Model-Based Systems Engineering: A Roadmap for Academic Research

Chris Paredis
Associate Director
Model-Based Systems Engineering Center
Georgia Tech
chris.paredis@me.gatech.edu

www.pslm.gatech.edu/courses
www.omg.org/ocsmp
Acknowledgments

◆ Collaborators
  – Fried Augenbroe
  – Leon McGinnis
  – Russell Peak
  – Yan Wang

◆ Grad Students / Postdocs
  – Aditya Shah
  – Alek Kerzhner
  – Axel Reichwein
  – Ben Lee
  – Brian Taylor
  – Edward Huang
  – George Thiers
  – Kevin Davies
  – Kysang Kwon
  – Ola Batarseh
  – Roxanne Moore
  – Sebastian Herzig
  – Stephanie Thompson
  – Wladimir Schamai
Context: MBSE and Decision Making

Goal of MBSE: \textbf{Improve Efficiency & Rationality}
- \textbf{Efficient} = Perform the SE process with fewer resources
- \textbf{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

- **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

Obstacle = Opportunity for Research
Obstacles on the MBSE Roadmap

- **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

**Obstacle = Opportunity for Research**
Proposed Path to Target

- **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

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

- Initial Model
- Transformations
- Final Model

Model Libraries

- pre-image (pattern) matches?
- Model Transformation
- then generate post-image
Model Transformation

- 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

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

(Alek Kerzhner, MS Thesis)

2008-2011 Copyright © Georgia Tech. All Rights Reserved.
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?
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

![Diagram of Hydraulic Log Splitter](credit: Dave Thompson)
Problem Definition: Requirements Decomposition

Hierarchy of Requirements

Test Cases verify requirements through algebraic mathematical models
Problem Definition: «testable» Requirements

Stereotyped Requirement

Additional Properties

Note: Stereotype = user-defined language extension
Problem Formulation: System Alternative

Internal Block Diagram

ibd [Block] System [ System ]

mech : Mechanical Subsystem
frame : Frame
housing : Flange

engine : Engine
out : Rotational

hyd : Hydraulic Subsystem
cylinder : Cylinder
housing : Flange

A : Hydraulic
B : Hydraulic
A : hydraulic
B : hydraulic
directionalValve : DirectionalValve

P : ~Hydraulic
T : ~Hydraulic

pump : Pump
P : Hydraulic
T : Hydraulic

B : Hydraulic
A : Hydraulic
tank : Tank

rod : Translational
control : Control

2008-2011 Copyright © Georgia Tech. All Rights Reserved.
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

Component Library
  - FluidPower
    - Valve
    - Volumes
    - Pumps
    - Actuator
  - Mechanical
    - Engines

GamsModelLibrary
  - Cost
  - Mass
  - FluidPower
  - Selection
  - Components
  - Connectors
  - Sizing

Correspondence Library
  - Cylinder2CylinderFP
    - analysisAspect = GAMS, Behavior
    - participant+descriptionEnd : Cylinder
    - participant+analysisEnd : CylinderFP

Component Library
  - Cylinder
    - description

GamsModelLibrary
  - CylinderFP
    - gamsModel

Cylinder2CylinderFP
  - structure2Analysis
Composable Analysis Models

GAMS Model: PumpFP

- Equations

\[
\begin{align*}
\text{flange}.w & \leq \text{size}.\text{maxOpSpeed} \times 2\pi / 60, \\
\text{flow} & = \text{size}.\text{displacement} \times \text{flange}.w / (2\pi), \\
\text{pr} & = \text{portP}.p - \text{portT}.p, \\
\text{portP}.p & \leq \text{size}.\text{maxOpPr}, \\
0 & = \text{portP}.q + \text{portT}.q, \\
\text{power} & = \text{flange}.w \times \text{flange}.\text{tau}, \\
\text{portP}.q + \text{flow} & = 0, \\
\text{flow} & = g = 1 \times 10^{-9}, \\
\text{flange}.\tau + \text{size}.\text{displacement} \times \text{pr} / (2\pi) & = 0.
\end{align*}
\]

- Values

- Ports
Composition of Analysis Models

Descriptive Systems Model

Analytical Systems Model

Model Transformation
Composition of Analysis Models

Descriptive Systems Model

Model Transformation

Correspondence Models

Descriptive Models

Analytical Models

Analytical Systems Model

Composition of Analysis Models
Composition of Analysis Models

Descriptive Systems Model

Model Transformation

Analytical Systems Model

* To use the same cylinder model twice, a copy with unique names must be created.
* There is no concept of objects, or model hierarchies, or reuse of the same model.

