A Rigorous Framework for Model-based Systems Engineering and Applications

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“The Nation that has the System Engineers has the Future”

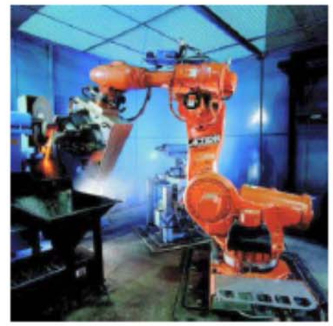
John S. Baras, *Systems and Signals*, Vol. 4.2, May 1990

The Next Frontier in Engineering Research and Education

- First 25 years of the 21st century will be **dominated** by advances in methods and tools for the **synthesis of complex engineered systems to meet specifications in an adaptive manner**
- Evident from the areas emphasized by governments, industry and funding agencies world-wide:
  - **energy and smart grids**
  - **biotechnology**
  - **systems biology**
  - **nanotechnology**
  - **the new Internet**
  - **collaborative robotics**
  - **software critical systems**
  - **homeland security**
  - **materials design at sub-molecular level**
  - **network science**
  - **environment and sustainability**
  - **intelligent buildings and cars**
  - **customizable health care**
  - **pharmaceutical manufacturing innovation**
  - **broadband wireless networks**
  - **sensor networks**
  - **transportation systems**
  - **security-privacy-authentication in wireless networks**
  - **cyber-physical systems**
  - **web-based social and economic networks**

NETWORKED EMBEDDED SYSTEMS AND CPS SEI

Automotive



Industrial automation

Robotics

Aeronautics

Elevators

Building automation

Virtual Engineering Everywhere

Helping over 30 different teams and skills in the company work together

Linking over 40 different EE design representations throughout the entire development process

Ensuring that the EE design flow is integrated at the same level of quality and performance as the 3D CAD system

Model based design and executable specification in the OEM/supplier chain

Albert Benveniste -- *INRIA*

Virtual Engineering Everywhere CAD models

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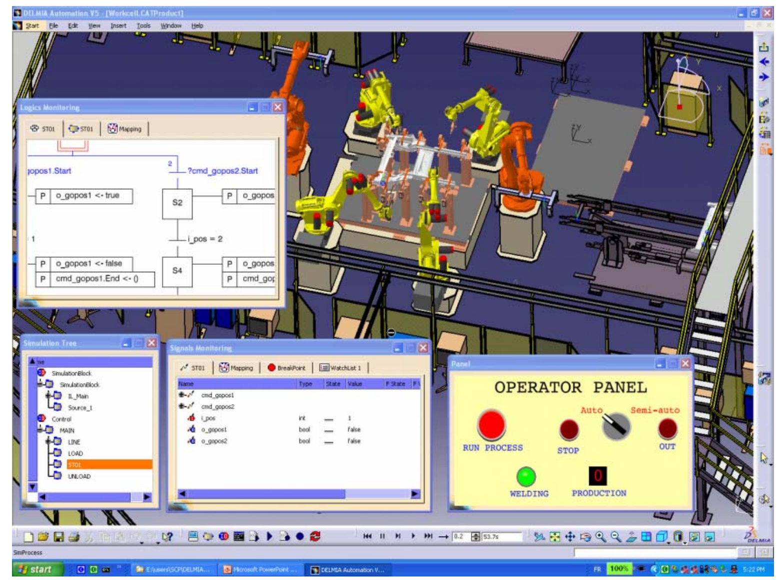

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Virtual Engineering Everywhere Multi-Physics models

Helping over 30 different teams and skills in the company work together

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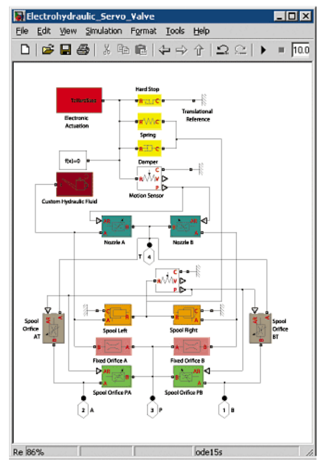

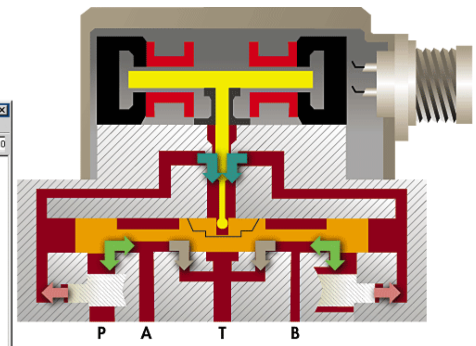

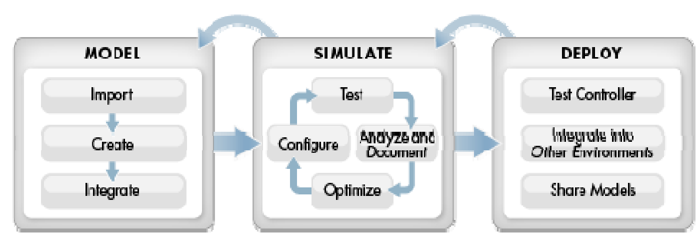

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Virtual Engineering Everywhere Embedded Software

Helping over 30 different teams and skills in the company work together

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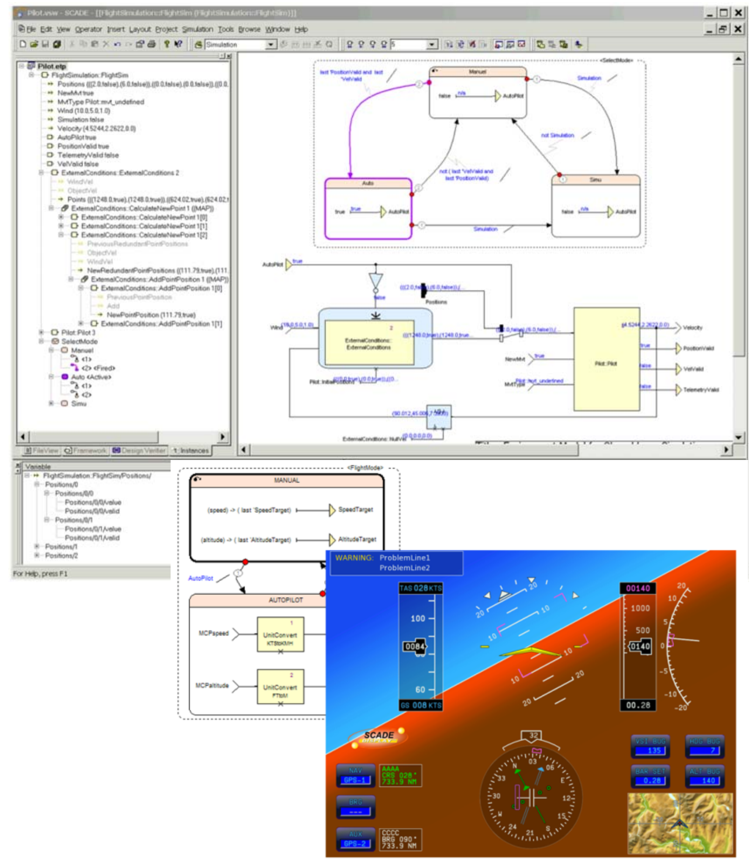

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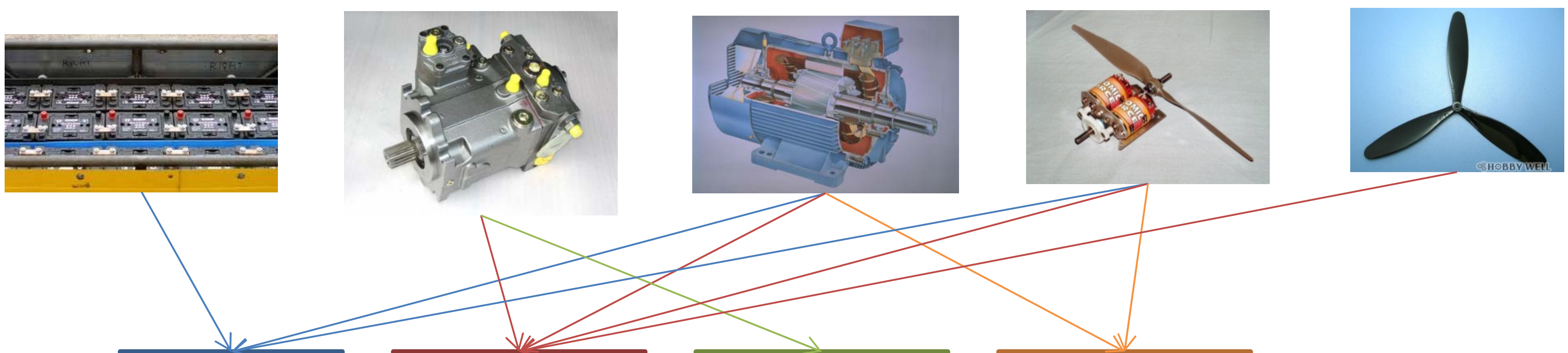
Model Integration Challenge: Physics

Heterogeneity of Physics

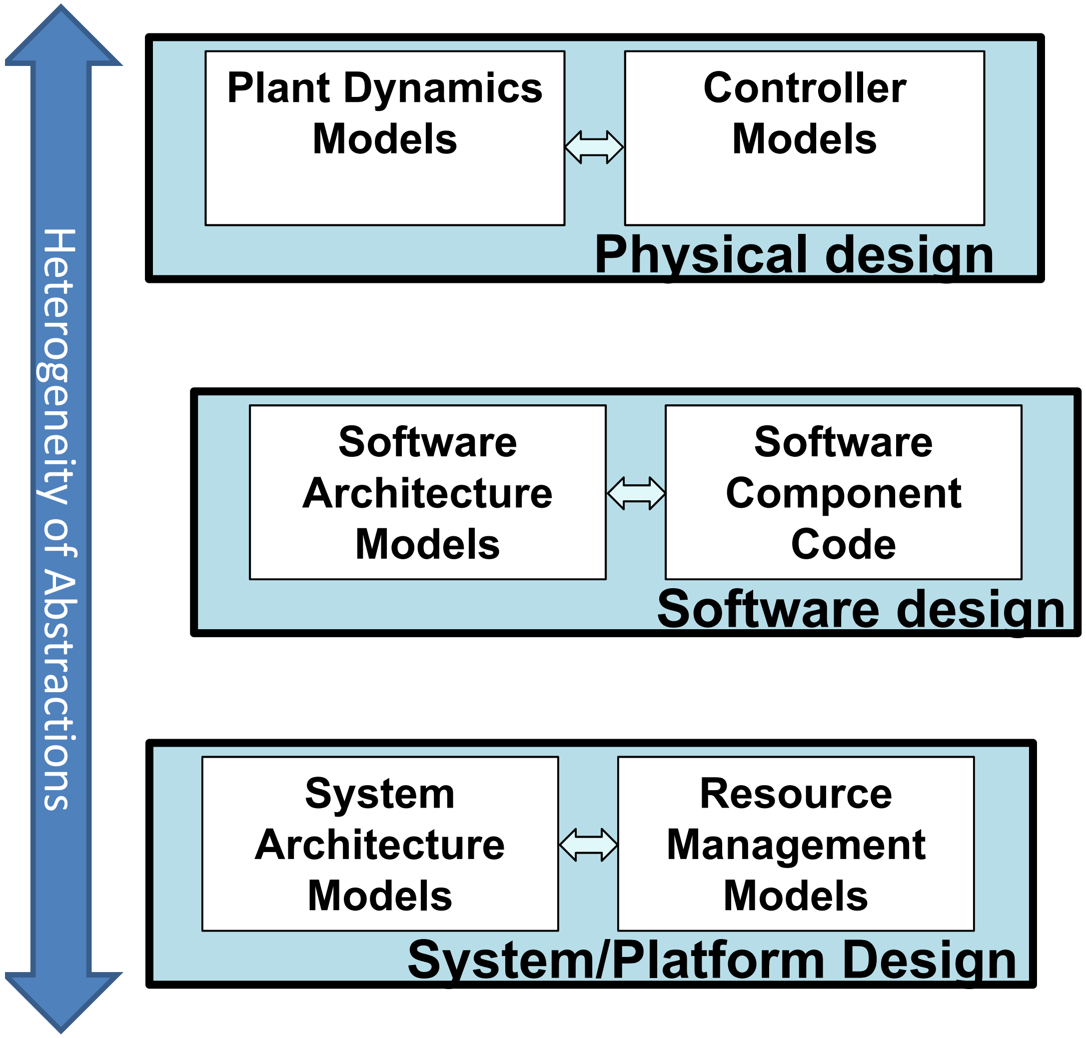


Electrical Domain	Mechanical Domain	Hydraulic Domain	Thermal Domain	• • •
Theories, Dynamics, Tools	Theories, Dynamics, Tools	Theories, Dynamics, Tools	Theories, Dynamics, Tools	

Physical components are involved in multiple physical interactions (multi-physics)
Challenge: How to compose multi-models for heterogeneous physical components

Janos Sztipanovits – *Vanderbilt Un.*

Model Integration Challenge: Abstraction Layers



Dynamics: $B(t) = \kappa_p(B_1(t), \ldots, B_j(t))$

- *Properties*: stability, safety, performance
- *Abstractions*: continuous time, functions, signals, flows,…

Software : $B(i) = \kappa_c(B_1(i), \ldots, B_k(i))$

- *Properties*: deadlock, invariants, security,…
- *Abstractions*: logical-time, concurrency, atomicity, ideal communication,..

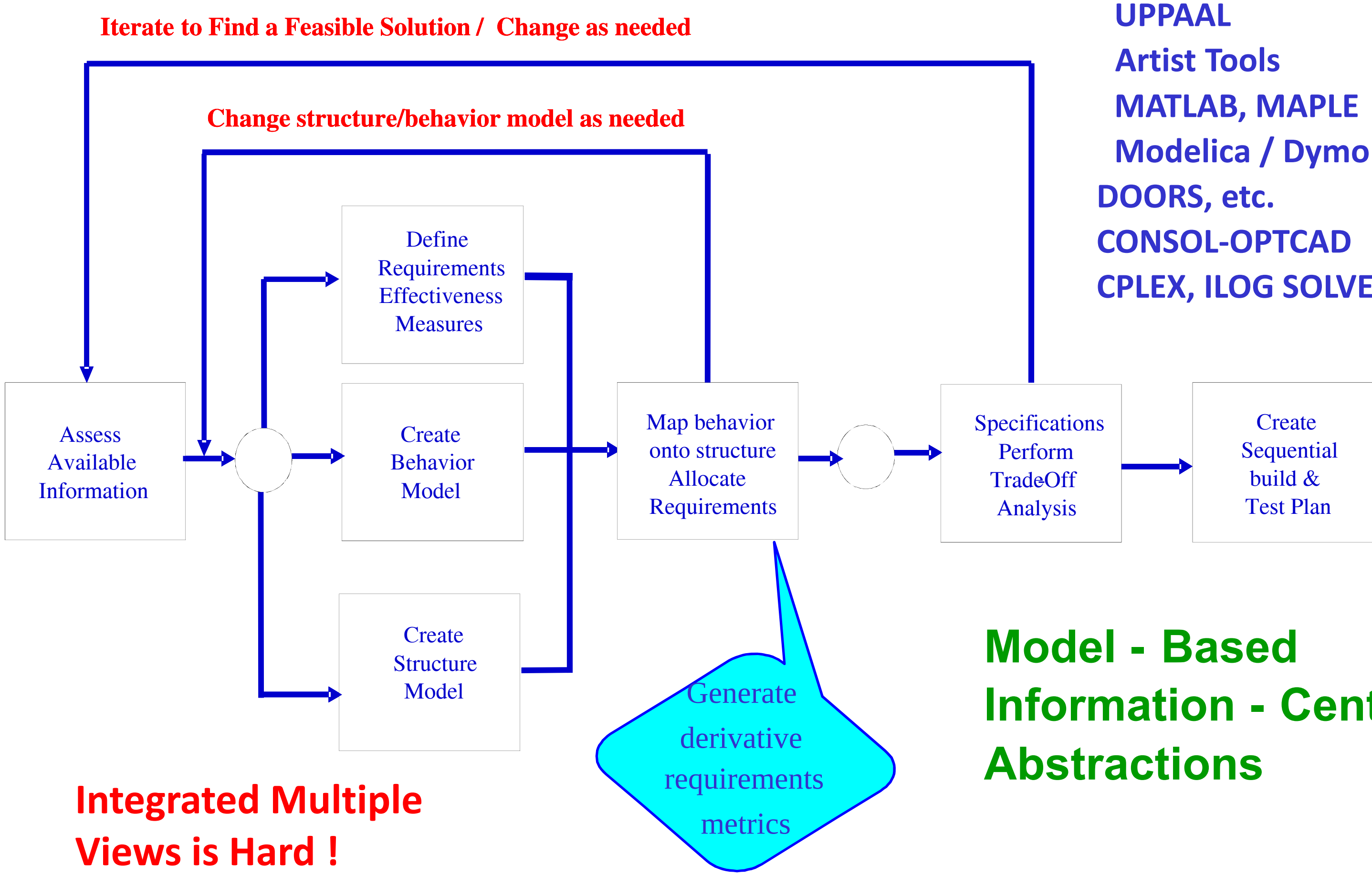
Systems : $B(t_j) = \kappa_p(B_1(t_i), \ldots, B_k(t_i))$

- *Properties*: timing, power, security, fault tolerance
- *Abstractions*: discrete-time, delays, resources, scheduling,

Cyber-physical components are modeled using multiple abstraction layers
Challenge: How to compose abstraction layers in heterogeneous CPS components?

COMPONENT- BASED SYSTEM SYNTHESIS

Integrated System Synthesis Tools - & Environments missing



Model - based

- UML - SysML - GME - eMFLON
- Rapsody, MagicDraw
- UPPAAL
- Artist Tools
- MATLAB, MAPLE
- Modelica / Dymola

DOORS, etc.

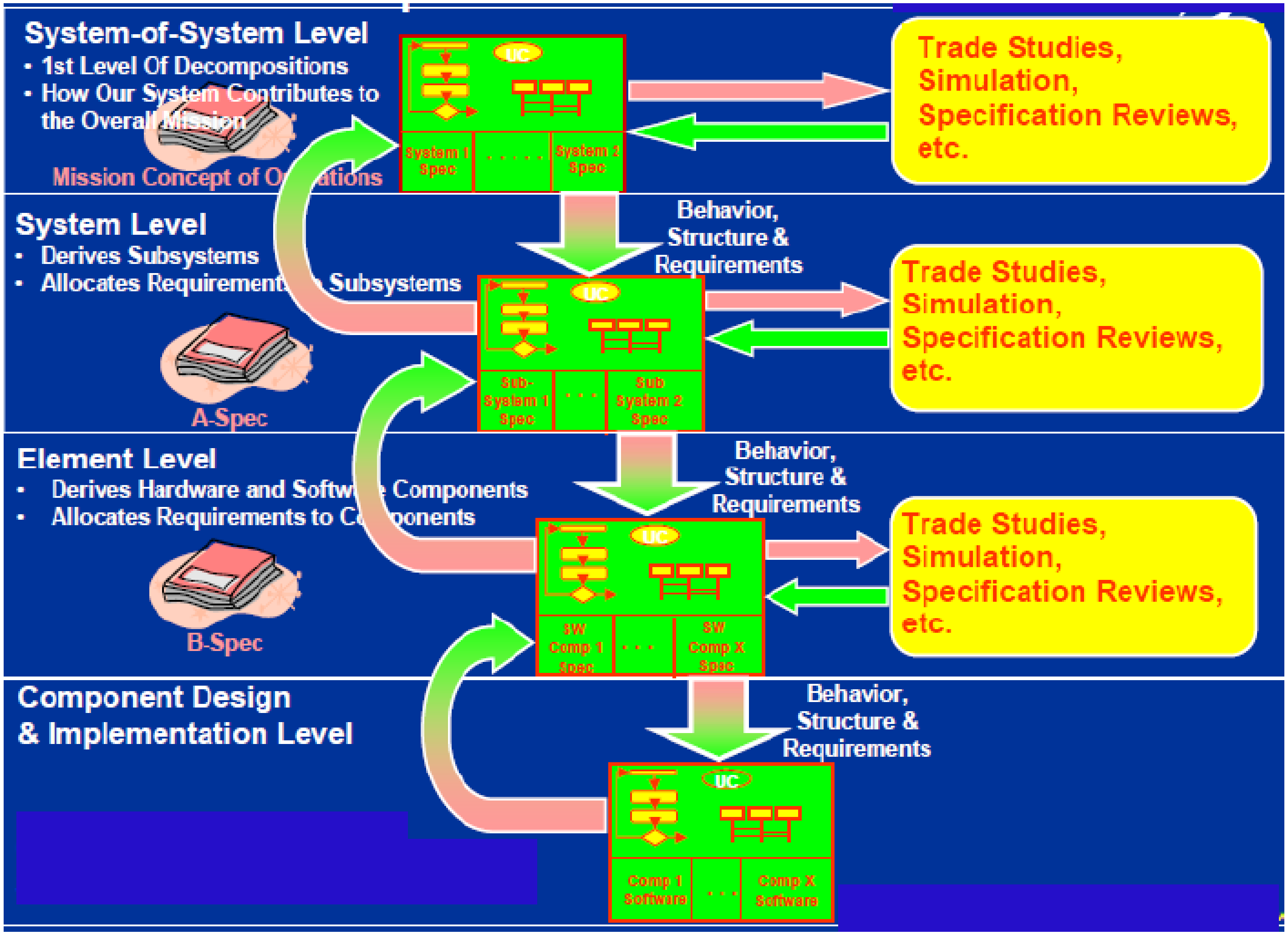
CONSOL-OPTCAD

CPLEX, ILOG SOLVER

Model - Based Information - Centric Abstractions

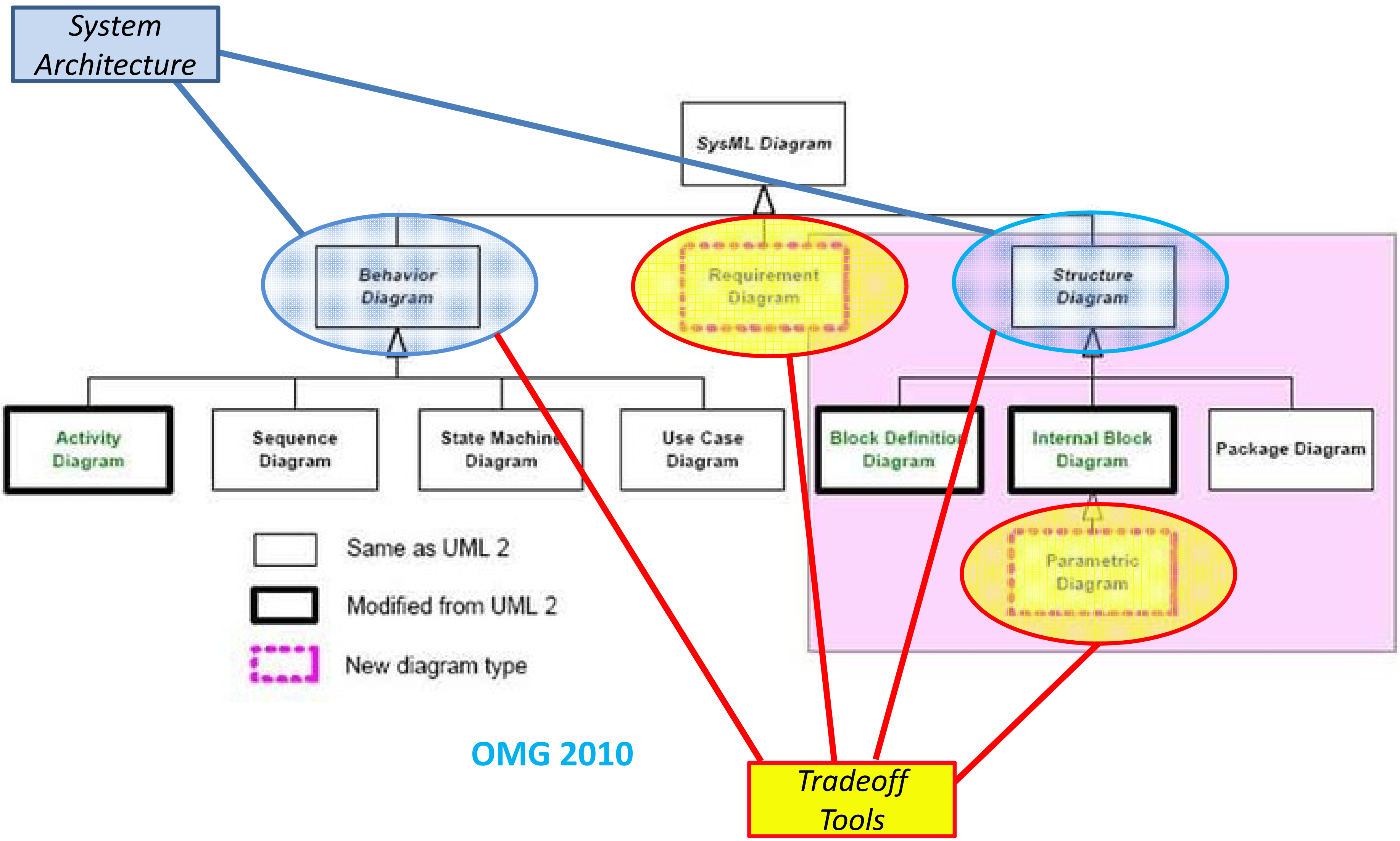
Integrated Multiple Views is Hard !

Layered MBSE -- Hierarchies



(Watson 2008, Lockheed Martin)

SysML Taxonomy



Four Pillars of SysML

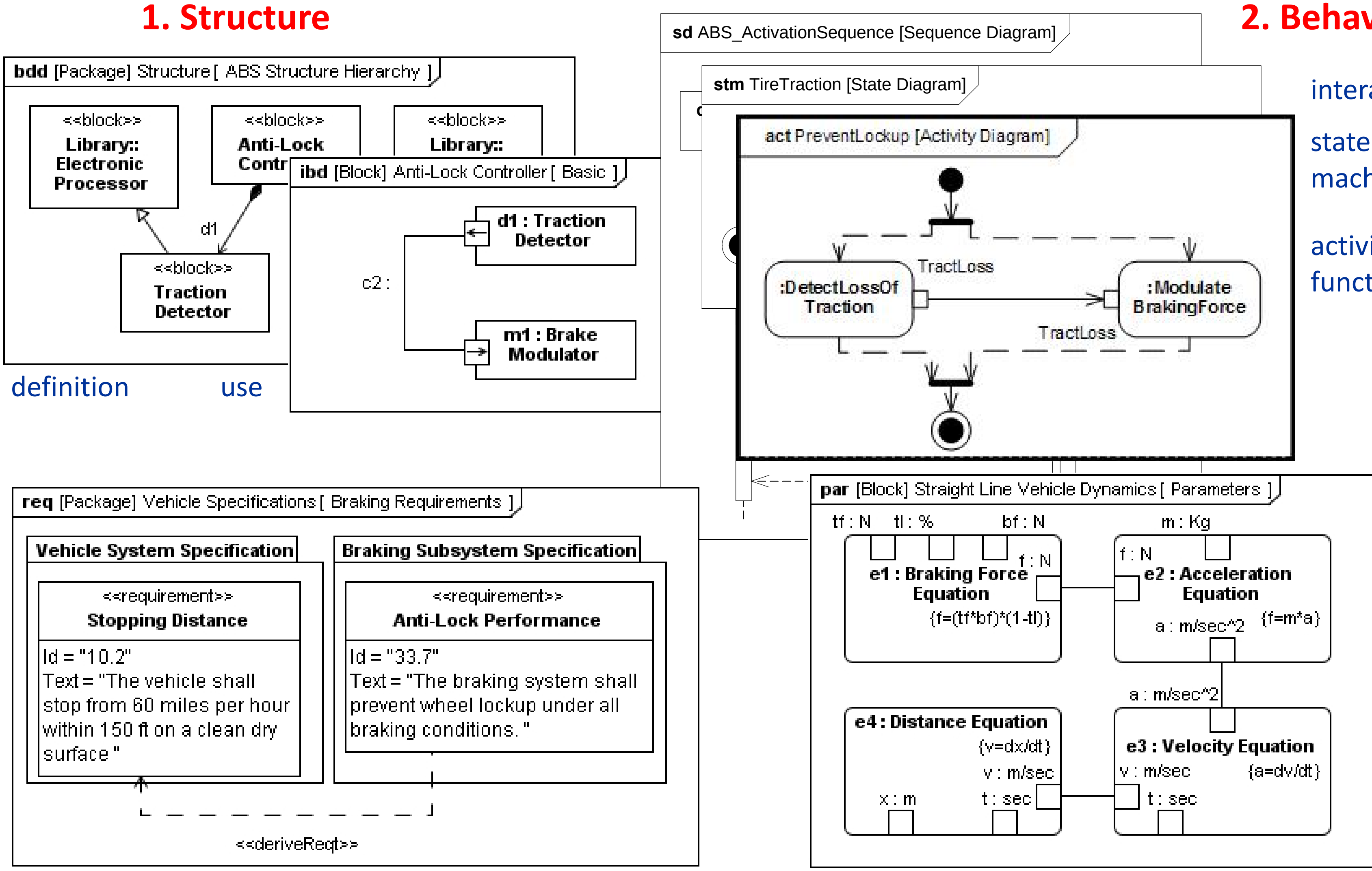
1. Structure

2. Behavior

interaction

state machine

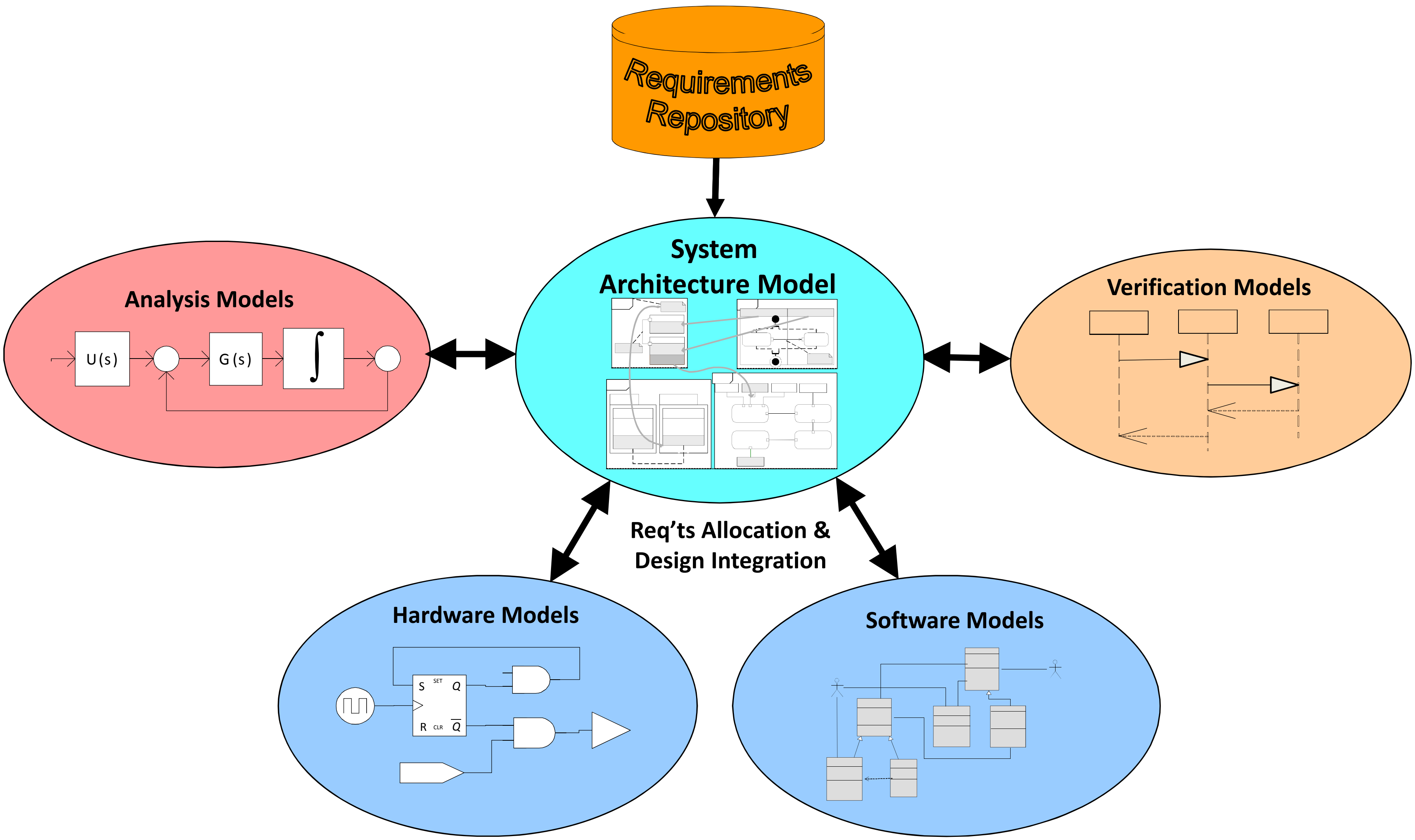
activity/ function



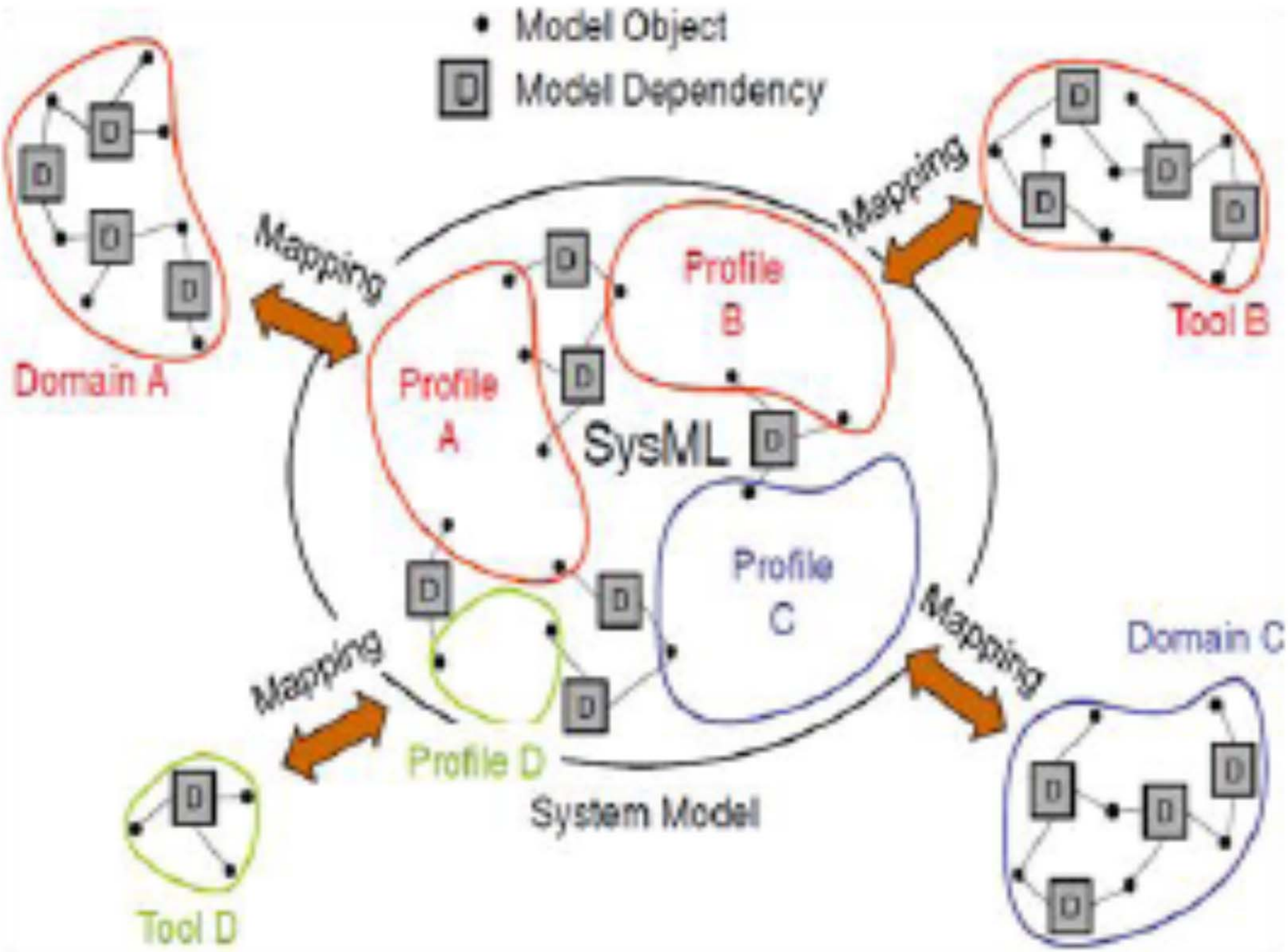
3. Requirements

4. Parametrics

Using *System Architecture Model* as an Integration Framework



System Modeling Transformations



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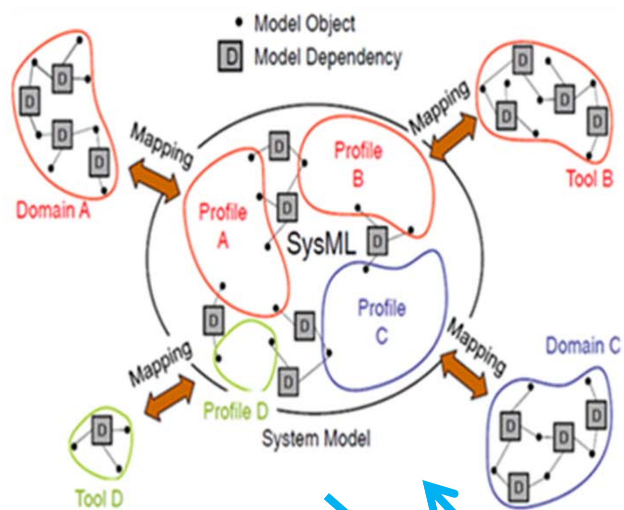
Integration of Design Space Exploration Tools with SysML– Integrated Models

The Challenge & Need:

Develop scalable holistic methods, models and tools for enterprise level system engineering

Multi-domain Model Integration via System Architecture Model (SysML)

System Modeling Transformations



" Master System Model"

Update System Model

ILOG SOLVER, CPLEX, CONSOL-OPTCAD

Tradeoff parameters

DB of system components and models

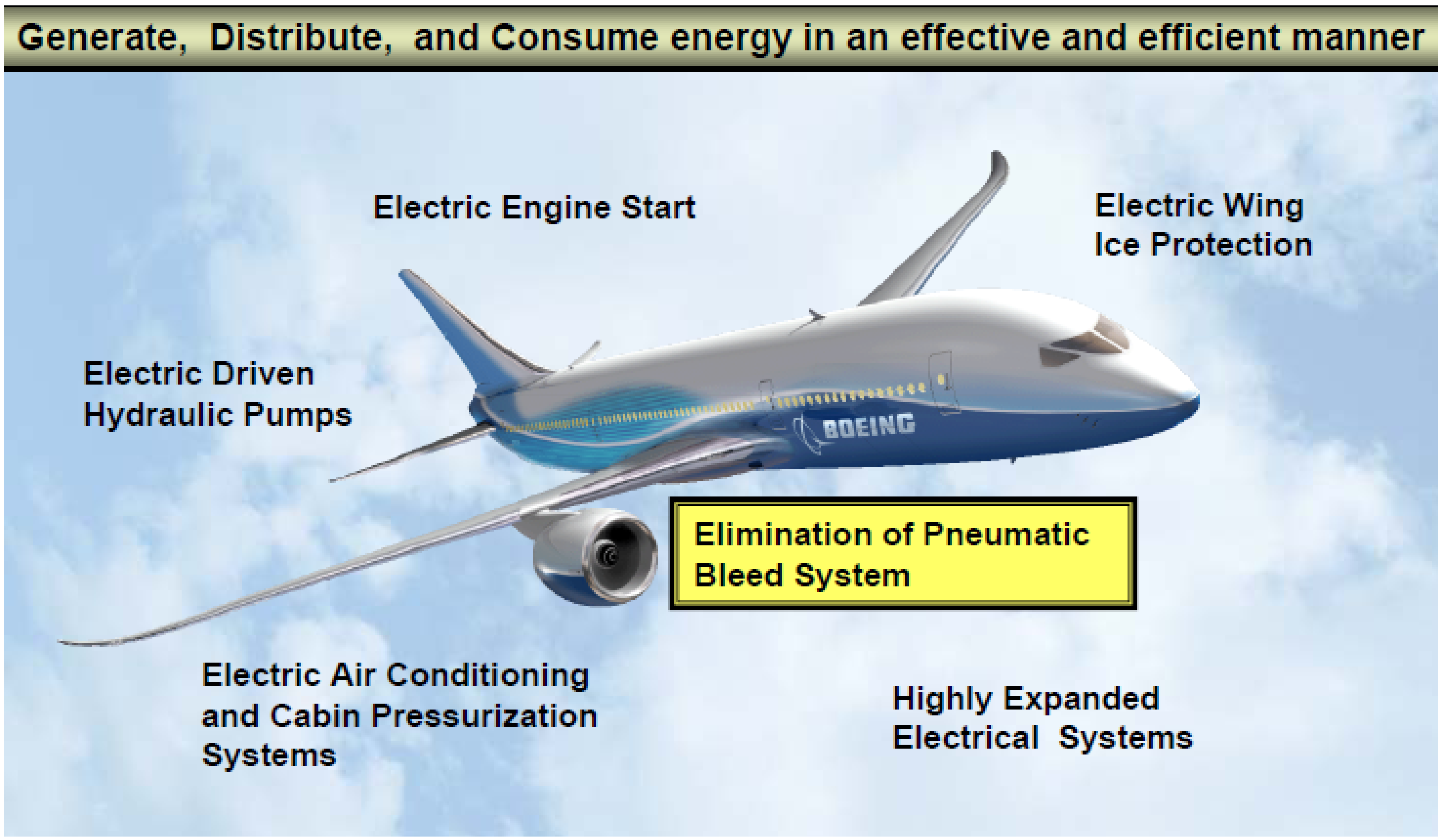
ADD & INTEGRATE

Multiple domain modeling tools
- **Tradeoff Tools (MCO & CP)**
- **Validation / Verification Tools**
- **Databases and Libraries of annotated component models from all disciplines**

BENEFITS
- **Broader Exploration of the design space**
- **Modularity, re-use**
- **Increased flexibility, adaptability, agility**
- **Engineering tools allowing conceptual design, leading to full product models and easy modifications**
- **Automated validation/verification**

APPLICATIONS
- **Avionics**
- **Automotive**
- **Robotics**
- **Smart Buildings**
- **Power Grid**
- **Health care**
- **Telecomm and WSN**
- **Smart PDAs**
- **Smart Manufacturing**

787 MEA ARCHITECTURE



Boeing

787: CLEANER, QUIETER, MORE EFFICIENT

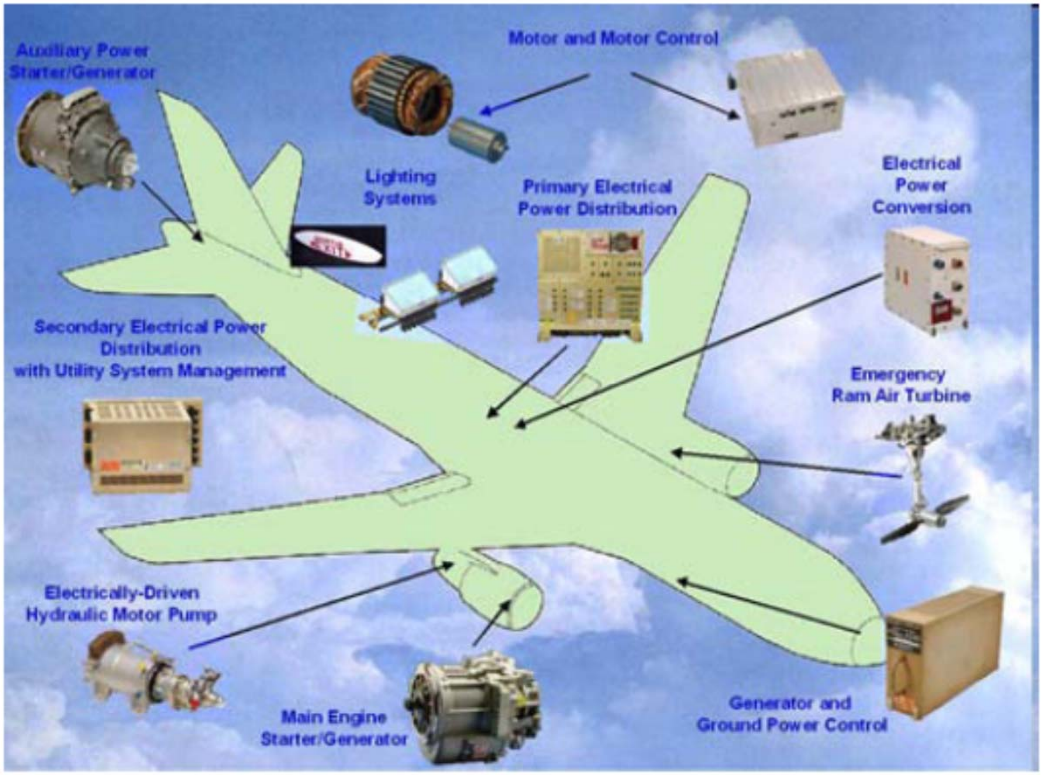
The 787 Dreamliner delivers:

*Relative to the 767

- 20%* reduction in fuel and CO_2
- 28% below 2008 industry limits for NOx
- 60%* smaller noise foot print

Boeing

MBSE for Fault Tolerant Vehicle Management Systems (Electrical, Hydraulic, etc.)

