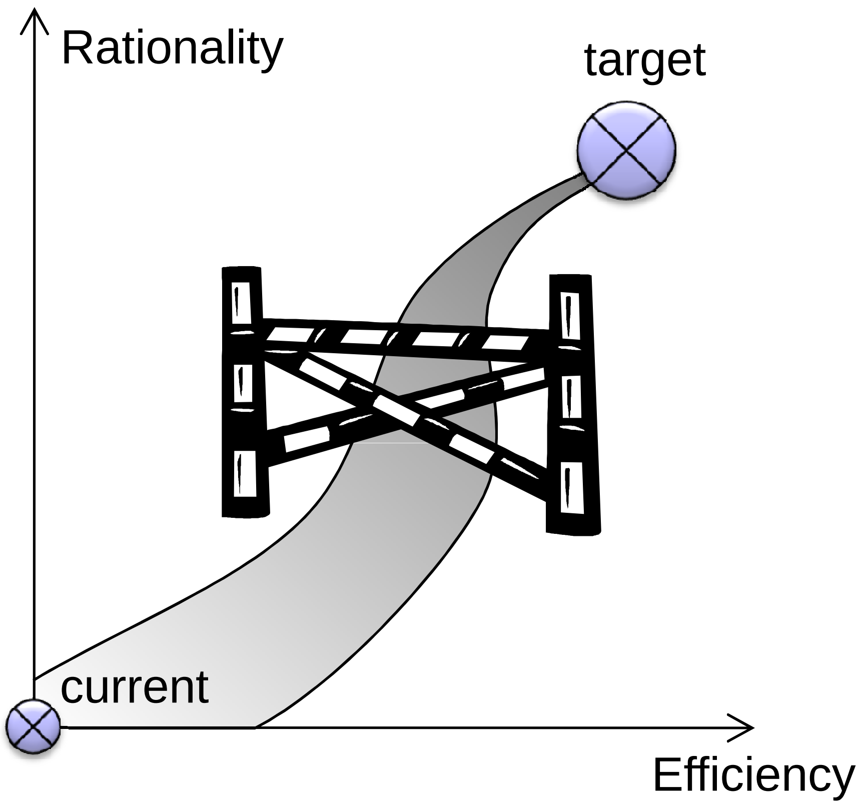
Target for the MBSE Roadmap



- Improve Efficiency
  - Reduce the cost and effort needed to identify, locate, access, and use information
- Improve Rationality
  - Make better decisions with the currently available information

How can we help system engineers to design more efficiently and rationally?

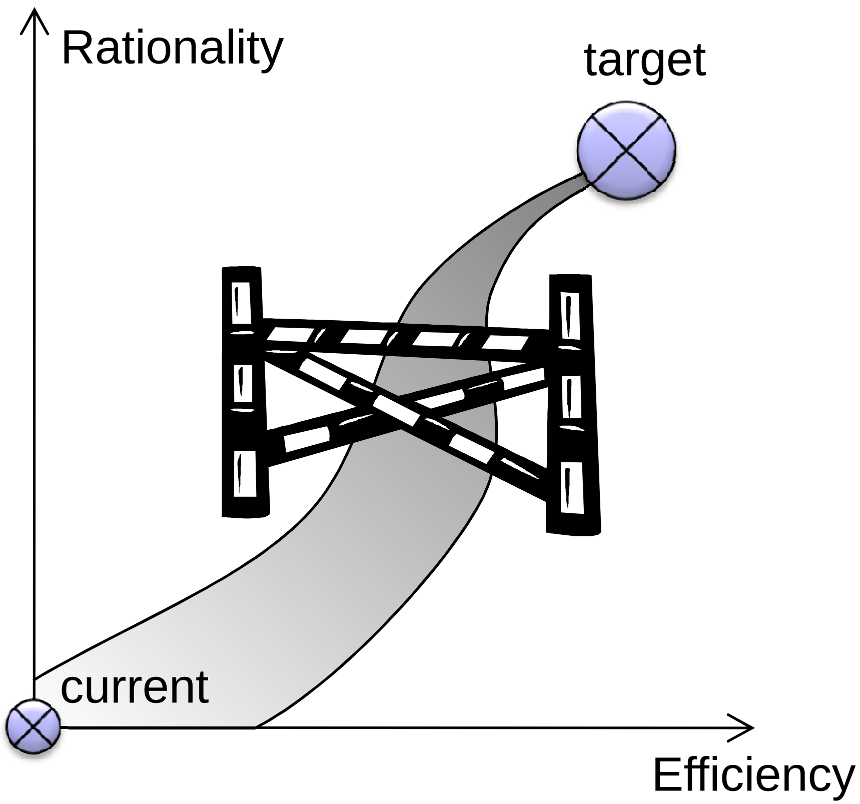
Obstacles on the MBSE Roadmap



Obstacle =
Opportunity for Research

- Obstacles for Efficiency:
  - Creating models (manually) is expensive
  - Performing analyses is time-consuming and cumbersome (due to lack of interoperability)
  - Rehashing the same information: e.g., writing design review reports
  - Maintaining dependencies between different model views of the same system is error-prone and time-consuming

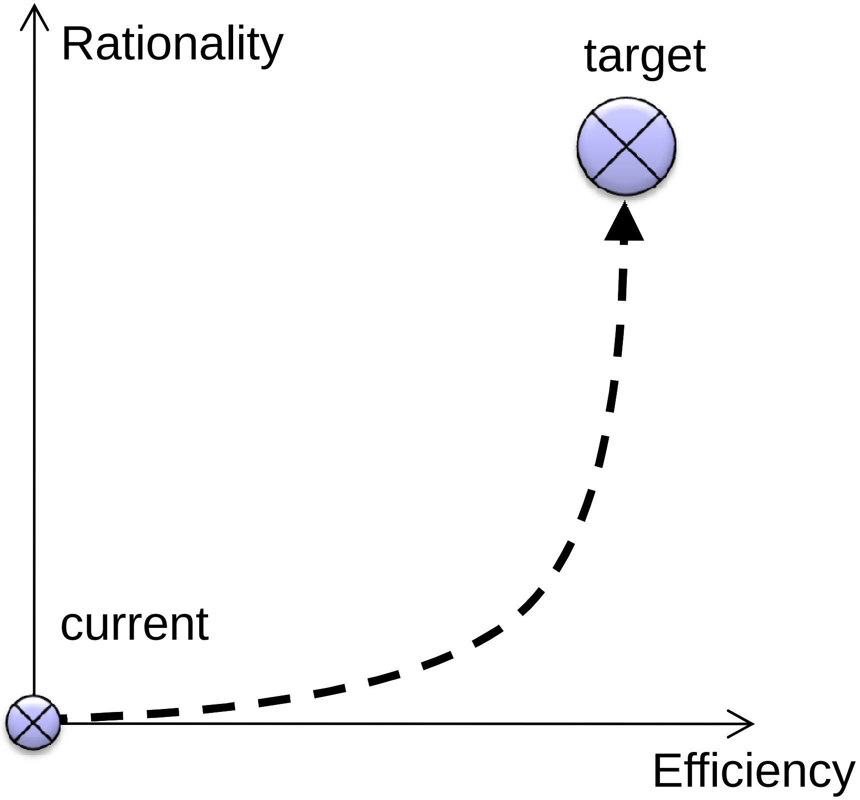
Obstacles on the MBSE Roadmap



Obstacle =
Opportunity for Research

- Obstacles for Rationality:
  - Consistency: Are models in sync with each other? With data? Conform to language?
  - Bounded rationality: too much information and knowledge for a human to take into account and process
  - Poor design methods: methods must be consistent with decision theory
  - Distributed decision making: different people = different beliefs and preferences → irrationality

Proposed Path to Target



How can we help system engineers to design more rationally and efficiently?

- Focus on efficiency first
  - Establish benefits of MBSE early on
  - Low-hanging fruit
- Address rationality gradually
  - Start with consistency
  - Requires significant change in mindset for SE practitioners
  - Requires further development of theory of Rational Design