* Cylinder Model 1
  set cylinderCatalog1 / SAE-64508, SAE-64008, HM
  parameter boreDiameterData1 / SAE-64508 0.1143, SAE-64008 0.1016 /
  variable cylinder_f1, cylinder_bore1, cylinder_rod1,
  equation cylinder_f_eq1;
  cylinder_f_eq1..cylinder_f1 =e= Pi*0.25*(sqr(cylinder_bore1)-sqr(cylinder_rod1));

* Cylinder Model 2
  set cylinderCatalog1 / SAE-64508, SAE-64008, HM
  parameter boreDiameterData1 / SAE-64508 0.1143, SAE-64008 0.1016 /
  variable cylinder_f1, cylinder_bore1, cylinder_rod1,
  equation cylinder_f_eq1;
  cylinder_f_eq1..cylinder_f1 =e= Pi*0.25*(sqr(cylinder_bore1)-sqr(cylinder_rod1));
Resulting Optimization Problem in GAMS

<table>
<thead>
<tr>
<th>System Requirements</th>
<th>Available Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{forward}} \geq 50,000 ) N</td>
<td>Engine – 45 options</td>
</tr>
<tr>
<td>( t_{\text{total}} \leq 20 ) s</td>
<td>Pump – 64 options</td>
</tr>
<tr>
<td>( C_{\text{total}} \leq 1000 )</td>
<td>Cylinder – 158 options</td>
</tr>
<tr>
<td>( m_{\text{total}} \leq 150 ) kg</td>
<td>Valve – 34 options</td>
</tr>
</tbody>
</table>

**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
  \( \rightarrow \) More efficient solution
## Some Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Component Sizing (Selection Id from Catalog)</th>
<th>Variable Values</th>
<th>CPU Execution Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder Id</td>
<td>Pump Id</td>
<td>Engine Id</td>
<td>Valve Id</td>
</tr>
<tr>
<td>Maximize Force (N)</td>
<td>HMW-5032</td>
<td>SKP1NN_012</td>
<td>DP340E</td>
</tr>
<tr>
<td>Minimize Total Time (s)</td>
<td>HMW-3010</td>
<td>SKP1NN_012</td>
<td>DP390E</td>
</tr>
<tr>
<td>Minimize Total Cost ($)</td>
<td>HMW-4010</td>
<td>SKP1NN_012</td>
<td>DP240</td>
</tr>
<tr>
<td>Minimize Total Mass (kg)</td>
<td>PMC-5414</td>
<td>SNP2NN_4_0</td>
<td>DP160V</td>
</tr>
<tr>
<td>Minimize Multiobjective z</td>
<td>HMW-5010</td>
<td>SKP1NN_012</td>
<td>DP390</td>
</tr>
</tbody>
</table>

\[ z = 0.25\times\left(\frac{\text{totalMass}}{300} + \frac{\text{totalTime}}{20} + \frac{\text{totalCost}}{1000} - \frac{\text{forwardForce}}{50000}\right) \]
Future: Architecture Exploration Framework
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 \rightarrow\text{descriptive}
- Predictive modeling of consequence \rightarrow\text{analytical}

More rational decision making with MBSE
- How to formulate design decisions?
Making Decisions: Focus on Outcomes

- 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

[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.
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

- Engine Size
- Pump/Motor Size
- Transmission Ratios
- Accumulator Size
- Hydraulic Oil
- Manufacturing Defects
- Driver Behavior
- Safety
- Reliability
- Noise
- Fuel Economy
- Top Speed
- Acceleration
- Production Cost
- Terrain
- Weather
- Market Perception
- Customer Demand
- Price
- Utility
- Customer Demand
- Price
- Utility
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?