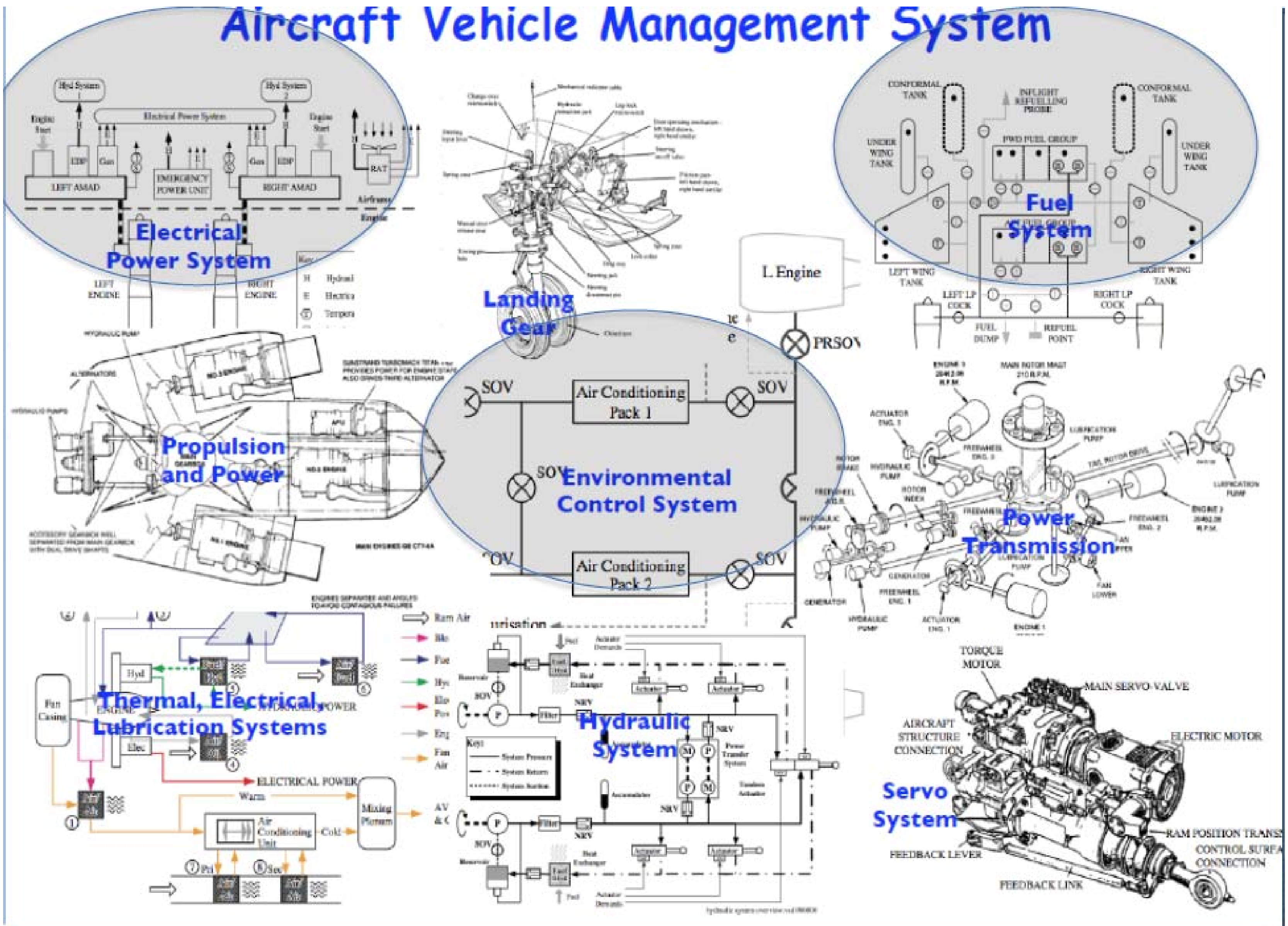


[Image: hamiltonsunstrand.com]

Goal: Synthesize logic to switch between generators and loads on-demand and to handle faults so as to stay within safe operating envelope

Joint with UTRC

Aircraft Vehicle Management System



MuSyC Avionics Design Challenge

- **Fig. 1**: Physical architecture of the modern aircraft power system
- **Fig. 2** : Requirements analysis and allocation
- **Fig. 3&4**: System behavior using SysML and Modelica
- **Fig. 5&6**: System structure and constraints using SysML diagrams

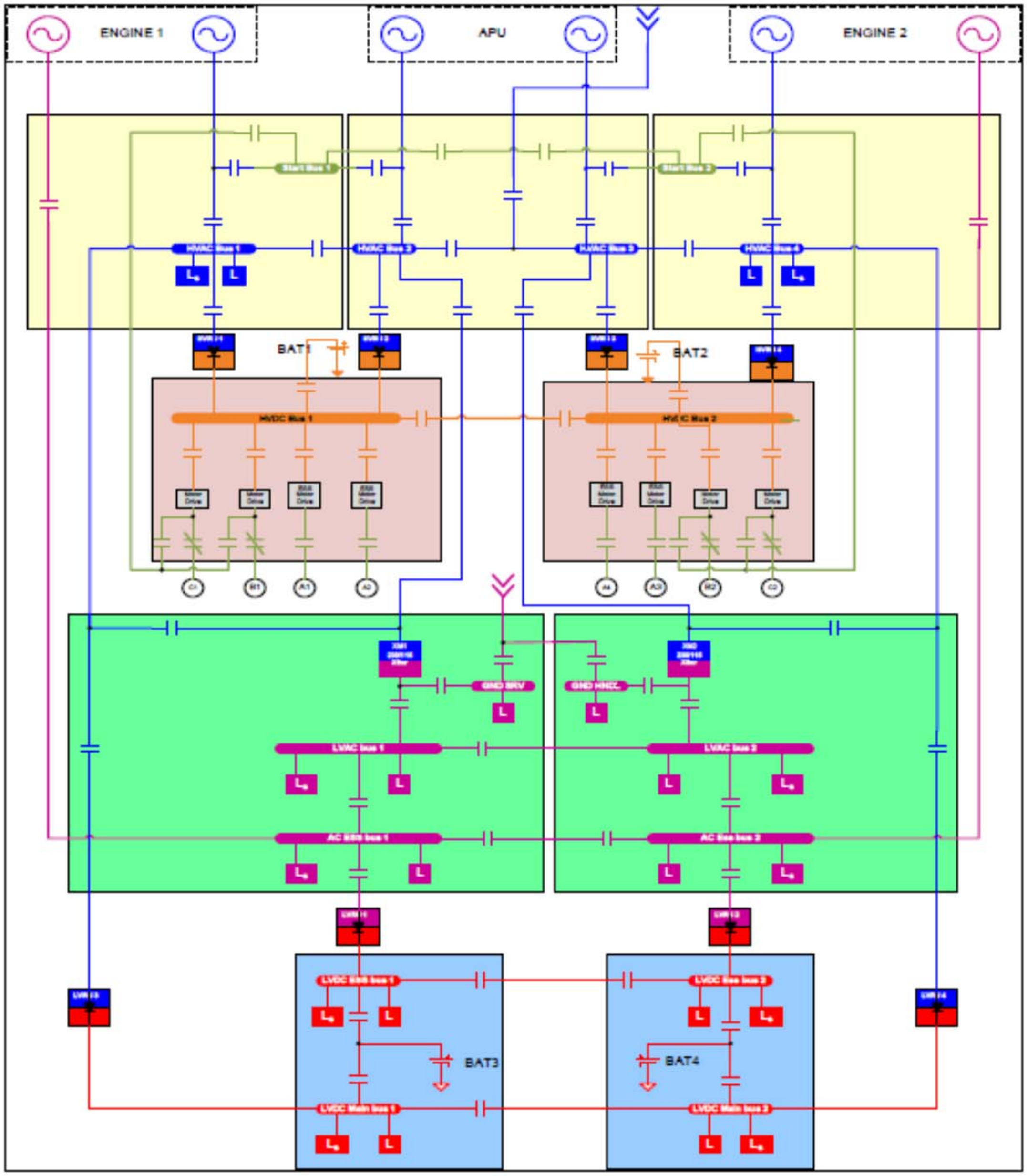
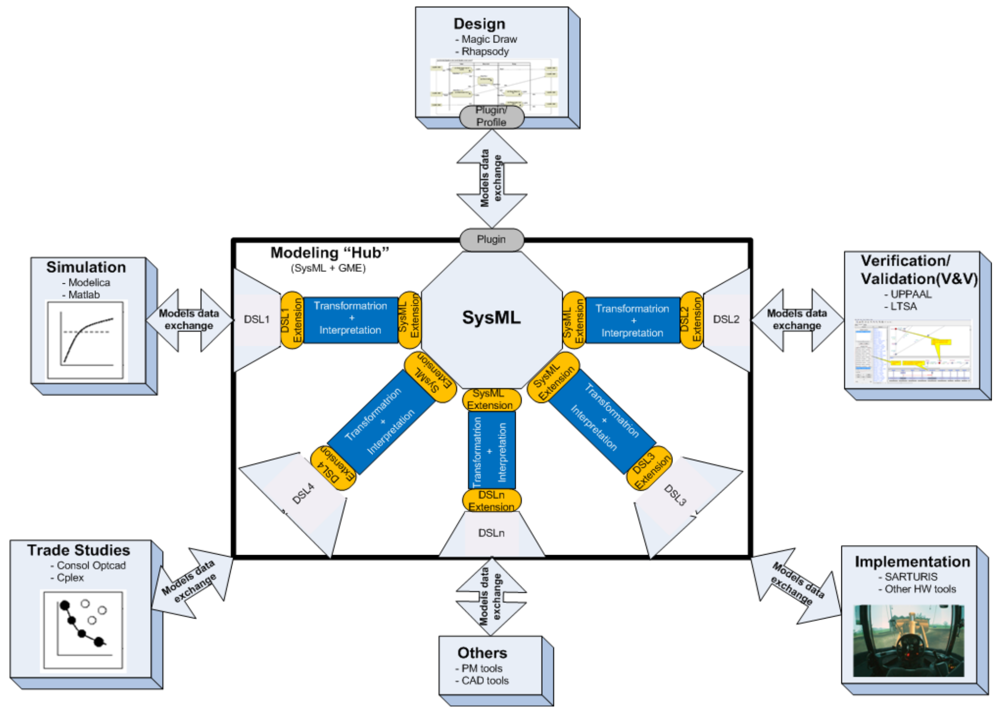


Figure 1: Single line diagram of an electric power system adapted from Honeywell Patent US 7,439,634 B2. Figure courtesy of Rich Poisson, Hamilton-Sundstrand.

Modeling ‘Hub’ Integrated with a Tradeoff Analysis Tool for VMS Design Challenge

Results / Contributions:

- Developed a framework for a Modeling ‘Hub’ integrated with a Tradeoff Analysis Tool; generation of some VMS EPS model artifacts from multiple DSL (Modelica, SysML) for proof of concept



- Extension of the SysML-based ‘Hub’ functionality with Generic Modeling Environment (GME) toolsuite: Metamodeling, model transformation and interpretation capabilities for formal across domain model integration

- Multi-criteria optimization and trade-off analysis are carried out using the integration of Consol-Optcad and the SysML-based modeling ‘Hub’

- Developed Modelica profile fro EPS in SysML and model creation and transgformation using Graph Rewriting and Transformation (GReAT) Language

Integrated Modeling Hub (IMH)

Objectives / Contributions

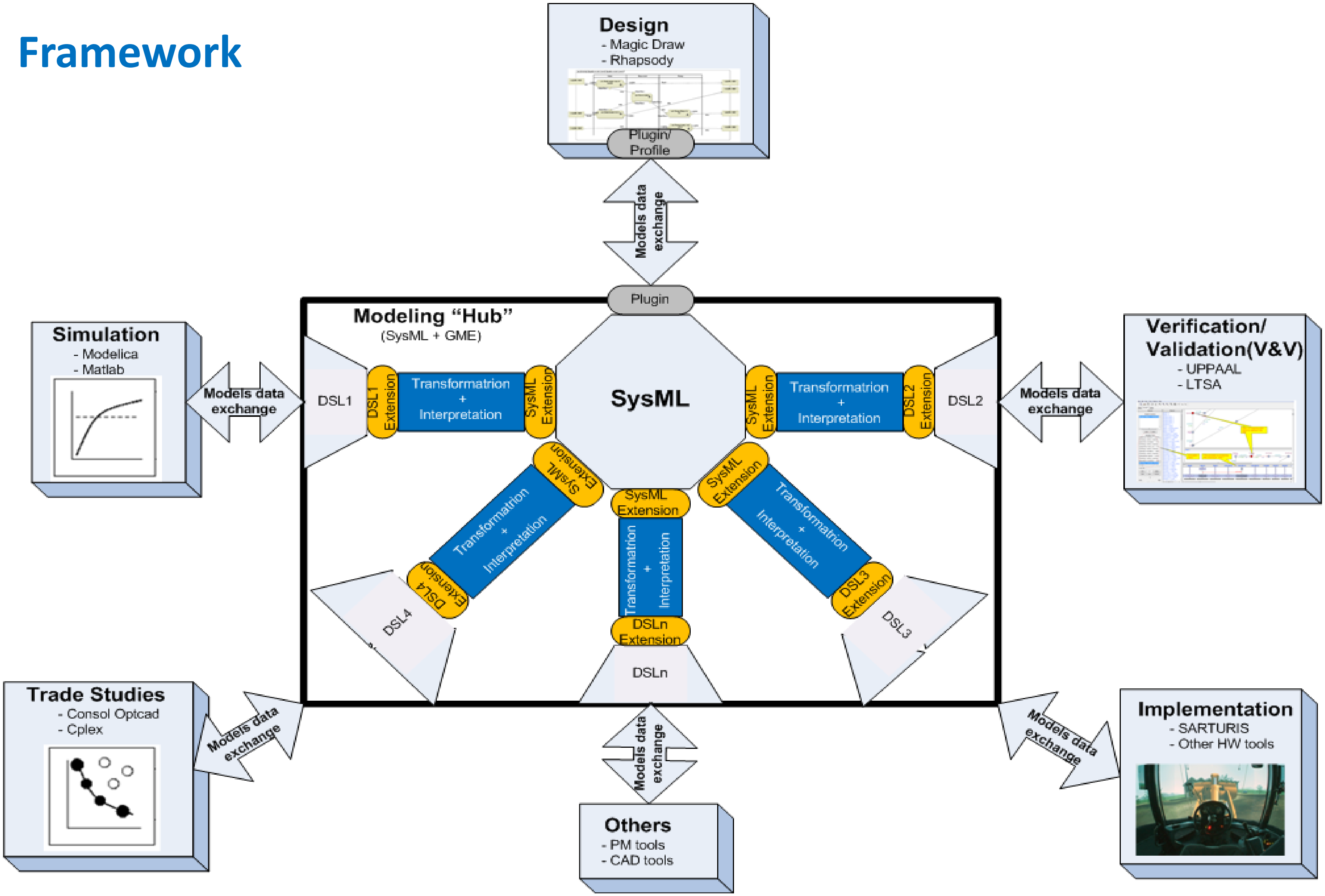
- A framework for a Modeling "Hub" integrated with a Tradeoff Analysis Tool is been developed ; use and generation of some VMS EPS model artifacts from multiple DSL (Modelica, SysML) for test case and proof of concept

- Extension of the SysML-based "Hub" functionality with Generic Modeling Environment(GME) toolsuite: Metamodeling, model transformation and interpretation capabilities to allow for formal across domain model integration

- Multi-criteria optimization and trade-off analysis are carried out using the integration of Consol-Optcad and the SysML-based modeling "Hub"

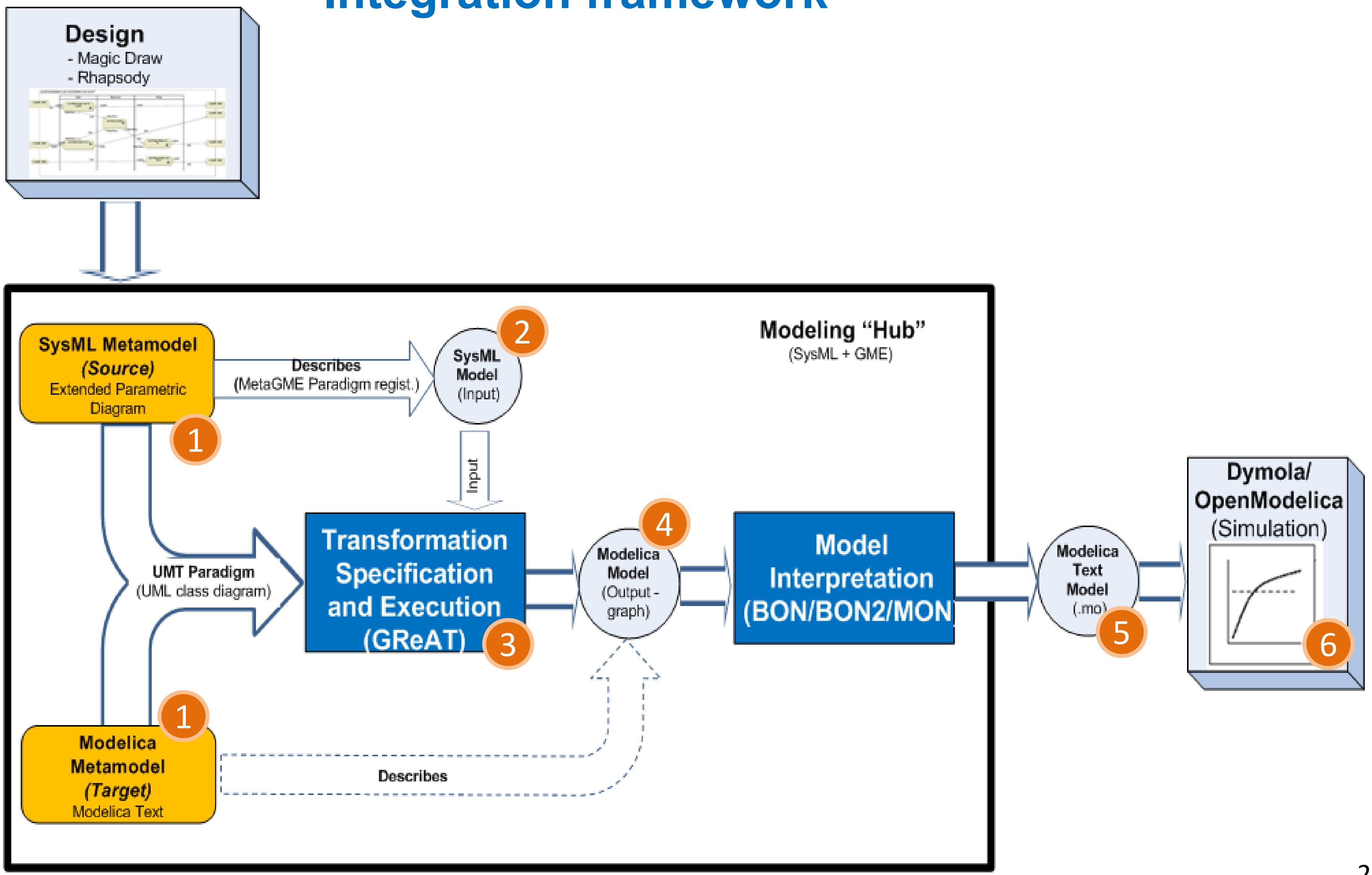
Integrated Modeling Hub

Framework



SysML and Modelica Integration

Integration framework



IMH : SysML and Modelica Integration

Implementation Results

- **Integrate SysML with Modelica through GME** for VMS EPS:

  SysML and Modelica metamodeling, model creation and transformation using Graph Rewriting and Transformation(GReAT) language

- **Exploration of bidirectional integration** :

  Modelica block view to SysML Block Definition Diagram (BDD) transformation – successful transformation of a Modelica Block to a SysML Block.

  Implementation of a **Modelica profile** for EPS in SysML (Magic Draw)

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SysML and Modelica Integration

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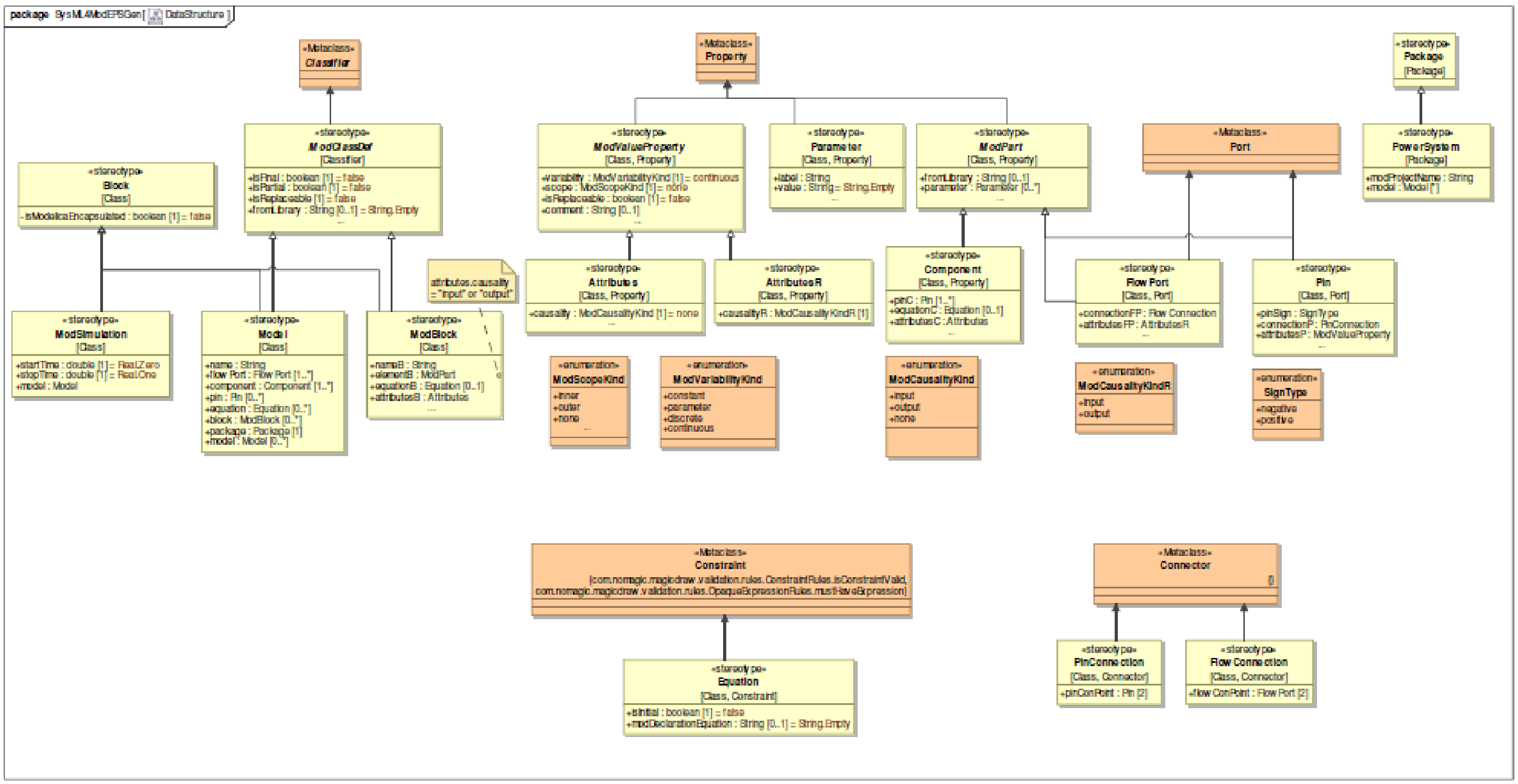
Modelica Profile

- Modelica profile in Magic Draw is built to extend SysML language and allows Modelica language constructs to be captured



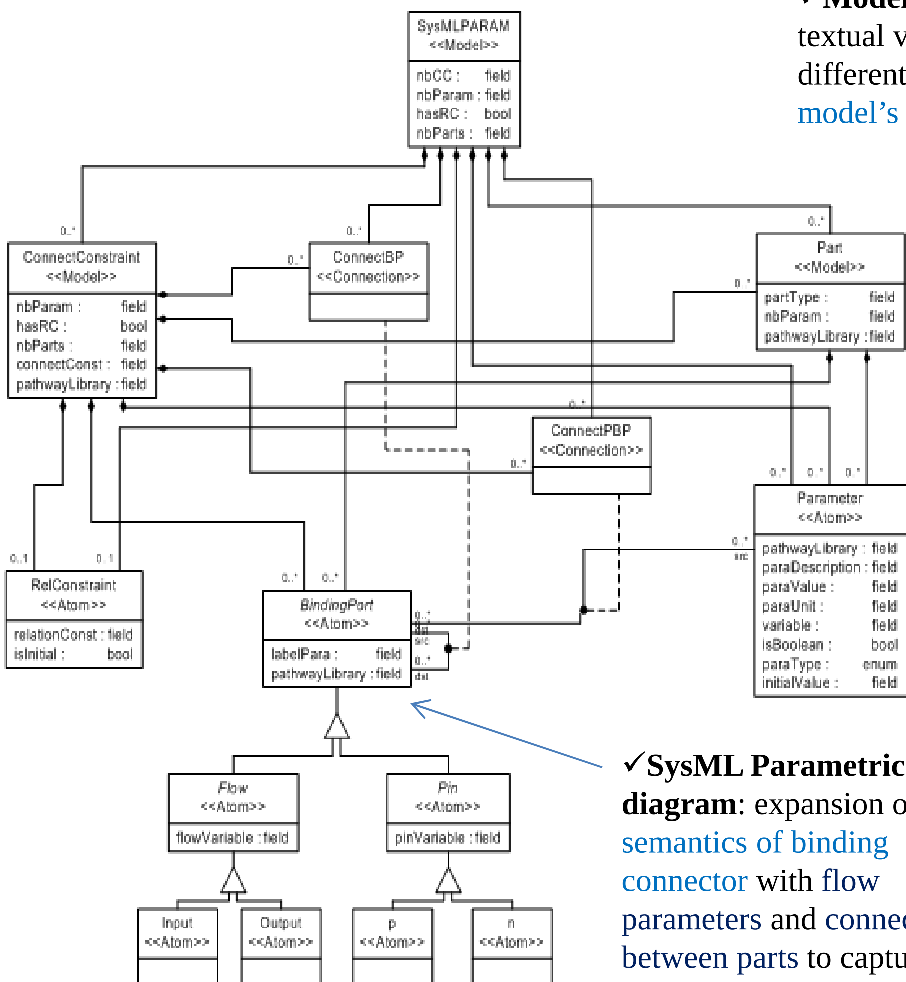
SysML and Modelica Integration

GME toolsuite contributions to the Integration framework

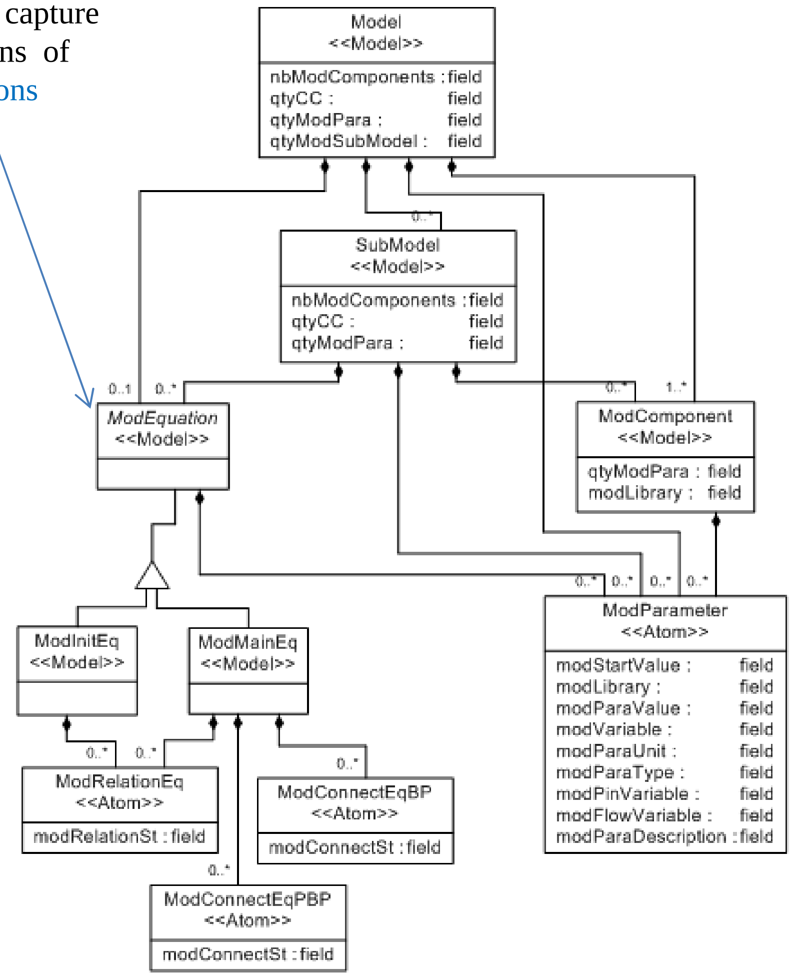
- Infrastructure to **create and add abstract syntax** to concrete syntax used to represent models in DSML and perform semantic mapping among DSML ➔ formulation of mathematical abstractions specifying meaning of models
- Support for the **rapid creation of domain specific modeling**, model analysis and program synthesis environments[1] ➔easy **metamodel** creation and extension specification for integration purposes
- **Transformation framework** (GReAT) built upon the formalism of **graph grammars** (input and output models are considered as graphs); use of Universal Data Model (UDM) framework as underlying data models for programmatic C++ access to transformation artifacts
- Multi-mechanism framework (raw COM, BON, BON2, MON) for creation of **multiple types of components** ➔ code generation of the model artifacts that can be executable in **specified DSL based tool**
- **Weaknesses**: Limited import options for external files (created out of the GME environment); Difficult debugging of errors: multiple/complex interactions among toolsuite components, proprietary constructs/syntax

SysML and Modelica Integration

Metamodels



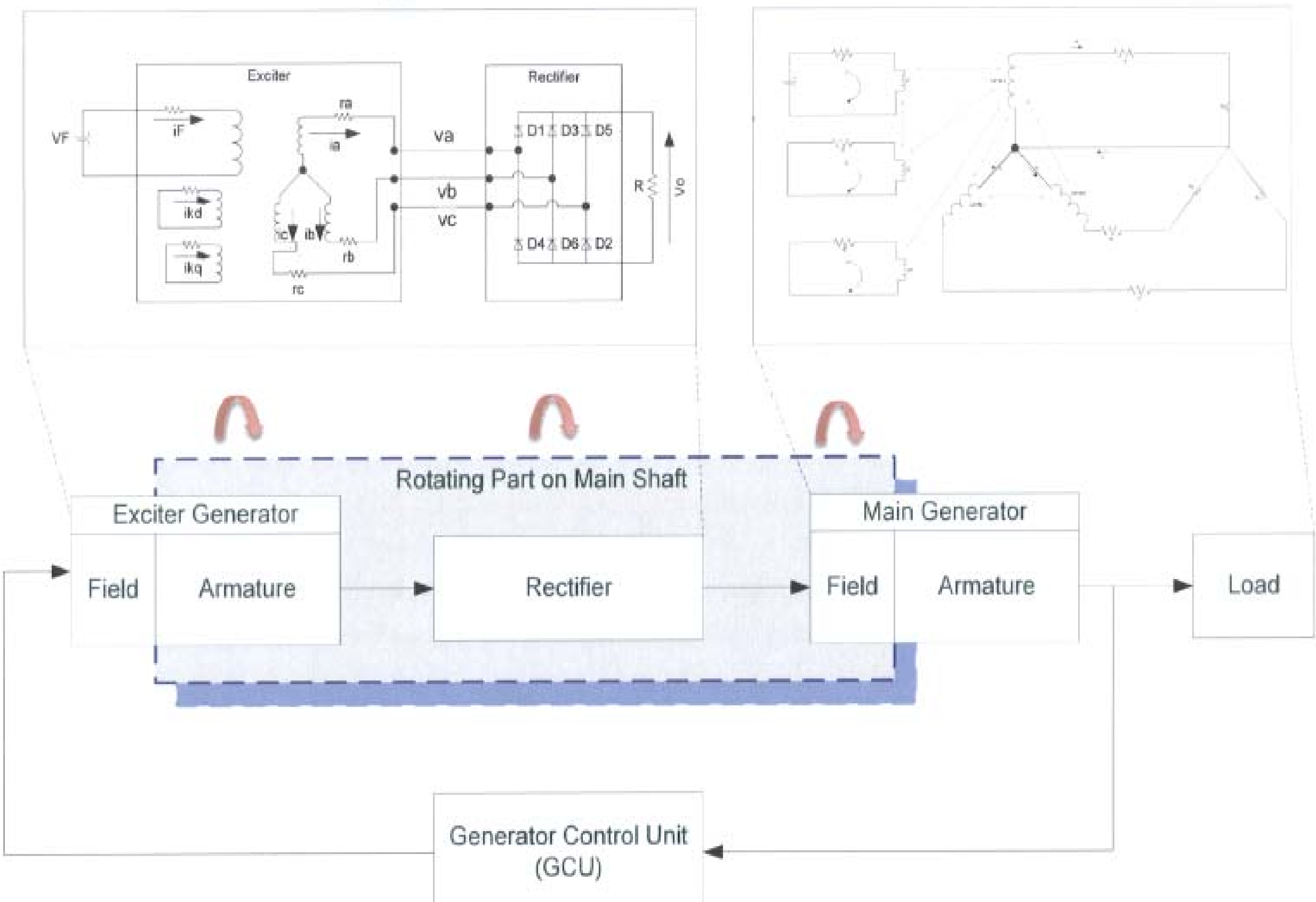
✓**Modelica** : focus on the textual view to capture different sections of model's equations



✓**SysML Parametric diagram**: expansion of semantics of binding connector with flow parameters and connections between parts to capture Modelica semantics

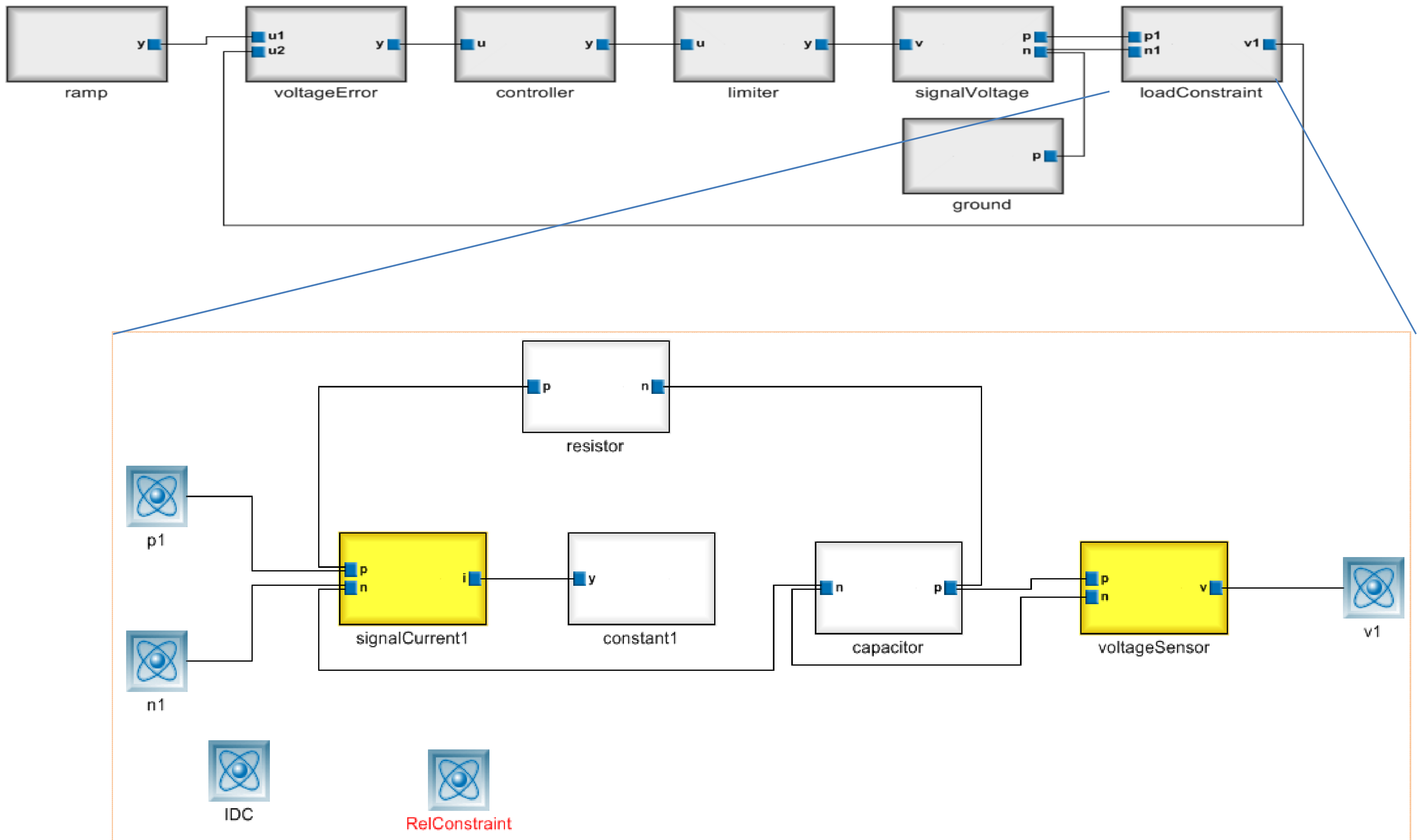
1 ***Fig. 1***: SysML (input) and Modelica metamodels (output)