Presentation Overview

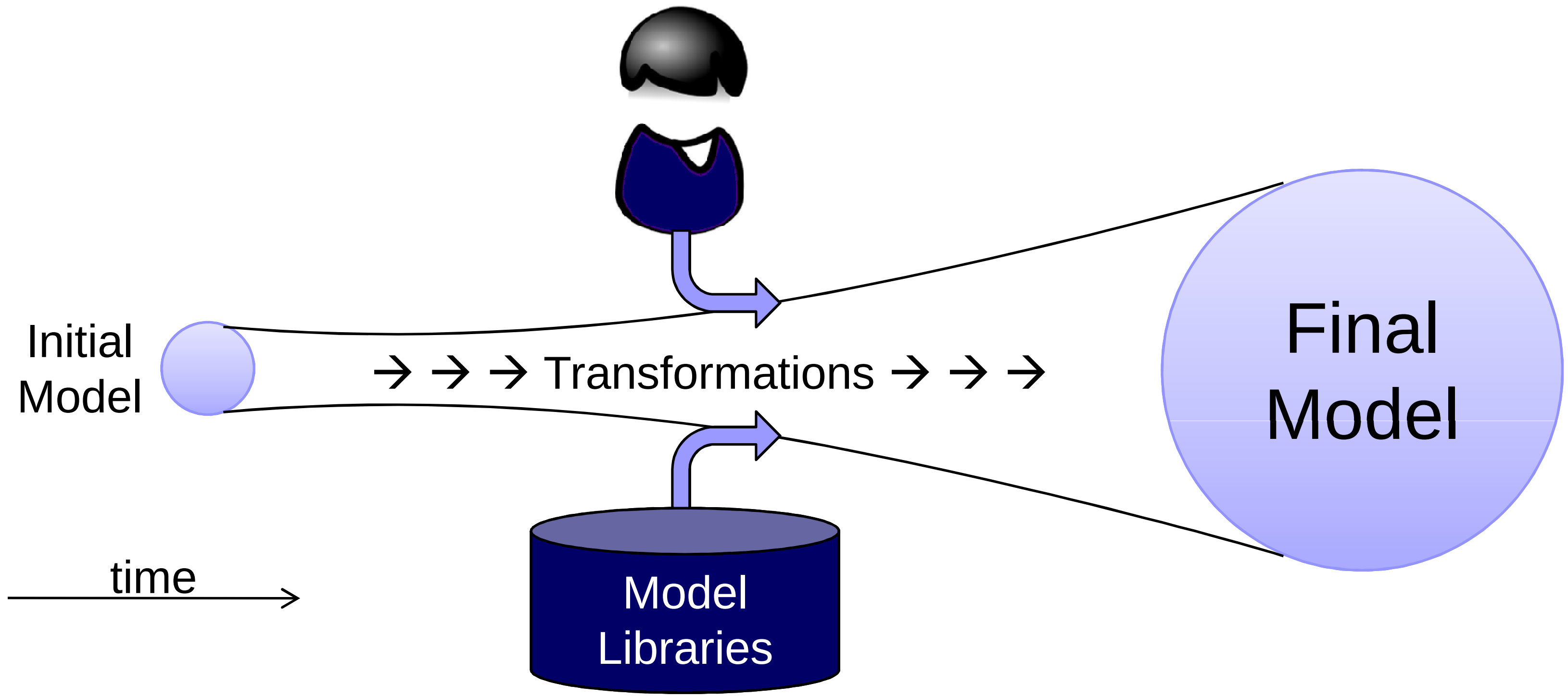
- Context: MBSE and decision making

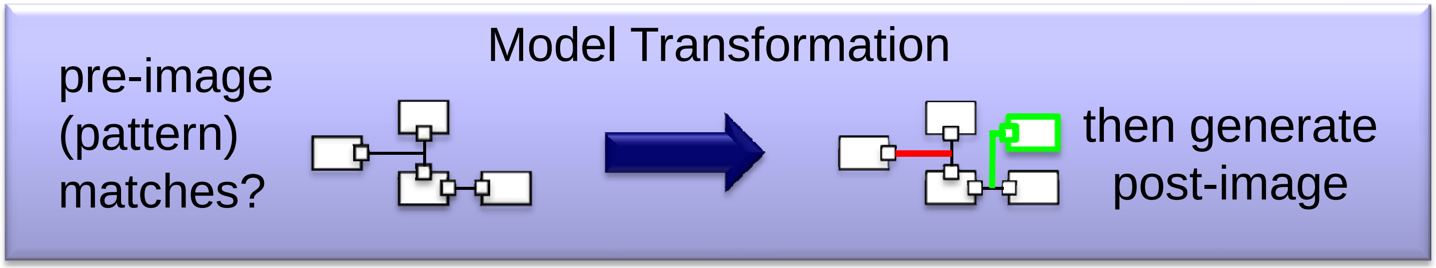
How can MBSE help us make better decisions?

➡ Common theme in research: Model Transformations

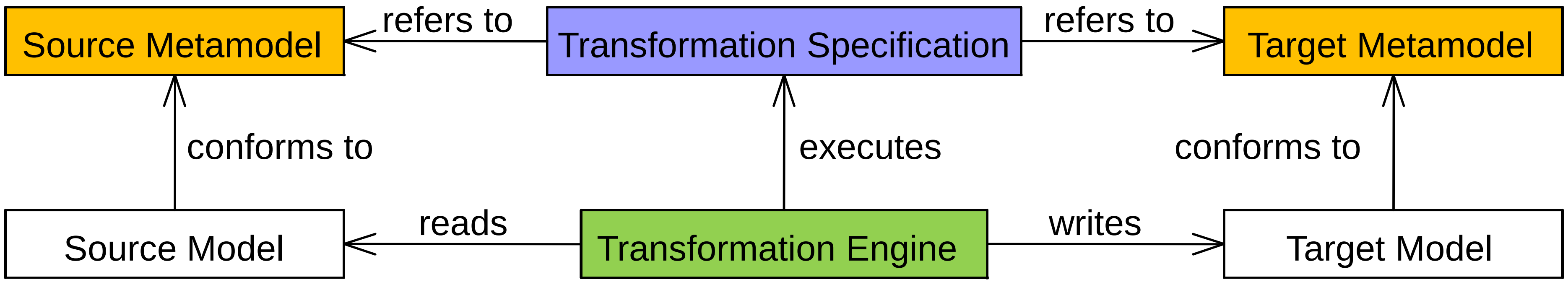
- More efficient decision making with MBSE
  - Modeling of system alternatives — descriptive
  - Predictive modeling of consequence — analytical
- More rational decision making with MBSE
  - How to formulate design decisions?

MBSE Process = Model Transformations





Model Transformation



(Czarnecki, K., & Hellen, S., 2006)

- Transformation Specification is also a Model
  → automated generation of transformation engine code
- Origins
  - Model Driven Architecture/ Engineering
- Tools
  - MOFLON, QVTo, ATL, GME/GReAT, VIATRA2, Kermeta,…
- Example Usages:
  - Automation of repeated modeling patterns
  - Tool interoperation
  - Document generation
  - Consistency checking
  - Dependency propagation

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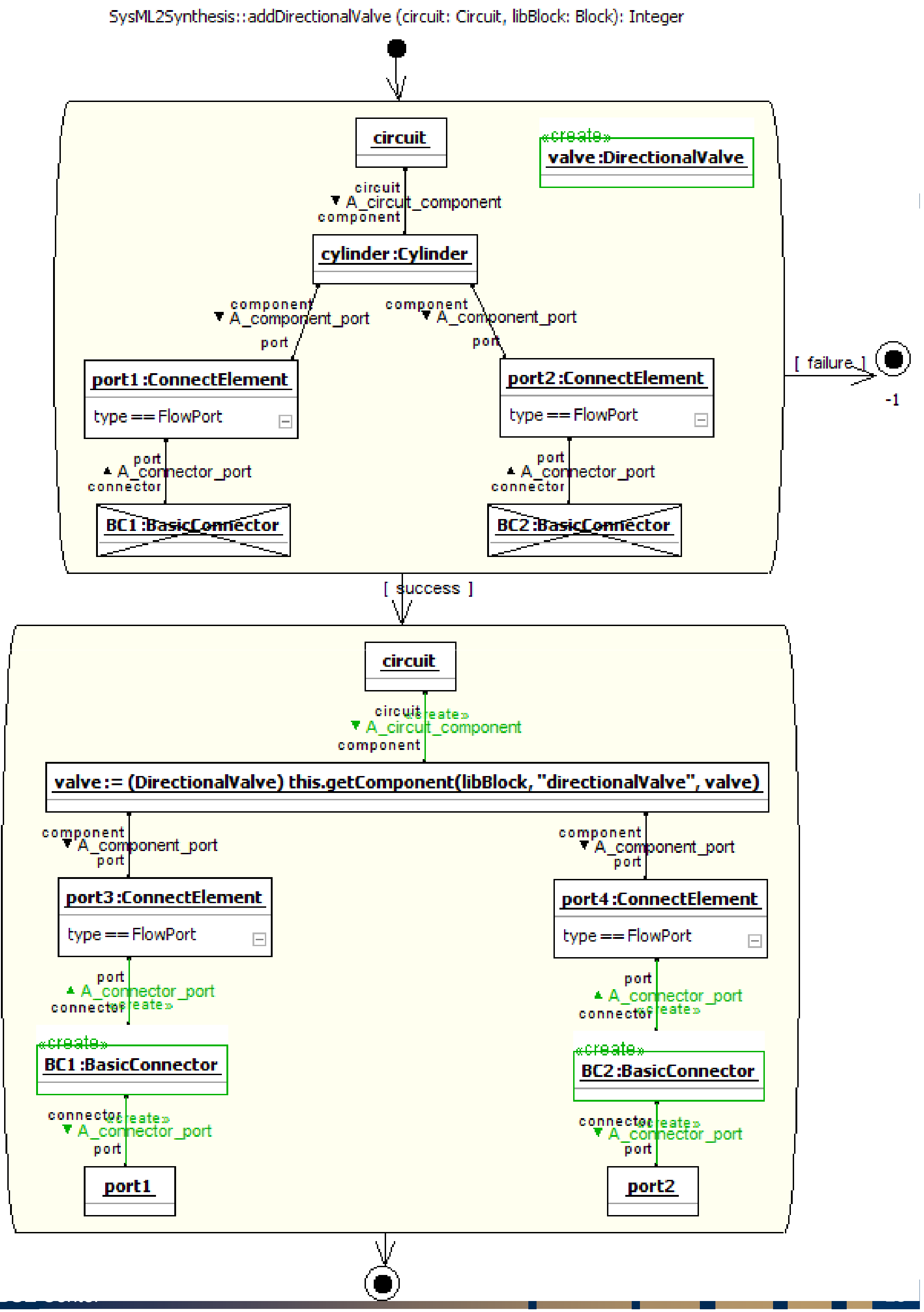
Modeling System Alternatives — Some Issues

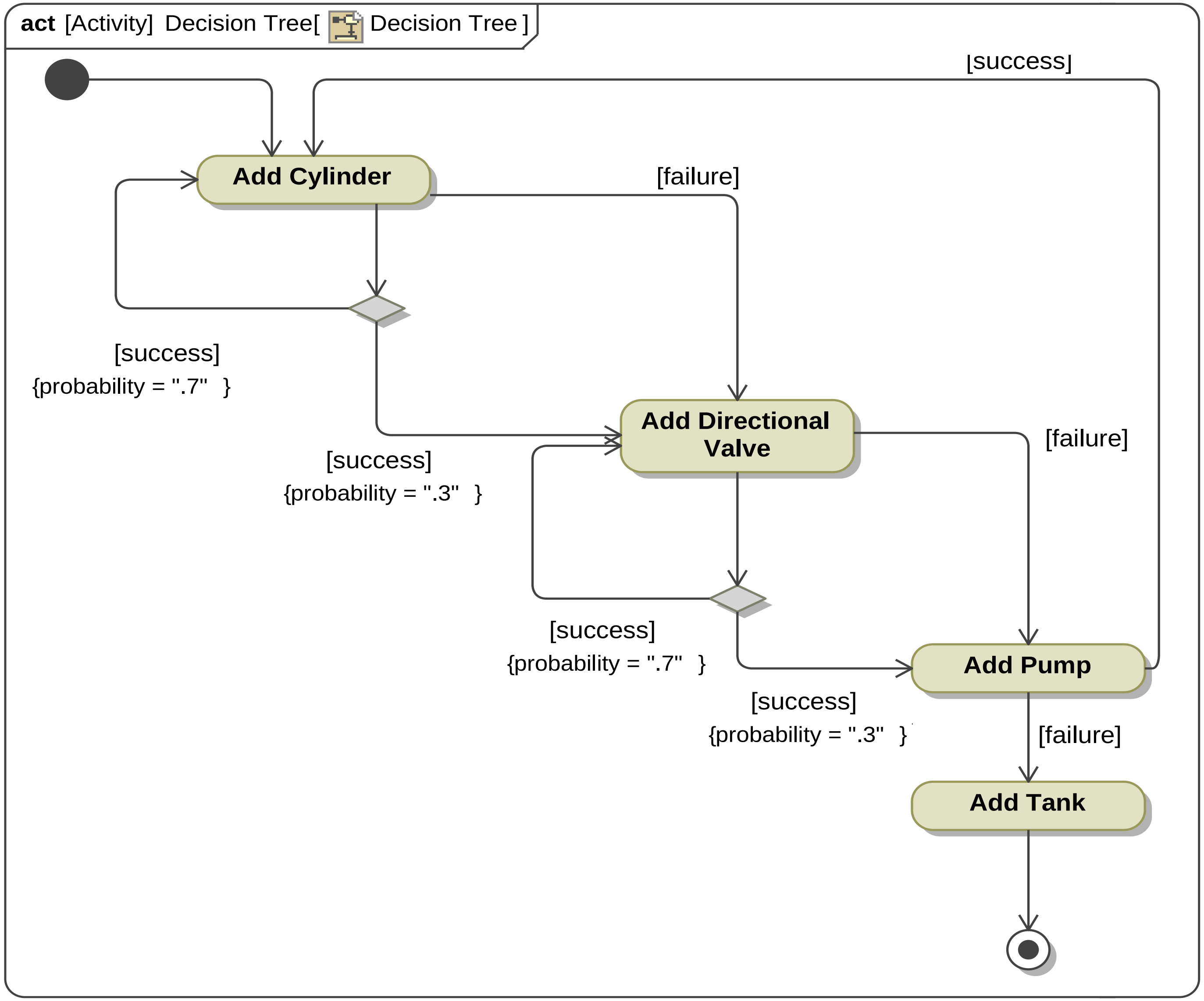
- SysML is well-suited for modeling a single alternative but…that is often not sufficient:
  - Modeling product families
  - Modeling systems throughout the development process
  - Modeling variants
    - » space of alternatives to be considered for design optimization
- Integration between many viewpoints, many in languages/tools other than SysML
- Maintaining consistency in the specification