IDG Electrical Subsystem Block Diagram



SysML and Modelica Integration

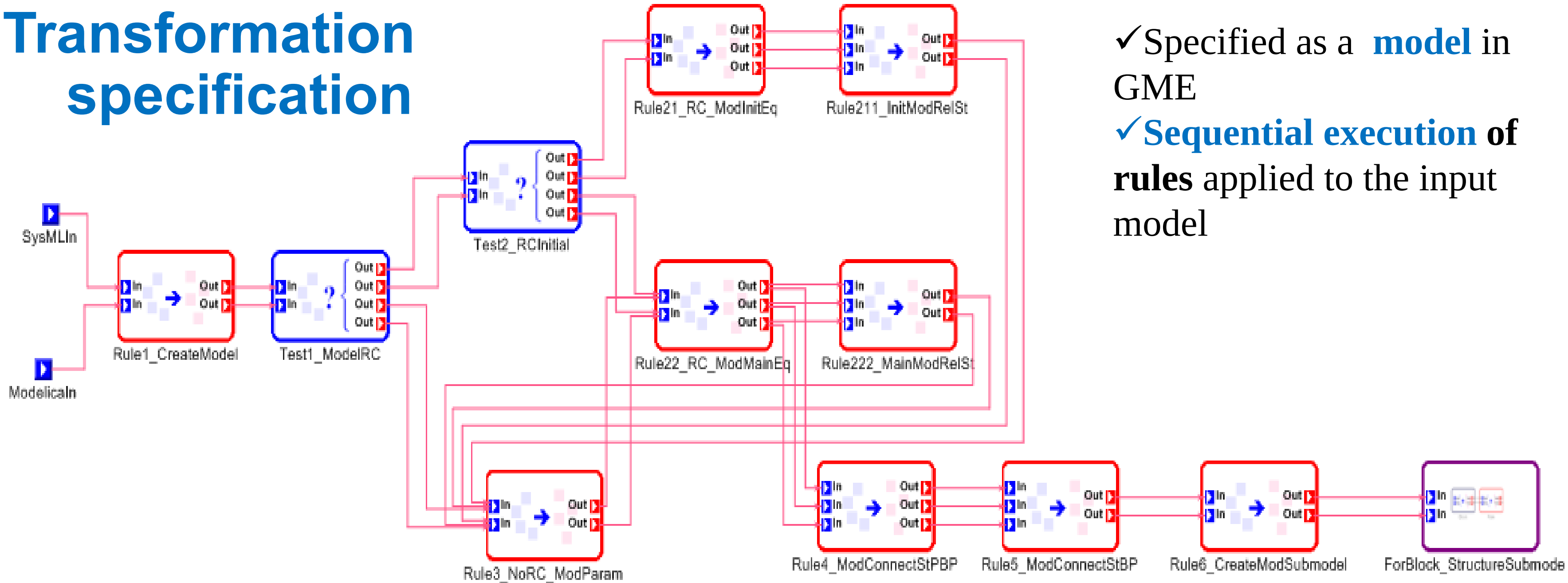
Input model



2 ***Fig. 2***: A simple EPS Parametric diagram in GME (input model)

SysML and Modelica Integration

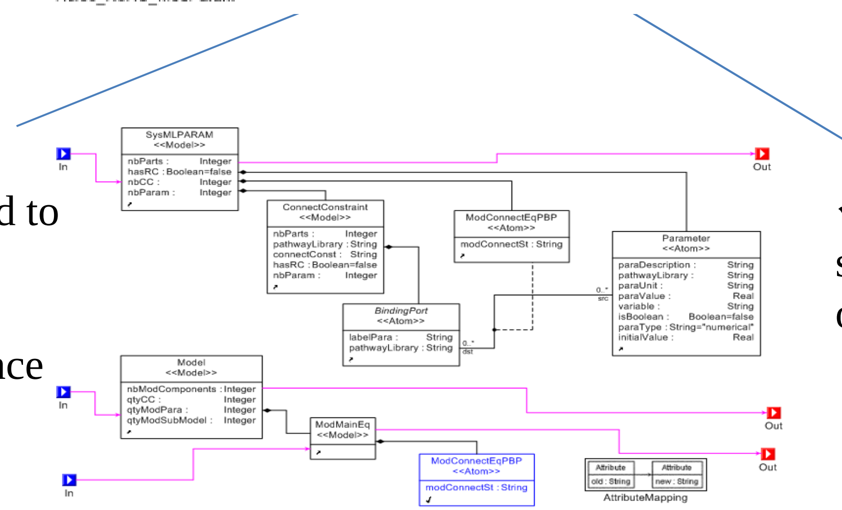
Transformation specification



✓Specified as a **model** in GME

✓**Sequential execution of rules** applied to the input model

✓**Left-hand side (LHS)**: used to define the graph pattern to be matched and actions to apply when conditions and occurrence are met

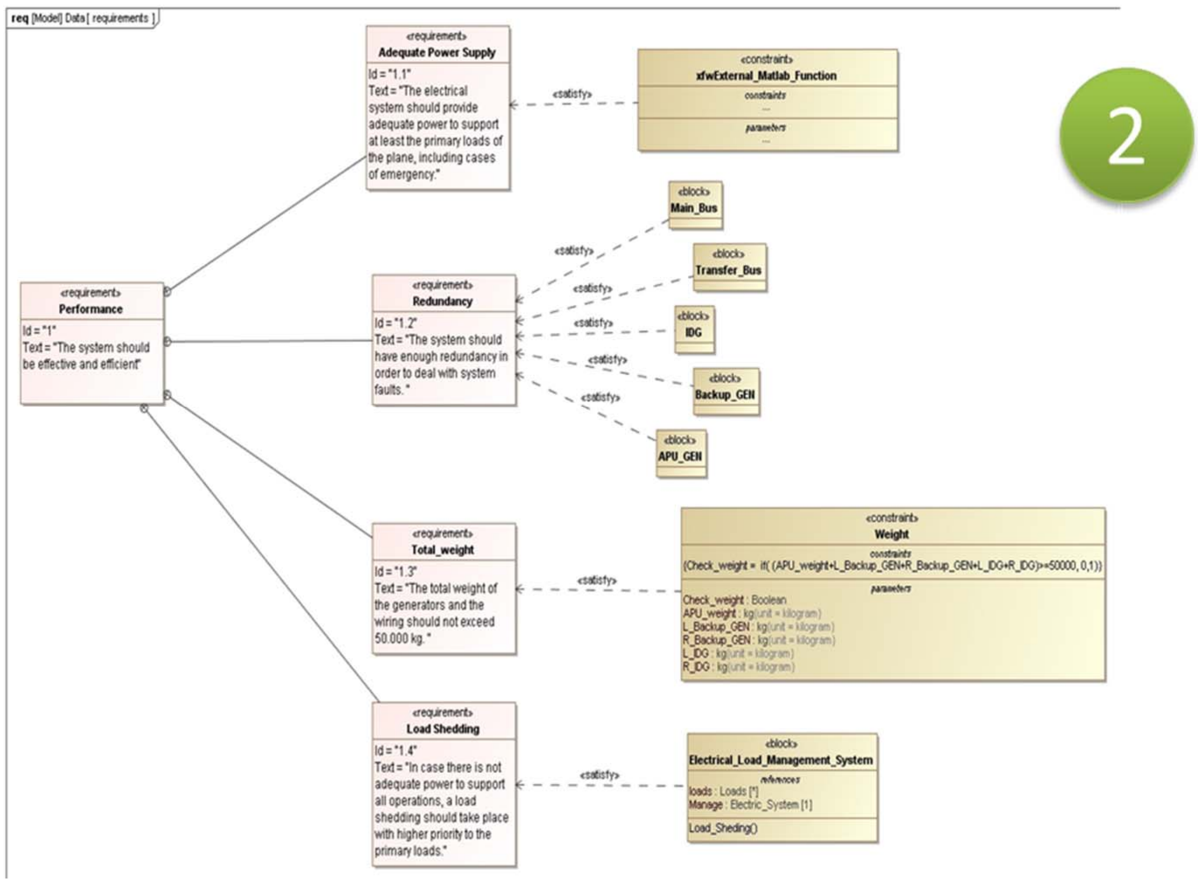


✓**Right-hand side (RHS):** specifies the output pattern of the rule

3 ***Fig. 3***: SysML-Modelica transformation specification in GME/GReAT

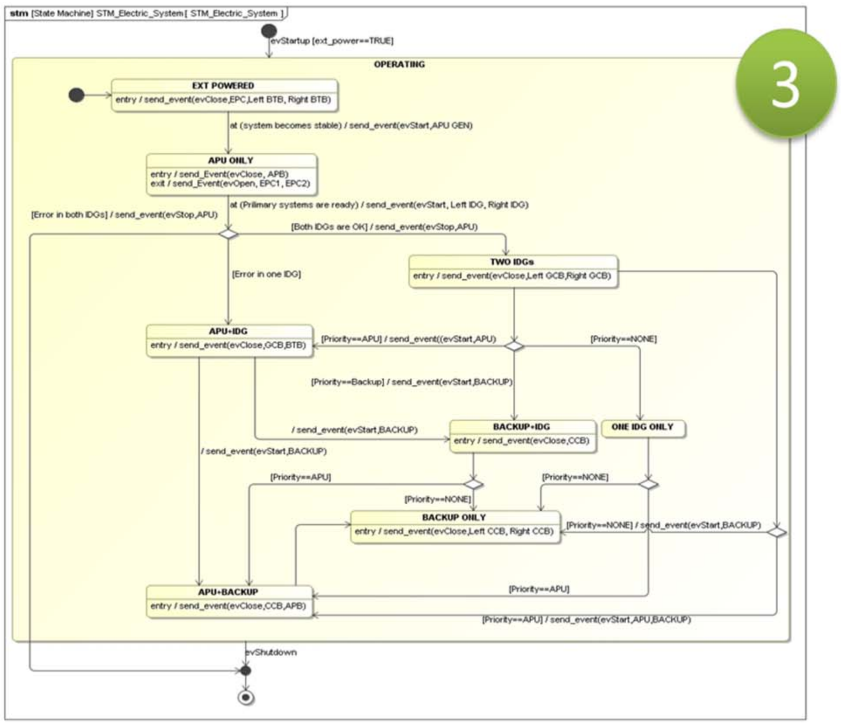
MuSyC Avionics Design Challenge (cont.)

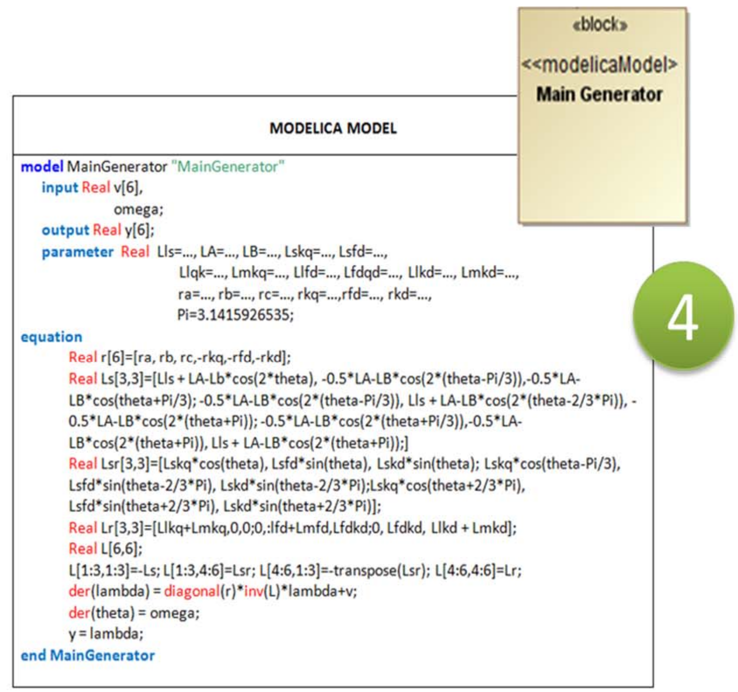
Requirements



MuSyC Avionics Design Challenge (cont.)

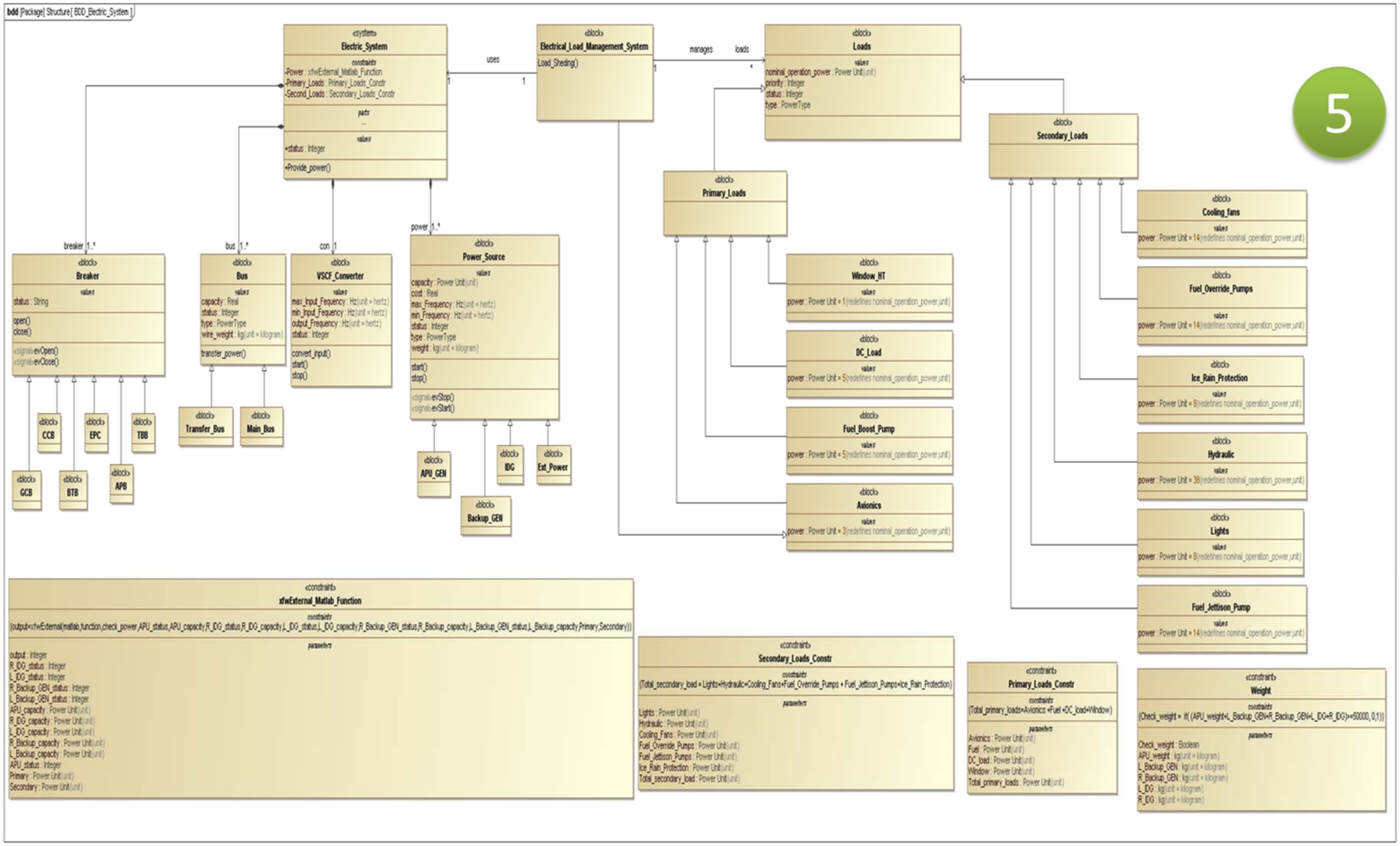
System Behavior



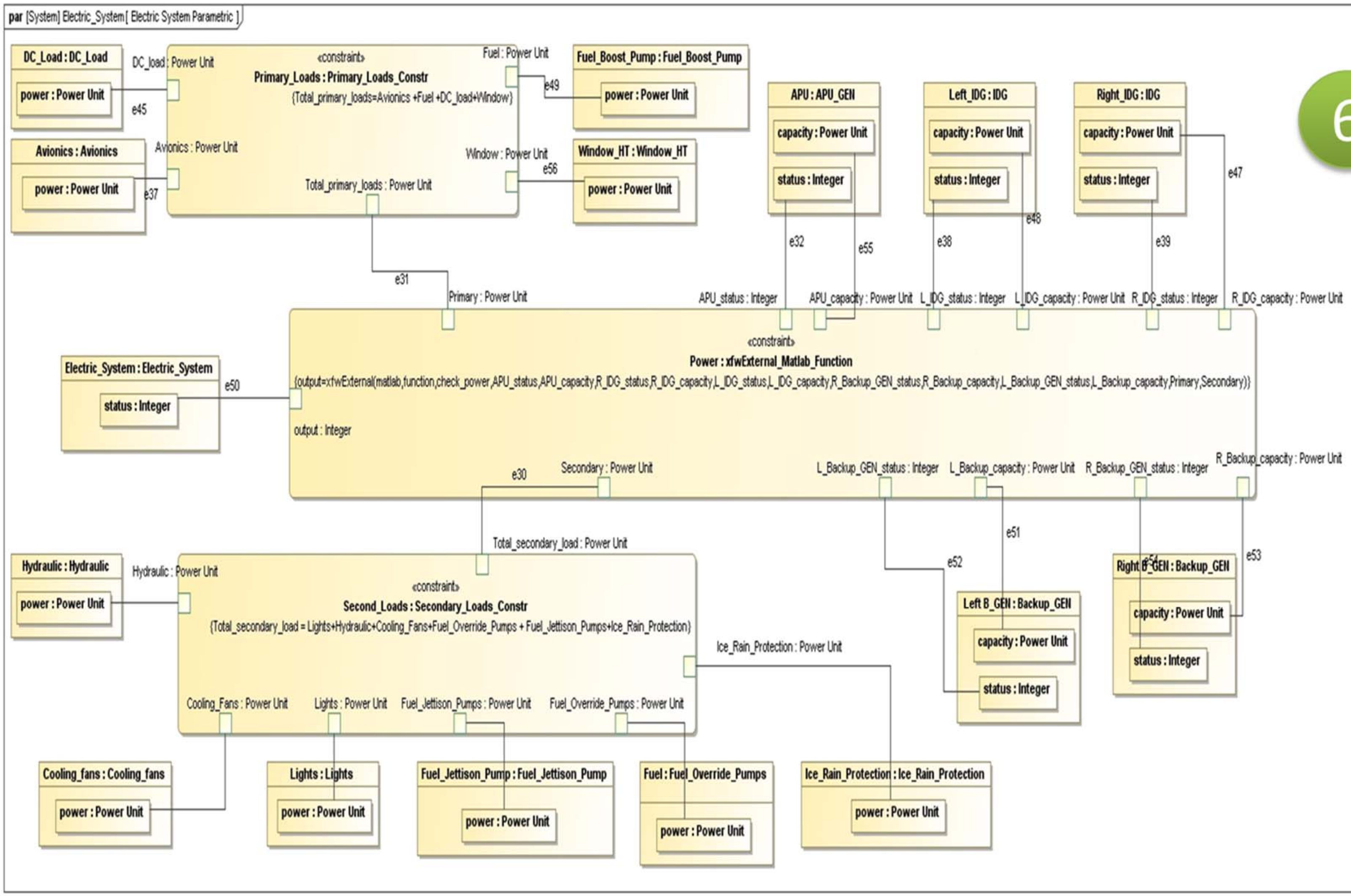


MuSyC Avionics Design Challenge (cont.)

System Structure



MuSyC Avionics Design Challenge (cont.)



6

Design Space Exploration: Integration of Logic and Optimization

- Expressed as **multi-objective optimization problem**
- **Approaches**
  - **Exact**: **Integer Linear Programming, Branch and Bound, Constraint Programming**

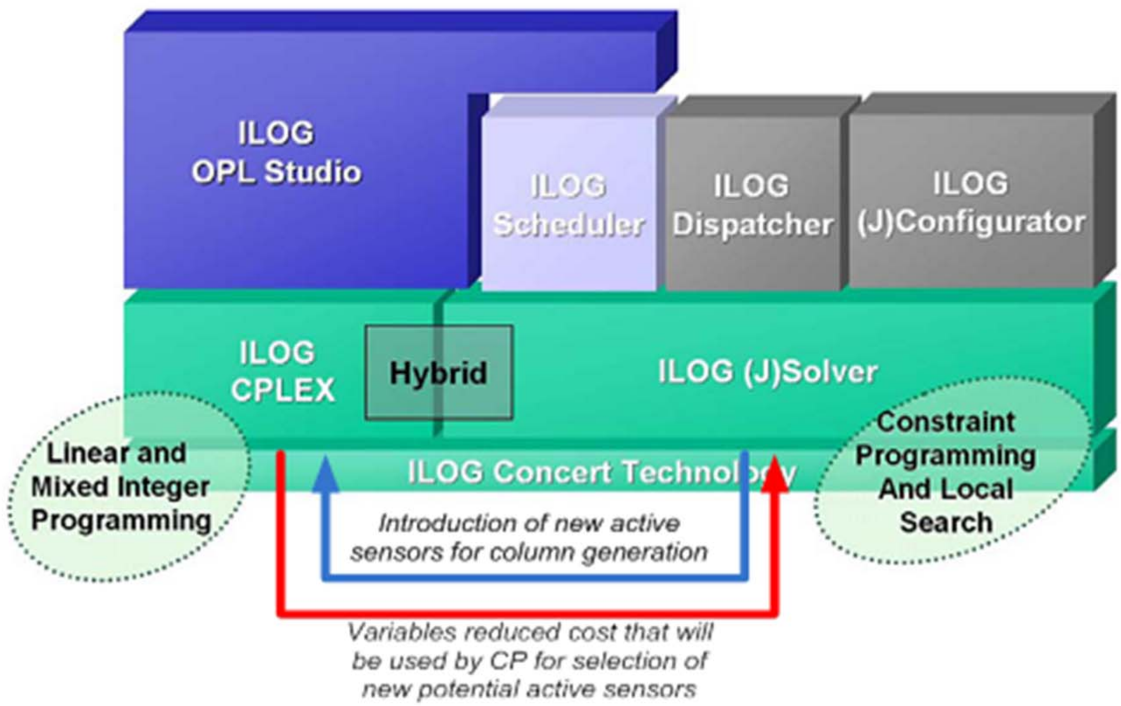
    $\Rightarrow$ **Prohibitive large computation times**
  - **Heuristics: Polynomial complexity, especially crafted for the particular optimization problem**

    $\Rightarrow$ **Reasonable quality solutions**
  - **Meta-heuristics: Simulated Annealing, Tabu Search, Evolutionary Algorithms**

    $\Rightarrow$ **Good quality in reasonable time**

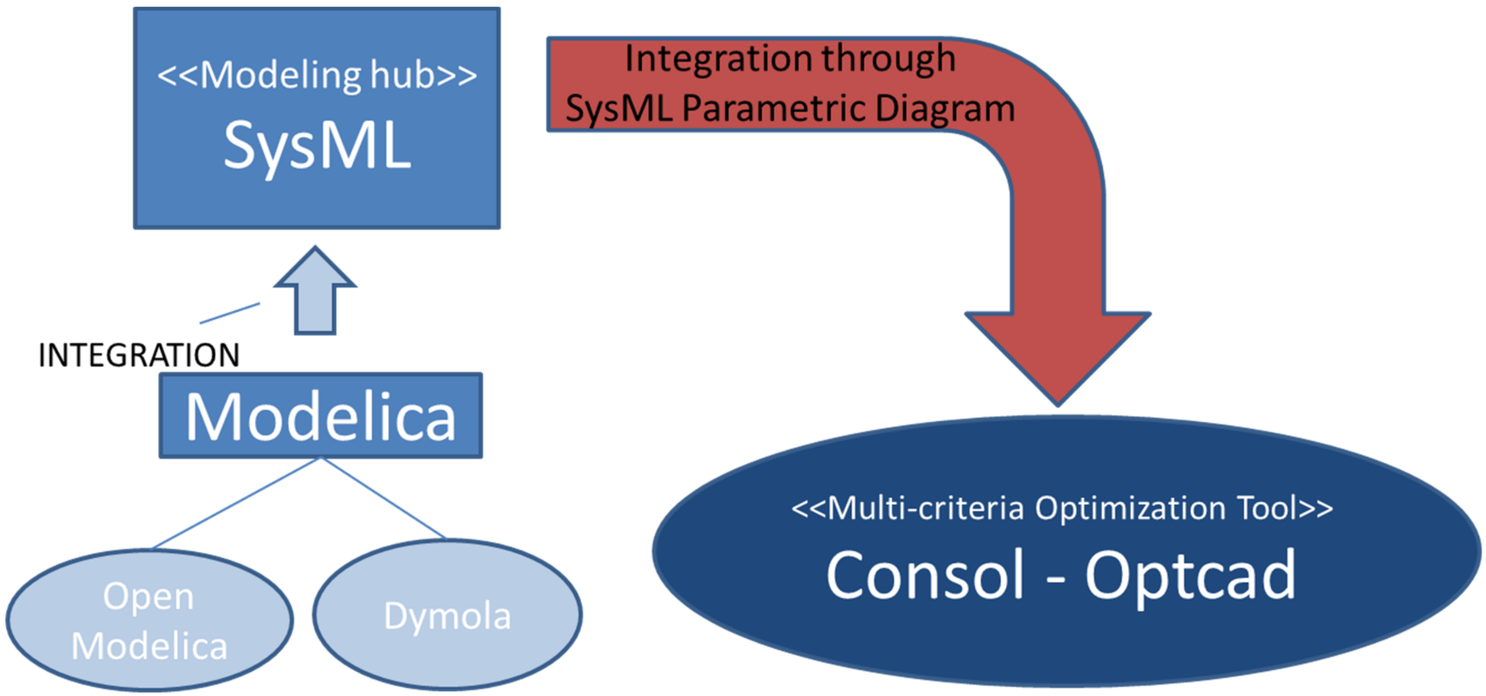
Integration of Constraint-Based Reasoning and Optimization for Networked CPS Tradeoff Analysis and Synthesis

To enable rich design space exploration across various physical domains and scales, as well as cyber domains and scales



Trade-off Analysis Integration with Modeling "Hub"

Integration of *SysML-Modelica-MATLAB "modeling hub"* with *UMD Consol-Optcad* tools for detailed trade-off analysis of complex systems with multiple objectives and for better design space exploration

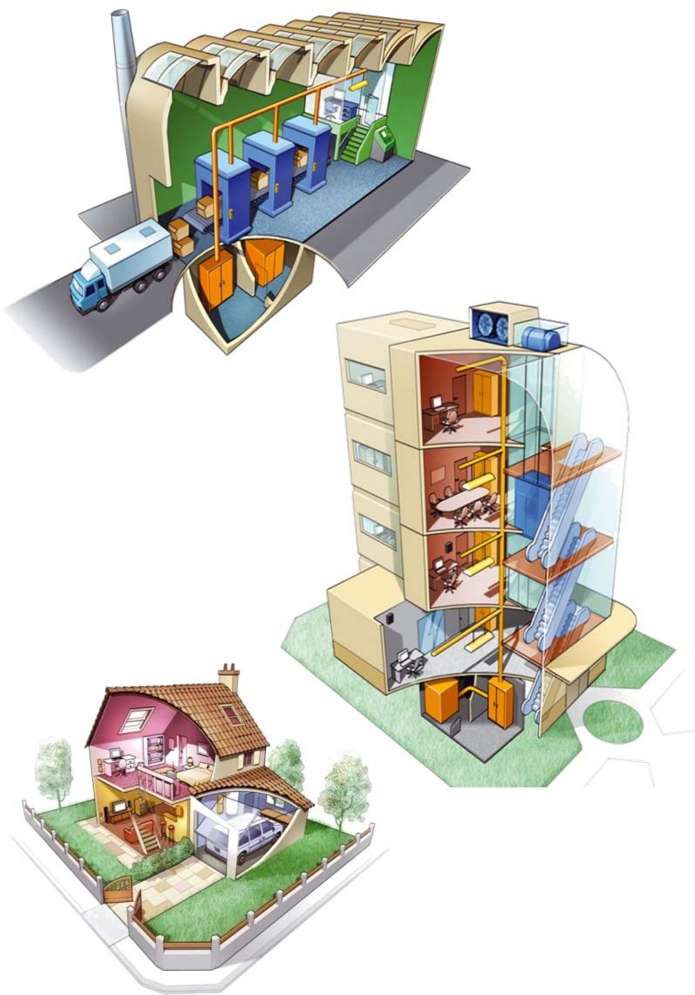


Implications along the complete Energy value chain

On the Supply Side

- **Optimize T&D infrastructure**
- **Optimize quality and availability of supplied power**
- **Influence demand consumption**
- **Deploy modern IT infrastructure**

SmartGrid-Energy Efficiency (cont.)

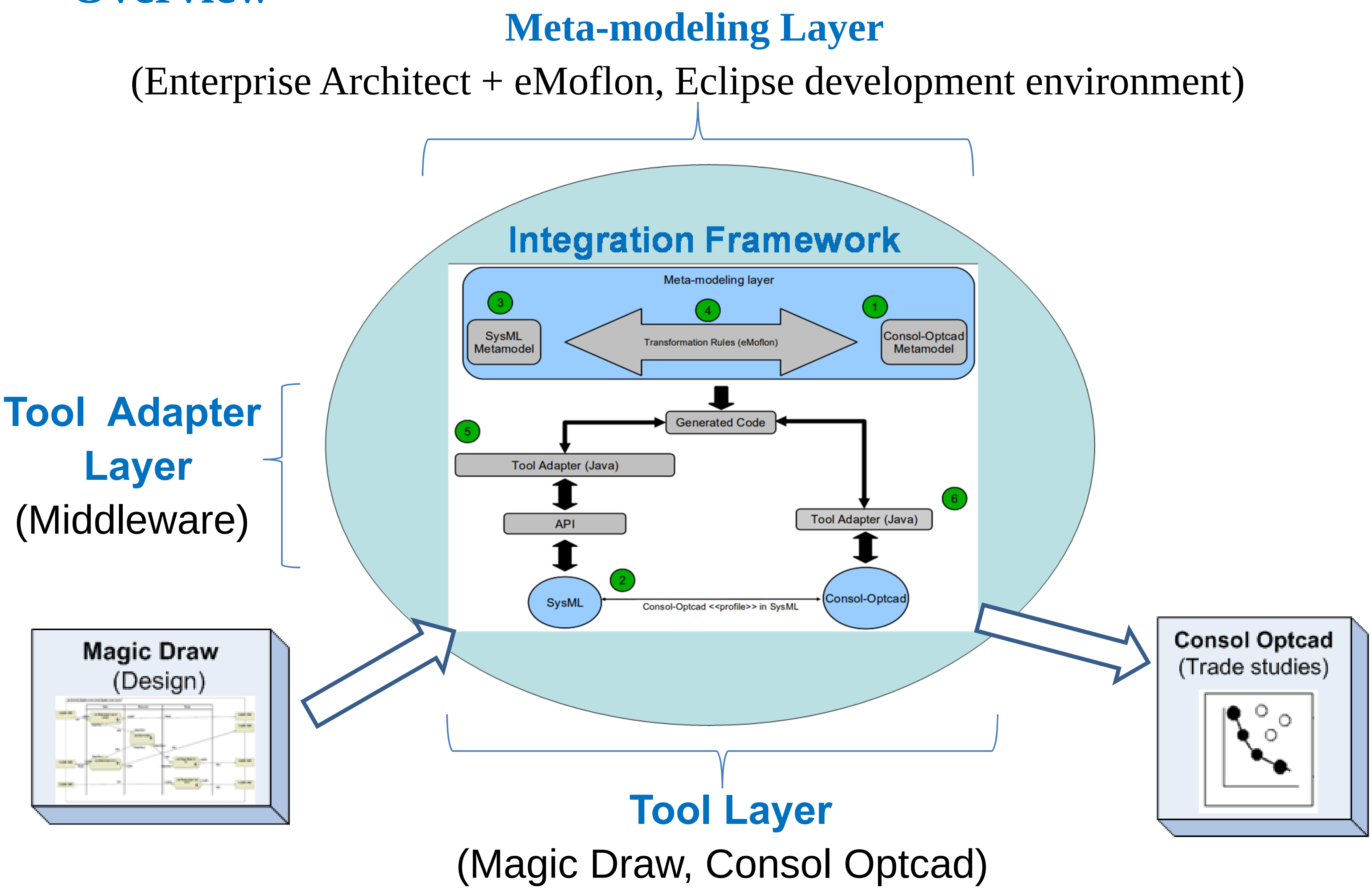


On the Demand Side

- **Act on Users**
- **Act on loads**
- **Optimize quality and availability of on-site power**
- **Optimize supply costs**

SysML and Consol-Optcad Integration

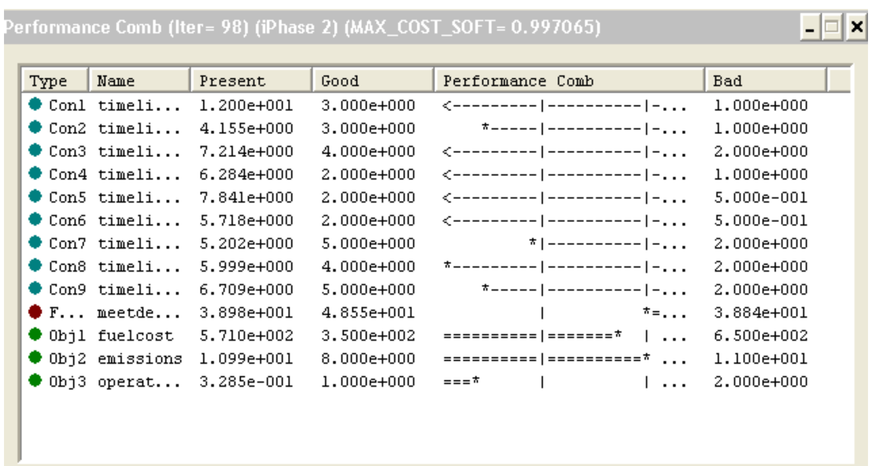
Overview



IMH and Consol-Optcad Integration

Consol-Optcad

- **Trade-off tool** that performs multi-criteria optimization for continuous variables (FSQP solver) – **Extended to hybrid** (continuous / integer)
- **Functional** as well as non-functional objectives/constraints can be specified
- Designer initially specifies **good** and **bad** values for each objective/constraint based on experience and/or other inputs
- Each objective/constraint value is scaled based on those good/bad values; fact that effectively treats **all objectives/constraints fairly**
- Designer has the flexibility to see results at every iteration (**pcomb**) and allows for **run-time changing** of good/bad values



Performance Comb (Iter= 98) (iPhase 2) (MAX_COST_SOFT= 0.997065)

<table>
<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
<tr><td>Con1</td><td>timeli...</td><td>1.200e+001</td><td>3.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con2</td><td>timeli...</td><td>4.155e+000</td><td>3.000e+000</td><td>*-----|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con3</td><td>timeli...</td><td>7.214e+000</td><td>4.000e+000</td><td><---------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con4</td><td>timeli...</td><td>6.284e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con5</td><td>timeli...</td><td>7.841e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con6</td><td>timeli...</td><td>5.718e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con7</td><td>timeli...</td><td>5.202e+000</td><td>5.000e+000</td><td>*|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con8</td><td>timeli...</td><td>5.999e+000</td><td>4.000e+000</td><td>*---------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con9</td><td>timeli...</td><td>6.709e+000</td><td>5.000e+000</td><td>*-----|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>F...</td><td>meetde...</td><td>3.898e+001</td><td>4.855e+001</td><td>| *=...</td><td>3.884e+001</td></tr>
<tr><td>Obj1</td><td>fuelcost</td><td>5.710e+002</td><td>3.500e+002</td><td>==========|=======* | ...</td><td>6.500e+002</td></tr>
<tr><td>Obj2</td><td>emissions</td><td>1.099e+001</td><td>8.000e+000</td><td>==========|==========* ...</td><td>1.100e+001</td></tr>
<tr><td>Obj3</td><td>operat...</td><td>3.285e-001</td><td>1.000e+000</td><td>===* | | ...</td><td>2.000e+000</td></tr>
</table>

Fig. 1: Pcomb

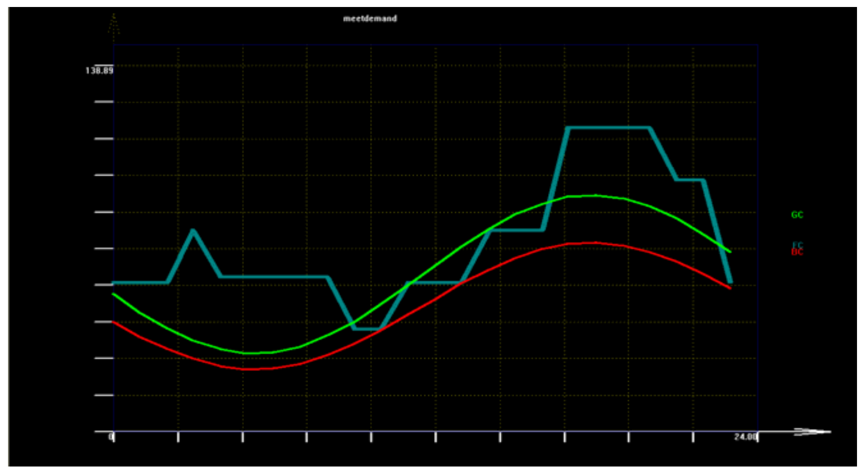


Fig. 2: Example of a functional constraint

IMH and Consol-Optcad integration

Metamodeling Layer

- Both **metamodels** are defined in Ecore format
- **Transformation rules** are defined within EA and are based on graph transformations
- **Story Diagrams** (SDMs) are used to express the transformations
- **eMoflon** (TU Darmstadt) plug-in generates code for the transformations
- An Eclipse project hosts the implementation of the transformations in Java

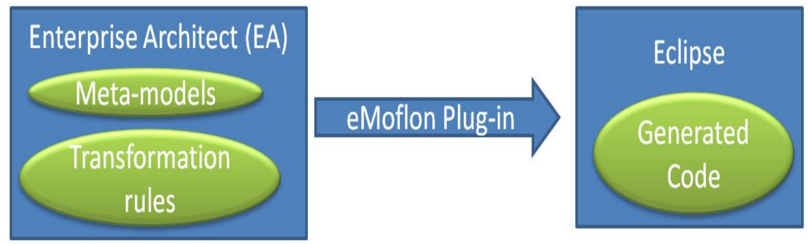


Fig. 3: eMoflon high-level architecture

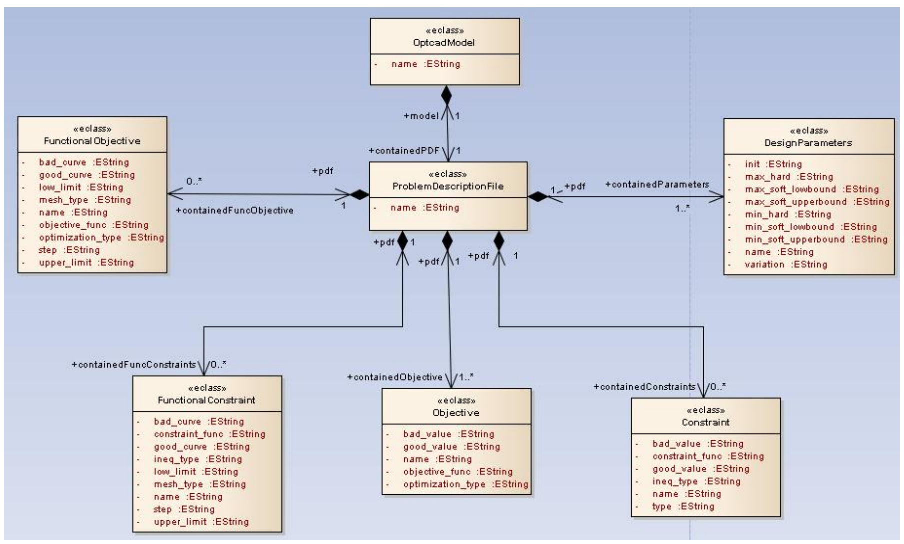


Fig. 4: Consol-Optcad metamodel

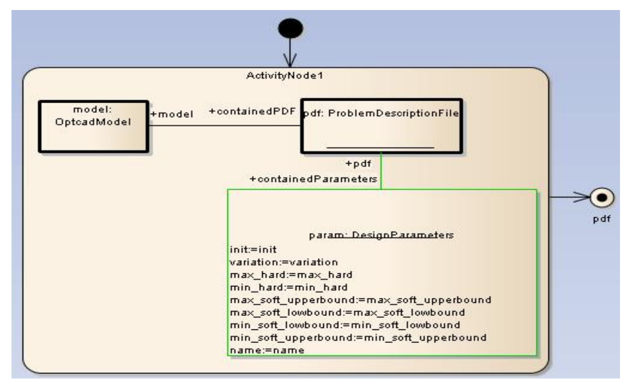


Fig. 5: Story diagram

IMH and Consol-Optcad Integration

Consol-Optcad Profile

- A profile is used to extend the notation of SysML language and allows Domain Specific Language constructs to be represented in SysML
- A profile is created by declaring new <<stereotypes>> , the relationships between them as well as the relationships with existing constructs

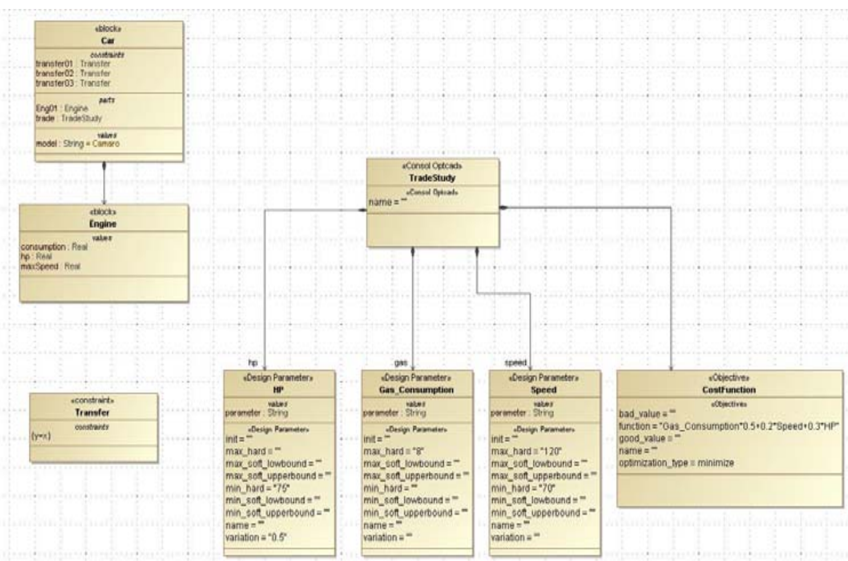


Fig. 6: Using constructs of Consol-Optcad profile in MagicDraw environment

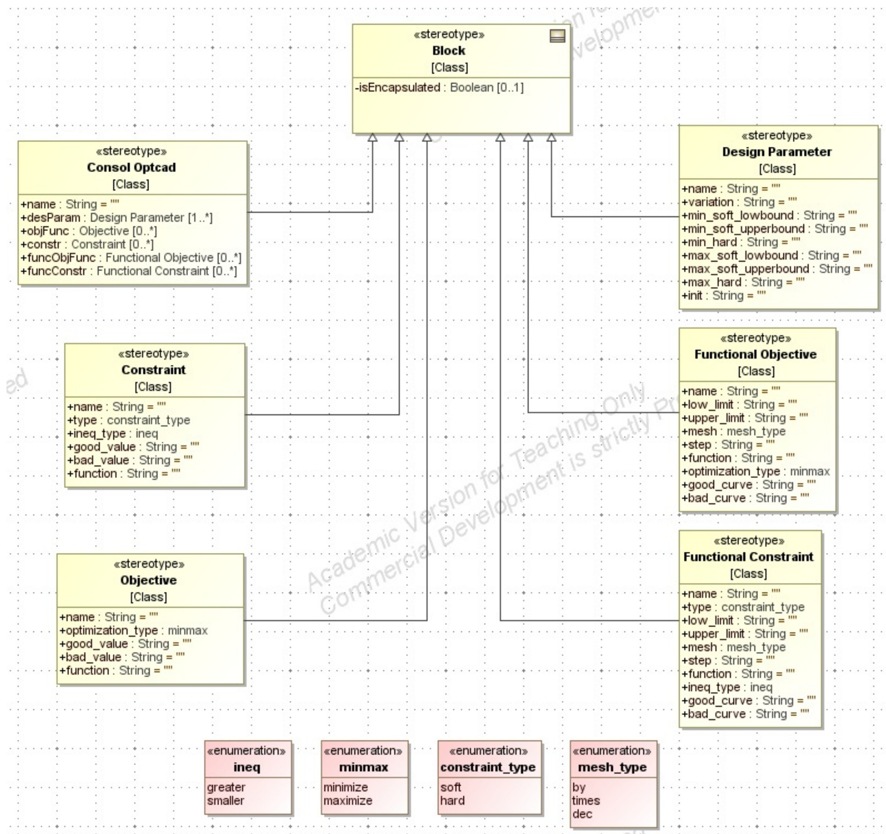


Fig. 7: Consol-Optcad profile in SysML

IMH and Consol-Optcad Integration

Tool Adapters

- Tool adapters **act as a middleware** between the generated code from the transformations and the tools (MagicDraw, Consol-Optcad)
- They are used to access/change the information contained within the models
- They perform the transformations by calling the generated Java methods
- Tool Adapter layer is implemented as a MagicDraw plug-in, inside the Eclipse environment

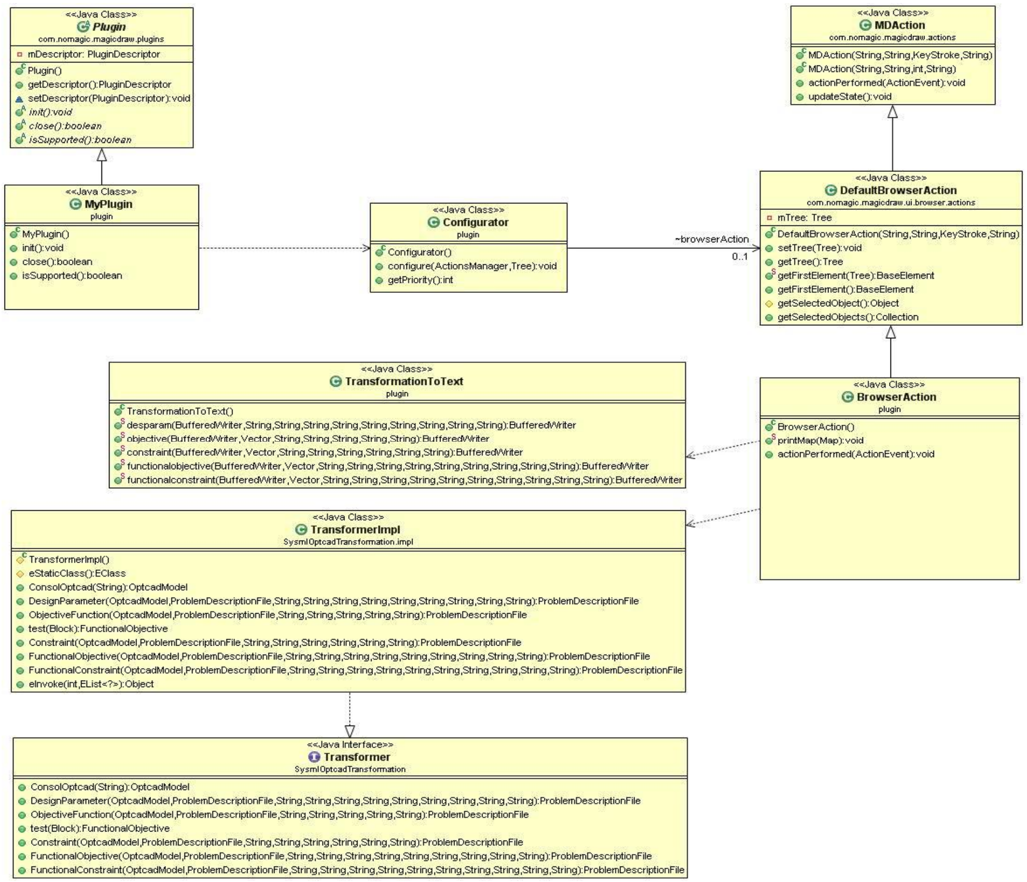


Fig. 8: Consol-Optcad MagicDraw plug-in class diagram

IMH and Consol-Optcad Integration

Parametric Diagram

- In SysML both the system model and the trade-off model are defined
- Parametric diagram is used to link the values of element attributes to the design parameters of the trade-off model
- From the parametric diagram the user can initiate the transformation process by calling the developed plug-in

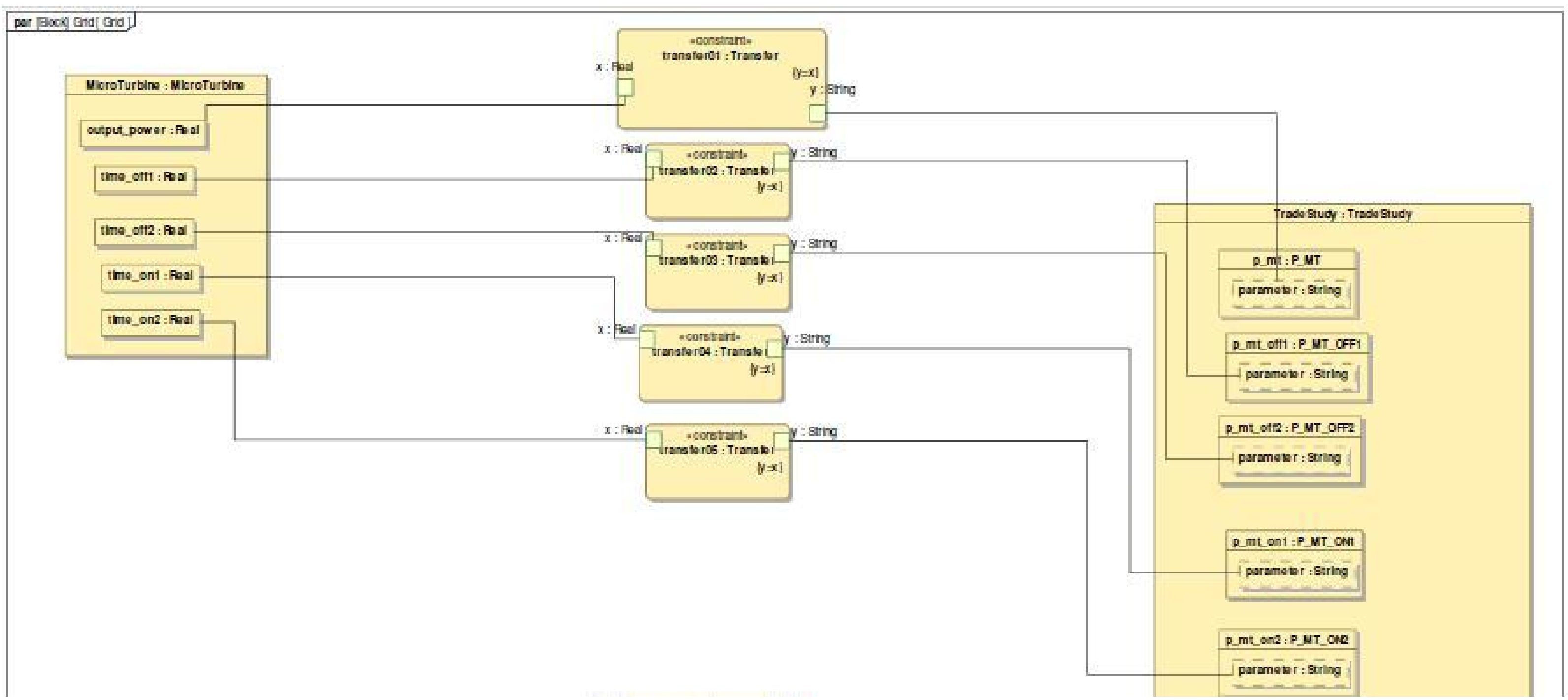


Fig. 9: Parametric diagram

IMH and Consol-Optcad Integration

The Institute for Systems Research

Working Example

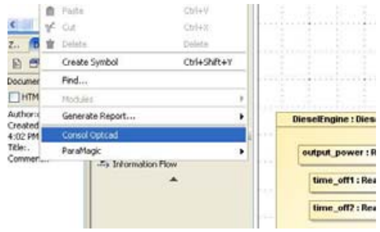


Fig. 11: Initiate transformation

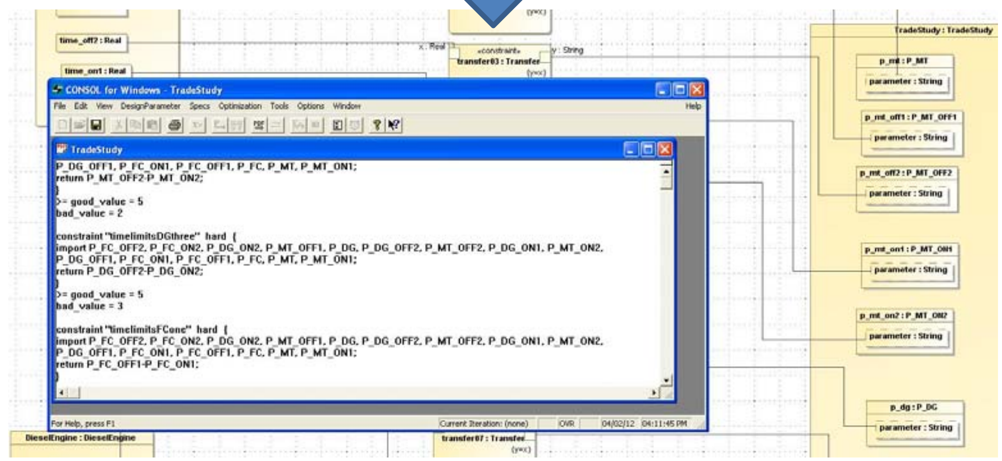


Fig. 12: Consol-Optcad environment

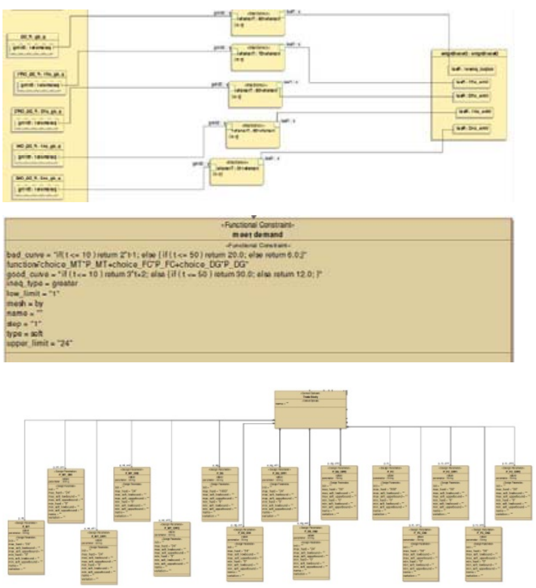


Fig. 10: Models in SysML

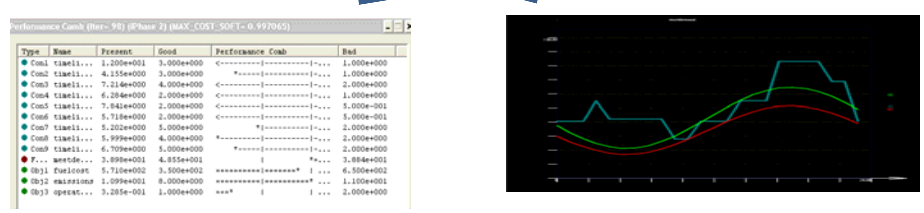


Fig.13: Perform trade-off analysis in Consol-Optcad

Microgrid Problem Formulation

Objectives

Minimize Operational Cost: $OM(\$)=\sum_{i=1}^{N} K_{OM_i} P_i t_{i_{operation}}$

Minimize Fuel Cost: $FC(\$)=\sum_{i=1}^{N} C_i \frac{P_i t_{i_{operation}}}{n_i}$

Minimize Emissions: $EC(\$)=\sum_{i=1}^{N}\sum_{i=1}^{M} a_k (EF_{ik} P_i t_{i_{operation}} /1000)$

P_i : power output of each generating unit

t_i : time of operation during the day for the unit i

n_i : efficiency of the generating unit i

N : number of generating units

M : number of elements considered in emissions objective

$K_{OM_i}, C_i, a_k, EF_{ik}$: constants defined from existing tables

Microgrid Problem Formulation

Constraints

- Meet electricity demand : $P_i \geq Demand(kW) = 50 \cdot (0.6\sin(\frac{\pi t}{12}) + 1.2)$

  Functional constraint and shall be met for all values of the free parameter *t*
- Each power source should turn on and off only 2 times during the day

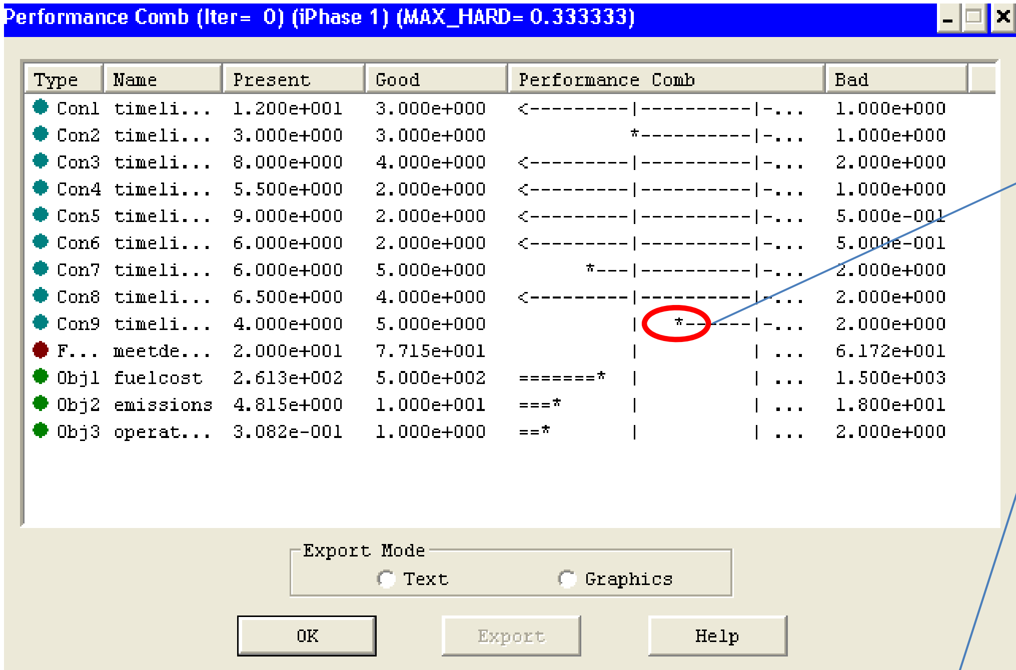
Constraints for correct operation of the generation unit

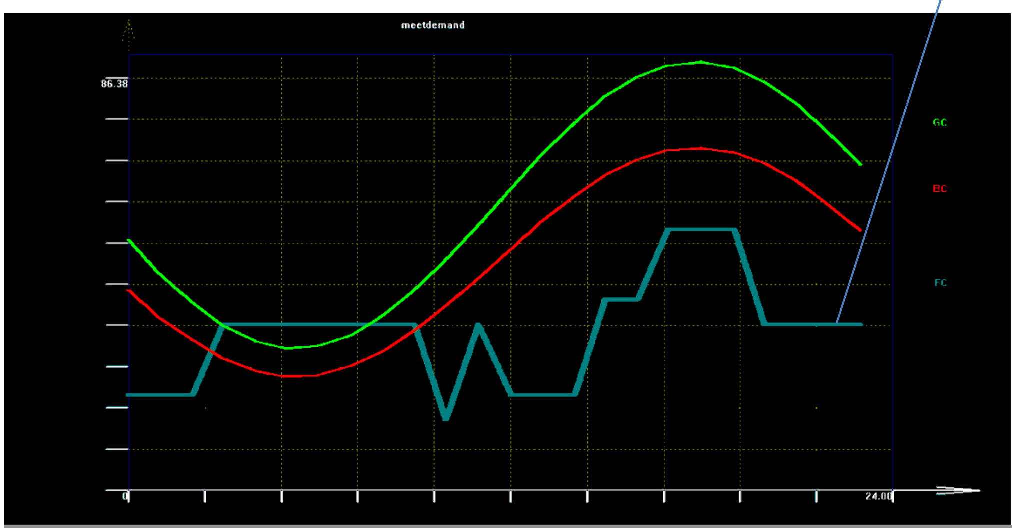
- Each generating unit should remain open for at least a period x_i defined by the specifications: $t_{i\_off\,1} - t_{i\_on1} \geq x_i$ and $t_{i\_off\,2} - t_{i\_on2} \geq x_i, \quad i = 1,2,\ldots N$

- Each generating unit should remain turned off for at least a period y_i defined by the specifications: $t_{i\_on2} - t_{i\_off1} \geq y_i, \quad i = 1,2,\ldots N$

The problem has a total of *15 design variables, 10 constraints and 3 objective functions*

Tradeoff Study in Consol-Optcad

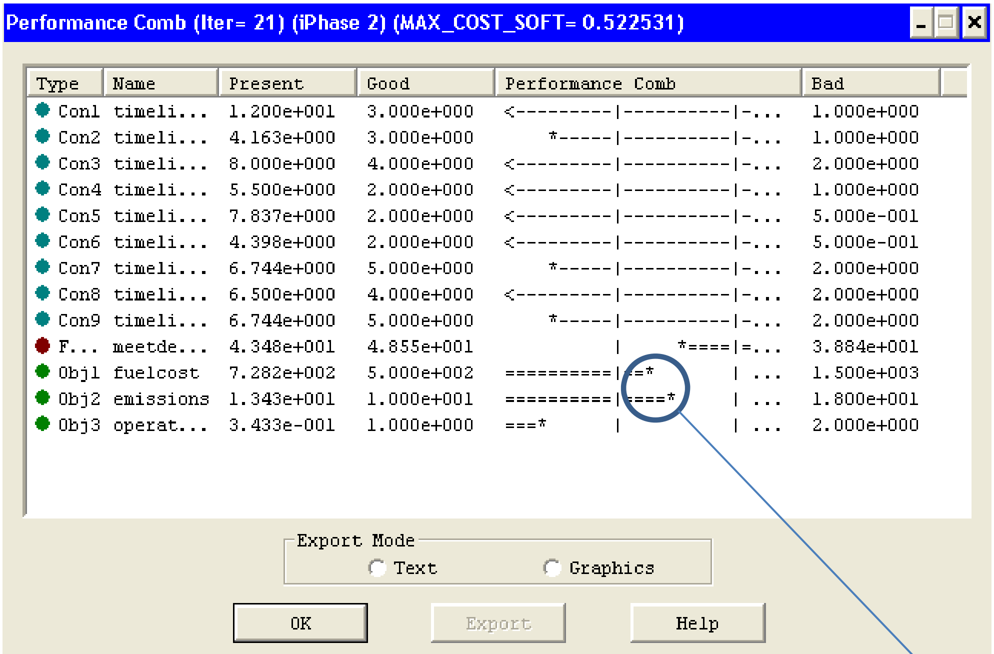




Iteration 1 (Initial Stage)

- ✓ Hard constraint not satisfied
- ✓ Functional Constraint below the bad curve
- ✓ All other hard constraints and objectives meet their good values
- ✓ Usually the user does not interact with the optimization process **until all hard constraints are satisfied**

Microgrid: Trade-off Study



Performance Comb (Iter= 21) (iPhase 2) (MAX_COST_SOFT= 0.522531)

Type	Name	Present	Good	Performance Comb	Bad
Con1	timeli...	1.200e+001	3.000e+000	<---------|----------|-...	1.000e+000
Con2	timeli...	4.163e+000	3.000e+000	*-----|----------|-...	1.000e+000
Con3	timeli...	8.000e+000	4.000e+000	<---------|----------|-...	2.000e+000
Con4	timeli...	5.500e+000	2.000e+000	<---------|----------|-...	1.000e+000
Con5	timeli...	7.837e+000	2.000e+000	<---------|----------|-...	5.000e-001
Con6	timeli...	4.398e+000	2.000e+000	<---------|----------|-...	5.000e-001
Con7	timeli...	6.744e+000	5.000e+000	*-----|----------|-...	2.000e+000
Con8	timeli...	6.500e+000	4.000e+000	<---------|----------|-...	2.000e+000
Con9	timeli...	6.744e+000	5.000e+000	*-----|----------|-...	2.000e+000
F...	meetde...	4.348e+001	4.855e+001	| *====|=...	3.884e+001
Obj1	fuelcost	7.282e+002	5.000e+002	==========|==* | ...	1.500e+003
Obj2	emissions	1.343e+001	1.000e+001	==========|====* | ...	1.800e+001
Obj3	operat...	3.433e-001	1.000e+000	===* | | ...	2.000e+000

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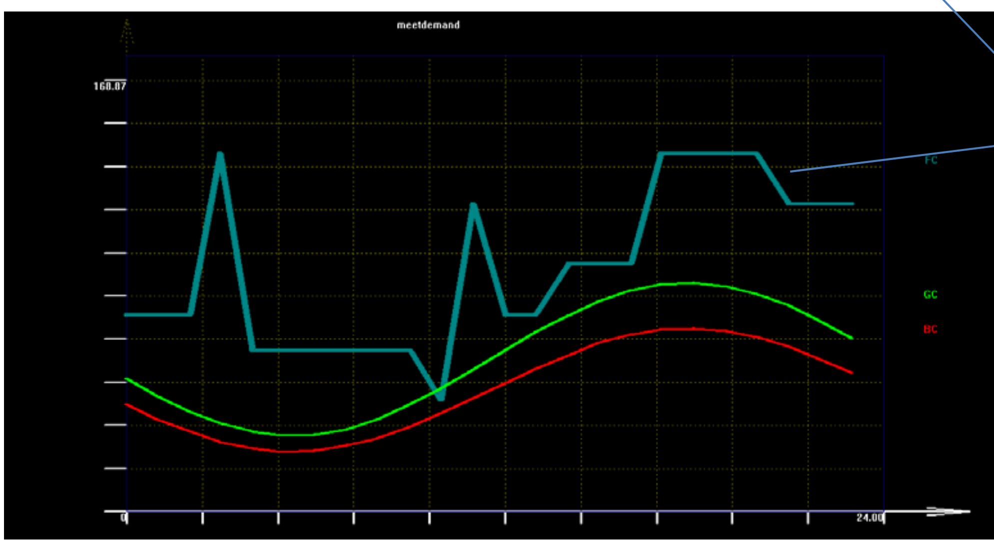


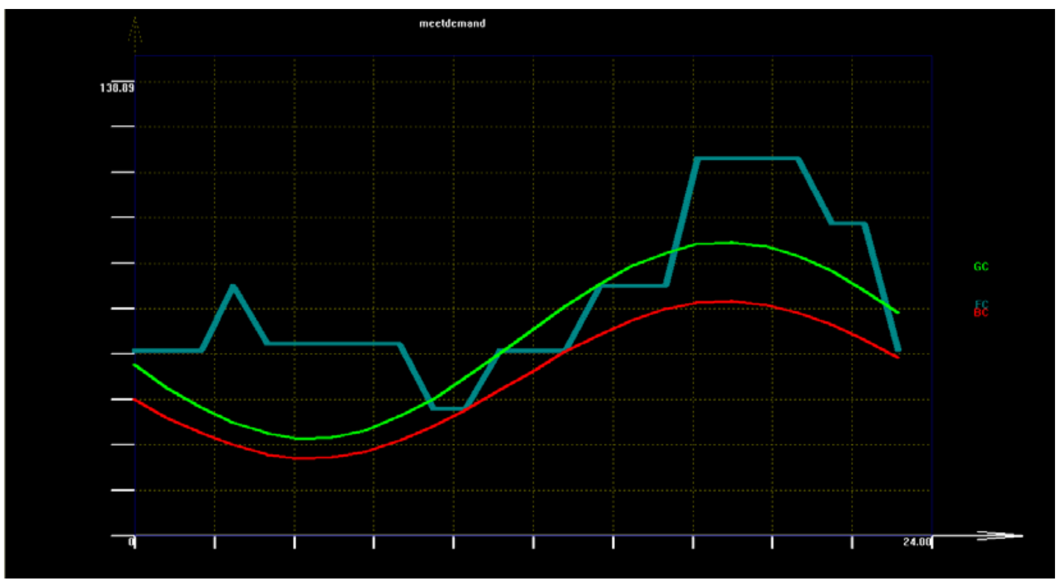
Iteration 28 (User Interaction)

- ✓ All hard constraints are satisfied
- ✓ Functional Constraint meets the specified demand. Goes below the good curve only for a small period of time but as a soft constraint is considered satisfied
- ✓ All objectives are within limits
- ✓ Because at this stage we generate a lot more power than needed we decide to make the constraints for fuel cost and emissions tighter
- ✓ At this stage all designs are feasible (FSQP solver)

Trade-off Study in Consol-Optcad

Performance Comb (Iter= 98) (iPhase 2) (MAX_COST_SOFT= 0.997065)

<table>
<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
<tr><td>Con1</td><td>timeli...</td><td>1.200e+001</td><td>3.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con2</td><td>timeli...</td><td>4.155e+000</td><td>3.000e+000</td><td>   *-----|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con3</td><td>timeli...</td><td>7.214e+000</td><td>4.000e+000</td><td><---------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con4</td><td>timeli...</td><td>6.284e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con5</td><td>timeli...</td><td>7.841e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con6</td><td>timeli...</td><td>5.718e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con7</td><td>timeli...</td><td>5.202e+000</td><td>5.000e+000</td><td>   *|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con8</td><td>timeli...</td><td>5.999e+000</td><td>4.000e+000</td><td>*---------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con9</td><td>timeli...</td><td>6.709e+000</td><td>5.000e+000</td><td>   *-----|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>F...</td><td>meetde...</td><td>3.898e+001</td><td>4.855e+001</td><td> | *=...</td><td>3.884e+001</td></tr>
<tr><td>Obj1</td><td>fuelcost</td><td>5.710e+002</td><td>3.500e+002</td><td>==========|=======* | ...</td><td>6.500e+002</td></tr>
<tr><td>Obj2</td><td>emissions</td><td>1.099e+001</td><td>8.000e+000</td><td>==========|==========* ...</td><td>1.100e+001</td></tr>
<tr><td>Obj3</td><td>operat...</td><td>3.285e-001</td><td>1.000e+000</td><td>===* | | ...</td><td>2.000e+000</td></tr>
</table>



Iteration 95 (Final Solution)

- ✓All hard constraints are satisfied
- ✓ All objectives are within the new tighter limits
- ✓ Functional Constraint meets the specified demand -- It never goes below the bad curve

VMS Problem Formulation

Objectives

Maximize serving of shedable loads: $\sum_{engine=1}^{M} (P_{engine} - \sum_{k=1}^{N_{eng}} (Load_{k\_non\_shedable} + Load_{k\_shedable}))$

Minimize Fuel Cost: $\sum_{i=1}^{M} C_i \frac{P_i}{n_i}$

Minimize Procurement Cost: $\sum_{i=1}^{M} P_i \cdot n_i^2$

Constraints

Meet demand for "normal flight configuration": $\forall engine \quad P_{engine} \geq \sum_{i=1}^{N} Load_{i\_non\_shedable}$

P_i : power output of each engine (design variable)

N : number of buses allocated to each engine

M: number of engines in the current configuration

n_i : efficiency of engine *i*

$Load_{i\_non\_shedable}$: constant - non-shedable load of bus *i*

$Load_{i\_shedable}$: constant - shedable load of bus *i*

C_i : constant - rate of consumption cost for each engine

VMS Tradeoff Study

Performance Comb (Iter= 1) (iPhase 2) (MAX_COST_SOFT= 1.10427)

<table>
<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
<tr><td>Con1</td><td>normal...</td><td>1.220e+005</td><td>9.800e+004</td><td><---------|----------|-...</td><td>9.700e+004</td></tr>
<tr><td>Con2</td><td>normal...</td><td>4.200e+004</td><td>1.390e+004</td><td><---------|----------|-...</td><td>1.380e+004</td></tr>
<tr><td>Con3</td><td>normal...</td><td>1.220e+005</td><td>9.800e+004</td><td><---------|----------|-...</td><td>9.700e+004</td></tr>
<tr><td>Con4</td><td>normal...</td><td>4.200e+004</td><td>1.390e+004</td><td><---------|----------|-...</td><td>1.380e+004</td></tr>
<tr><td>Obj1</td><td>utility</td><td>-2.880e+004</td><td>-3.000e+004</td><td>*|==========|=...</td><td>-5.000e+004</td></tr>
<tr><td>Obj2</td><td>fuel cost</td><td>7.364e+004</td><td>3.500e+004</td><td>==========|==========|*...</td><td>7.000e+004</td></tr>
<tr><td>Obj3</td><td>procur...</td><td>9.417e+004</td><td>5.000e+004</td><td>==========|==========|*...</td><td>9.000e+004</td></tr>
</table>

Iteration 1 (Initial Stage)

- ✓ Hard constraints are satisfied
- ✓ One out of three objectives within limits

Performance Comb (Iter= 16) (iPhase 2) (MAX_COST_SOFT= 1.10046)

<table>
<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
<tr><td>Con1</td><td>normal...</td><td>1.220e+005</td><td>9.800e+004</td><td><---------|----------|-...</td><td>9.700e+004</td></tr>
<tr><td>Con2</td><td>normal...</td><td>4.200e+004</td><td>1.390e+004</td><td><---------|----------|-...</td><td>1.380e+004</td></tr>
<tr><td>Con3</td><td>normal...</td><td>1.220e+005</td><td>9.800e+004</td><td><---------|----------|-...</td><td>9.700e+004</td></tr>
<tr><td>Con4</td><td>normal...</td><td>4.200e+004</td><td>1.390e+004</td><td><---------|----------|-...</td><td>1.380e+004</td></tr>
<tr><td>Obj1</td><td>utility</td><td>-2.880e+004</td><td>-3.000e+004</td><td>*|==========|=...</td><td>-5.000e+004</td></tr>
<tr><td>Obj2</td><td>fuel cost</td><td>7.352e+004</td><td>3.500e+004</td><td>==========|==========|*...</td><td>7.000e+004</td></tr>
<tr><td>Obj3</td><td>procur...</td><td>9.402e+004</td><td>5.000e+004</td><td>==========|==========|*...</td><td>9.000e+004</td></tr>
</table>

Iteration 16 (User Interaction)

- ✓ Objectives still not satisfied
- ✓ Very small improvement on the worst objective function value from 1st iteration
- ✓ We decide to make the utility objective (maximize serving of shedable loads) less tight

Trade-off Study in Consol-Optcad

```
Performance Comb (Iter= 29) (iPhase 2) (MAX_COST_SOFT= 0.883388)

Type  Name         Present      Good         Performance Comb               Bad
Con1  normal...    1.138e+005   9.800e+004   <---------|----------|-...     9.700e+004
Con2  normal...    3.382e+004   1.390e+004   <---------|----------|-...     1.380e+004
Con3  normal...    1.138e+005   9.800e+004   <---------|----------|-...     9.700e+004
Con4  normal...    3.382e+004   1.390e+004   <---------|----------|-...     1.380e+004
Obj1  utility      -6.150e+004  -3.500e+004            |         *|-...     -6.500e+004
Obj2  fuel cost    6.592e+004   3.500e+004   ==========|========*|-...      7.000e+004
Obj3  procur...    8.534e+004   5.000e+004   ==========|========*|-...      9.000e+004
```

Iteration 29 (Final Solution)

- ✓ Hard constraints are satisfied
- ✓ All objectives within specified limits

```
========================================
  File Name: c:\documents and settings\dimitris\desktop\conoptcad\vms    Time: 09:26:21
========================================

PRINT --- the 29(th) iteration
====================================

Name       Value          Variation      Wrt 0     Wrt Prev    Freeze
P_ENG1_L   3.382e+004     1.000e+000     -19%      0%          UnFrozen
P_ENG1_R   1.138e+005     1.000e+000      -6%      0%          UnFrozen
P_ENG2_L   3.382e+004     1.000e+000     -19%      0%          UnFrozen
P_ENG2_R   1.138e+005     1.000e+000      -6%      0%          UnFrozen
n_lf       5.376e-001     1.000e+000     -10%      0%          UnFrozen
n_hf       5.376e-001     1.000e+000     -10%      0%          UnFrozen
```

Results

- ✓ Values of the design variables
- ✓ Percentage of change from the initial value

Wireless Sensor Networks

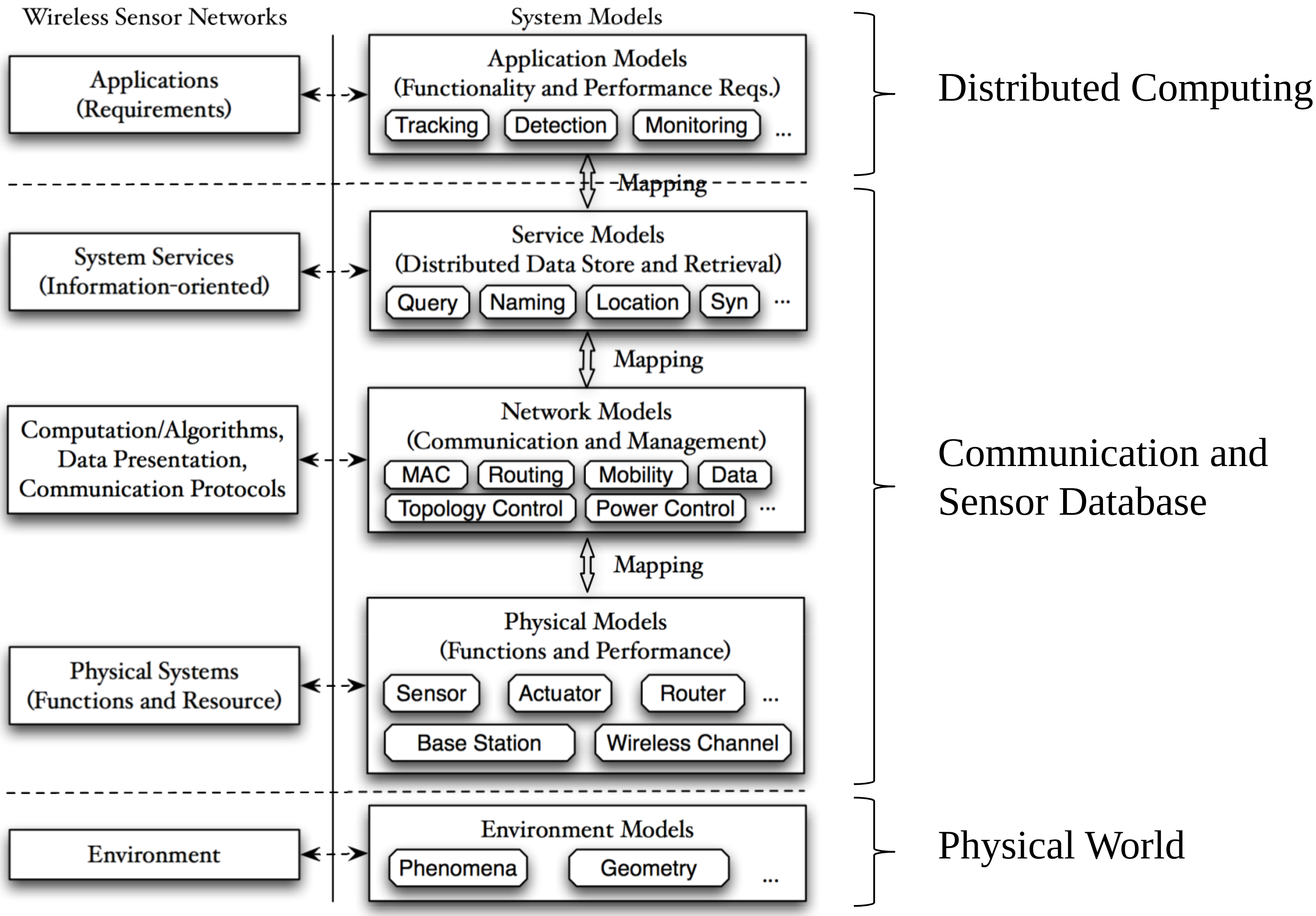
MBSE for Wireless Sensor Networks: Contributions

- Propose a model-based system design framework for WSNs
  - Integrate both event-triggered and continuous-time dynamics
  - Provide a hierarchy of system model libraries
- Propose a system design flow within our model-based framework
  - Based on an industry standard tool
  - Simulation codes (Simulink and C++) are generated automatically
  - Support trade-off analysis and optimization

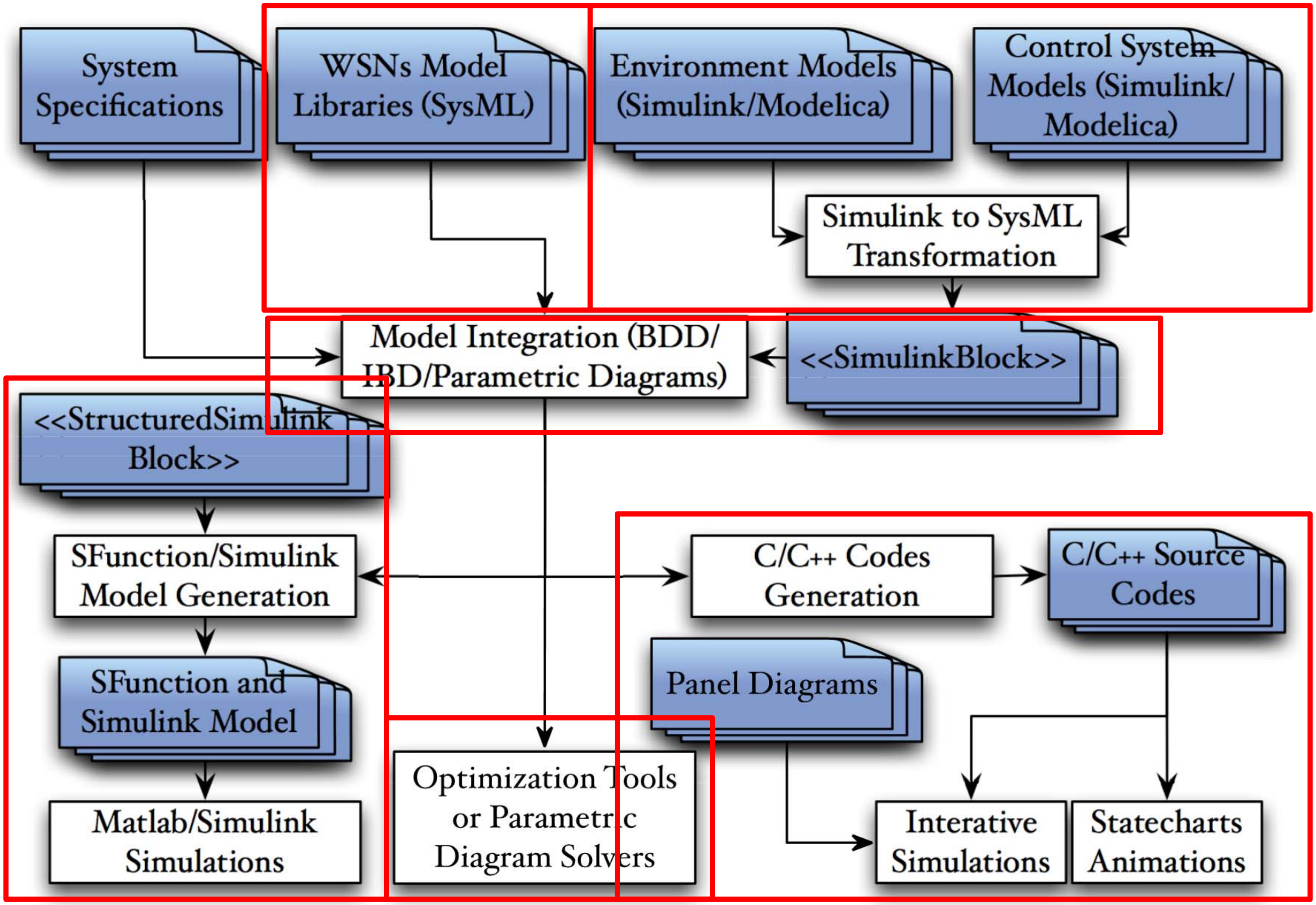
System Framework

- Model libraries
  - Application Model Library
  - Service Model Library
  - Network Model Library
  - Physical System Model Library
  - Environment Model Library
- Development Principles
  - Event-triggered: Statecharts in SysML
  - Continuous-time: Simulink or Modelica