Generative Grammar for Design Synthesis

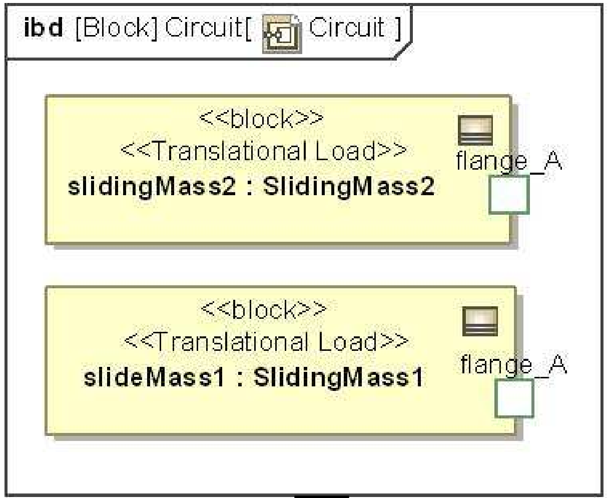
- Graph Transformation rules to generate systems
- Generate random system alternatives by applying rules in randomized order



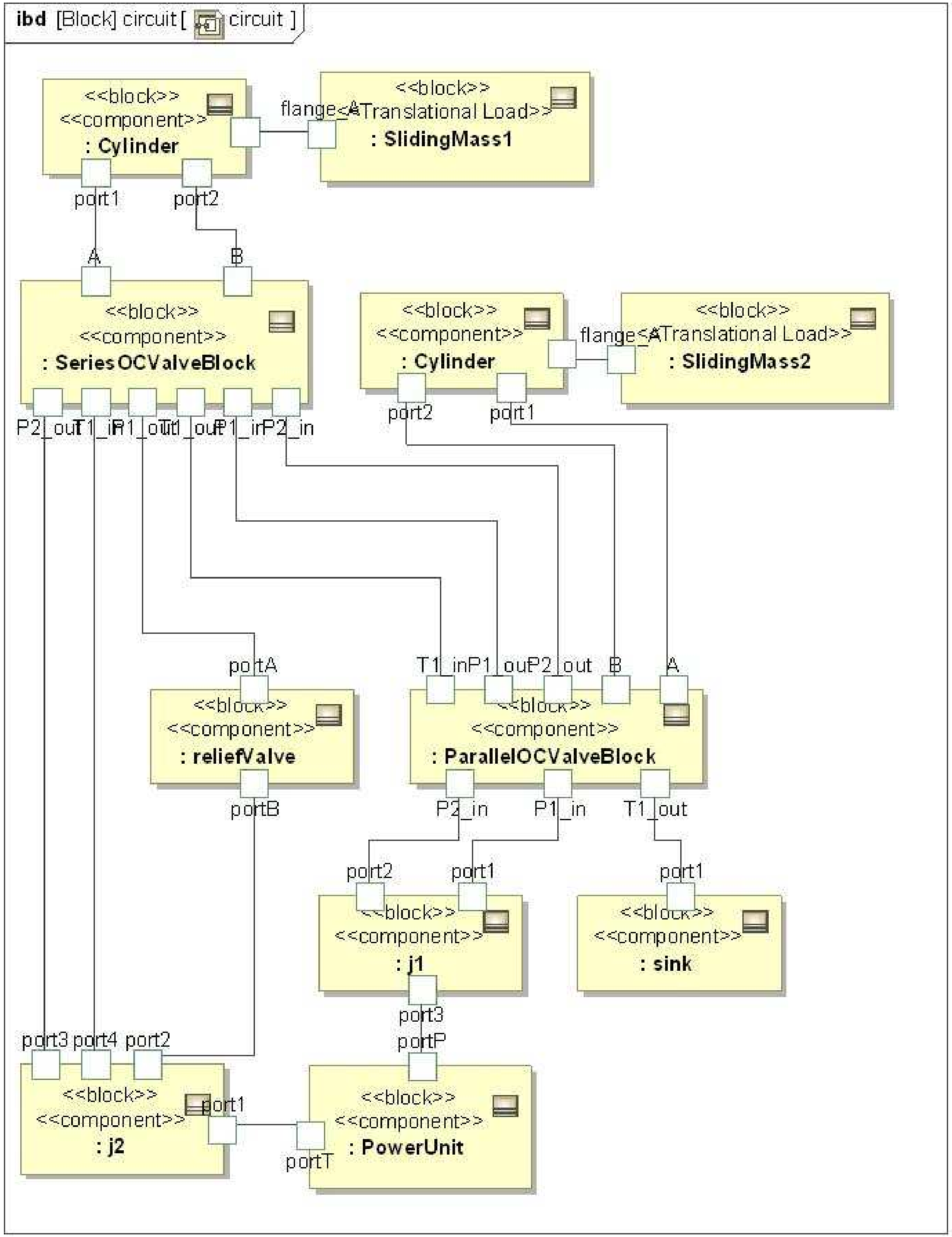
Decision Tree of Generation Process



Design Grammar Example



Apply Model Transformations



(Alek Kerzhner, MS Thesis)

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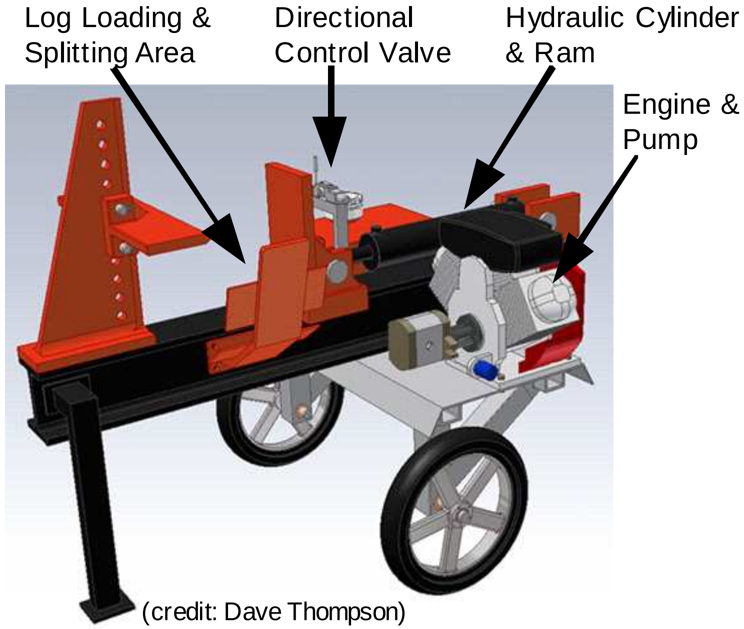
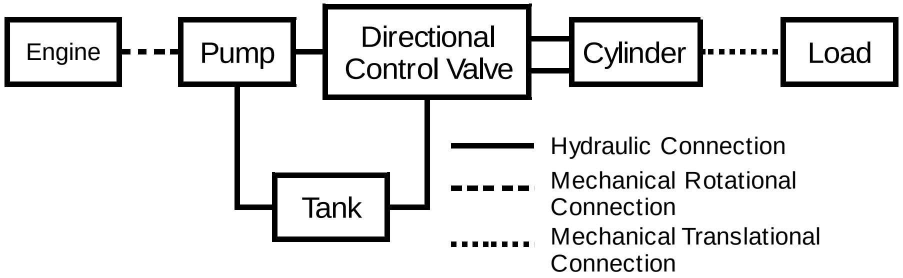
Analysis Modeling — Some Issues

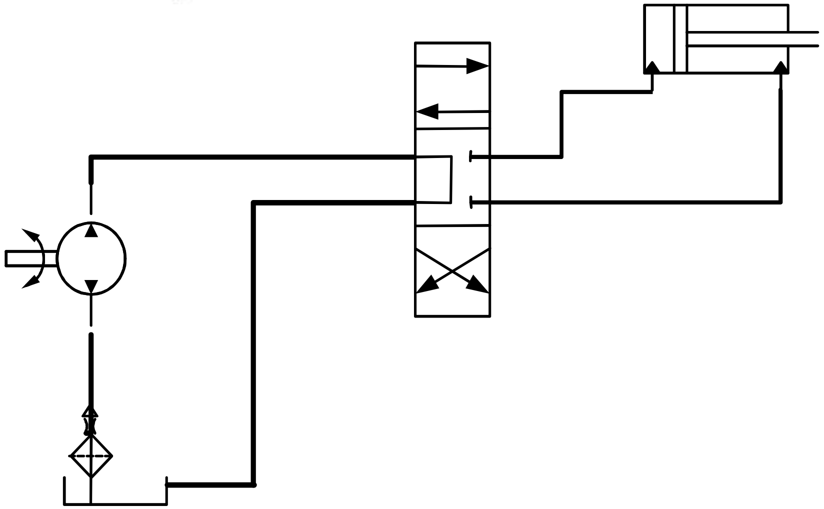
- Expanding the expressivity of parametrics:
  - SysML4Modelica for Differential Algebraic Equations
  - ModelCenter for networks of black-box analysis models
- Model reuse through composition
  - Composition knowledge in transformations
  - Model context: assumptions, applicability
- Declarative, equation-based modeling
  - More efficient solving through symbolic manipulation
- Abstraction levels
  - Best value: cost of creating/using model vs. benefit
- Predictive modeling
  - probability of future event

Example: Hydraulic Log Splitter

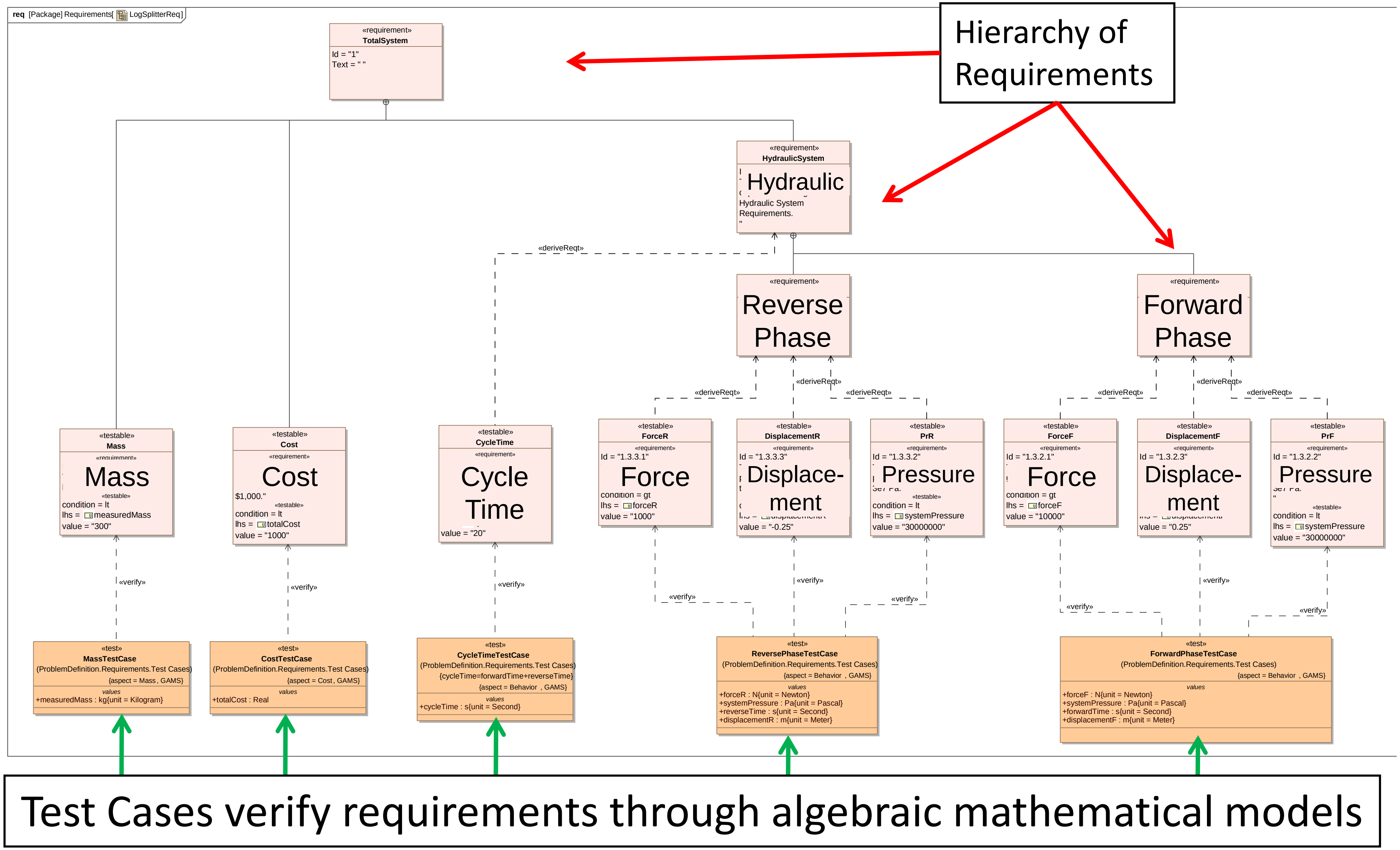
- Competing Requirements (Force, Total Time, Cost, Mass)
- Multiple Analyses (Fluid Power, Cost, Mass)
- Multiple use-phases (Forward, Reverse)
- Many components to select from



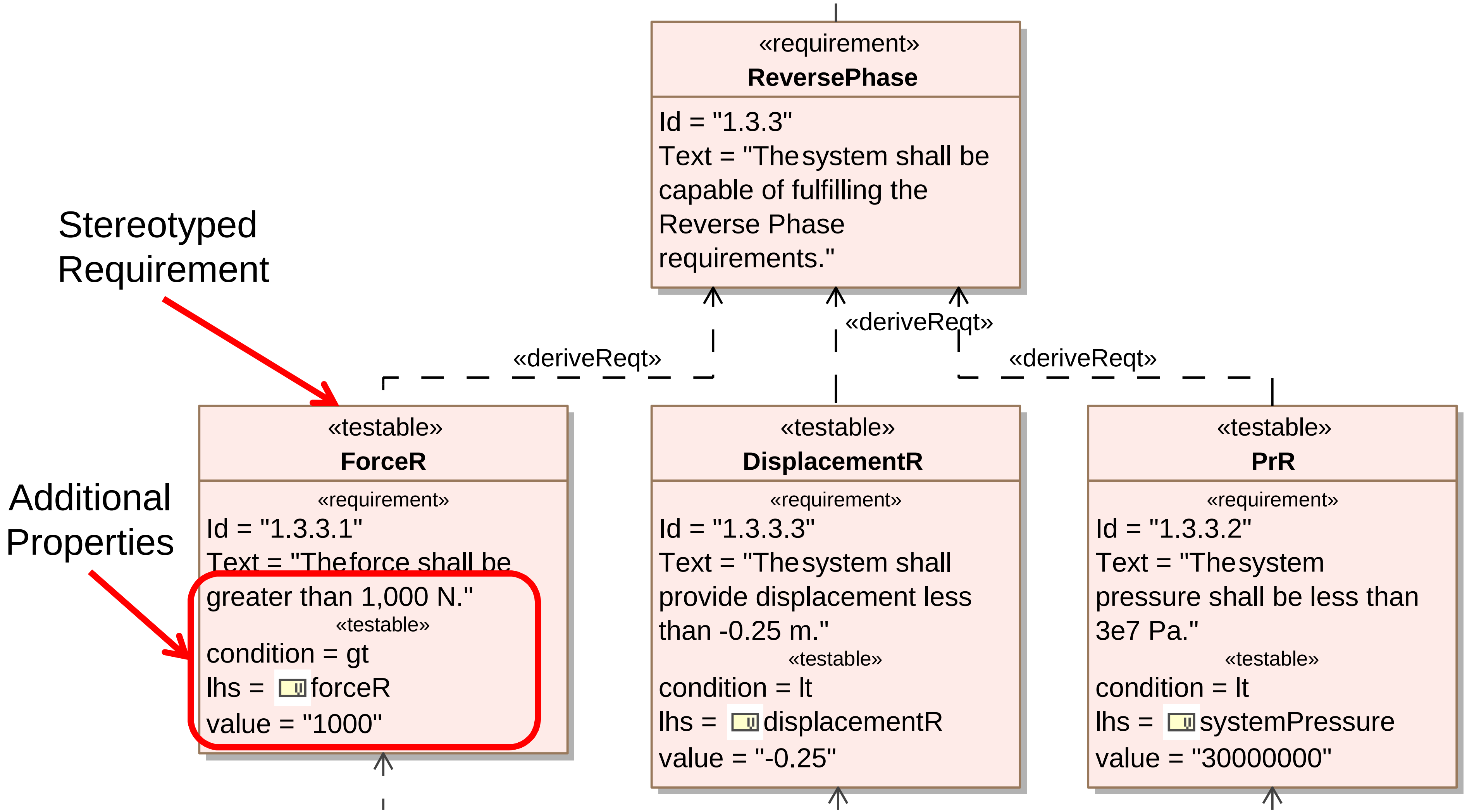




Problem Definition: Requirements Decomposition



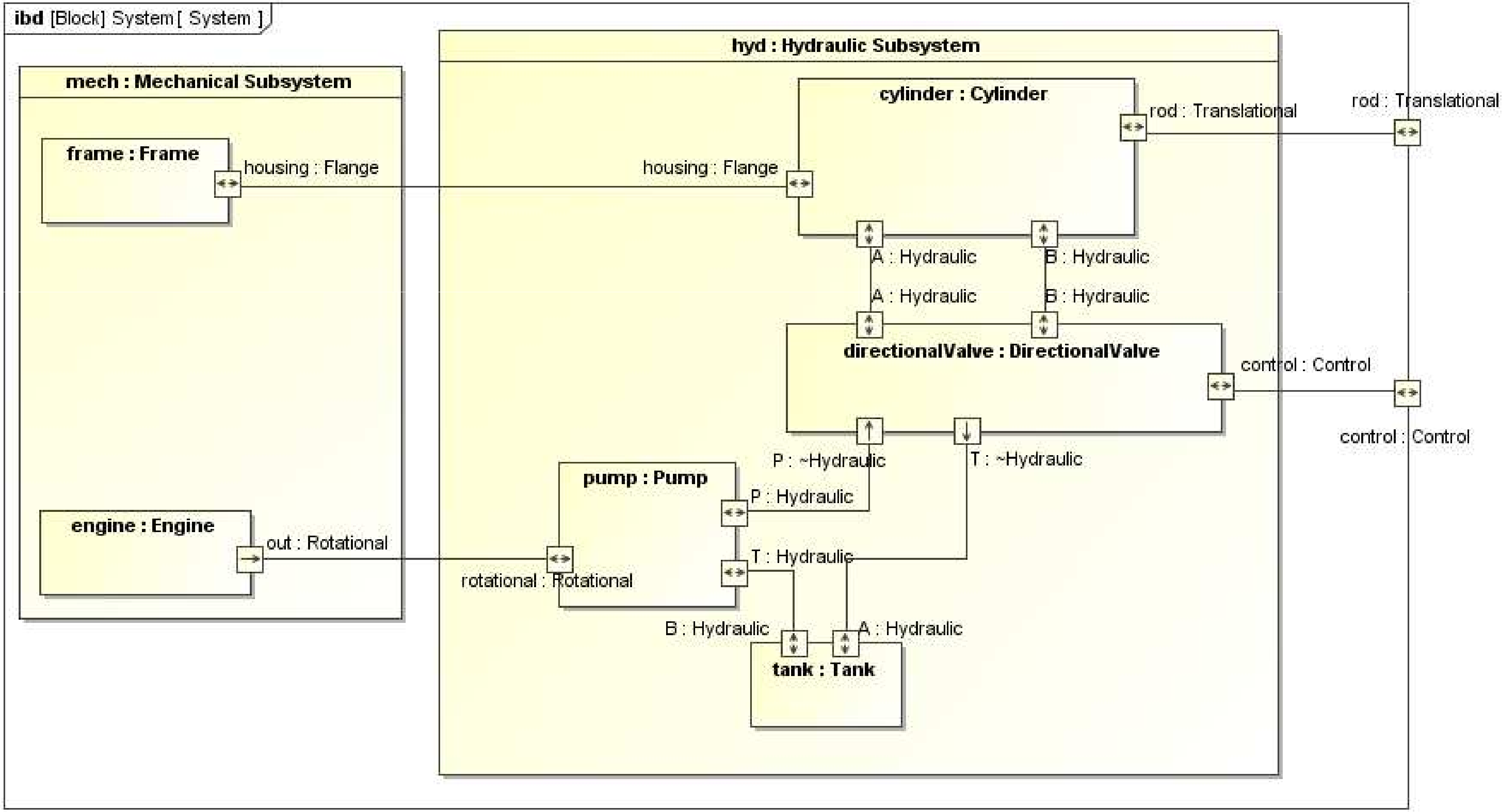
Problem Definition: «testable» Requirements