System Framework



System Design Flow

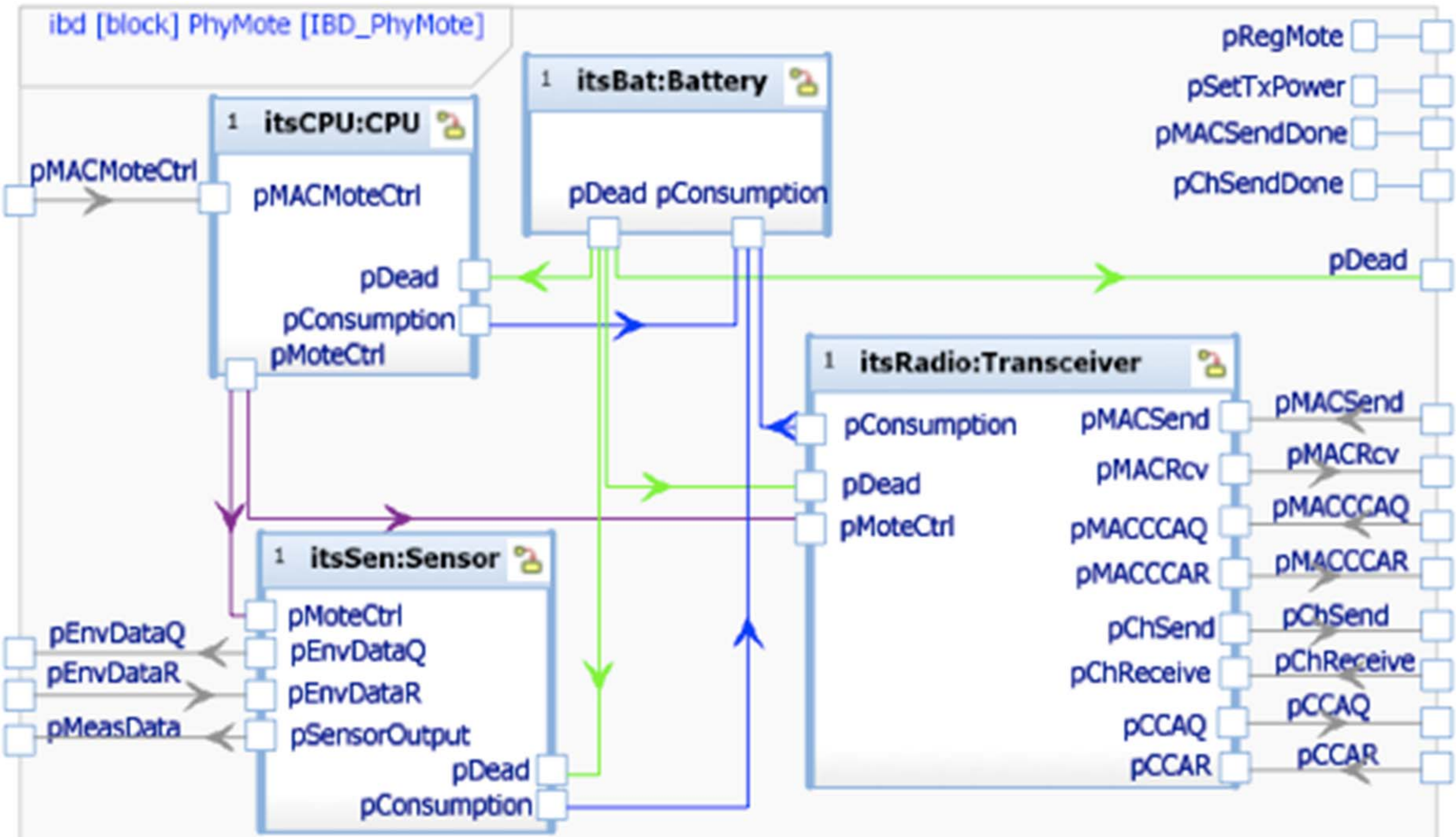


System Design Flow

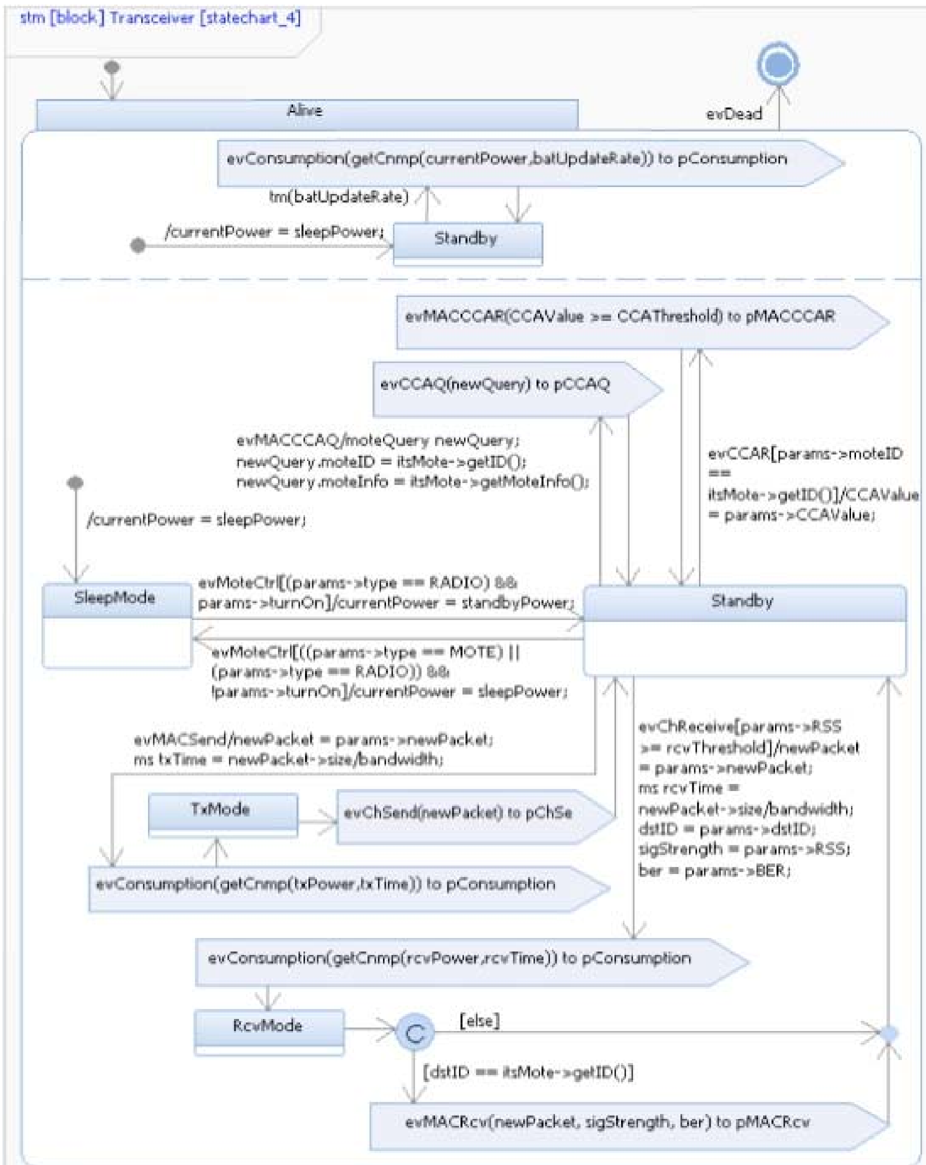
- Trade-off analysis and design space exploration
  - Each component is described with performance index
  - Parametric Diagrams
  - Parametric Constraint Evaluator or CPLEX
- Simulate in Matlab/Simulink
  - All SysML blocks are transformed into a single S-function
  - Generate Simulink source file
- Simulate in IBM Rational Rhapsody
  - Generate C/C++ source code
  - Statechart animation
  - Interactive simulation

Model Libraries

- Physical Platforms
  - Battery, CPU, sensors and transceiver



Model Libraries

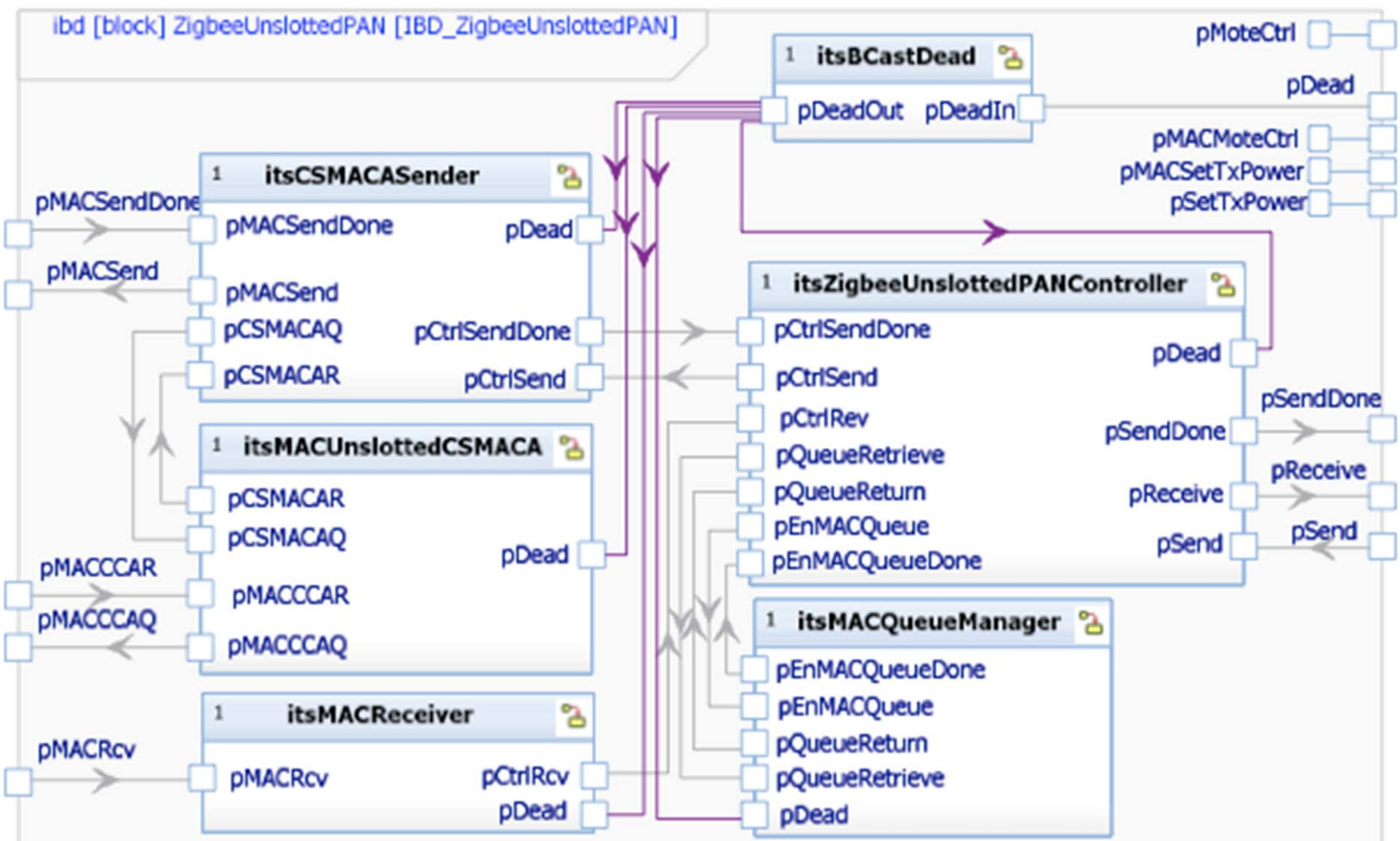


Example: behavior model of a transceiver using Statechart in IBM Rhapsody

Model Libraries

- MAC Layer Components
  - Low Power Listener: adjust radio's power state based on channel activity
  - CSMA/CA Channel Access: gain channel access right in CSMA/CA mechanisms
  - CSMA/CA Sender: send one packet with retransmissions in CSMA/CA mechanisms
  - MAC Controller: specify the control logic of a MAC protocol (ports are defined, but behavior should be customized for each protocol)
  - Slot Manager, Queue Manager, TDMA Sender, Receiver …

Model Libraries

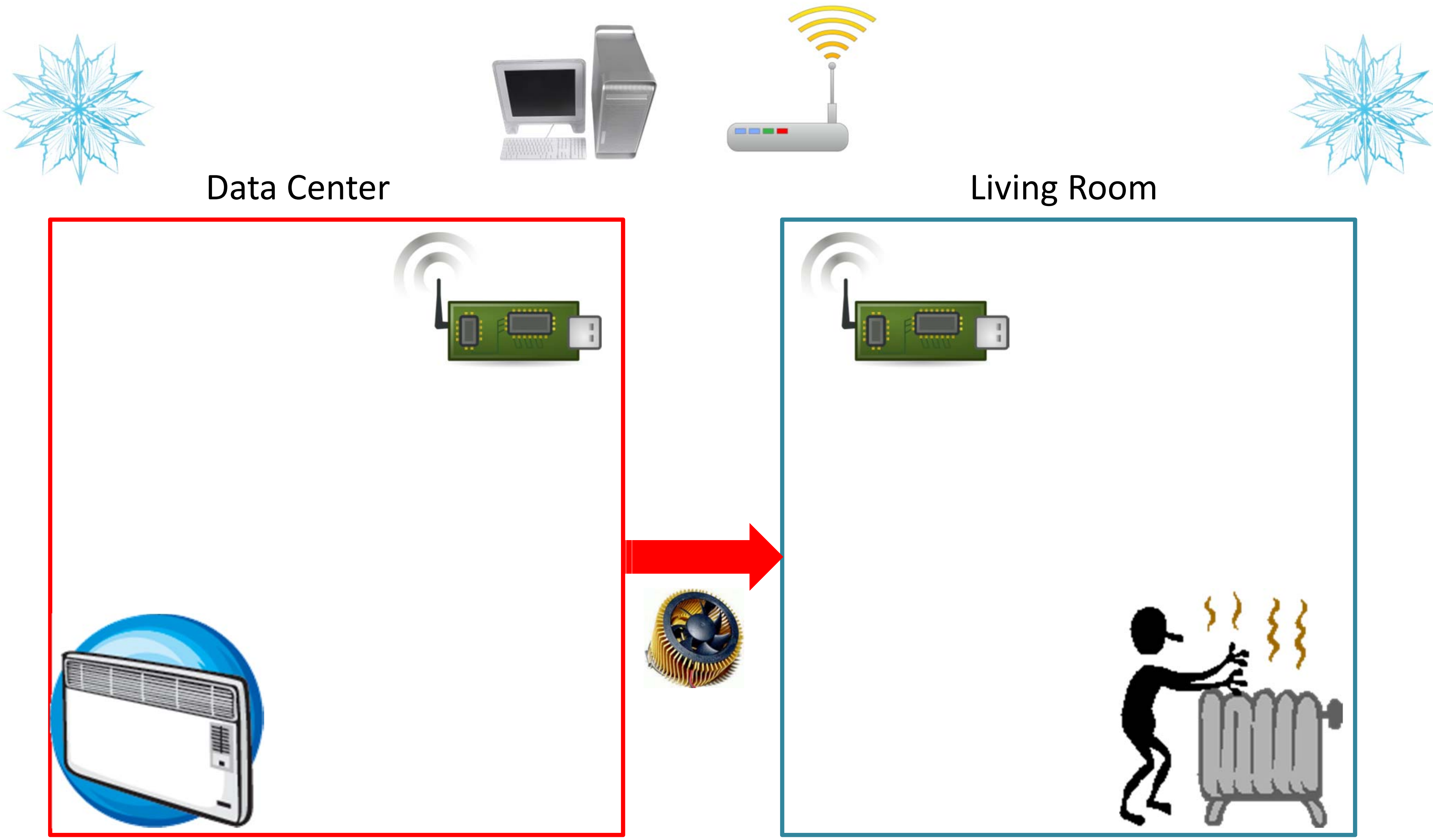


Example: IEEE 802.15.4 unslotted mode for Controller

Model Libraries

- Physical Environment
  - Modeled using Simulink or Modelica
  - Built using the Embedded Coder to generate C/C++ codes
  - Imported as SysML blocks
  - New environment information are pushed to event-triggered blocks periodically
- Wireless Channels
  - Radio propagation models, channel fading models and BER under different modulation schemes
  - Currently support: free space model, UDG model, ITU indoor model and Rayleigh fading model

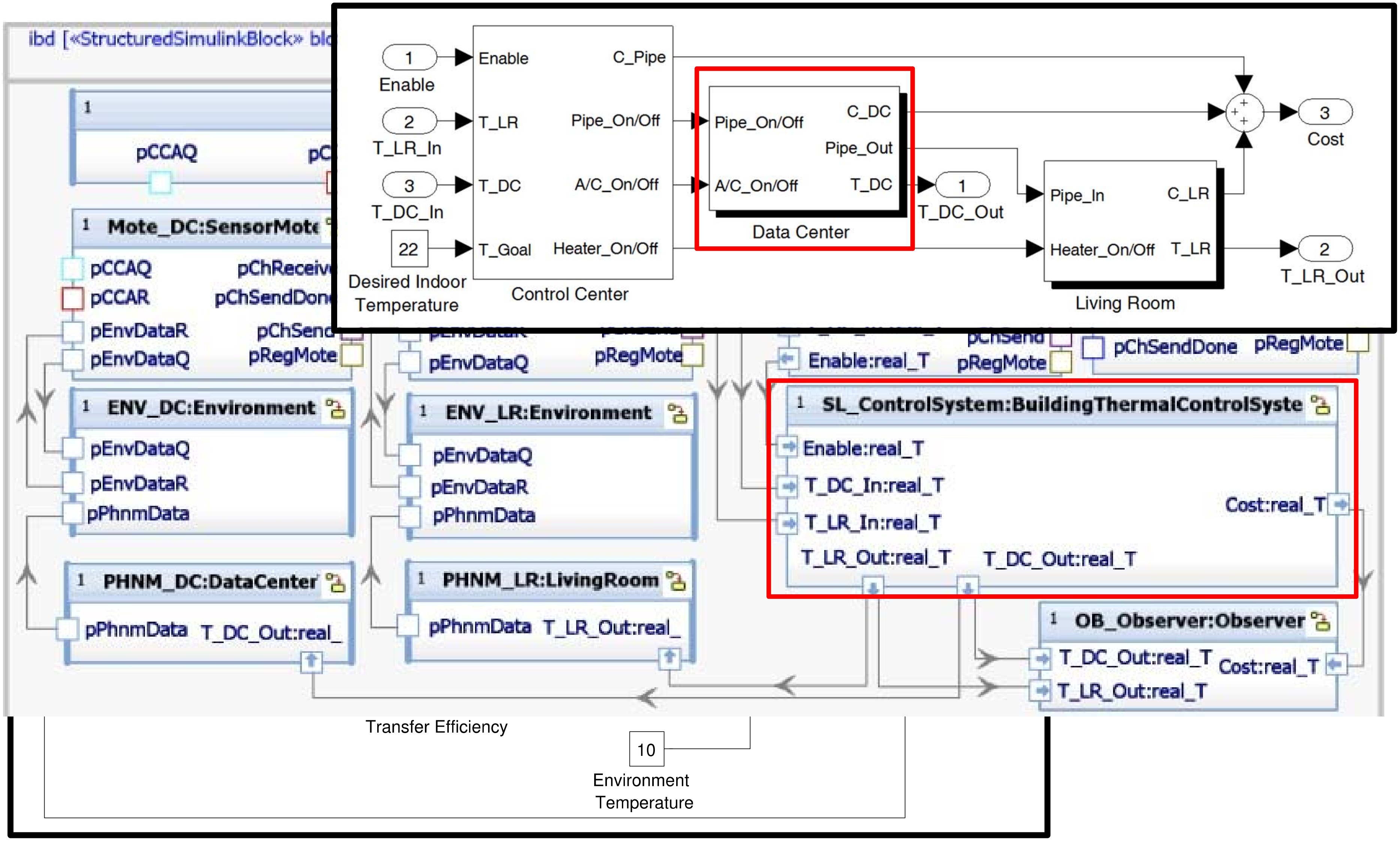
Case Study



Case Study

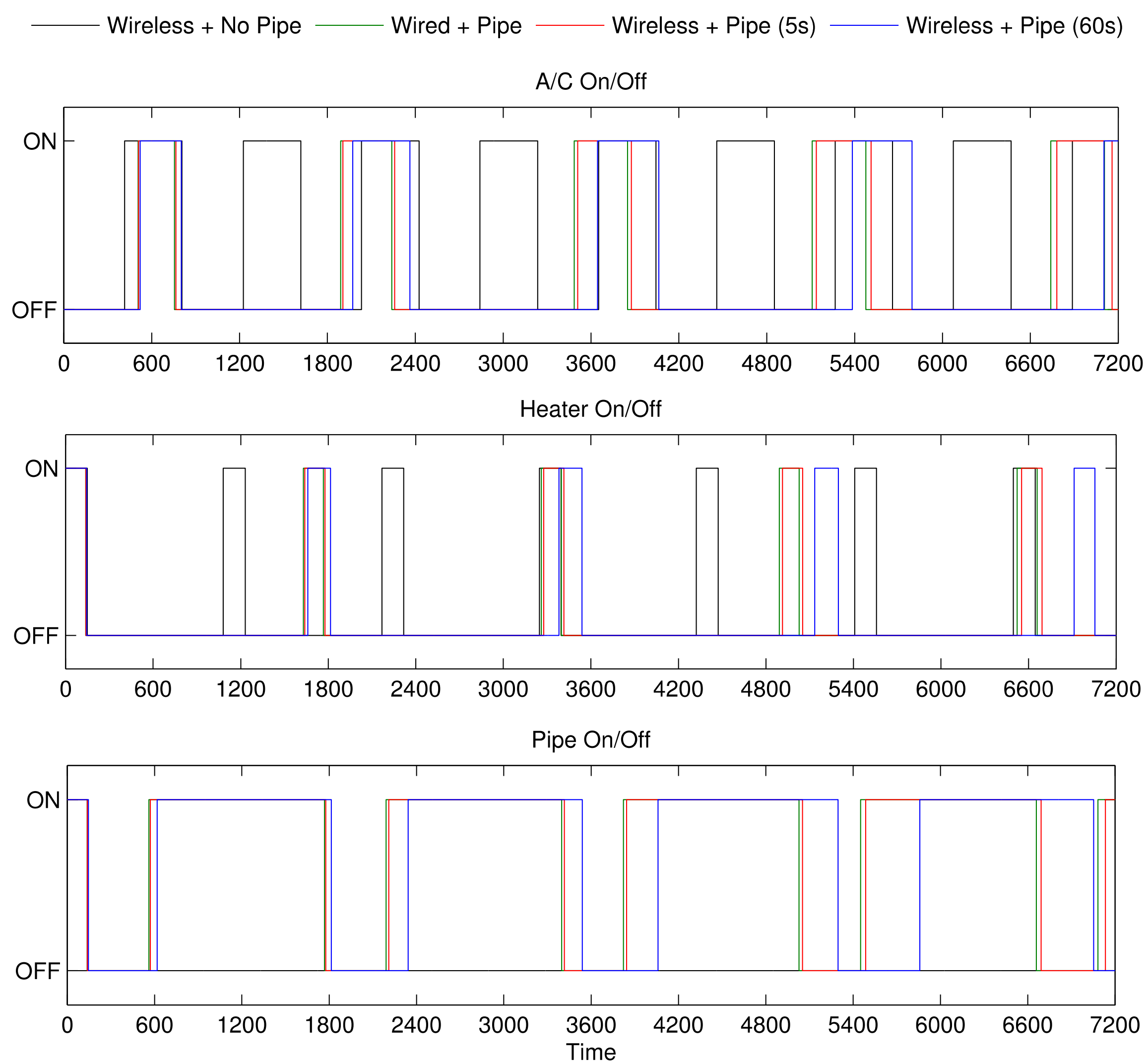
- Simulation scenarios
  - Wireless + No Pipe: disable pipe, send data wirelessly, measure period is 5 seconds
  - Wireless + Pipe (5s): similar to above, but pipe is enabled
  - Wireless + Pipe (60s): similar to above, but measure period is 60 seconds
  - Wired + Pipe: temperature data are available immediately and directly

Case Study



ibd [«StructuredSimulinkBlock» blo
1
Enable
2
T_LR_In
3
T_DC_In
22
Desired Indoor Temperature
Enable
T_LR
T_DC
T_Goal
C_Pipe
Pipe_On/Off
A/C_On/Off
Heater_On/Off
Control Center
Pipe_On/Off
A/C_On/Off
C_DC
Pipe_Out
T_DC
Data Center
1
T_DC_Out
Pipe_In
Heater_On/Off
C_LR
T_LR
Living Room
3
Cost
2
T_LR_Out
pCCAQ
Mote_DC:SensorMote
pCCAQ
pCCAR
pEnvDataR
pEnvDataQ
pChReceiv
pChSendDon
pChSend
pRegMote
ENV_DC:Environment
pEnvDataQ
pEnvDataR
pPhnmData
PHNM_DC:DataCenter
pPhnmData
T_DC_Out:real_
pEnvDataQ
pRegMote
ENV_LR:Environment
pEnvDataQ
pEnvDataR
pPhnmData
PHNM_LR:LivingRoom
pPhnmData
T_LR_Out:real_
Enable:real_T
pChSend
pRegMote
pChSendDone
pRegMote
SL_ControlSystem:BuildingThermalControlSyste
Enable:real_T
T_DC_In:real_T
T_LR_In:real_T
Cost:real_T
T_LR_Out:real_T
T_DC_Out:real_T
OB_Observer:Observer
T_DC_Out:real_T
Cost:real_T
T_LR_Out:real_T
Transfer Efficiency
10
Environment Temperature

Simulate Results



Design Space Exploration Problem

- Large, complex systems have many tunable parameters
- To perform **tradeoff analysis at system level**, a simplified view of the underlying components must be available
- **Challenge**: create an abstract, tractable representation of underlying components.
- **Hypothesis**: Although components are not perfectly decoupled, structure provides useful information for parametric decomposition

Factor Join Trees in Systems Design Space Exploration and Decomposition

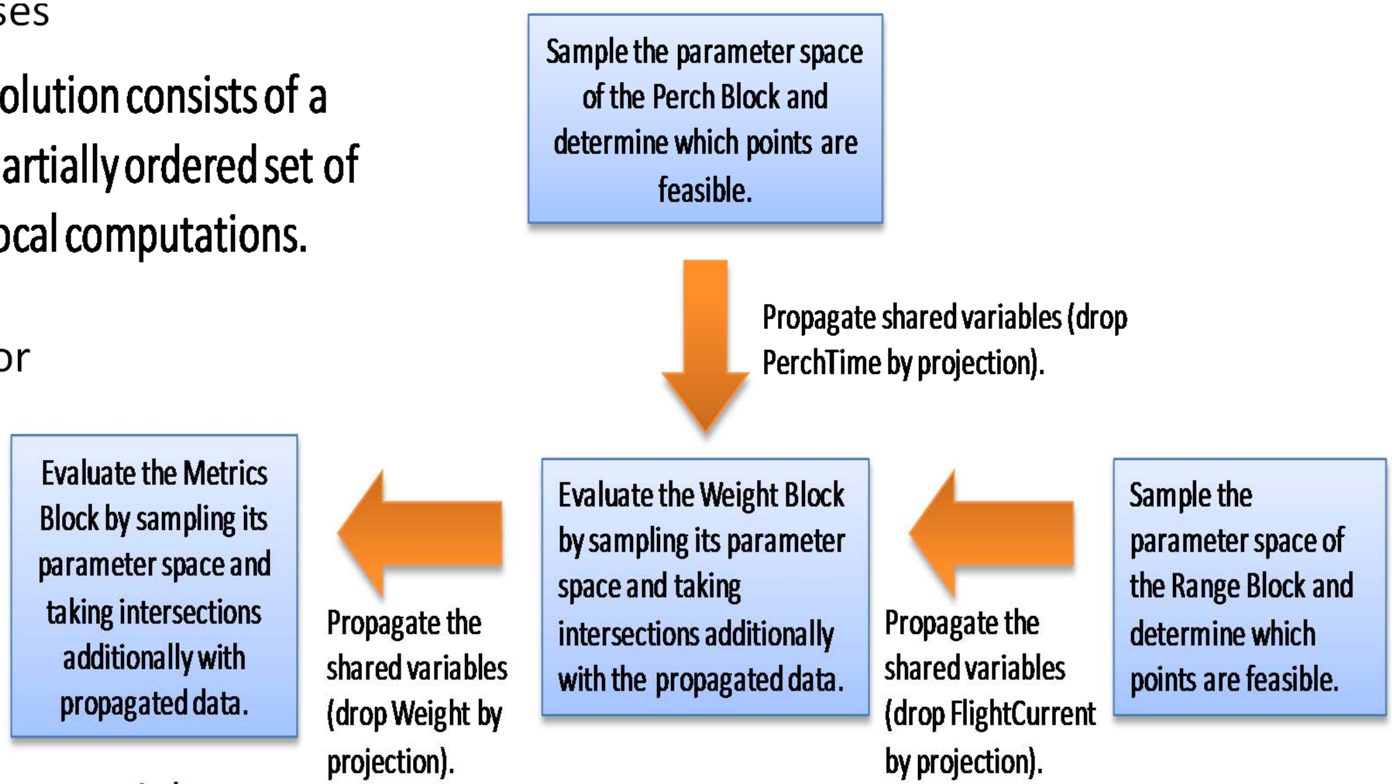
- To perform **tradeoff analysis at system level**, of complex systems a simplified view of the underlying components must be available
- **Challenge**: create an abstract, tractable component representation
- **Hypothesis**: Although components are not perfectly decoupled, structure provides useful information for parametric decomposition
- **Results/Contributions:**
- Starting from an undirected graph representation of the system developed a "divide and conquer" methodology and tool to choose subsets of nodes that completely separate the graph
- Separation produces interfaces -- leads to system decomposition in trees; "width" of a decomposition the size of the largest system component while "treewidth" is the minimum possible width over all tree decompositions
- Decomposition complexity is exponential in treewidth and linear in problem size
- By using novel organization of tradeoff queries for design space exploration, the method leads to chordal systems – decomposition performed in **linear time**

System Complexity Analysis and Control

Verification of Hybrid Automata via reachability analysis. Designer specifies a region of undesired behavior and method determines whether the system will exhibit it.

More recent method uses system locality to increase the efficiency of rigorous analysis via optimization, probabilistic inference or logical inference by embedding system in special structure.

Solution consists of a partially ordered set of local computations.



Complexity grows linearly in the size of the system vs exponential

Whole is greater than the sum of its parts -- **Divide and Conquer**

Divide and Conquer

- Defeat in detail.
- Wedge issues.
- Divide and rule.

- Separation effective because the "*whole is greater than the sum of its parts*".
  - Difficulty of problem grows faster than the sum.
  - An enemy group of size *N* has strength $\propto N^2$. *strength* $\propto$ *firepower* * *durability*. Both firepower and durability grow ~linearly with *N*.

- System analysis.
  - Analysis complexity grows ~exponentially with system size measured in the number of parameters.

Wedging Systems

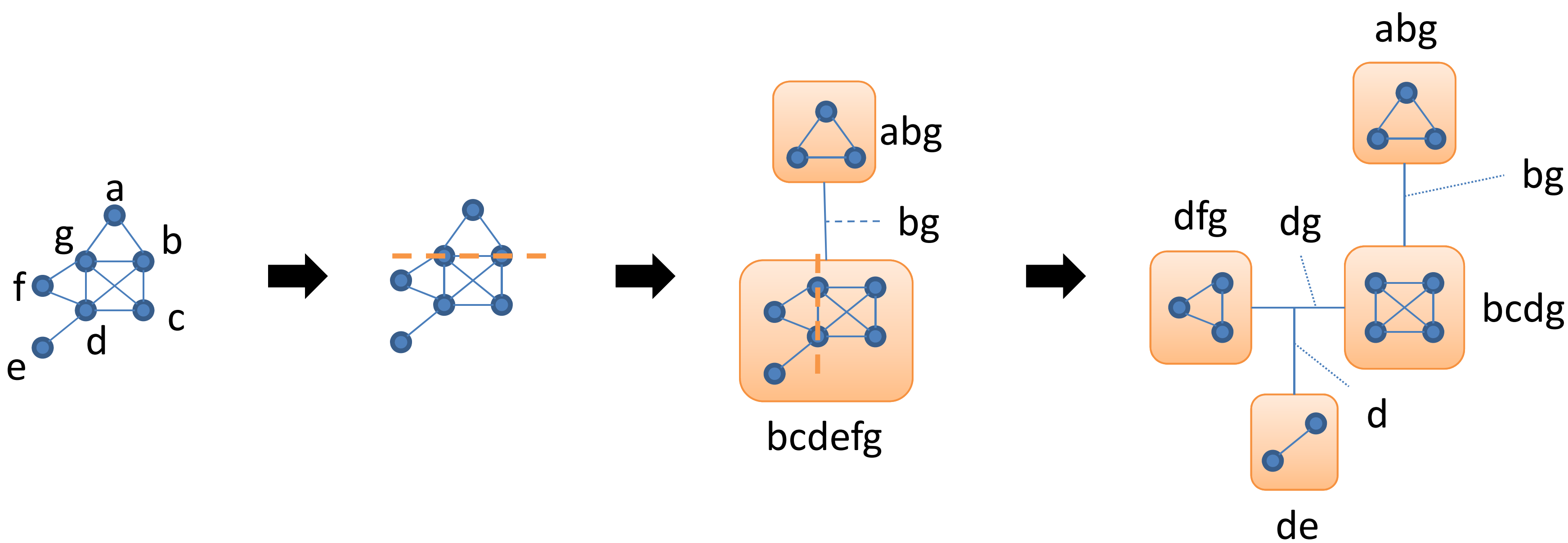
- System represented by an undirected graph *G* = <*V*,*E*>.
  - Nodes, *V*, correspond to variables.
  - A formula $f(x_1, \ldots, x_n) = C$ induces edges (x_i, x_j) $\forall i \neq j \in [1, n]$.
  - Edge, $(x, y) \in E$, means that variables x, y are in mathematical relation.

- Rules of system partitioning.

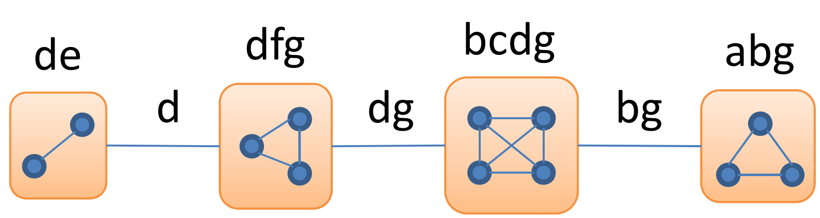
1. Choose a subset of nodes that *completely separate* the graph into subgraphs.
2. Separation produces an *interface relation* that contains all the nodes in the separator.
   - By adding links, brings resulting subsystems closer to *inseparability*.

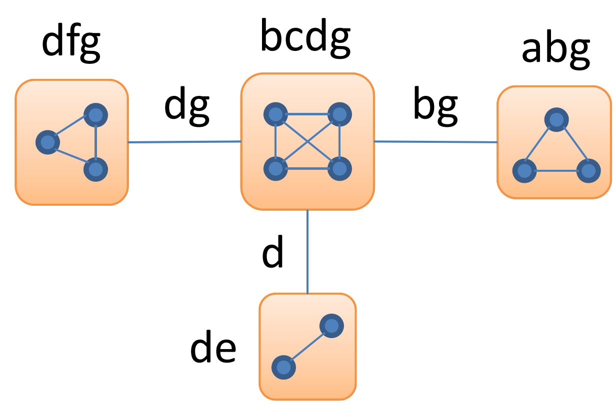
- Due to recursive partitioning this decomposition results in *trees*.

Tree Decomposition by Creating Interfaces (Chordal Example)

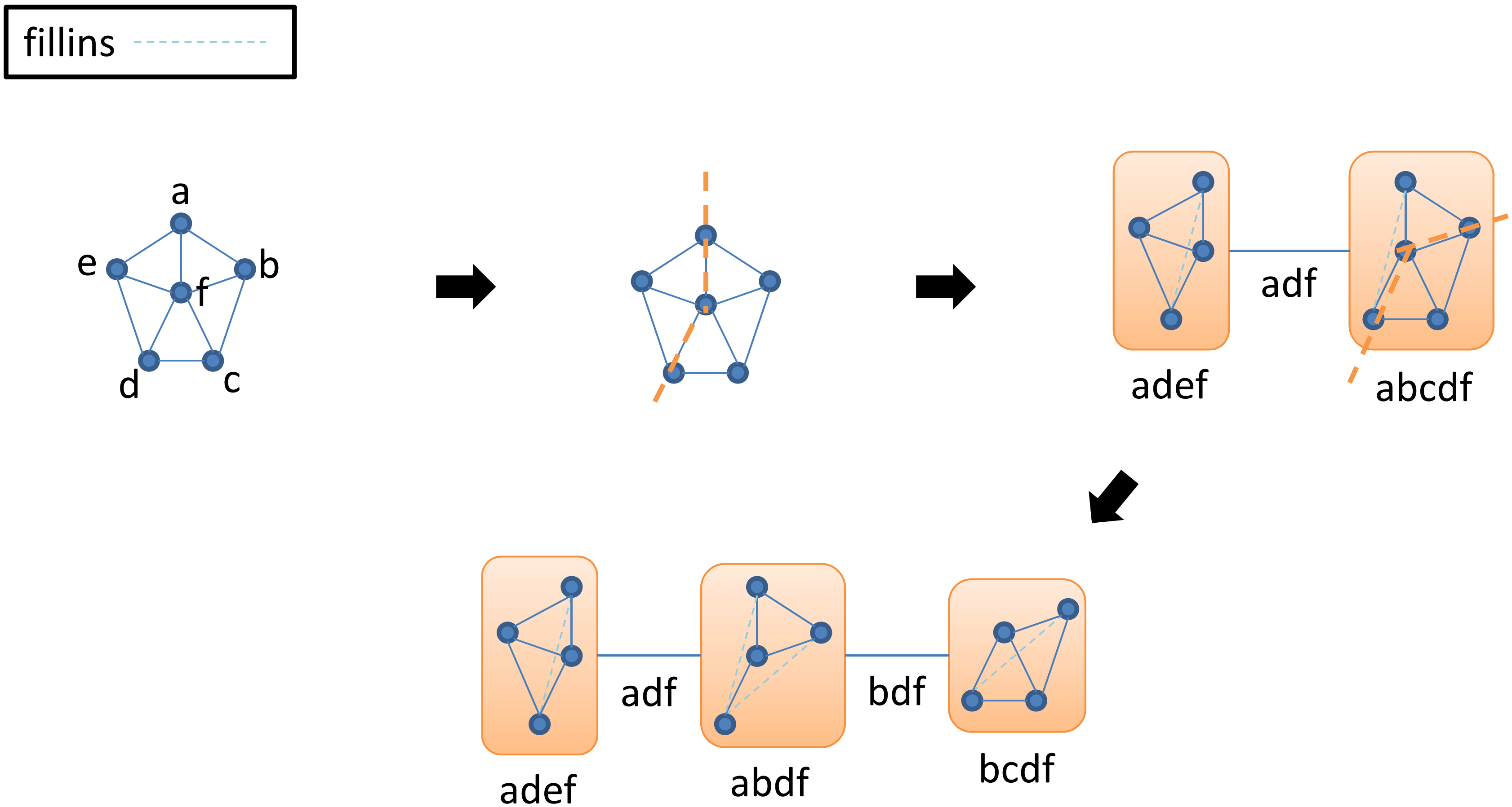


Two possible tree decompositions.





Tree Decomposition (Non-Chordal Example)



Treewidth Definition

- The "width" of a decomposition can be defined as the size of the largest component in that system.
- The treewidth is the minimum possible width over all tree decompositions-1.
- In general treewidth is NP-hard to compute.
- For many NP-complete problems on graphs, including vertex cover, independent set, dominating set, graph k-colorability, Hamiltonian circuit, network reliability, and dynamic programming , the ***complexity is exponential in treewidth and linear in problem size***.