Note: Stereotype = user-defined language extension

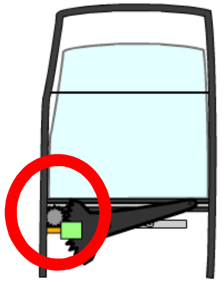
Problem Formulation: System Alternative

Internal Block Diagram



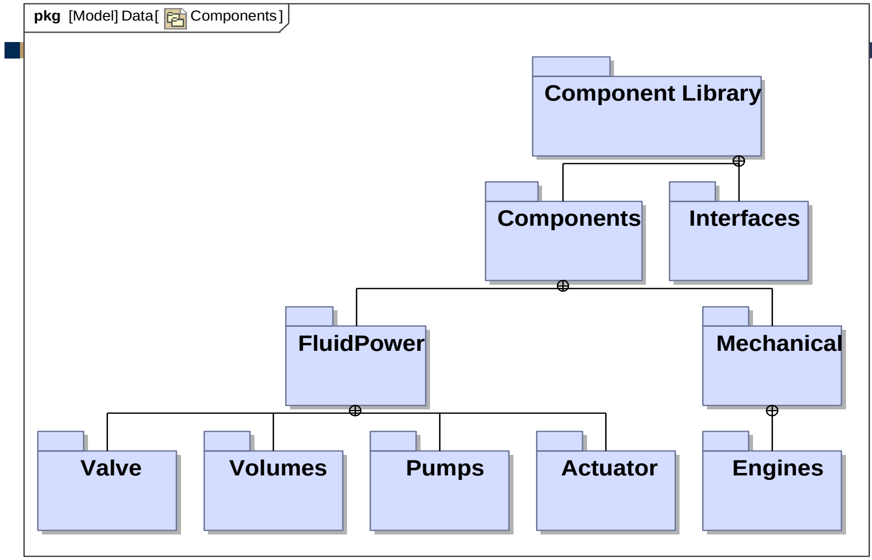
Reusable Components → Reusable Models

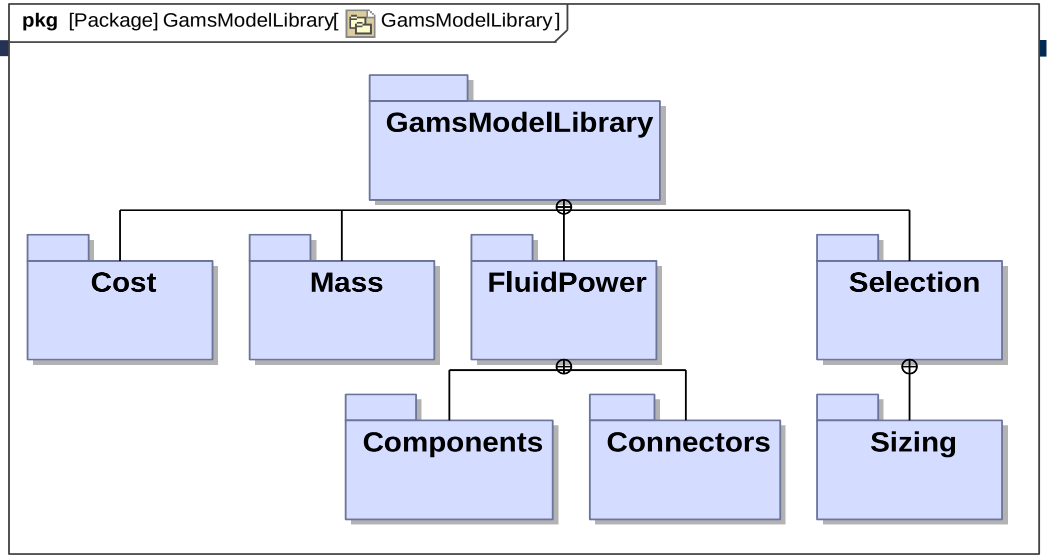
- Physical components are reused
- Portions of the system model repeat
- Patterns for instantiating these portions

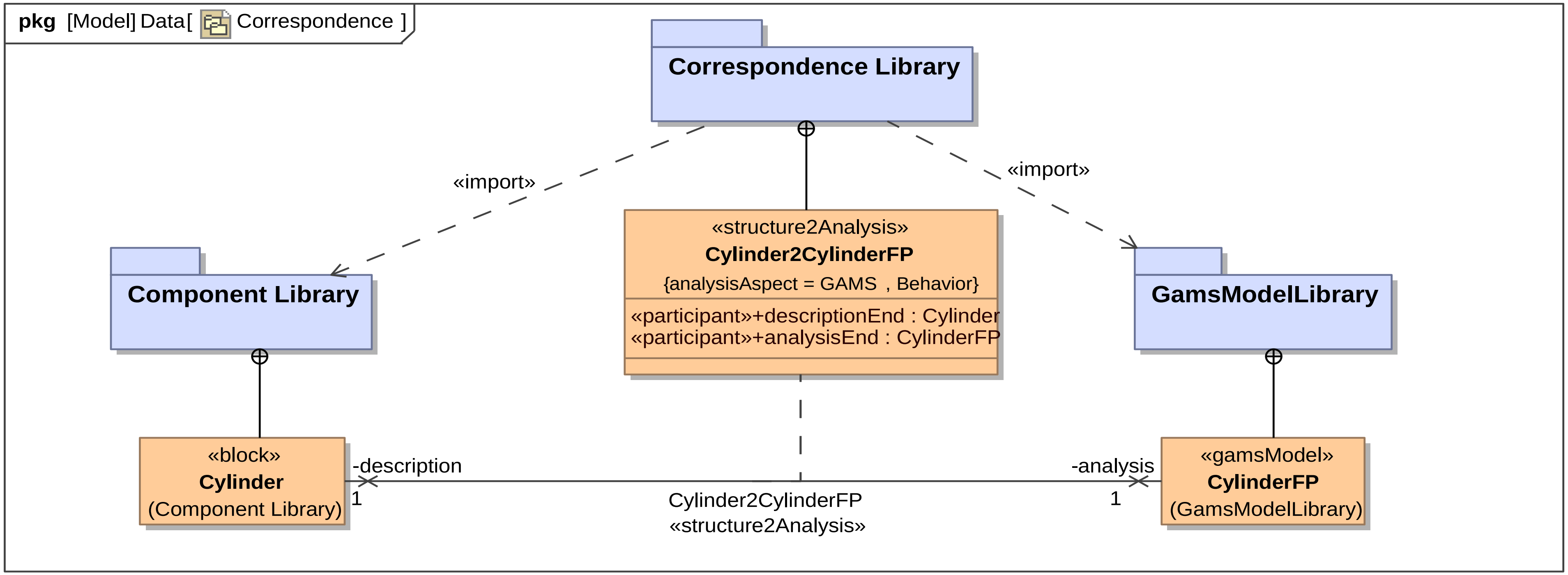


- Component models → Domain specific model libraries
- Application of pattern = Model transformations