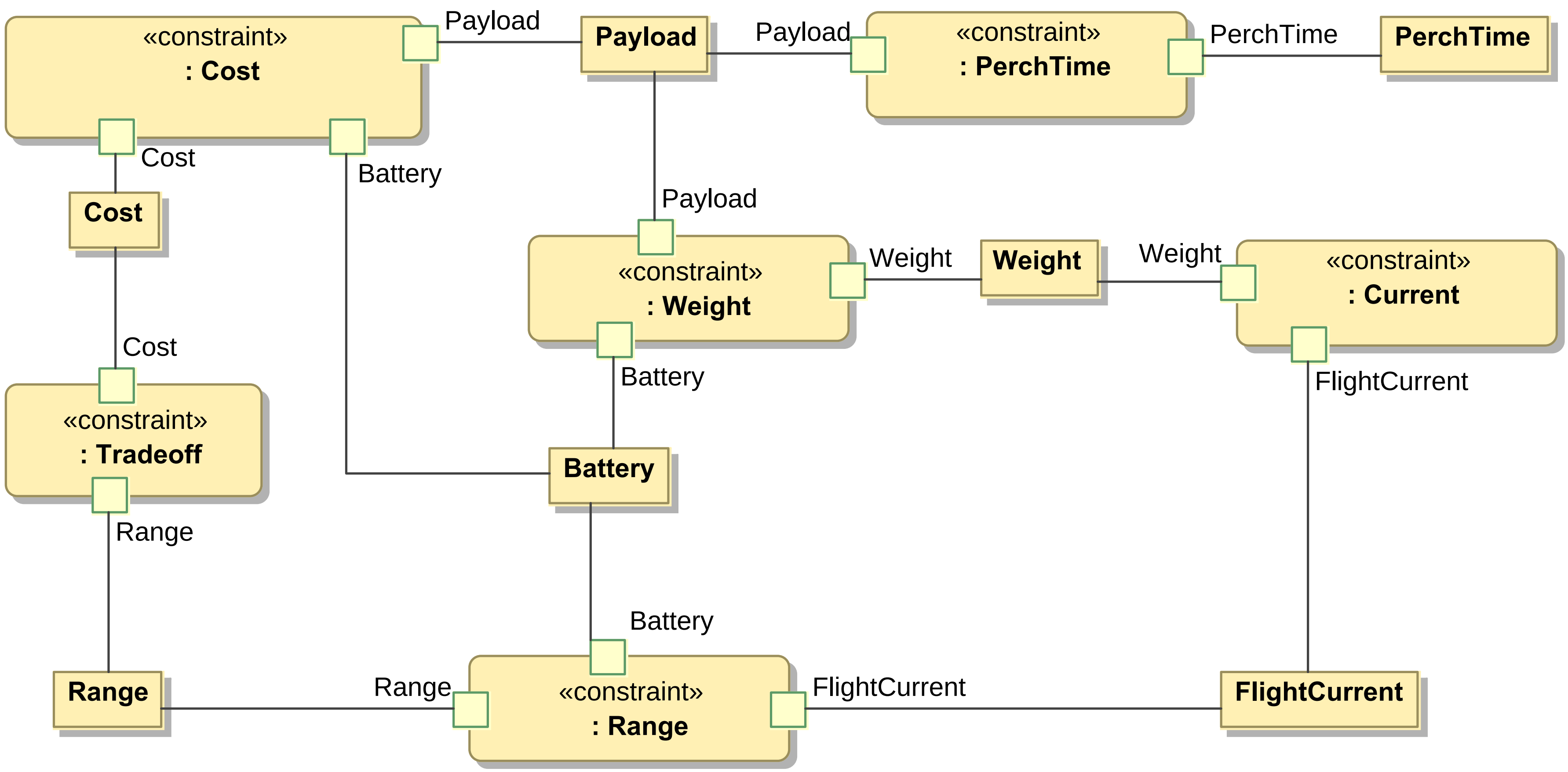
Differences Between Chordal and Non-chordal Systems

- **Chordal** : all cycles of length >3 are bridged by a chord.

- In chordal systems, decomposition is *unique* and can be performed in *linear time* using maximum cardinality search (MCS).
- Contrast with non-chordal systems where decomposition is *not unique* and *NP*-hard.

- Chordal decompositions create *no fillins*.
- *Fillins needed* in non-chordal systems.

Quadrotor Parametric Diagram

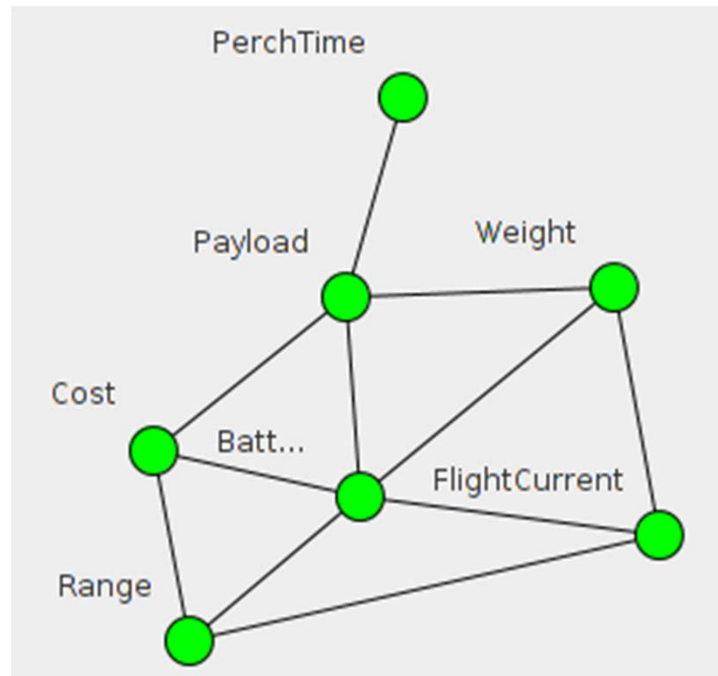


Quadrotor Analysis

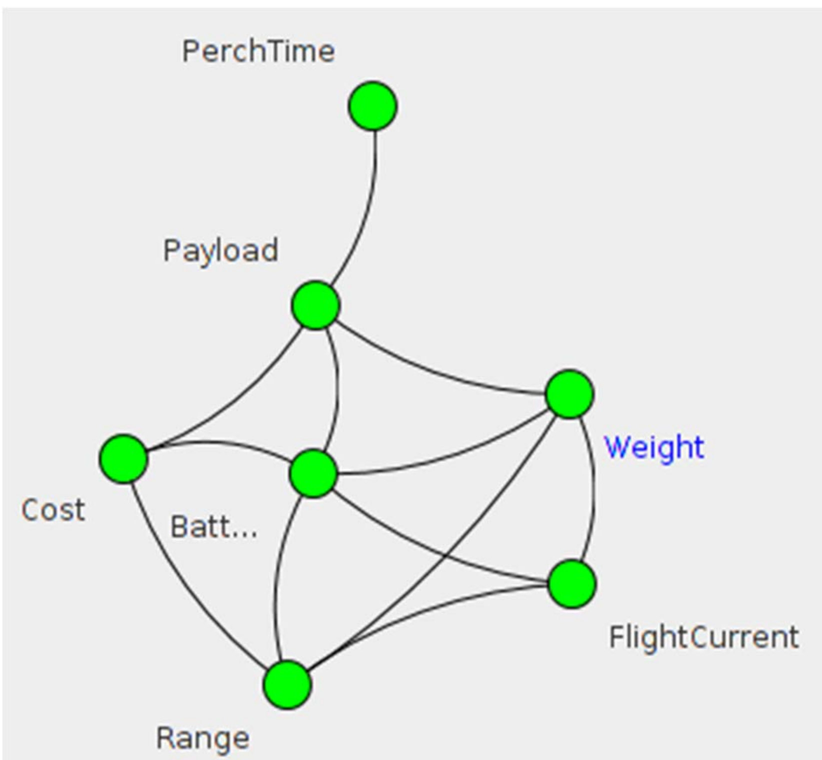
The

NO	Func Name	
1	Cost	Cost,Battery,Payload
2	Tradeoff	Cost,Range
3	Range	Battery,Range,FlightCurrent
4	Weight	Weight,Battery,Payload
5	PerchTime	Payload,PerchTime
6	Current	FlightCurrent,Weight

Tool input from parametric diagram.

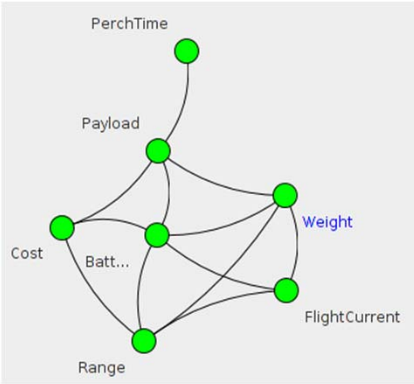


Initial graph.

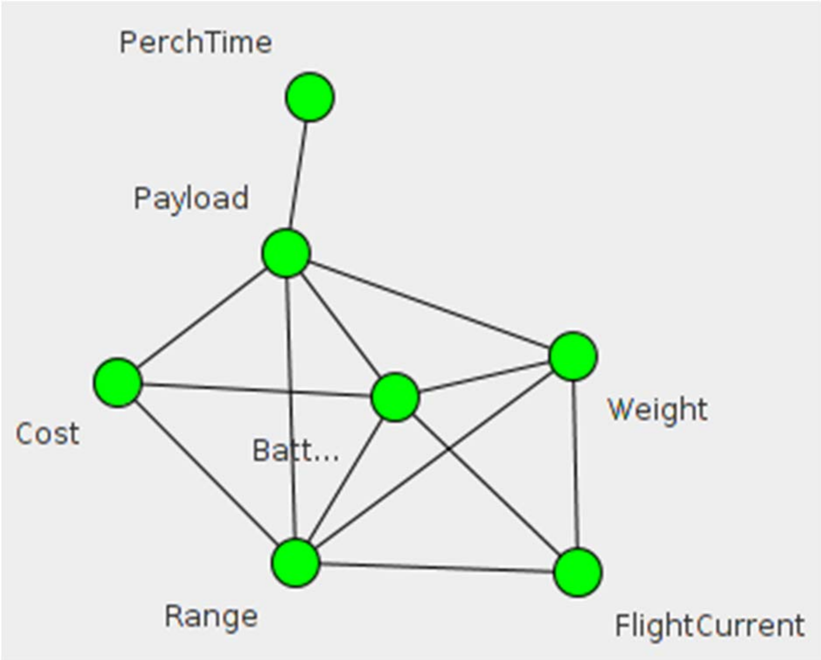


Weight to range fillin created.

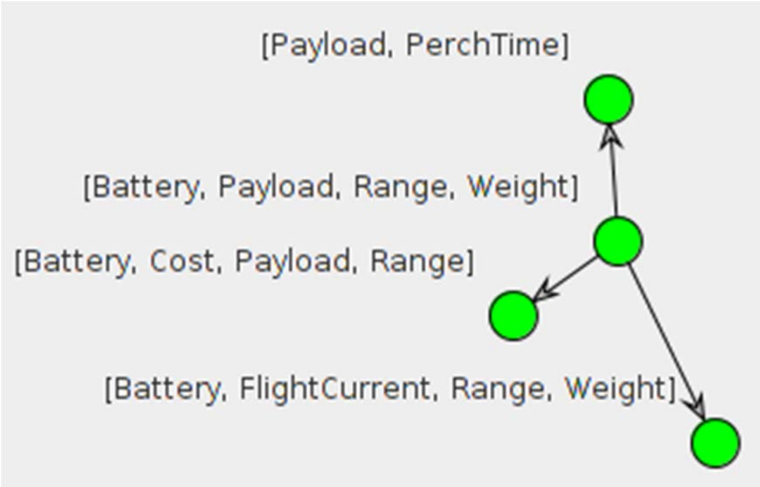
Quadrotor Analysis (cont.)



Weight to range fillin created.



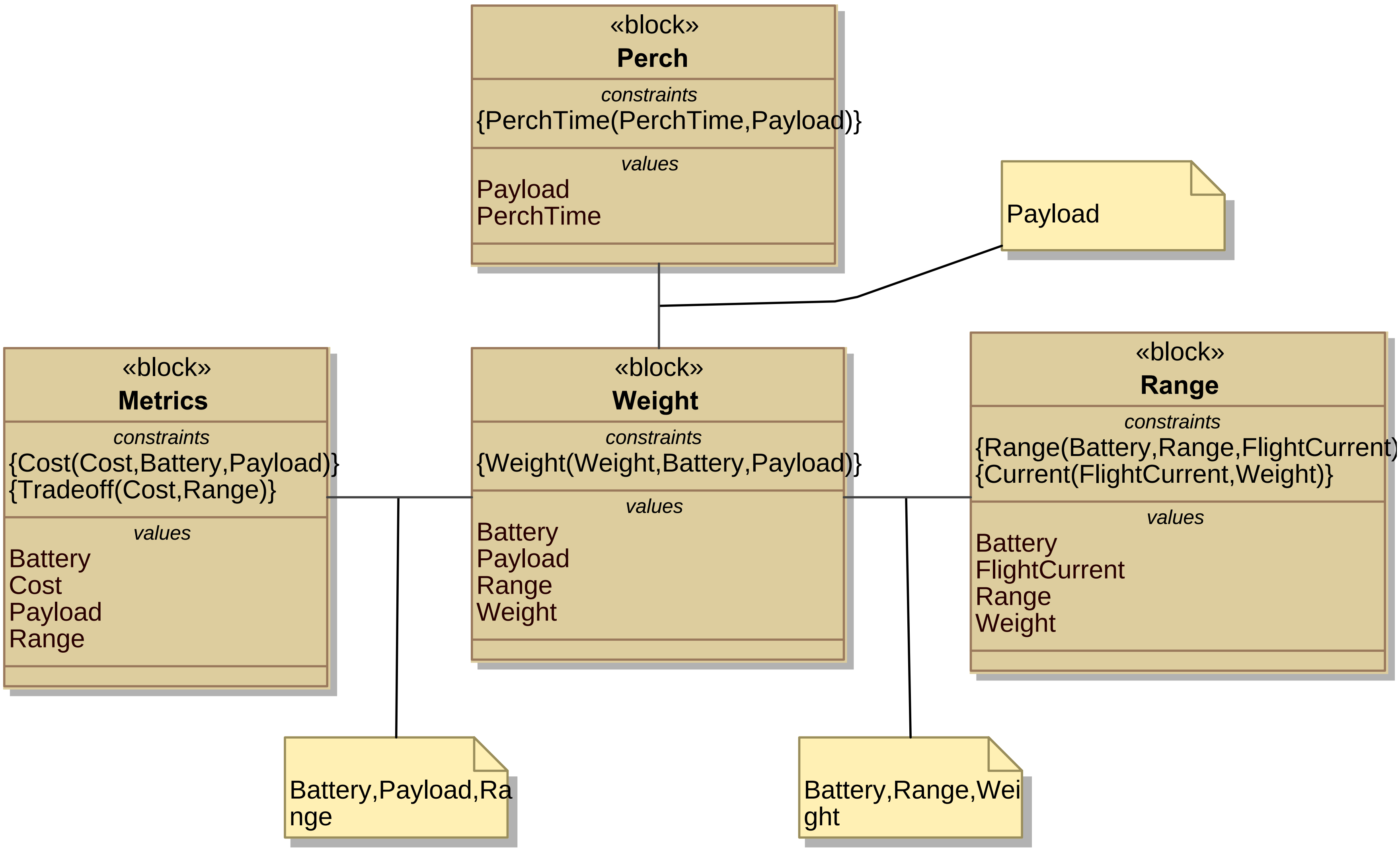
Payload to range fillin created. Graph is now chordal.



Join tree created.

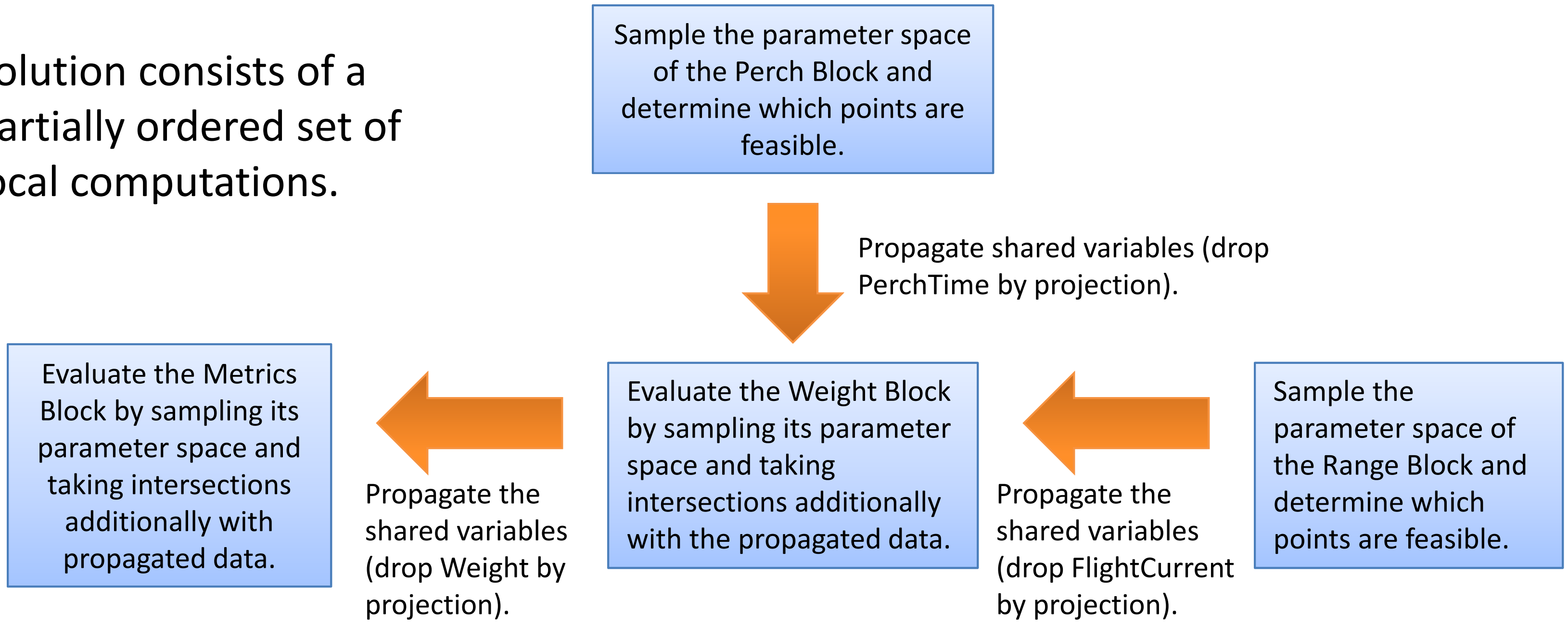
The tool implemented currently uses **elimination order** rather than **separators** to perform analysis. They are mathematically equivalent. An implementation using separators is underway.

Quadrotor Factor Join Tree



Tradeoff Analysis using Summary Propagation

Solution consists of a partially ordered set of local computations.



- Builds tables of feasible values for each of blocks.
- Uses (weighted) *natural-semijoin* on tables to propagate information.
- Applies (aggregated) *projection* on tables to hide unnecessary information.

Summary Propagation Detail

Range: d^4 complexity of construction

Battery	FlightCurrent	Range	Weight

Weight: d^4 complexity of construction

Battery	Payload	Range	Weight

projection

T3

Battery	Range	Weight

$\otimes$

Weighted Natural Join

Removes elements from *Weight* that do not occur in T3.

T4: Natural semijoin of *Range* and *Weight*.

Battery	Payload	Range	Weight

Tradeoff Queries

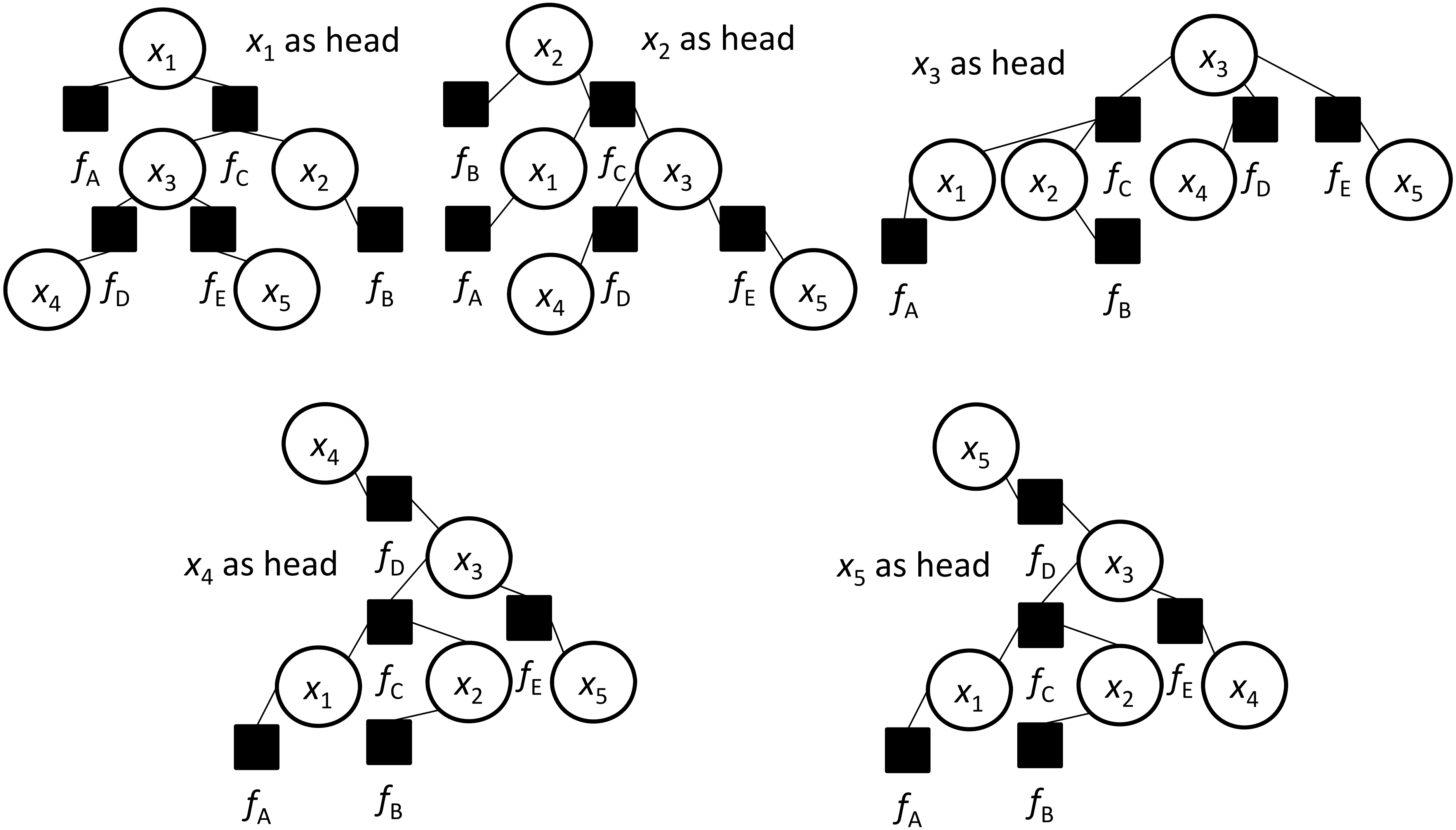
- The query itself influences the shape of the resulting graph
- A query that is not local can create links between non-local variables

- The resulting graph and *analysis complexity is dependent on the query*

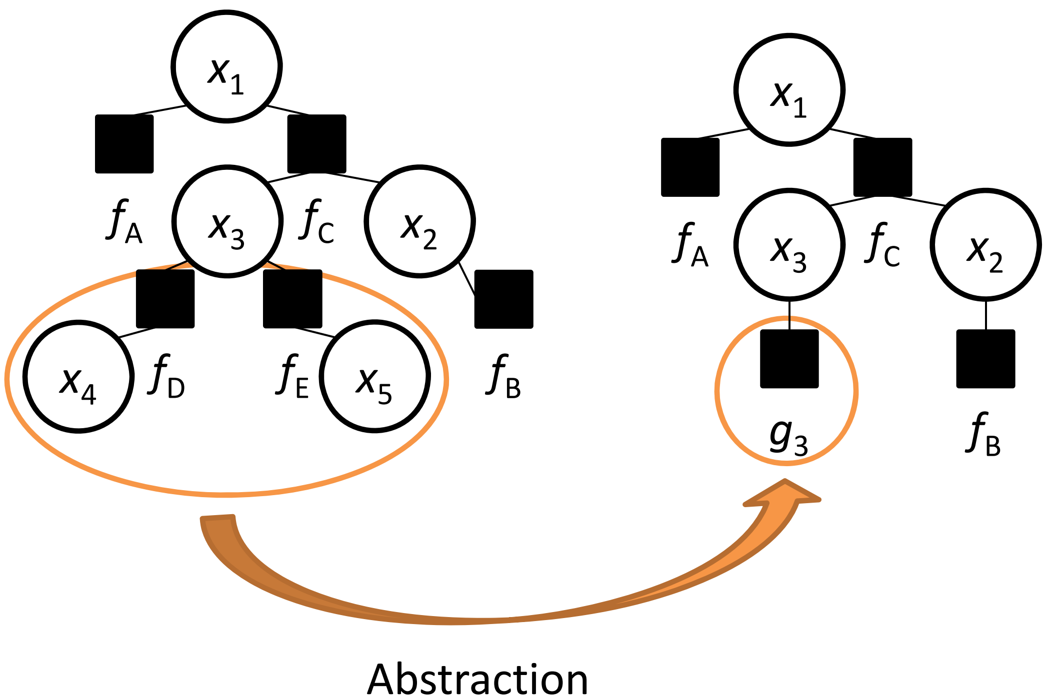
Factor Graphs Useful in Many Systems Exploration Type Problems

- Quintessential factor graph problem:
  - $\sum \cdots \sum f(X)$
  - Where $f(X)$ is a product, for example $f(X) = f_A(x_1) f_B(x_2) f_C(x_1, x_2, x_3) f_D(x_3, x_4) f_E(x_3, x_5)$
- Applicable to any commutative semiring.
  - (R,max,+) (tropical) : for optimization problems, including integer programming
  - $(\{0,1\}, \vee, \wedge)$: Boolean inference
  - $([0,1], +, \cdot)$: Bayesian inference

Query Induced Hierarchies



Abstraction as Summation/ Aggregation



Abstraction by applying $\sum_{x_4} \sum_{x_5} f(X)$

$$= \sum_{x_4} \sum_{x_5} f_A(x_1) f_B(x_2) f_C(x_1, x_2, x_3) f_D(x_3, x_4) f_E(x_3, x_5)$$

$$= f_A(x_1) f_B(x_2) f_C(x_1, x_2, x_3) \sum_{x_4} \sum_{x_5} f_D(x_3, x_4) f_E(x_3, x_5)$$

Summation remains local!

- Summing out variables creates abstract, higher level views of the data.

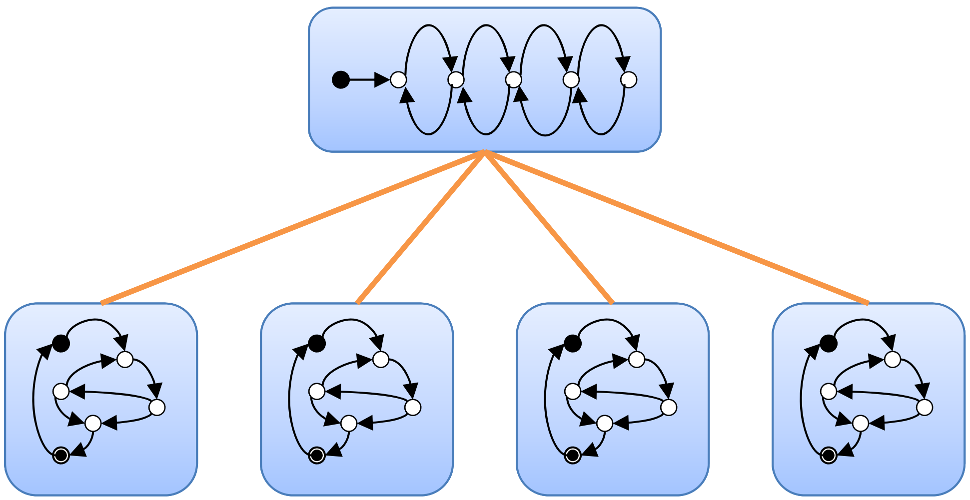
Distributed / Parallel Implementations

- Trees and a query define a partial order so parallelism exists to be exploited.

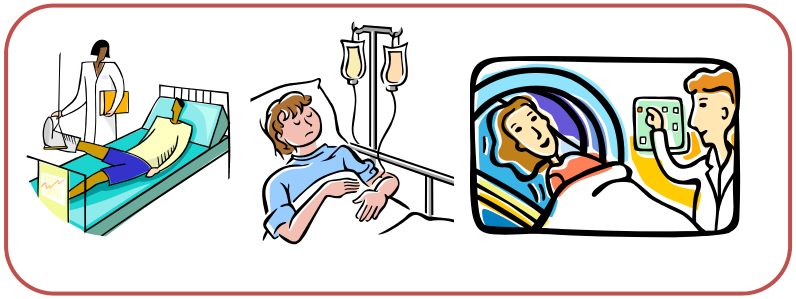
- Cliques define *local, encapsulated calculations*. These are suitable for distributed evaluation, either by computers or by teams of engineers.

Behavioral Generalization (Ongoing Work)

- The systems examined thus far can be treated statically. What happens when the components have behavior?
- [Ferrara 2005] proves that evaluating this is EXPSPACE hard in general.



Model-Based Systems Engineering for ITU Management



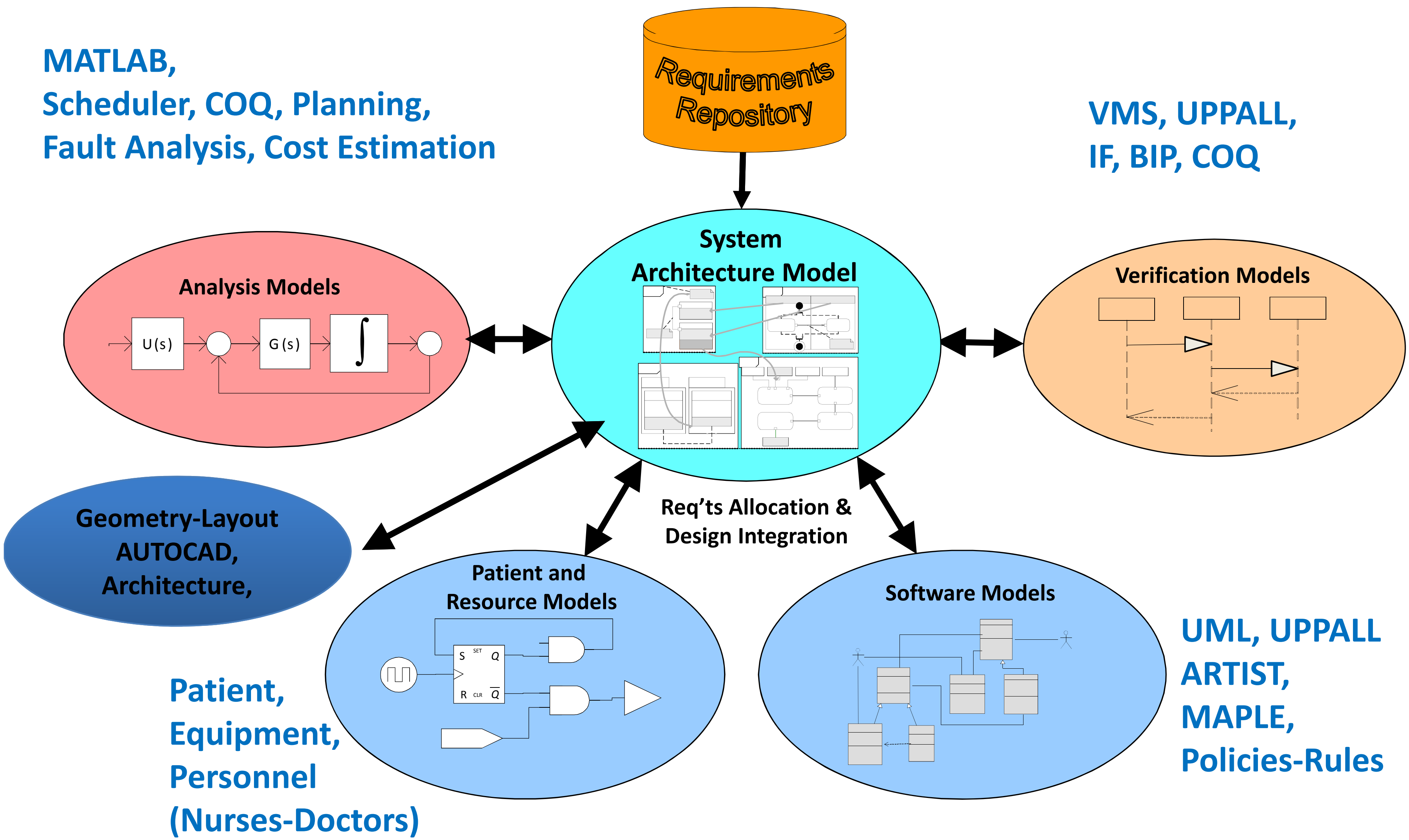
Healthcare operations

Monitor performance,
generate ideas,
implement changes

Build models,
analyze operations,
predict changes

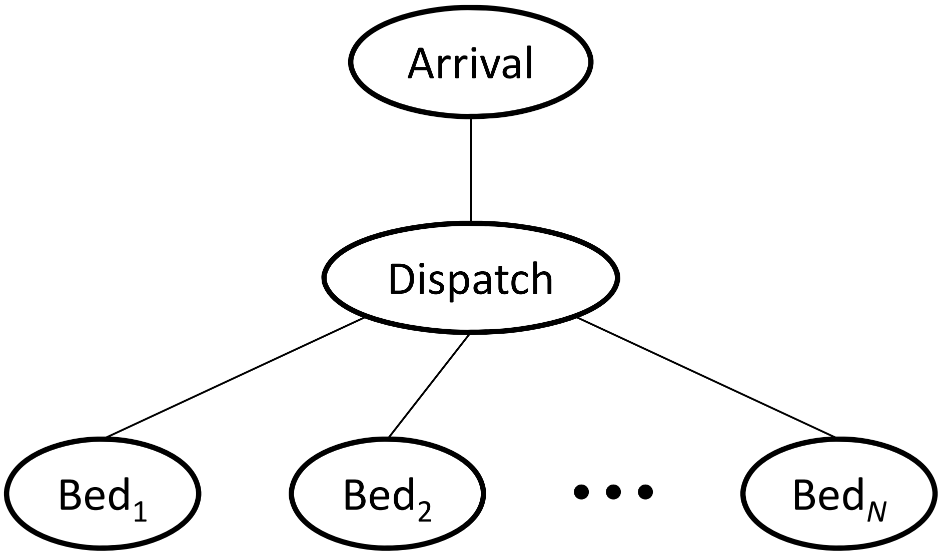
The Institute for Systems Research

Using *System Architecture Model* as a MODEL Integration Framework



Initial ICU Model Local Topology

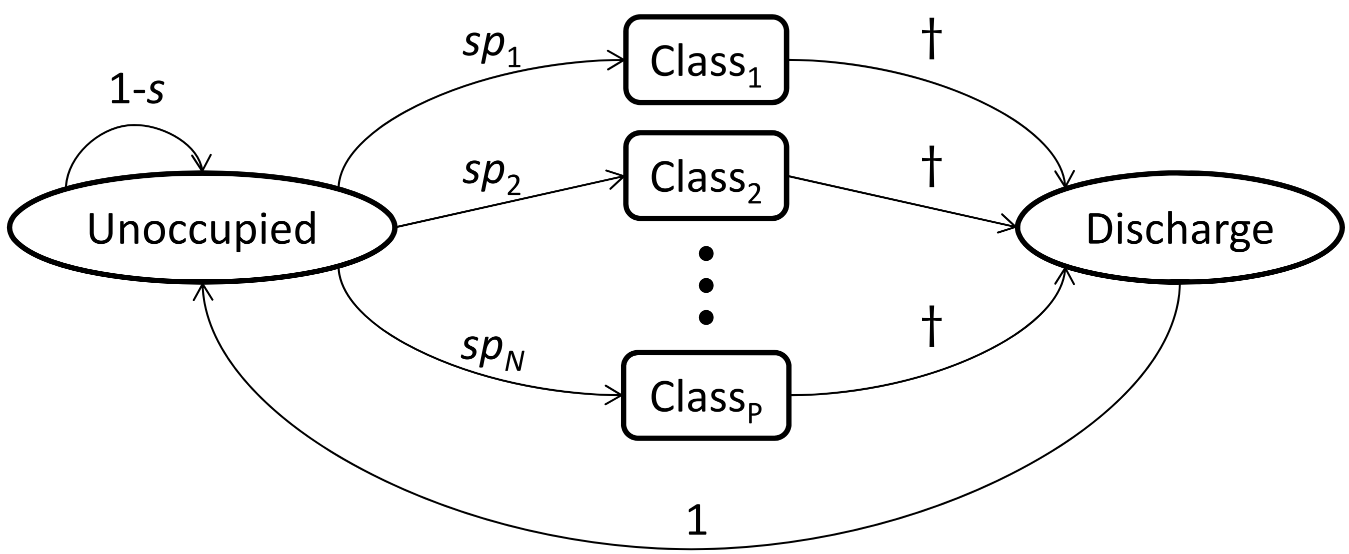
- Discrete Markov chain consisting of communicating subchains.
- **Time is discretized**.
- Interarrival times are **geometrically distributed**.
- Dispatcher allocates arriving patients to the appropriate bed.
- Patients are modeled as classes of discrete phase type distributions.
- Each state of the patient chain is associated with an **associated cost vector**.
- **Blocking probability** given by the probability that all the beds are full.
- **Expected cost per unit time** evaluated as a function of the **stationary distribution**.
- *N* beds.



Bed

- Patient class modeled after arrival to bed by a probability mass function.
- It addition to patient states, Bed has states **unoccupied** and **discharge**.

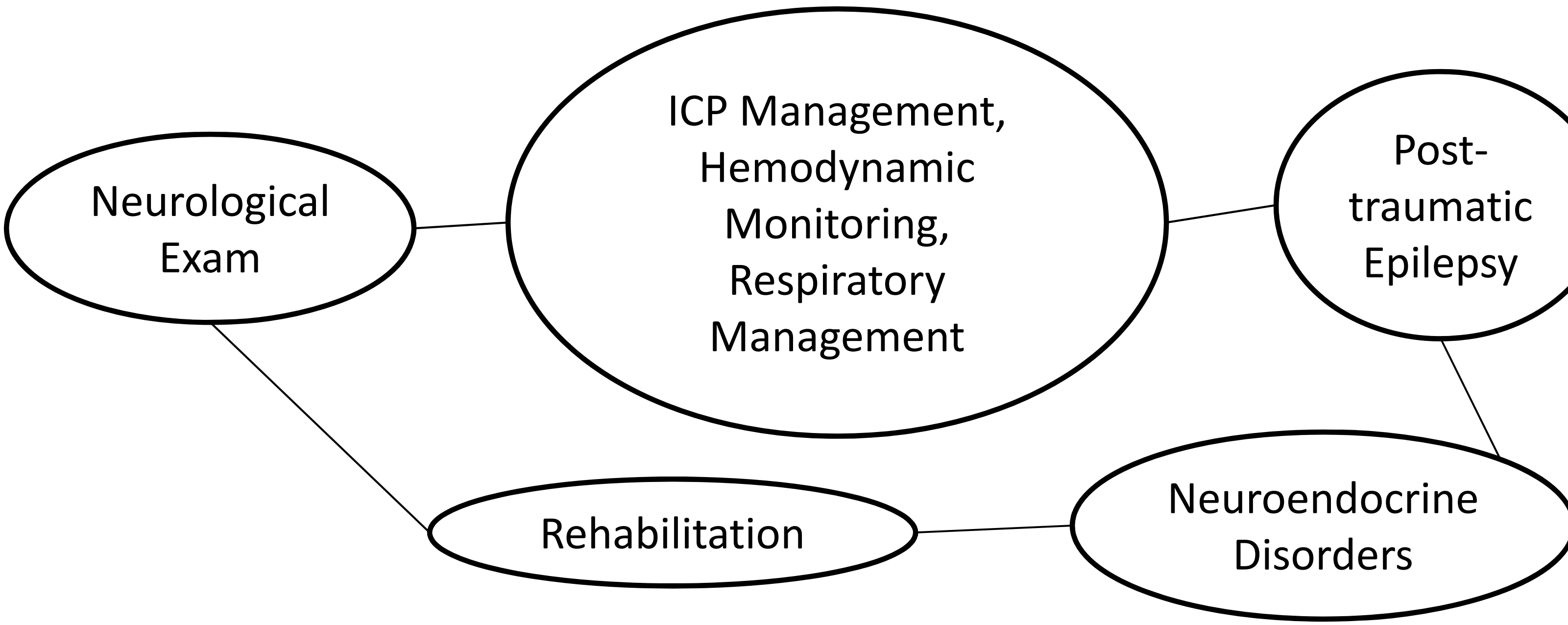
s is information from Dispatch. It is 0 if this bed is **unoccupied** and 1 if this bed is **occupied**.



† These are exiting transitions from the classes with well defined probabilities possibly representing multiple exit paths.