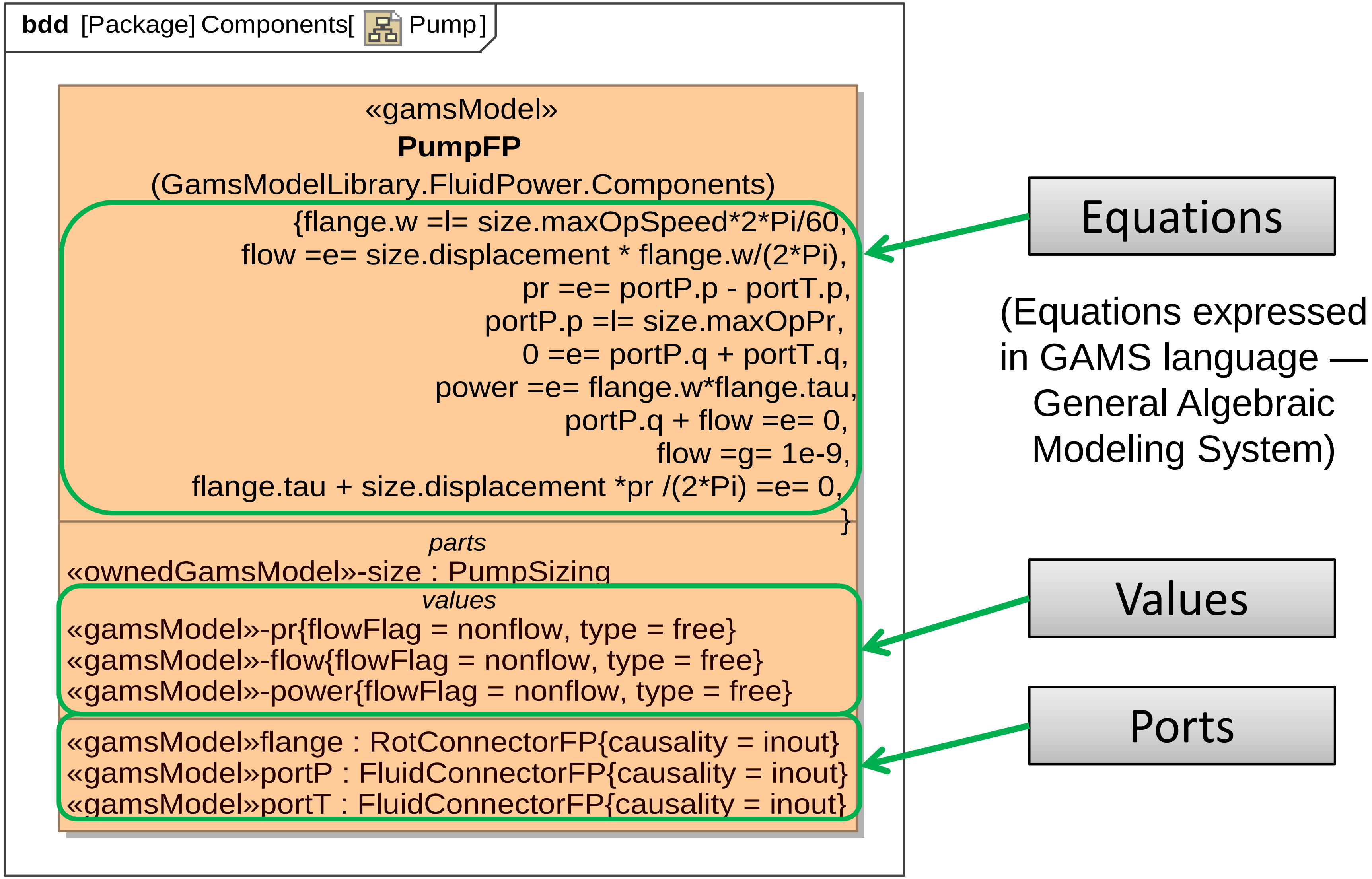
Model Libraries and Correspondences



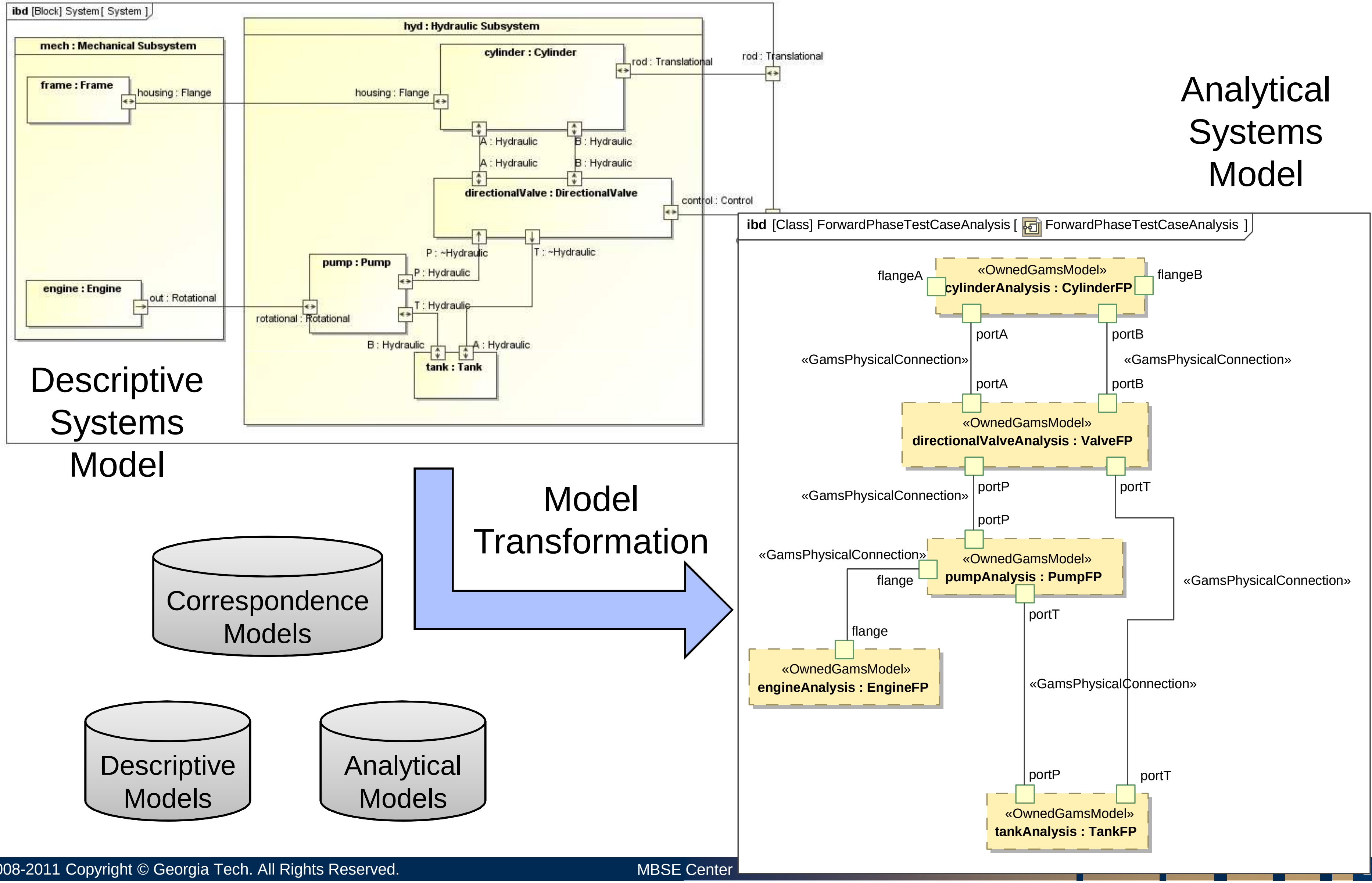




Composable Analysis Models



Composition of Analysis Models



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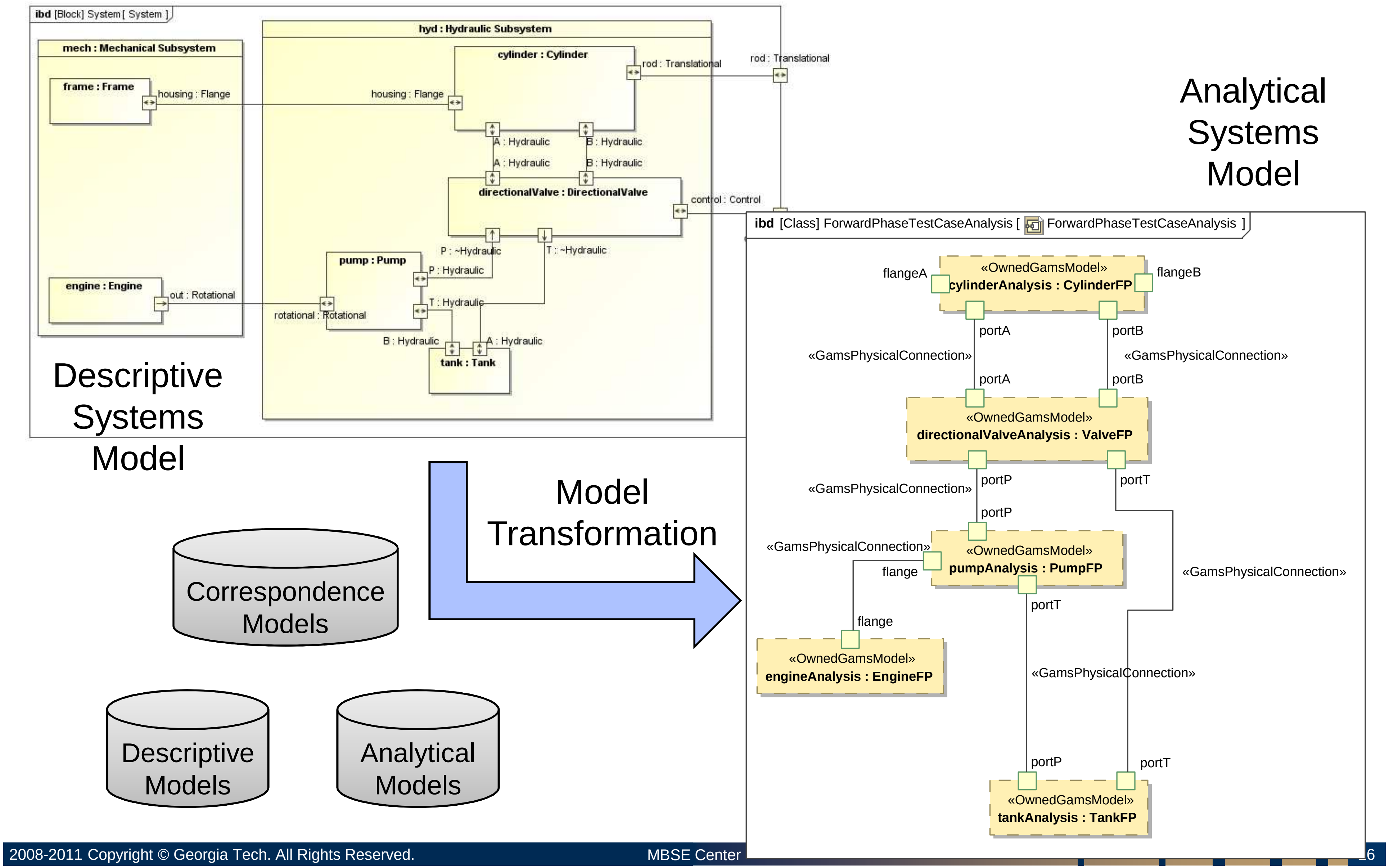
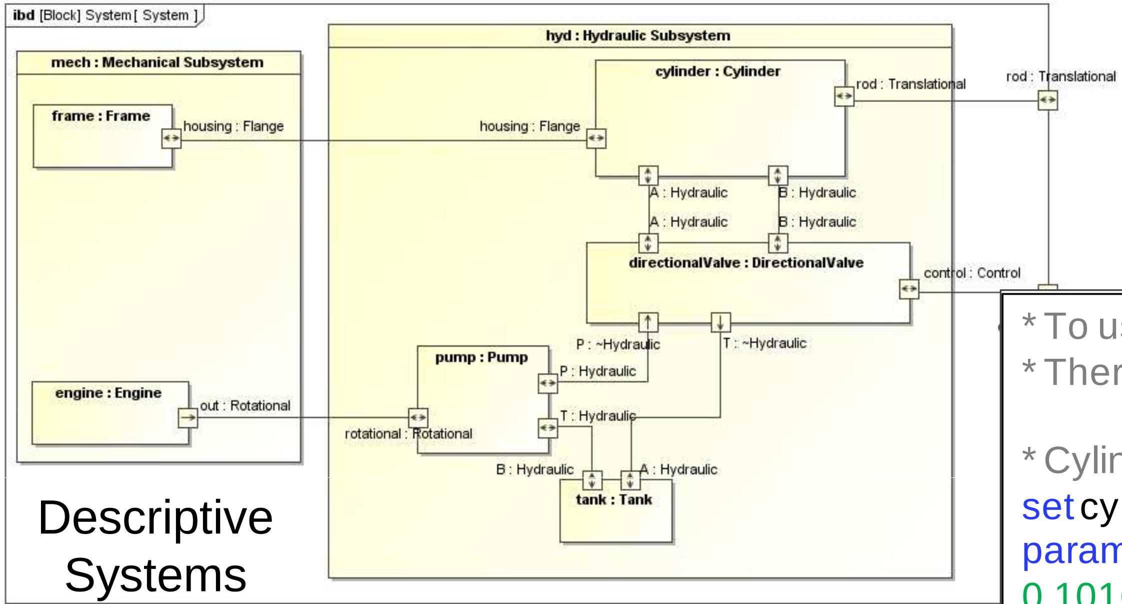
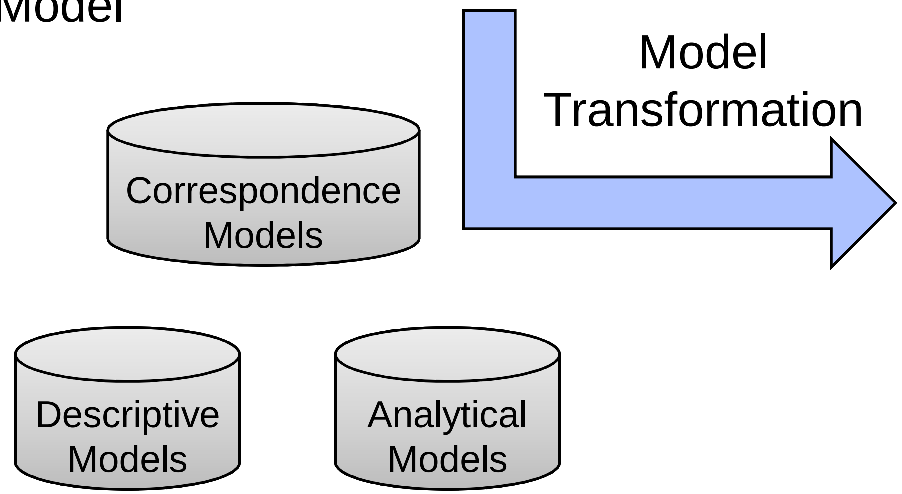