Patient Class

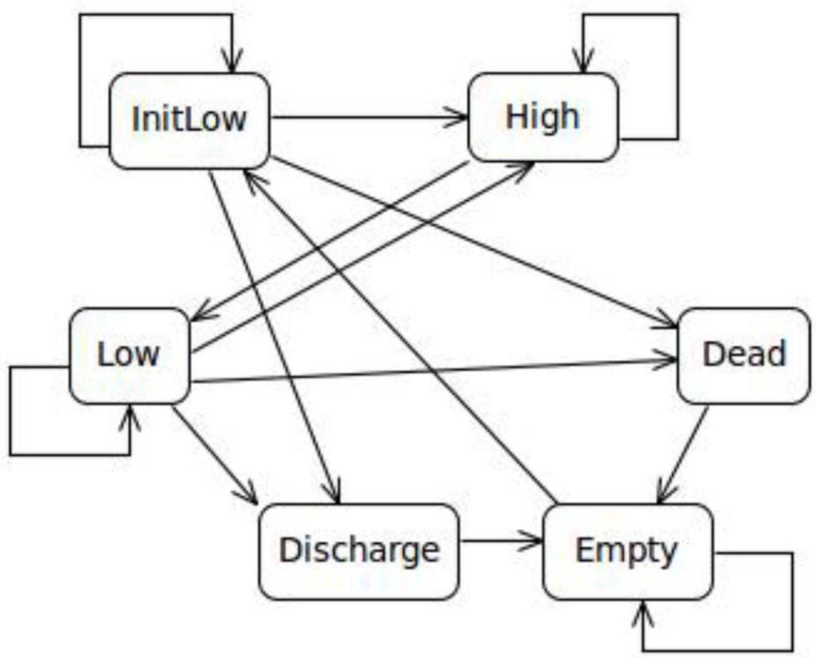
- Discrete phase type distributions.
- Time evolving Bayesian Network (reducible to finite state Markov chain).
- Each state associated with some cost vector.



UMMC STC protocols can be used here, but need ***further data on transition probabilities, timing and cost information***.

Patient Progression Model

- Finite state Markov chain
- States associated with patient clinical stage
- Each state associated with some cost vector



Nurse Resource Model and Cost

- [Litvak 2009] describes the cost of nursing as dependent on the occupancy in the following manner.
  - Nurses are staffed to maintain a constant ratio with the varying ICU occupancy.
  - Nurses may be either
    - roster nurses, who are constantly employed, independent of demand
    - or supplementary nurses, who ~4x more.
- The stationary occupancy distribution can be computed from Dispatch states.
- Each occupancy level is associated with a cost based on the above so expected cost can be computed from the occupancy distribution.
- Nurse model can depend on several other parameters

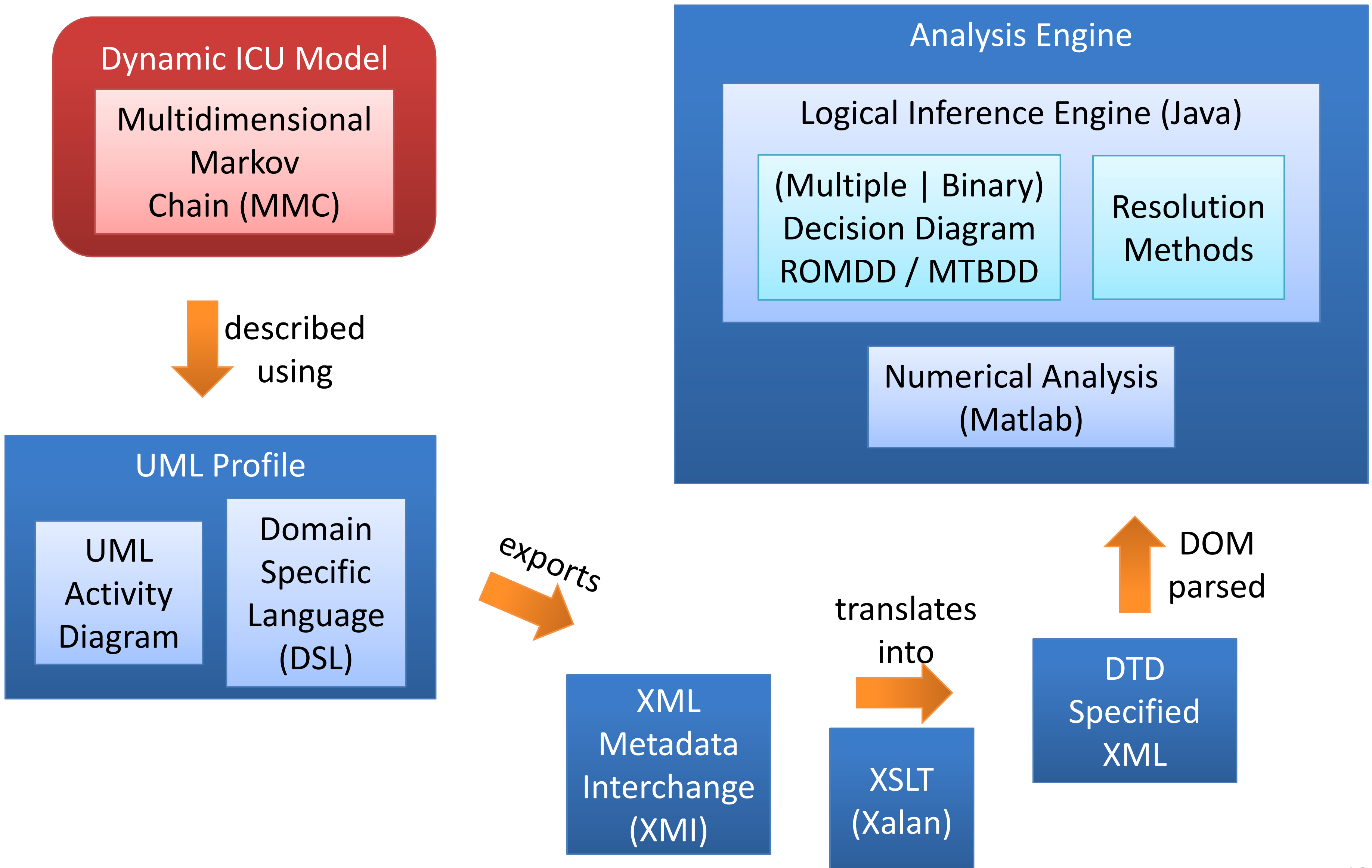
Cost Evaluation

- Determine the stationary distribution of the Markov chain, giving the probabilities of each state
- This leads to the expected cost
- Alternatively we can use "operational" analysis, i.e. non stochastic models – this allows time varying models
- Operational analysis also links cost models with patient states and progression

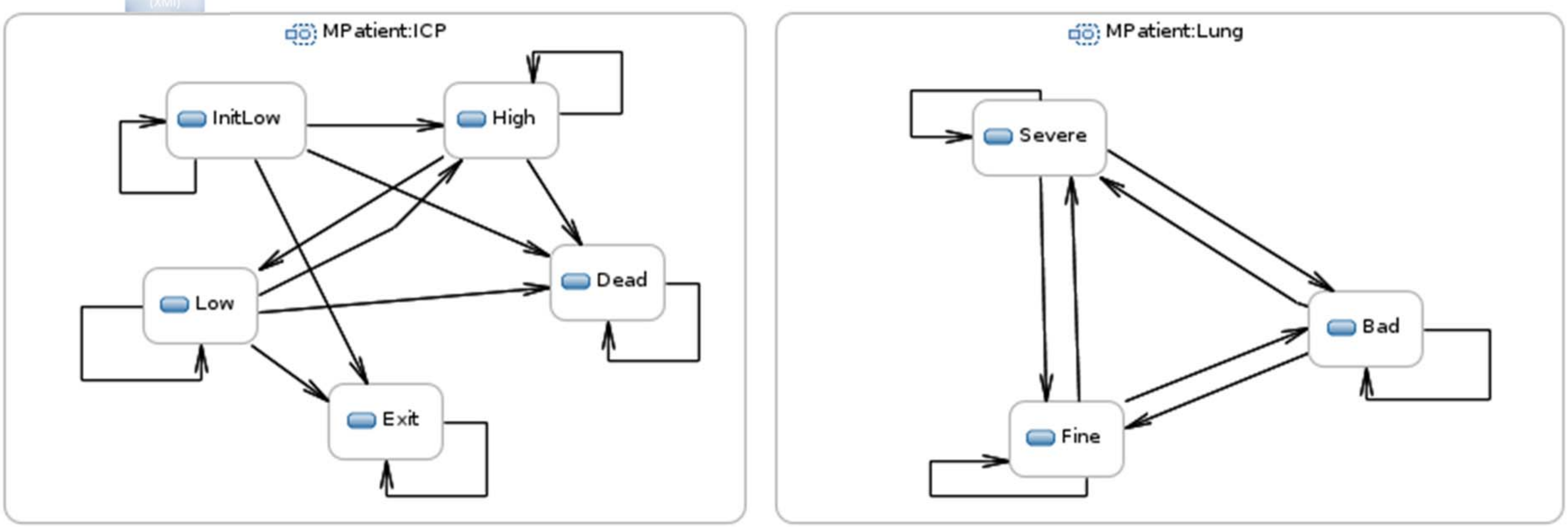
State Space Explosion

- Composition of Markov chains creates enormous state spaces (from patients, nurses, doctors, equipment …)
- For example
  - Assume we are composing N Markov chains.
  - Assume each chain has $|Q|$ states.
  - There are then $|Q|^N$ states in the composed machine.
- This is an *exponential* dependence between the number of components and the complexity the resulting system.
- Storing or performing any computations on such large systems is difficult.

Implementation (cont.)



Multi-dimension Markov Chain Patient Progression Model



- UML2 for Eclipse is used to describe the Markov chain.
- We parse the XMI exported from this tool.
- This *should* mean that we can easily parse the XMI generated by other UML tools.

Summary Product Works

- It reduces the number of states of the machines tested by several fold.
  - One ICU model tested was reduced from 17496 to 3071 states.
  - The reduction was achieved this primarily by symmetry reduction.
  - The models are input as products of identical patient state machines.
  - This is simple for the user to input, but leads to redundancy in the model.
  - There is no explicit symmetry reduction code, but the splitting algorithm of Valmari does it implicitly.

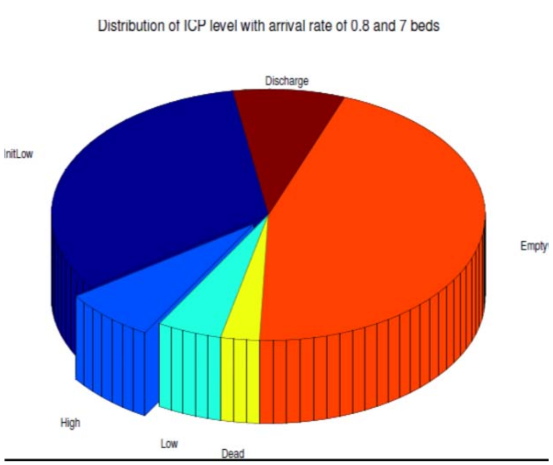
  - We verified the stationary distribution computed by the eigenvector of the reduced machine against Monte Carlo simulation and the results were very close.

- However, memory is a bottleneck.
- Even very modestly sized Markov Chains (>7000 states) lead to out of memory errors.
  - If the matrices are dense (as the reduced machines are), 7000*7000 = 50 million transitions.
  - This becomes tricky to analyze and further work will be needed.

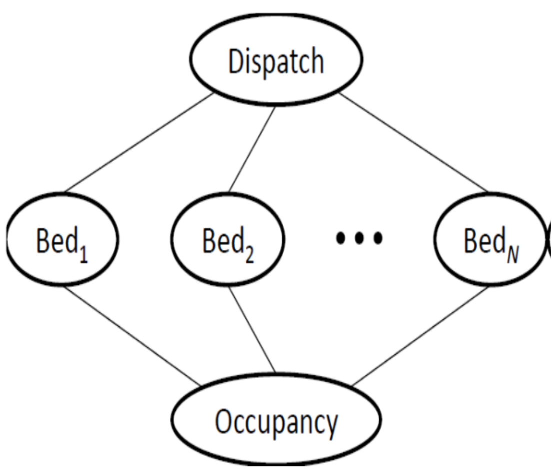
- Even though the example has 17496 states, no more than ~6000 states are ever simultaneously examined due to the summary product strategy.

Preliminary Results

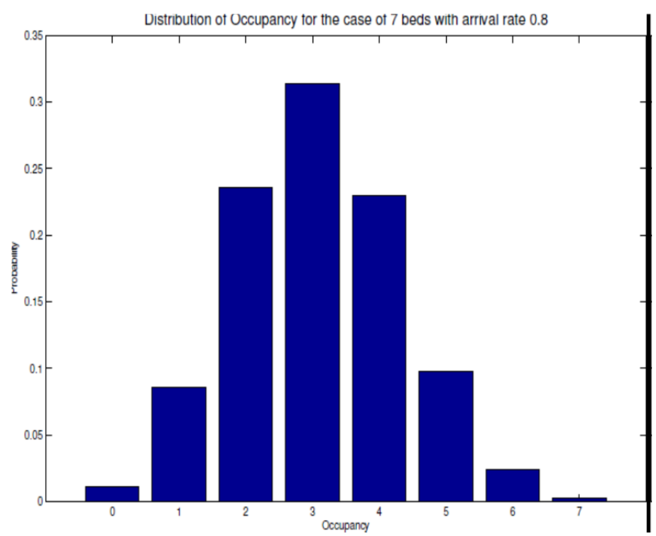
- Measure the overflow probability, the occupancy and the expected cost.



Stationary distribution of one bed

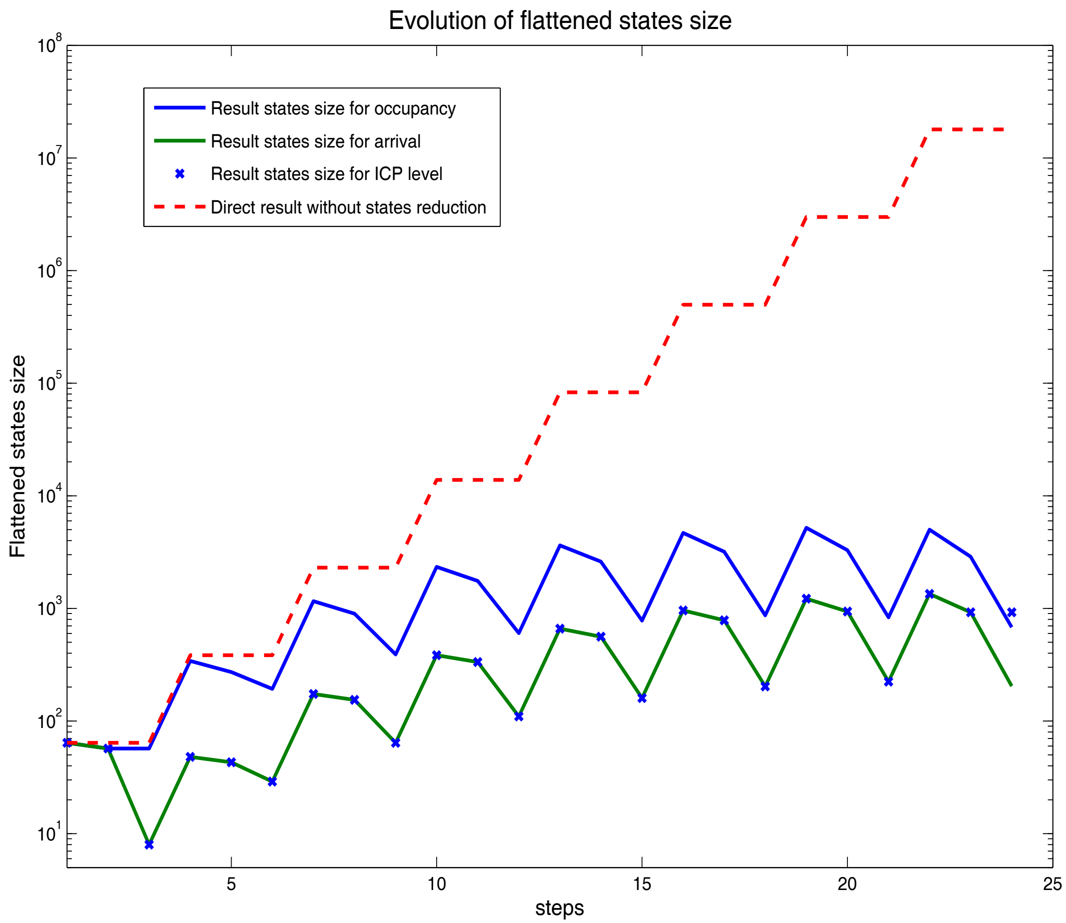


DBN used to query occupancy – observer added



Stationary occupancy distribution as observed by occupancy observer

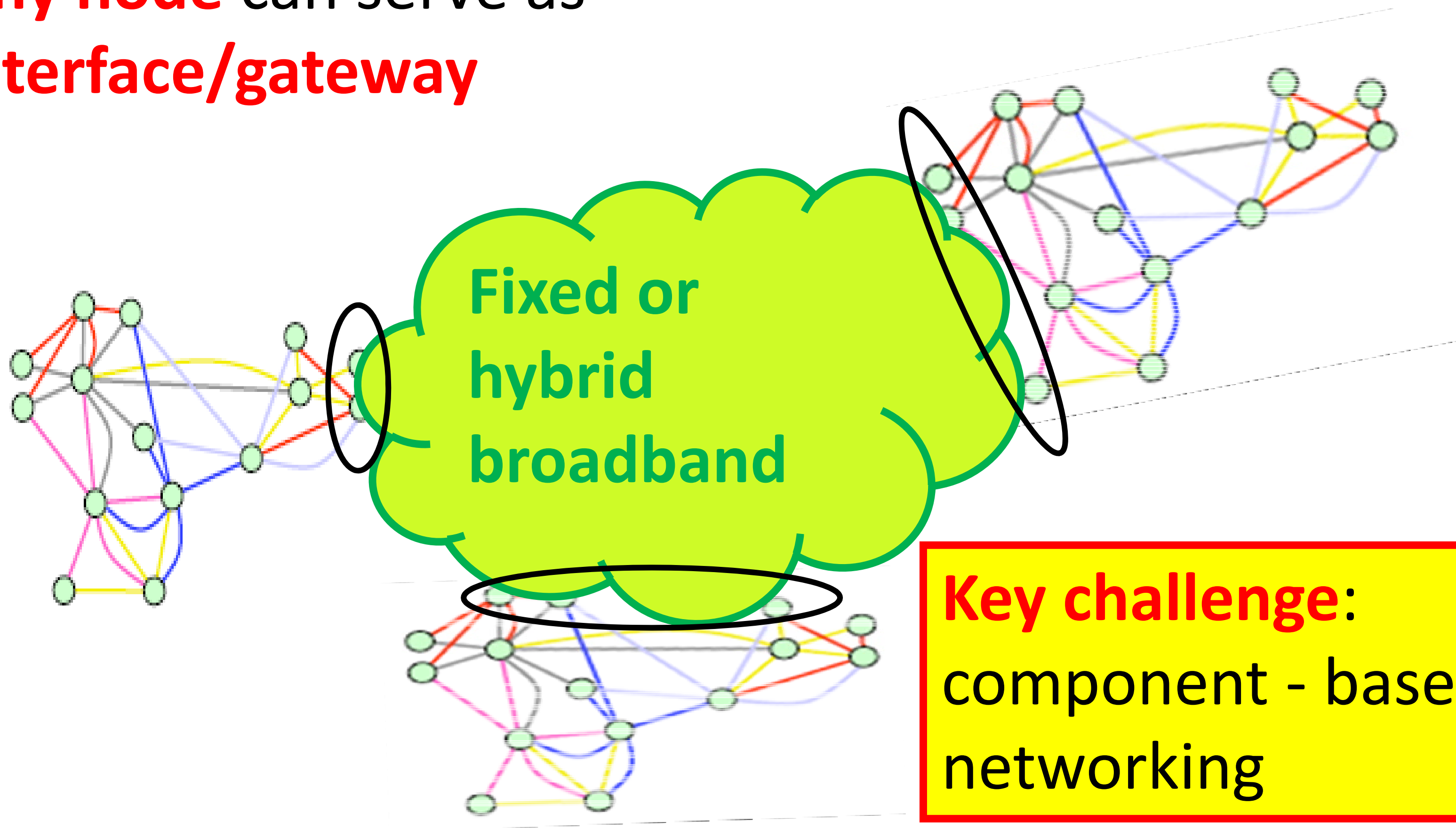
State Reduction Achieved



Number of states as a fcn of number of steps in inference
Sawtooth pattern is the result of the project-compose pattern

Mobile Broadband Wireless: Dynamic Interconnection and Interoperability

- Broadband wireless nets capable for **multiple dynamic interface** points
- **Any node** can serve as **interface/gateway**



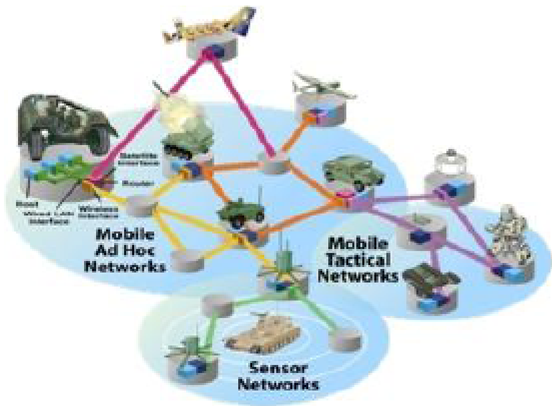
Key challenge: component - based networking

Component Based Networking: Network MBSE for MANET

J. Baras UMD), V. Tabatabaee (Broadcom), K. Somasundaram (Qualcomm) and M. Austin (UMD)

The Challenge & Need:

Design DoD and Commercial MANET Adaptive to Dynamic Mission Requirements



Dynamic Interconnection and Interoperability

- Broadband wireless nets capable for multiple dynamic interface points
- Any node can serve as interface/gateway

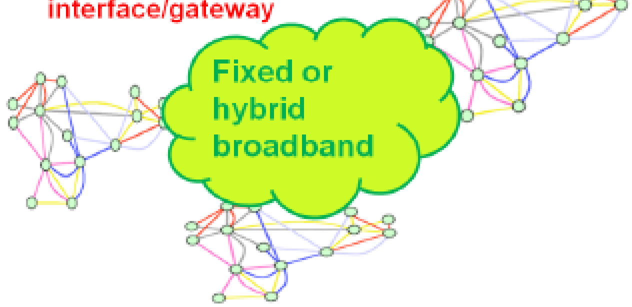
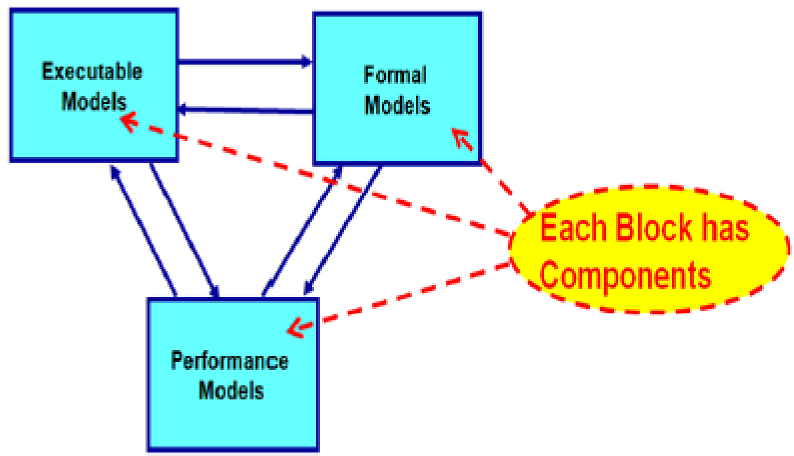


Fig.1: Intelligent Wireless Multi-Nets

Fig.2: Component Based Networking



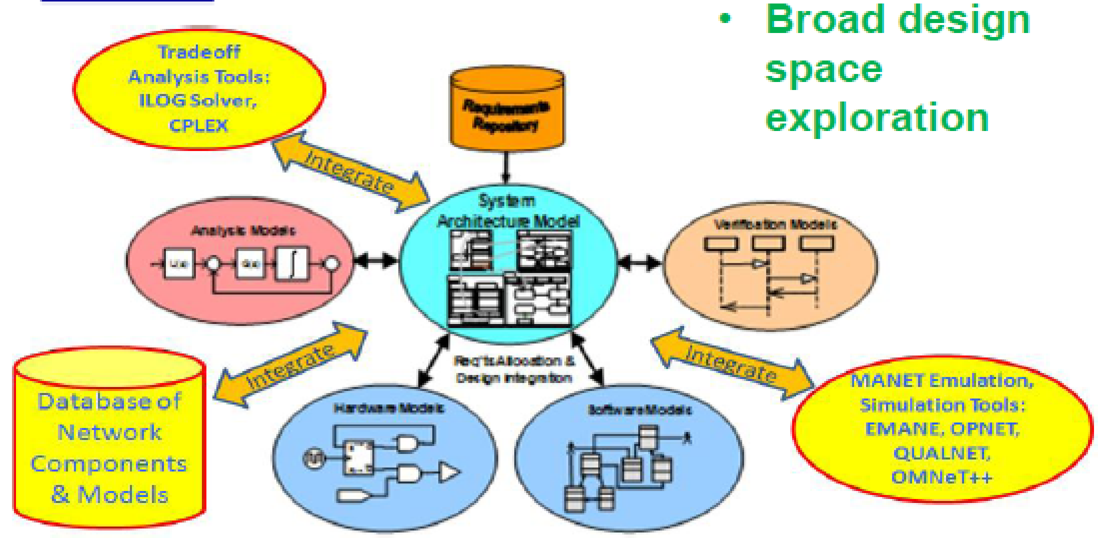
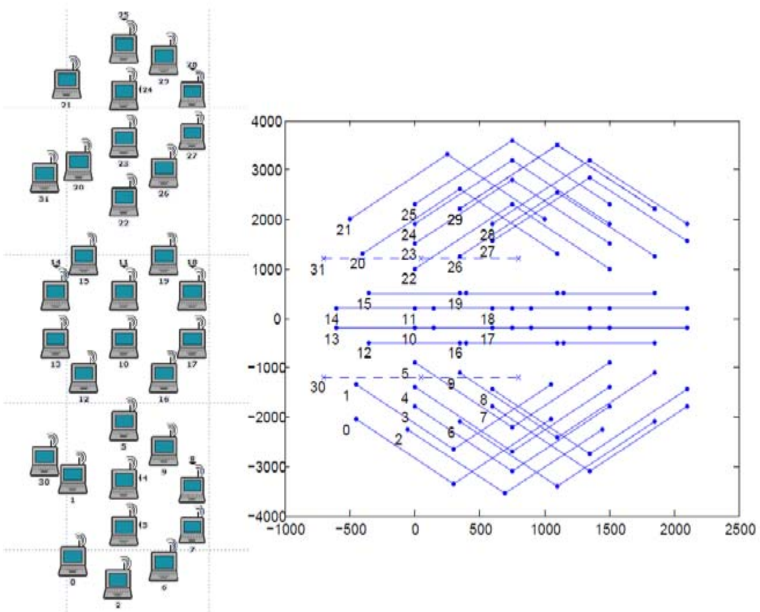


Fig. 3: Network MBSE Toolset : integrating **SysML** Architecture Model with DB of network models, emulation-simulation models, tradeoff tools

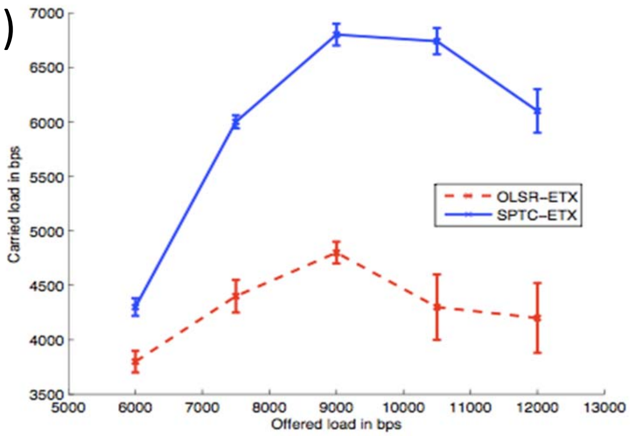
BENEFITS

- Reduced MANET cost and fielding time
- Modularity and re-use
- Increased agility in designing, modifying and fielding new MANET
- Broad design space exploration

3 Platoon Mobility Scenario



Long connection from 20 to 0 (platoon heads)



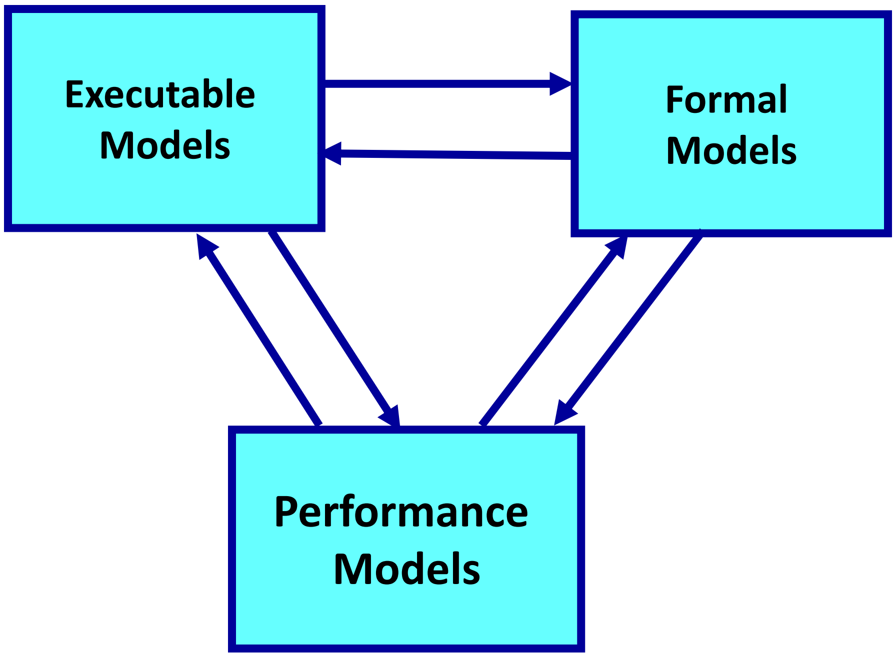
	OLSR-ETX	SPTC-ETX
Saturation CL	~ 2 Mbps	~ 2 Mbps
TC message rate	923 kbps	890 kbps

Type	Connection	Offered-load
Intra-platoon	(1,3),(2,9),(4,6),(7,5),(20, 29), (14,17),(16,11),(17,18),(19,12), (21,22),(23,27),(23,28)	12 kpbs
Inter-platoon	(1,18) (20,11),(20,0) (10,1),(21,10)	2.4 kbps 6 kbps 12 kbps

Security and Trust for Broadband Wireless Networks and Devices

- It is not just the DoD need and domain
- There are huge commercial markets where there is critical need for an "integrated security"
- Commercial-DoD Convergence: several DoD services moving towards broader use of COTS as components
- Need to compose evidence from several domains (no one security or authentication mechanism will solve the problem) – compositional security
- Be aware of "fusion" of evidence! Many known instances of wrong ways to do it ….
- Secure by design devices and networks? Reality or Dream?
- Distributed availability of validation data or features. Do we need third parties? Architectures?
- Timing issues – several: real-time, asynchronous operation

Component-base Networks and Compositional Security



Studying compositionality is necessary!

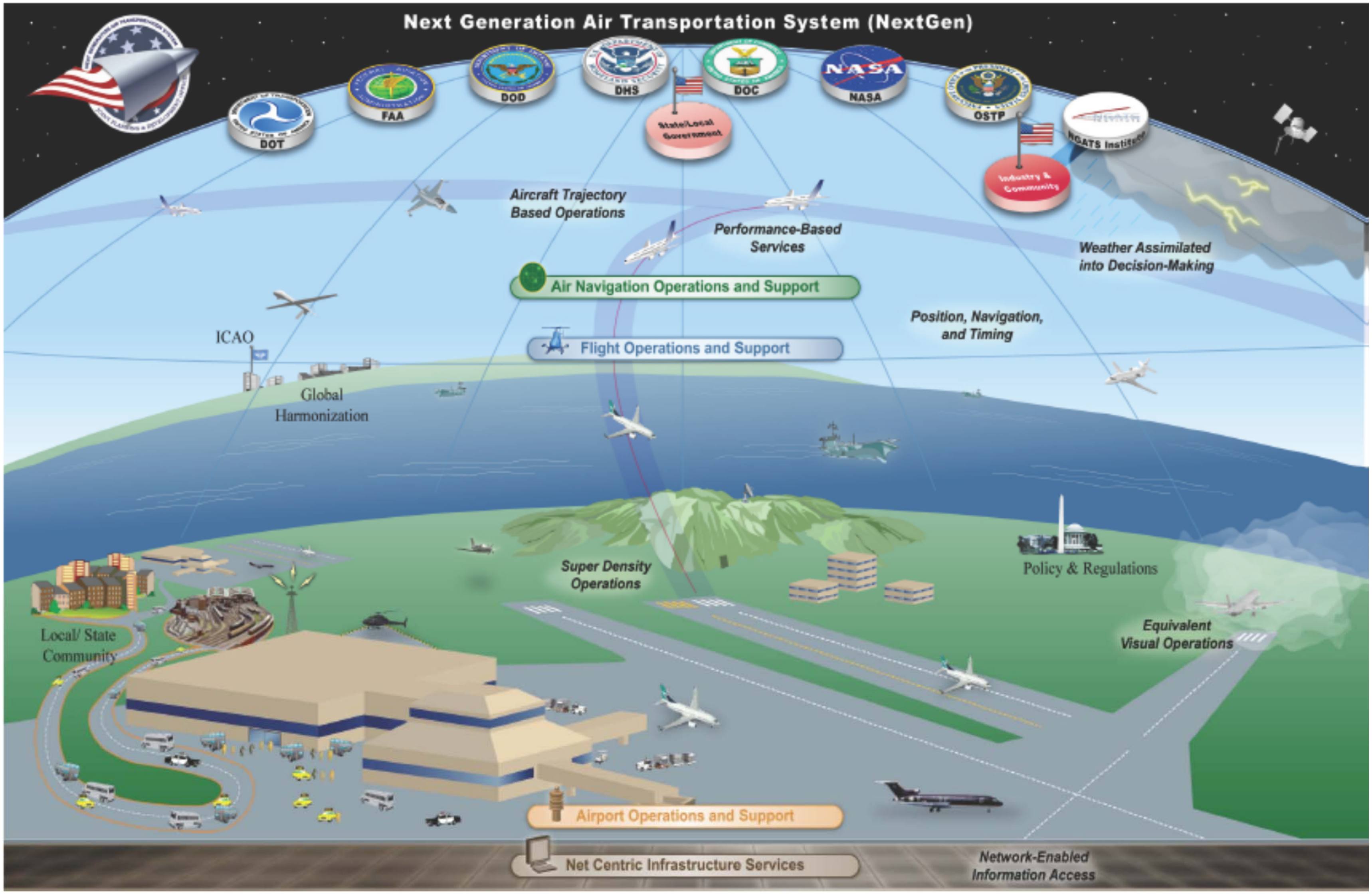
Universally Composable Security of Network Protocols:

- Network with many agents running autonomously.
- Agents execute in mostly asynchronous manner, concurrenty several protocols many times. Protocols may or may have not been jointly designed, may or not be all secure or secure to same degree.

Key question addressed :

- **Under what conditions can the composition of these protocols be provably secure?**
- **Investigate time and resource requirements for achieving this**

FAA NEXTGEN



Next Generation Air Transportation System (NextGen)
DOT
FAA
DOD
DHS
DOC
NASA
OSTP
State/Local Government
Industry & Community
NGATS Institute
Aircraft Trajectory Based Operations
Performance-Based Services
Weather Assimilated into Decision-Making
Air Navigation Operations and Support
Position, Navigation, and Timing
ICAO
Flight Operations and Support
Global Harmonization
Super Density Operations
Policy & Regulations
Local/ State Community
Equivalent Visual Operations
Airport Operations and Support
Net Centric Infrastructure Services
Network-Enabled Information Access

MBSE Approach to Energy Efficient Buildings

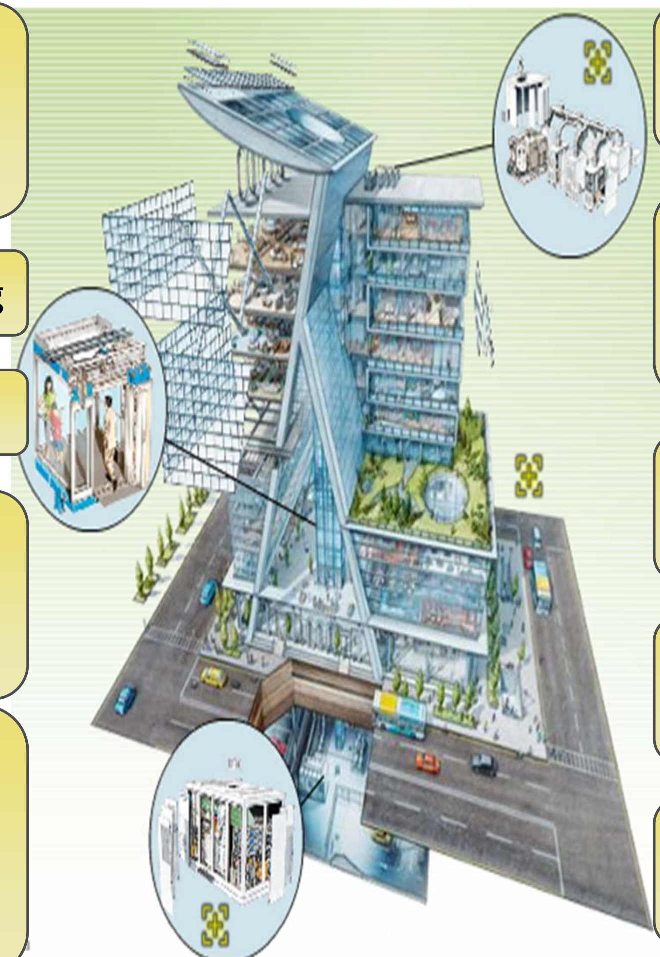
Buildings Design Energy and Economic Analysis

Windows and Lighting

HVAC

Domestic/International Policies, Regulation, Standards, Markets

Demonstrations, Benchmarking, Operations and Maintenance



Natural Ventilation, Indoor Environment

Networks, Communications, Performance Database

Sensors, Controls, Performance Metrics

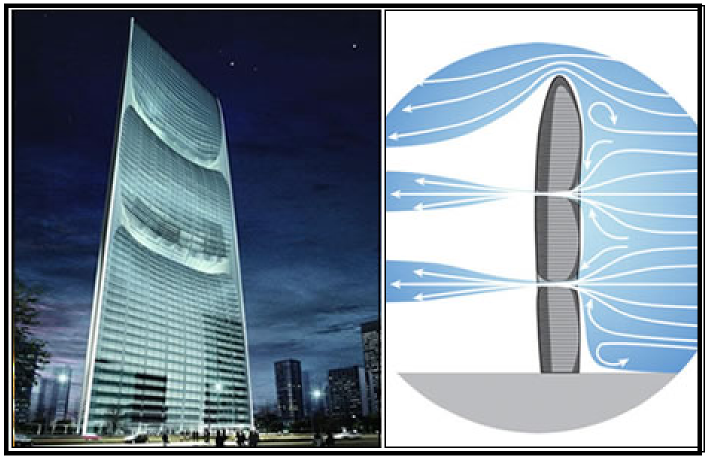
Power Delivery and Demand Response

Building Materials, Misc. Equipment

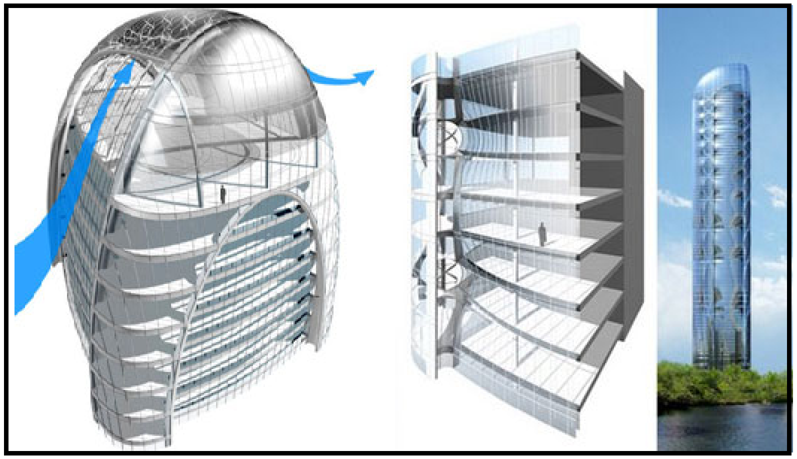
Cyber-Physical Building Systems

- **Research focus:** Platform-Based Design for Building-Integrated Energy Systems.