Composition of Analysis Models



Descriptive Systems Model

Analytical Systems Model




```
* To use the same cylinder model twice, a copy with
* There is no concept of objects, or model hierarchi

* Cylinder Model 1
set cylinderCatalog1 / SAE-64508, SAE-64008, HM
parameter boreDiameterData1 / SAE-64508 0.114
0.1016 /;
variable cylinder_f1, cylinder_bore1, cylinder_rod1,
equation cylinder_f_eq1;
cylinder_f_eq1.. cylinder_f1 =e= Pi*0.25*( (sqr(cylin
                                   (sqr(cylinder_bore1)-sqr(
* Cylinder Model 2
set cylinderCatalog1 / SAE-64508, SAE-64008, HM
parameter boreDiameterData1 / SAE-64508 0.114
0.1016 /;
variable cylinder_f1, cylinder_bore1, cylinder_rod1,
equation cylinder_f_eq1;
cylinder_f_eq1.. cylinder_f1 =e= Pi*0.25*( (sqr(cylin
                                   (sqr(cylinder_bore1)-sqr(
```

Resulting Optimization Problem in GAMS

System Requirements	Available Components
$F_{forward} \geq 50{,}000$ N $t_{total} \leq 20$ s $C_{total} \leq \$1000$ $m_{total} \leq 150$ kg	Engine – 45 options Pump – 64 options Cylinder – 158 options Valve – 34 options **Total Combinations – 15.5 million**

- Mixed Integer Nonlinear Programming (MINLP)
  - Discrete component selection
  - Algebraic equations expressing all requirements and objectives
- Declarative equations
  - Symbolic manipulation
  - Interval computation
  - Constraint propagation
  - Reduction

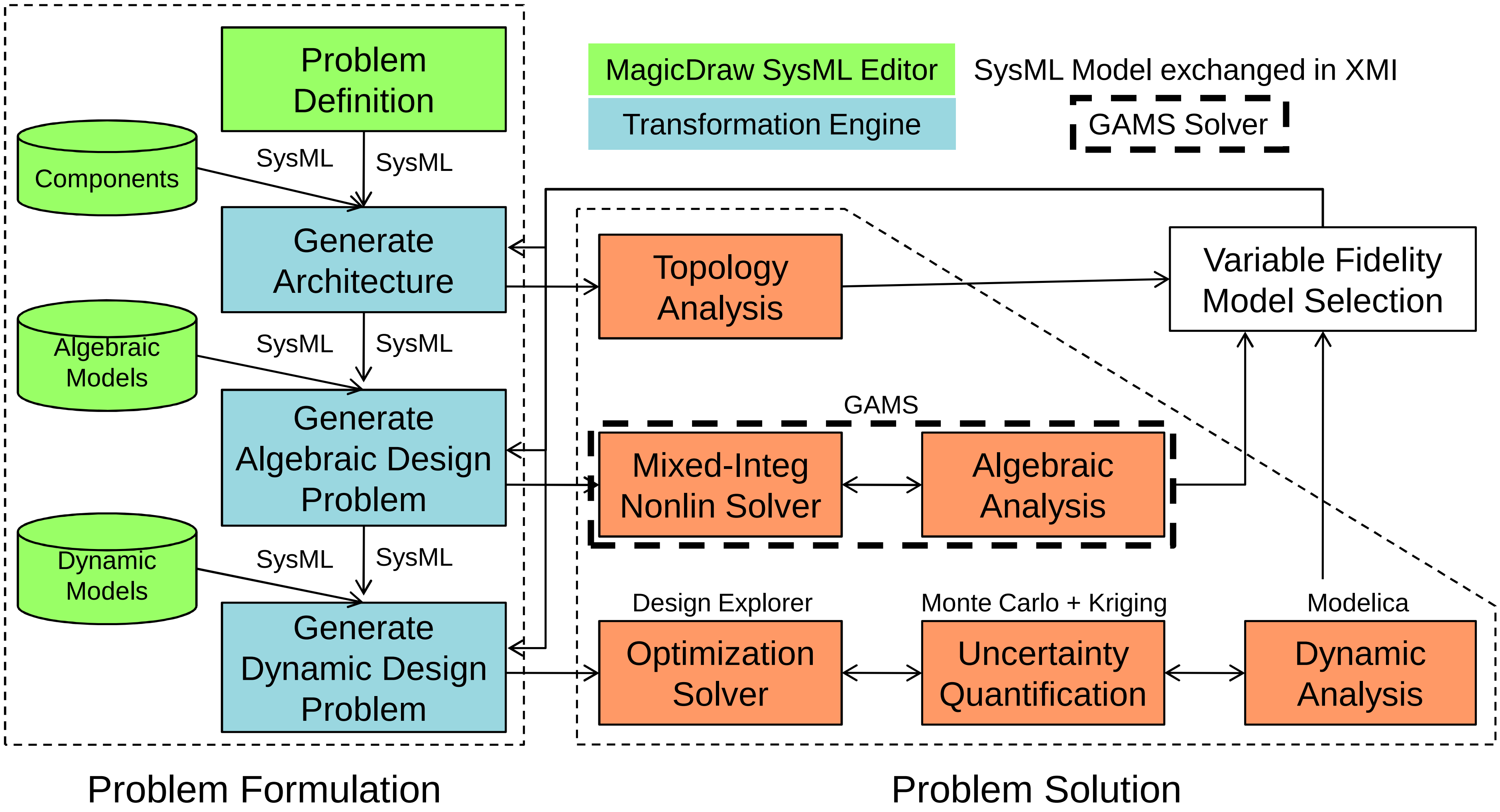
  → More efficient solution

Some Results

Scenario	Component Sizing (Selection Id from Catalog)				Variable Values					CPU Execution Time (s)
	Cylinder Id	Pump Id	Engine Id	Valve Id	Forward Force (N)	Total Mass (kg)	Total Cost ($)	Total Time (s)	z	
Maximize Force (N)	HMW-5032	SKP1NN_012	DP340E	NT-2020	139,833	94.9	993.5	20	0.40	2.82
Minimize Total Time (s)	HMW-3010	SKP1NN_012	DP390E	NT_Prince-2036	50,000	51.87	843.97	4.896	0.25	3.54
Minimize Total Cost ($)	HMW-4010	SKP1NN_012	DP240	NT-2020	53,698	51.3	657.4	9.69	0.26	2.45
Minimize Total Mass (kg)	PMC-5414	SNP2NN_4_0	DP160V	MSCDirect-01825629	52,013	32.25	708.6	9.15	0.25	78.13
Minimize Multiobjective z	HMW-5010	SKP1NN_012	DP390	NT-2020	147,437	71.53	866.3	13.79	-0.39	5.65

$$z = 0.25*((totalMass/300) + (totalTime/20) + (totalCost/1000) - (forwardForce/50000))$$

Future: Architecture Exploration Framework



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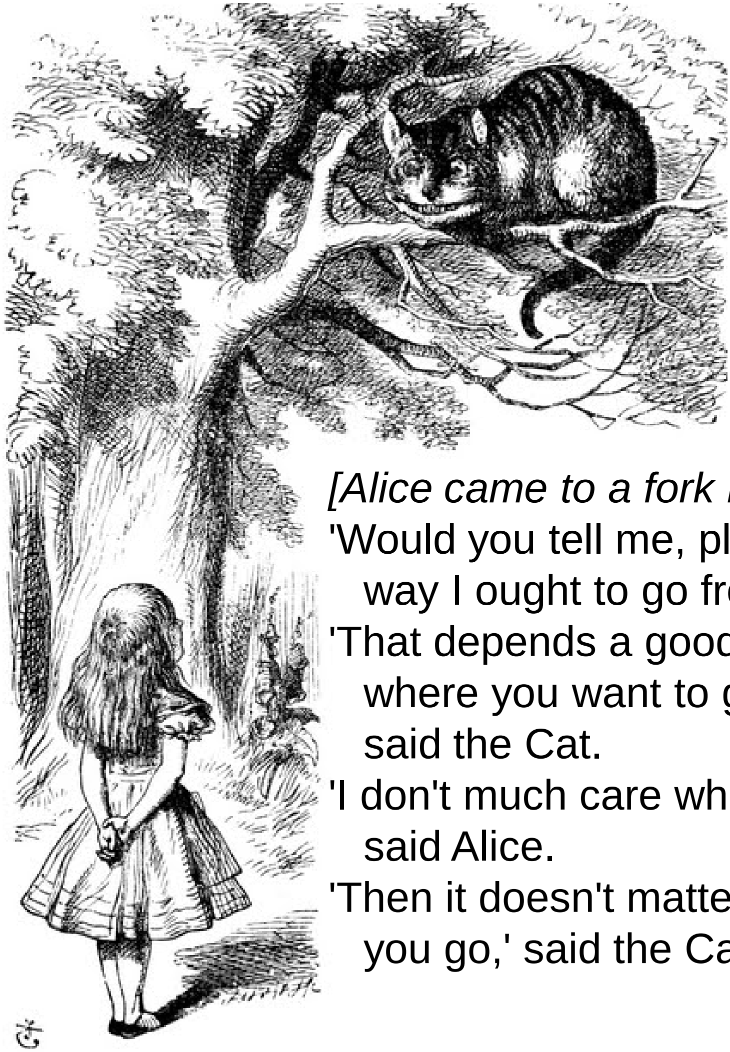
Making Decisions: Focus on Outcomes



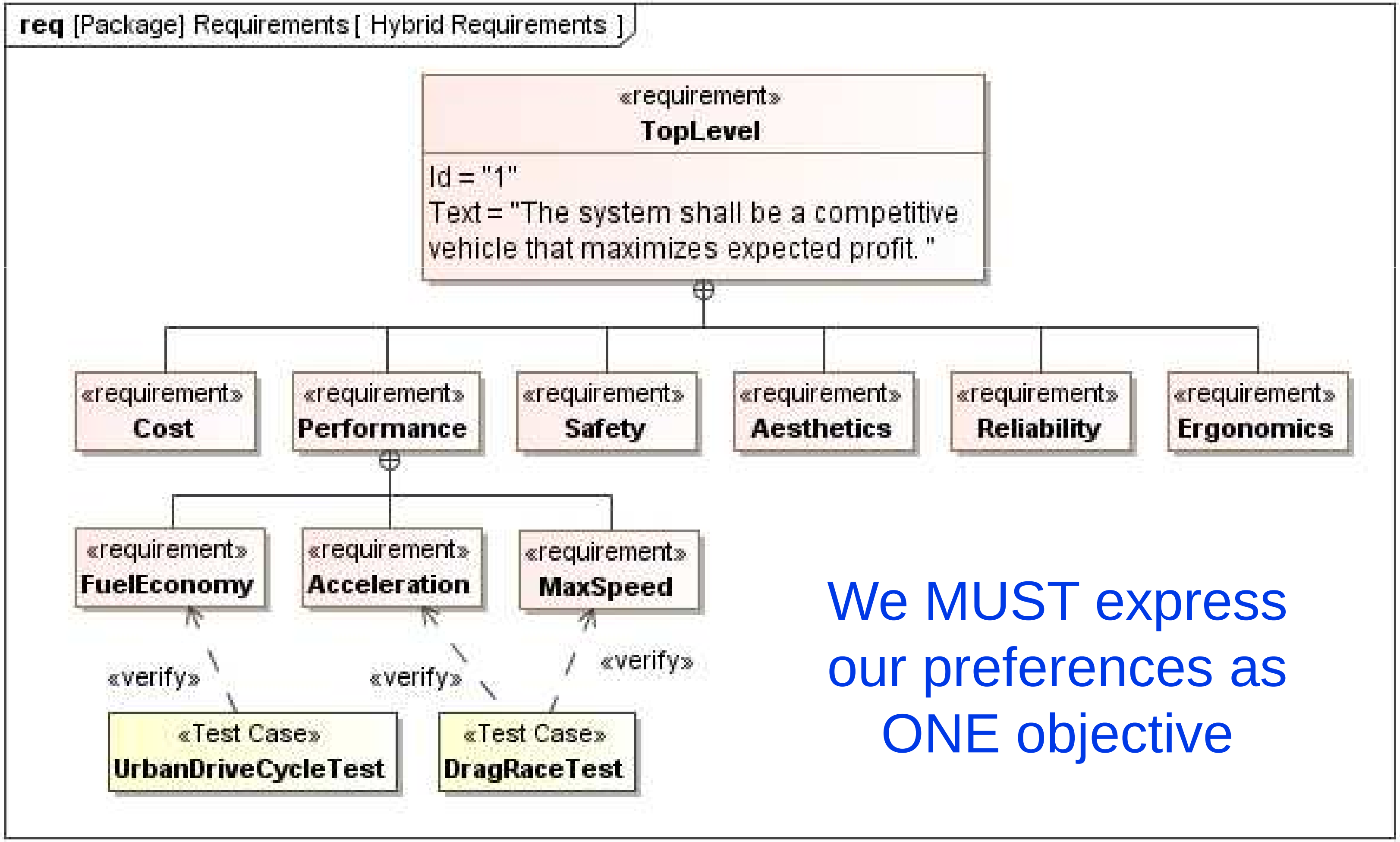
[Alice came to a fork in the road.]
'Would you tell me, please, which way I ought to go from here?'
'That depends a good deal on where you want to get to,' said the Cat.
'I don't much care where—' said Alice.
'Then it doesn't matter which way you go,' said the Cat.

- Design decisions should be made based on desired *outcomes* — What do we want to achieve?

- An *objective* is a direction in which one strives to do better
- An *attribute* is a quantity by which the attainment of an objective can be measured

What When We Have Multiple Objectives?

- Means Objectives versus Fundamental Objectives



We MUST express our preferences as ONE objective

Only One Objective: Value

- Voice of the Customer:

  “I want a car that goes from 0-60 mph in 3 seconds, gets 200 mpg and costs nothing.”

- Is it really in your best interest to build this car?

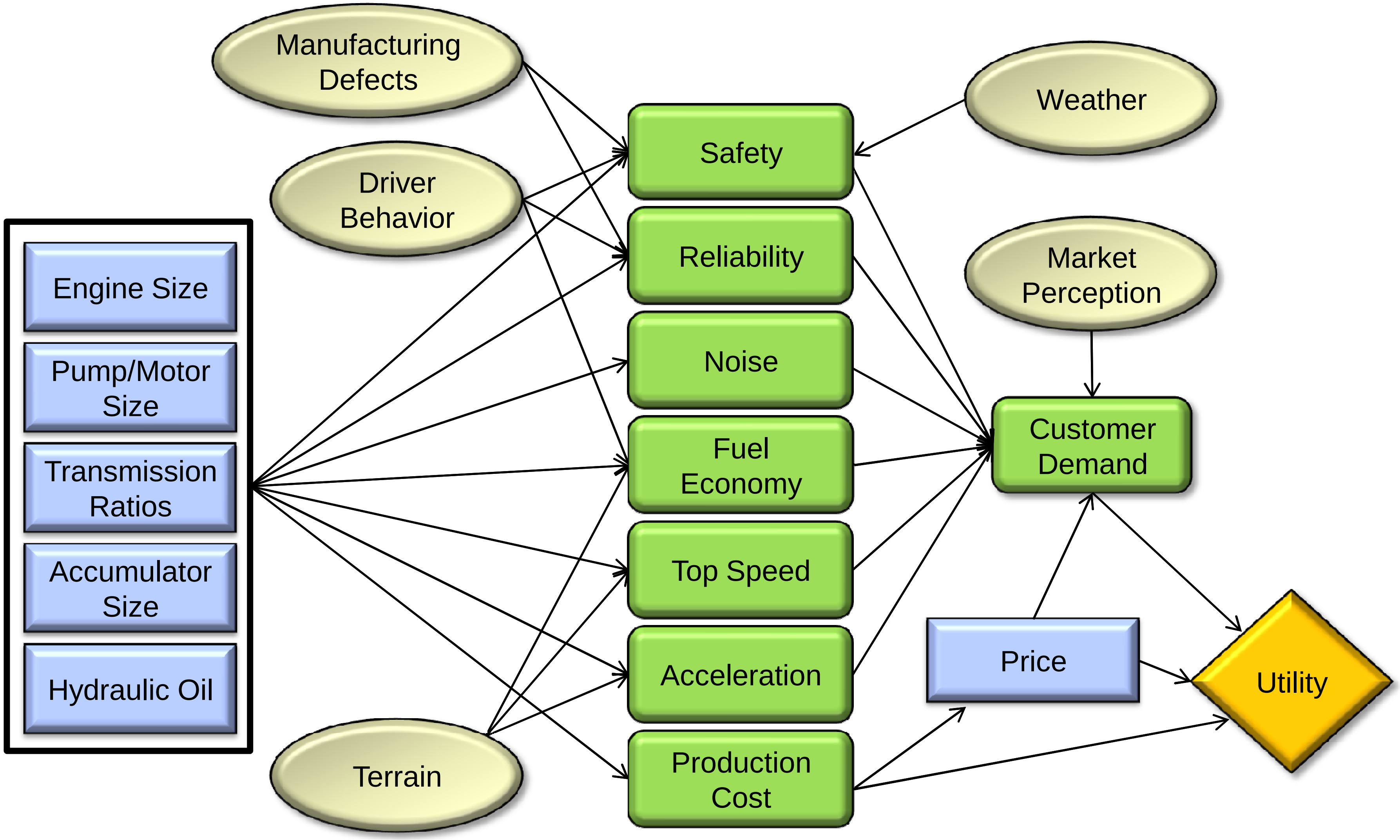
- Maximize profit
  - Voice of customer → demand → profit

Value-Driven Design

Value-Centric or Value-Driven Design

- How to express Value?
  - Maximize probability of success of a weapons system
  - Maximize the benefit to society for a non-for-profit
  - Maximizing the market share for a start-up
  - Maximizing the scientific value for a spacecraft
- Related research:
  - Paul Collopy
  - Harry Cook
  - Paul Eremenko
  - George Hazelrigg
  - Ralph Keeney
  - Jeremy Michalek
  - Joe Saleh
  - …

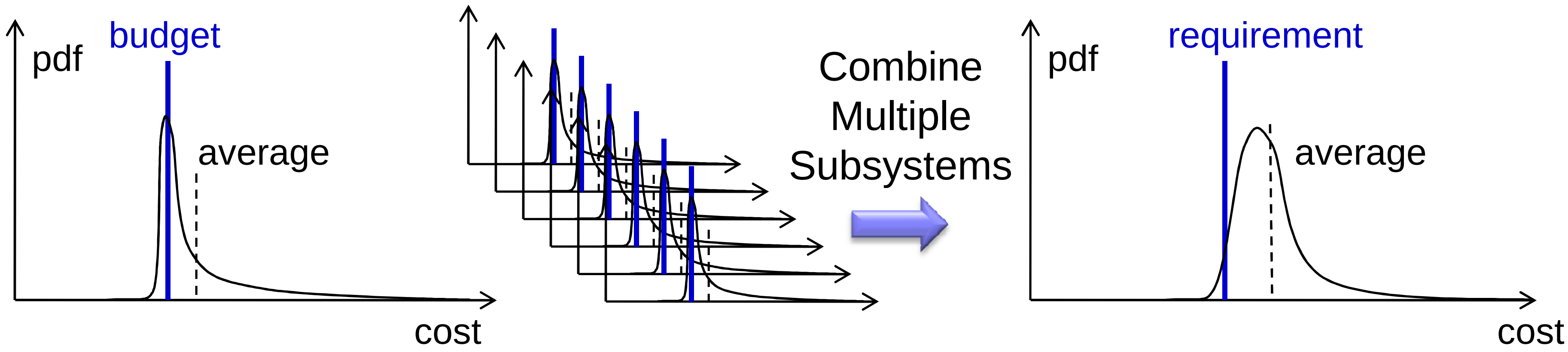
Example:
Value-Centric Design of Hydraulic Hybrid Vehicle



How About Requirements?

- Requirements as expressions of preferences
  - Requirements express only what is NOT acceptable

- Derived Requirements
  - Budgets for mass, cost, etc. provide no incentive to do better than budget
    → on average the budget constraint is violated



Summary

How can MBSE help us make better decisions?

- Goal: Improve Efficiency and Rationality
- Key Enabler: Model Transformations

- We must improve our SE methods… otherwise,

we are sure to get somewhere,
but it may not be where we wanted to go

Questions?