Pearl River Tower Complex

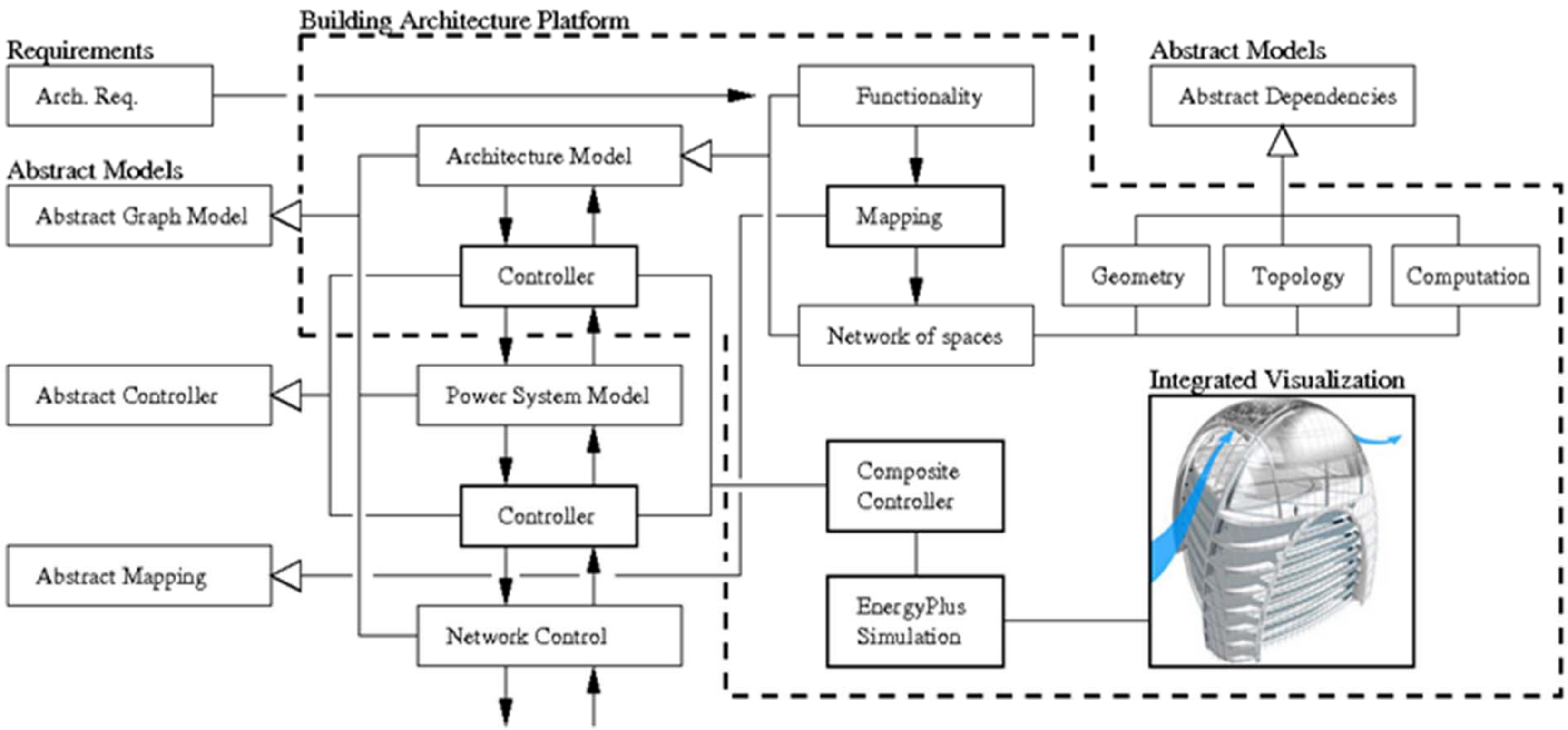


Green Technology Tower –– Architectural Proposal for Chicago

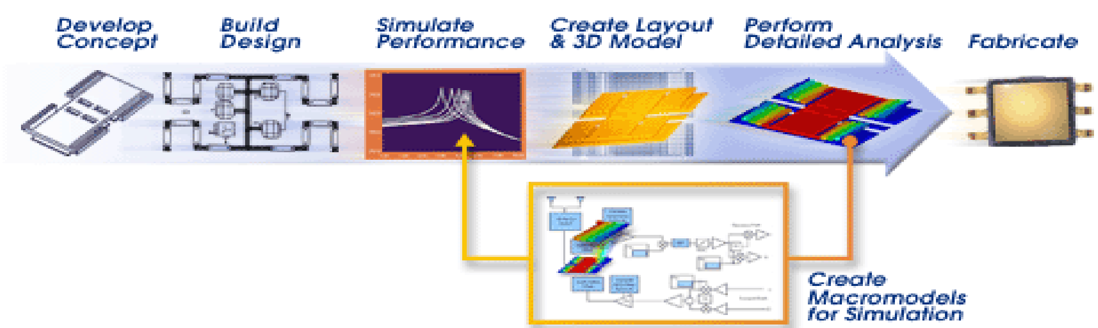


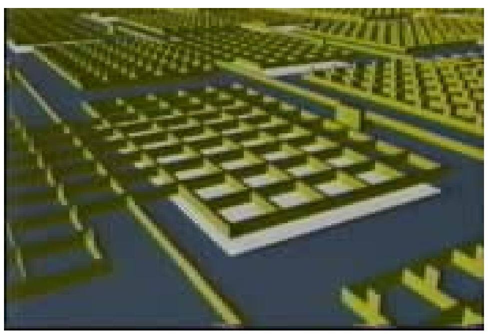
Design Platforms for SE Building-Integrated Energy Systems

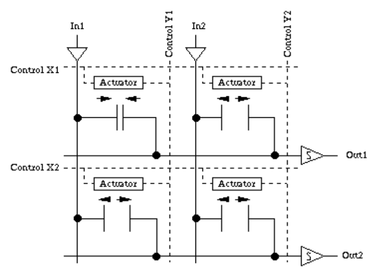
Extensible framework for assembly of (model, controller, simulation, viewpoint) process networks and communication for platform-based design of building-integrated energy systems

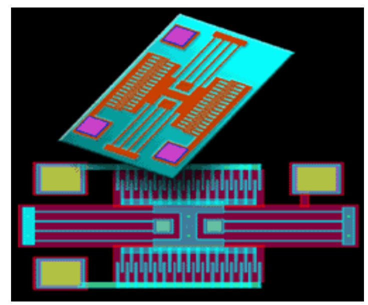


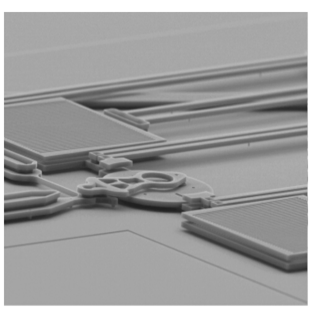
How to go From IT Abstractions to "Hardware" for MEMS and NANOS

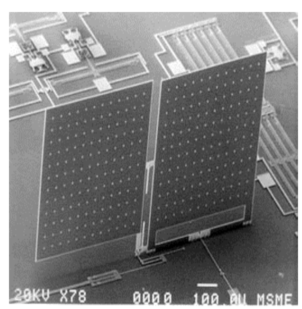


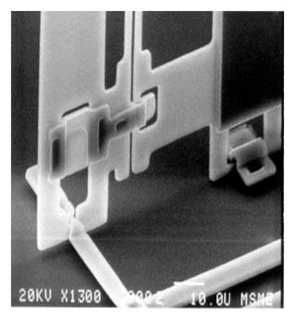


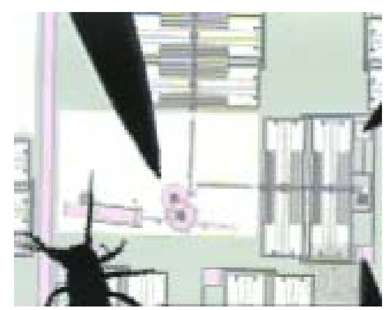








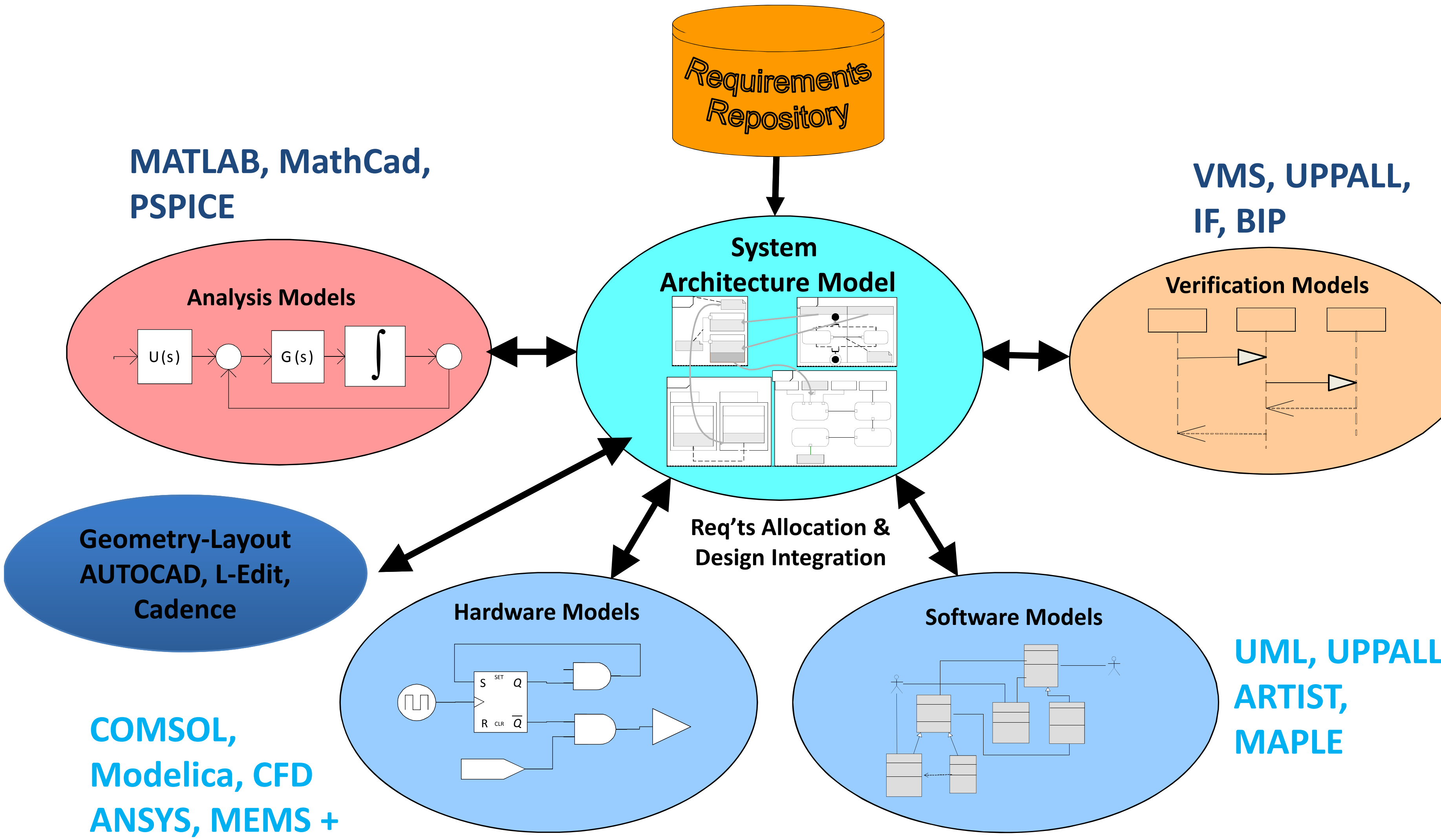




Integrated MEMS and IC Design Flow – Current Limitations

- **Need for a "structured" automated design flow, that links MEMS 3D design with custom IC design**
- Modeling approach defined up front repeatable, rather than made up on the fly to suit each new design
- Process variables, material properties, and geometric properties (lengths, widths, thicknesses) should be parametric to provide maximum design flexibility
- A well-characterized library of reusable MEMS building blocks (can be assembled into arbitrarily complex designs)
- Each block should have a 3D view (structure) and a behavioral model supporting all types of simulations
- Extraction and design-rule checking for MEMS devices

Using *System Architecture Model* as a MODEL Integration Framework



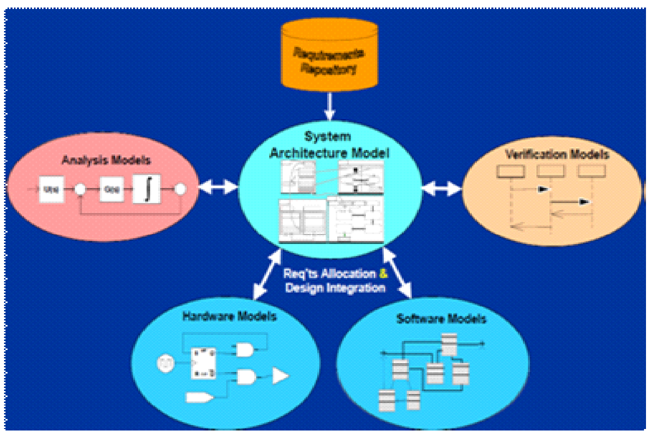
Integrated Design Environment for MEMS & NANOS

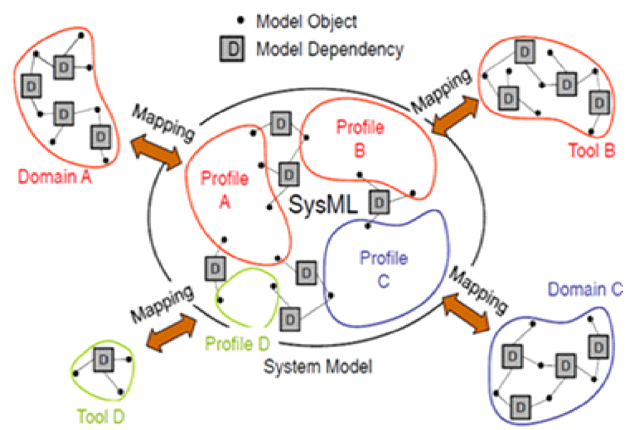
The Challenge & Need:

Develop scalable holistic methods, models and tools for MEMS & NANOS system engineering

Multi-domain Model Integration via System Architecture Model (SysML)

System Modeling Transformations





BENEFITS

- **Broader Exploration of the design space**
- **Modularity, re-use**
- **MEMS & NANO Systems Design tools allowing conceptual design, leading to full product models and easy modifications**
- **Automated validation/verification**

Update System Model

ILOG SOLVER, CPLEX

“ Master System Model”

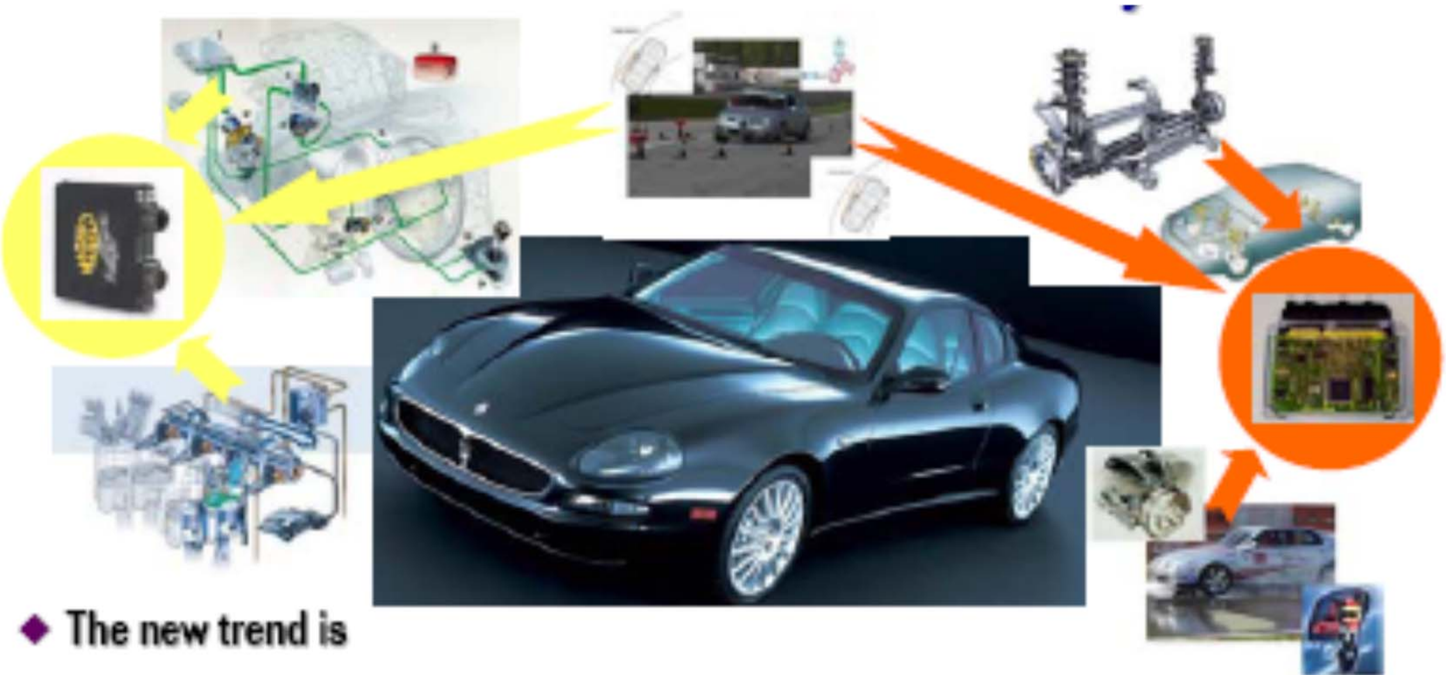
ADD & INTEGRATE

- **Multiple domain modeling tools**
- **Tradeoff Tools (MCO & CP)**
- **Validation / Verification Tools**
- **Databases and Libraries of annotated MEMS, NANO component models**

Tradeoff parameters

DB of system components and models

Automotive



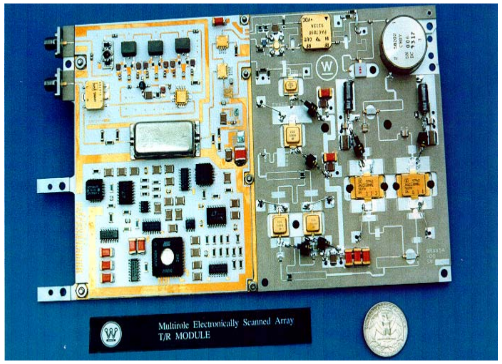
- The new trend is
  - Break the "one-subsystem one-ECU" paradigm
  - Distribute functionalities over several nodes to optimize number and cost of ECUs
- Advantages
  - flexibility, cost reduction, redundancy (fault-tolerance)
  - more sophisticated control enabled by more powerful hardware

SMART MANUFACTURING

- Flexible production lines
- Robotics and humans integrated
- Reduce manufacturing to compilation
- Custom materials
- Materials as a design variable
- Composite materials design

Model-based systems engineering –
manufacture to component models

Integrated Product and Process Design of T/R Modules



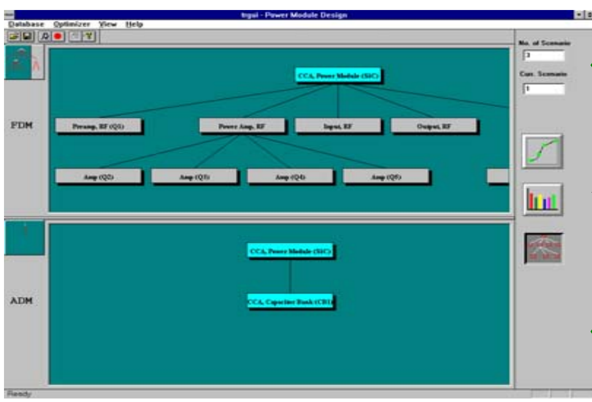
PROBLEM

Integrate Electronic and Mechanical Design
- information interchange among tools used by designers

Identify alternative components
- integration with part catalogs, corporate databases

Help generate and evaluate alternative designs
- estimate cost, manufacturing time, reliability, etc.evaluate tradeoffs

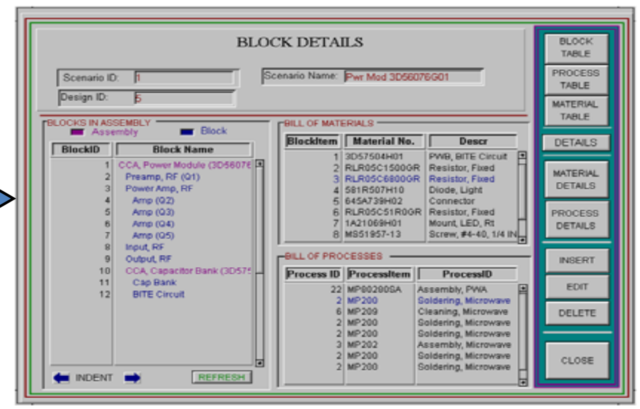
Help generate process plans
- process parameters, time estimates, etc.



Assembly Data Model
Process Designer View

Entity-Relation Diagrams

Functional Data Model
Product Designer View



SOLUTION

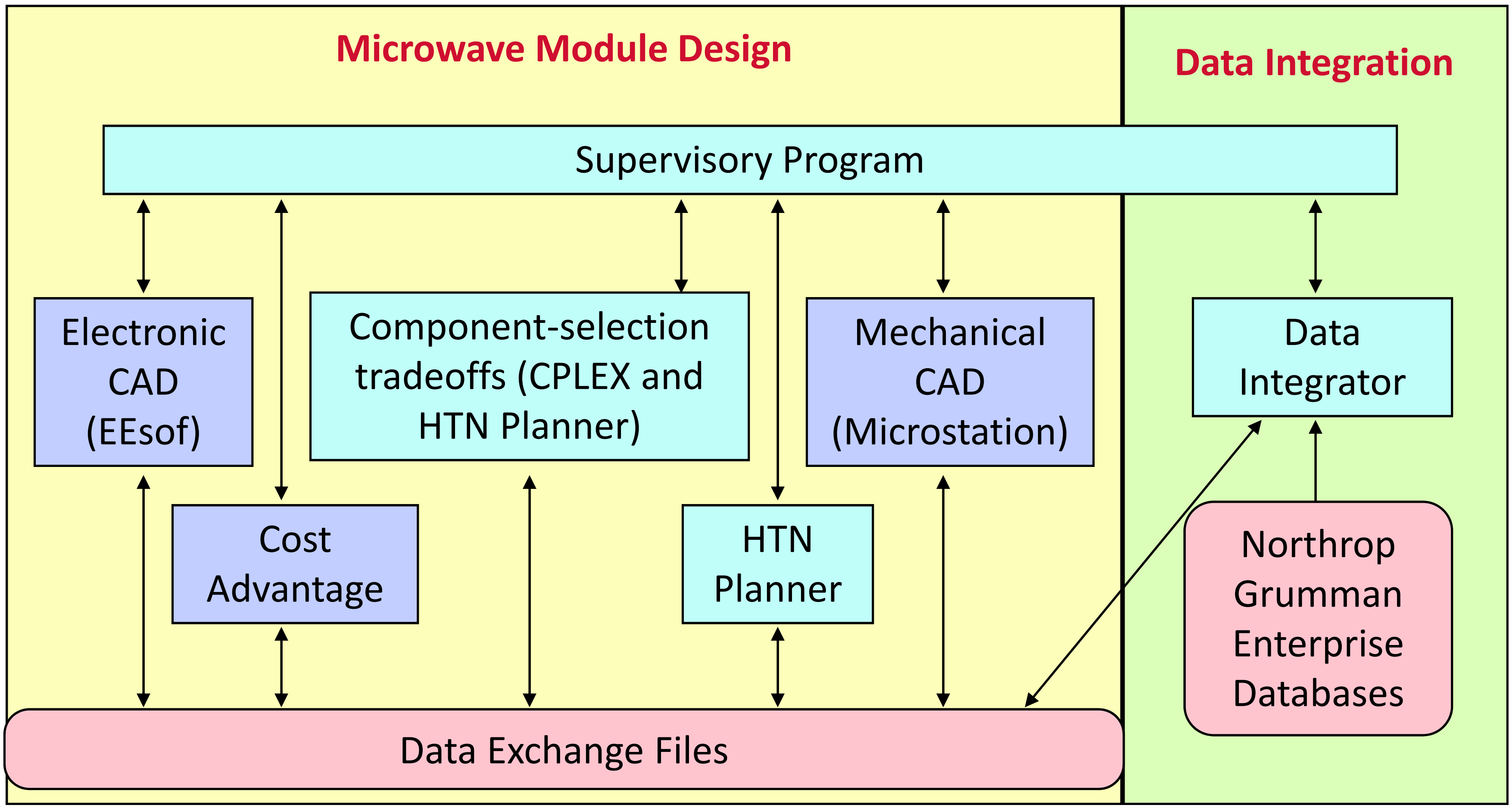
Object-Relational Databases and Middleware to integrate heterogeneous distributed data sources:
multi-vendor DB, text, data, CAD drawings, flat, relational, object DBs

Entity-Relation Diagrams to provide multiple expert views of the data and integrate product and process design phases into a single system environment

Hierarchical Task Network planning to explore alternate options at each level of the product: parts and material, processes, functions assemblies

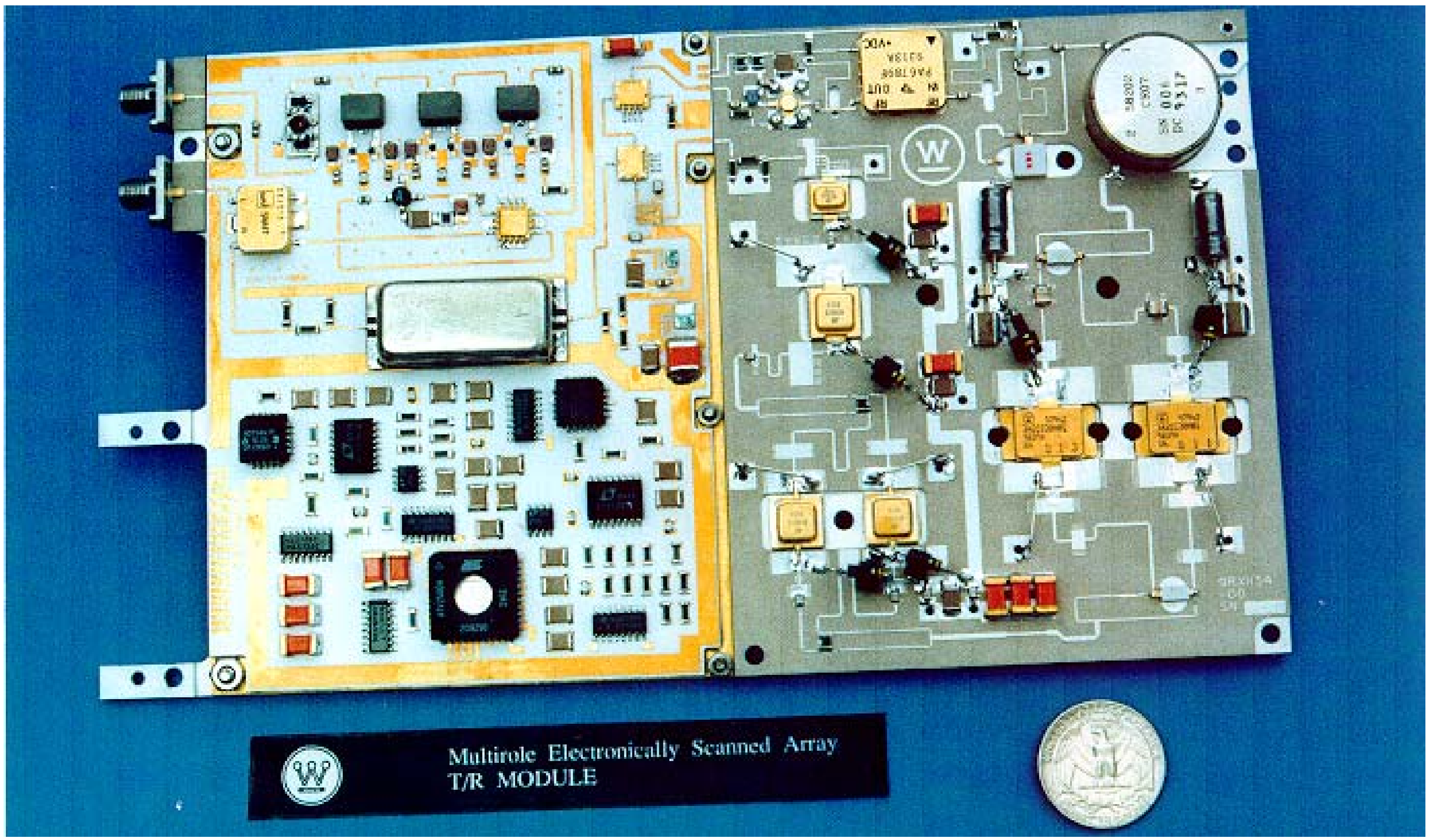
Multicriteria Optimization for trade-offs: cost, quality, manufacturability, ...

IPPD System Architecture

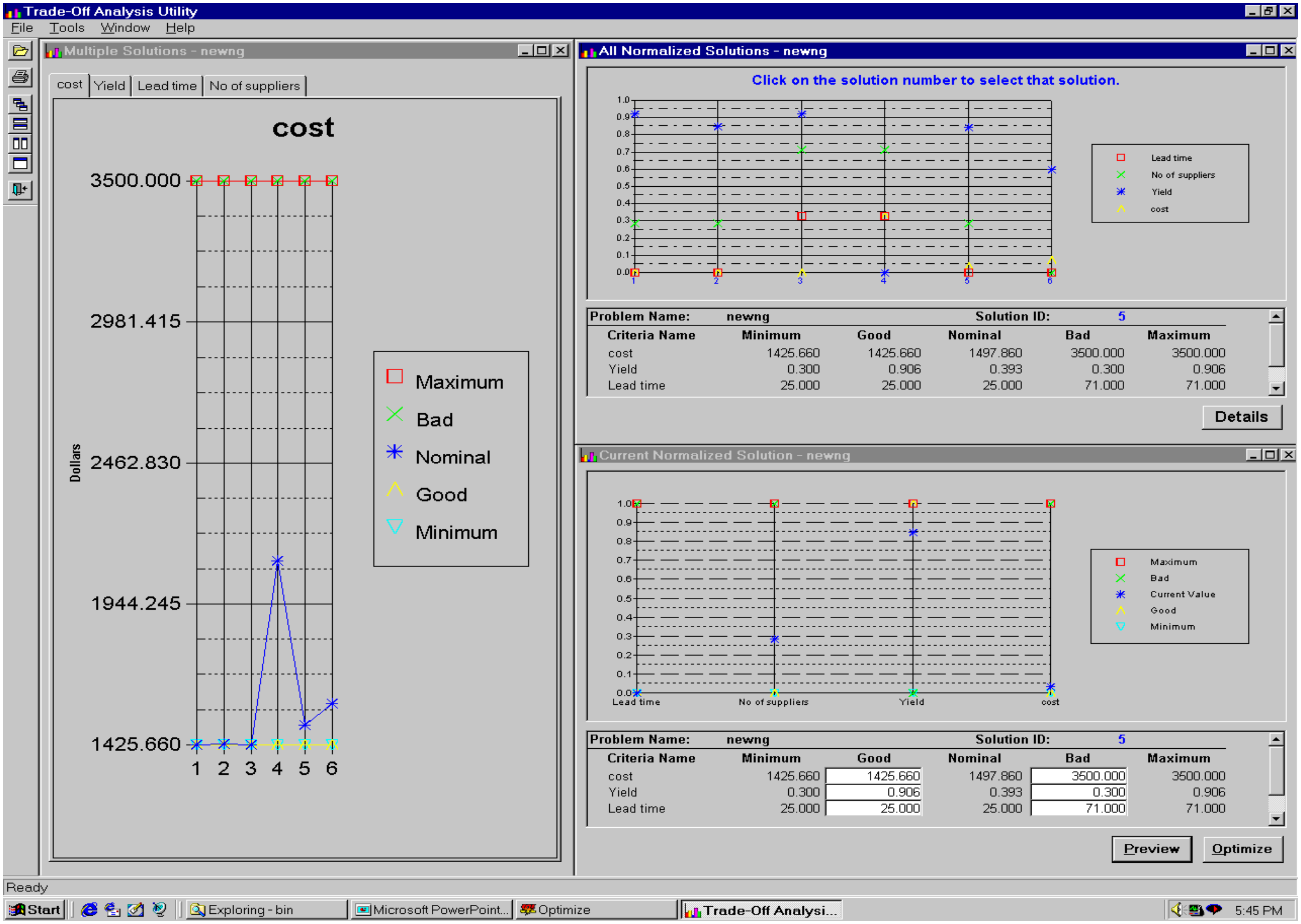


Microwave Transmit/Receive Modules

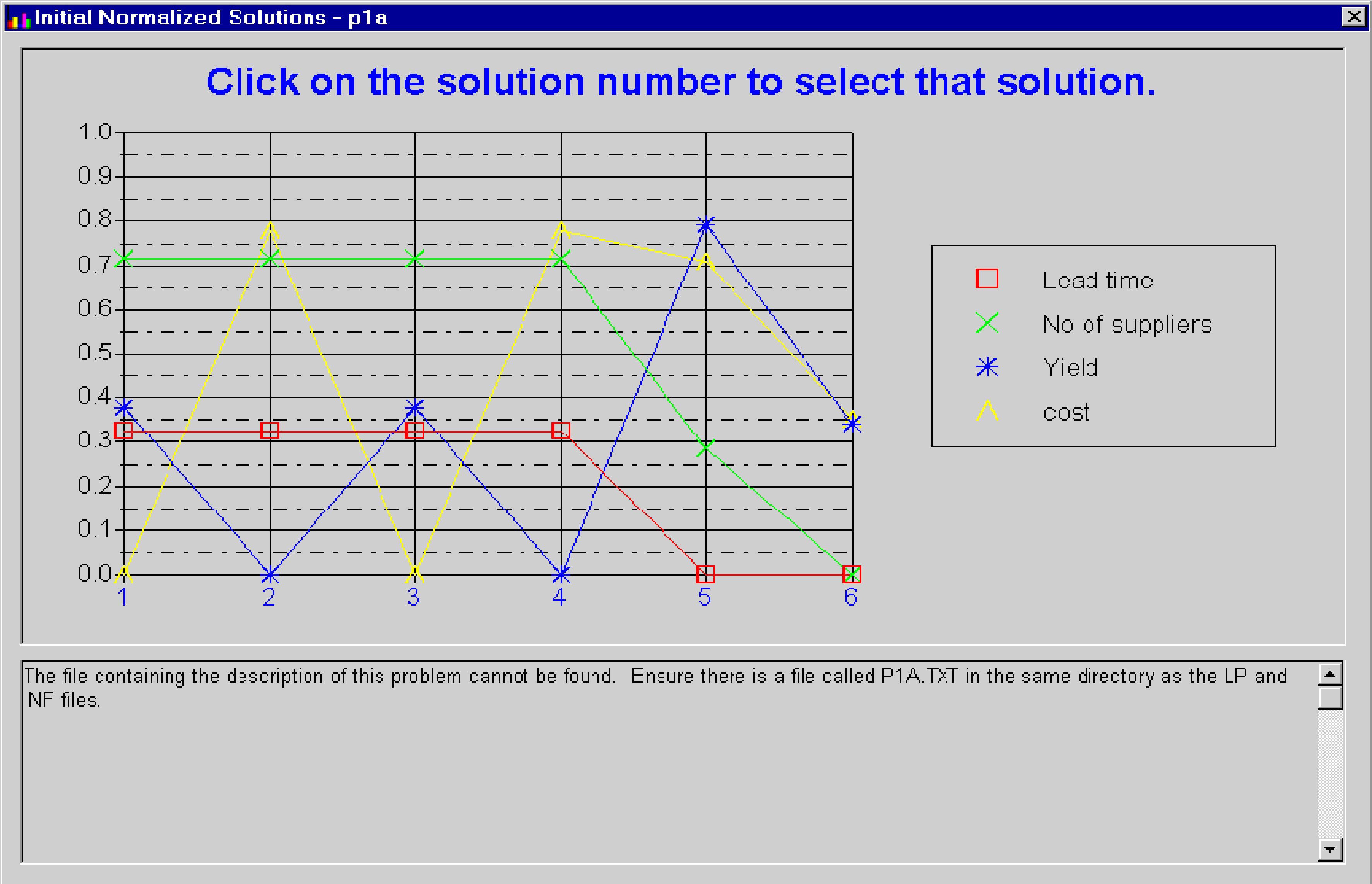
- 1-20 GHz frequency range (radars, satellite communications, etc.)
- Difficult and expensive to design and manufacture



Tradeoff Analysis via Multicriteria Optimization



Tradeoff Analysis via Multicriteria Optimization (cont.)

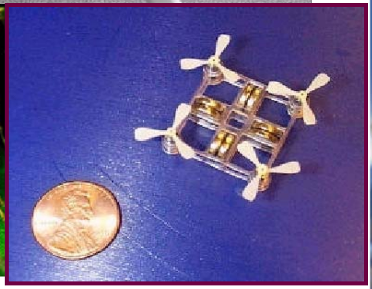


MBSE for Robotic Arms and Grippers

- Transcend areas of application: from space to micro robotics
- Include material selection in design
- Include energy sources, resilience, reliability, cost
- Include validation-verification and testing
- Use integrated SysML and Modelica environment
- Link it to tradeoff tools CPLEX and ILOG Solver
- Demonstrate reuse, traceability, change impact and management

AUTONOMOUS SWARMS – NETWORKED CONTROL

- *Component-based Architectures*
- *Communication vs Performance Tradeoffs*
- *Distributed asynchronous*
- *Fundamental limits*



New Home Health Platforms

- Digital home entertainment infrastructure can be used for health
- Everyday health through everyday devices
- Personalized, proactive health info/reminders/agents

INTEL'S PROACTIVE HEALTH LAB

SYSTEMS BIOLOGY – THE ULTIMATE SYSTEMS CHALLENGE

The Institute for Systems Research

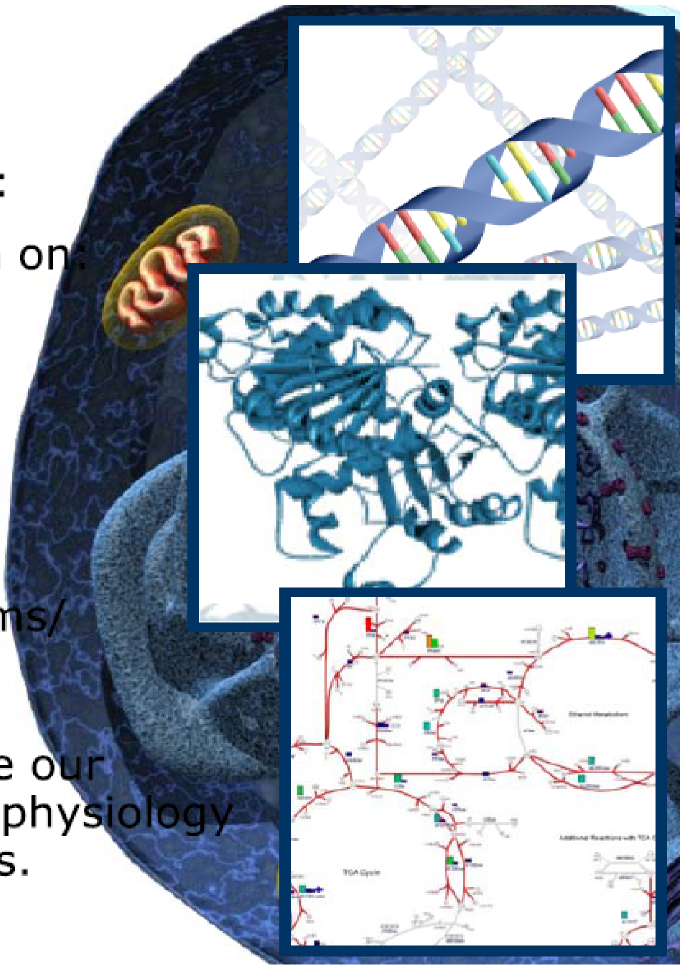
Systems Biology

Goal of systems biology:

To integrate information on:

- Genes
- Proteins
- Molecular interactions
- Metabolism
- Other biological systems/ networks

... in order to improve our understanding of the physiology of cells and organisms.



SYSTEMS BIOLOGY

Integrative approach in which scientists study pathways and networks ***will touch all areas of biology, including drug discovery***

Requires

- ***Quantitative models of properties of components and their interactions***
- ***Computational methods to manage complexity***

A Systems Biology Model for Alzheimer's Disease

- **Study the roles of cholesterol, LRP, ApoE and inflammation in disease pathogenesis**
- Studied effect of simvastatin treatment on LRP and ApoE levels, in addition to changes in Aβ
- Developed a mathematical model that integrates energy & lipid metabolism, the inflammatory response & expression of key proteins
- Model results were verified using results from experiments
- **No previously developed model has used systems biology nor multi-level networks to study AD**

The Institute for Systems Research

Forefront of AD research:

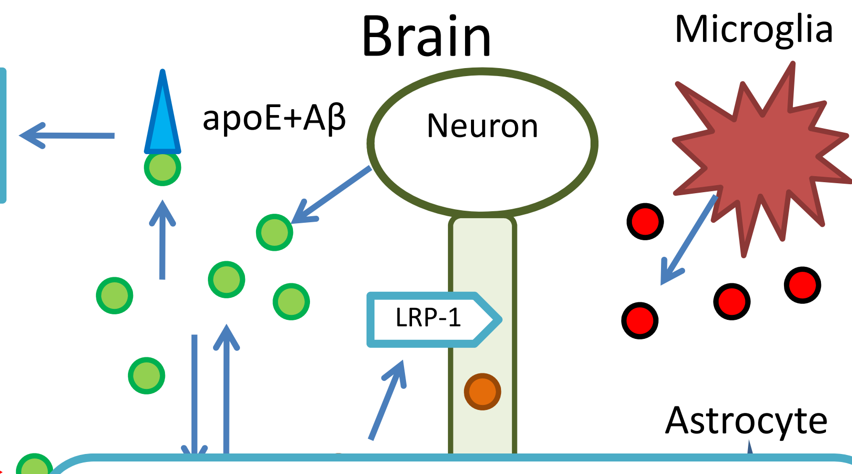
Interplay between lipid metabolism & inflammation

apoE:
- Coordinates re-distribution of cholesterol during growth, repair &

IL-1:
- Pro-inflammatory cytokine
- Expressed by microglia in response to:
  - Stress
  - ↑ Aβ
  - ↑ Glutamate
- Functions:
  - ↑ neurotransmitter turnover rate
  - ↓ activation threshold for HPA axis
  - Causes hypoglycemia
  - ↑ Acetylcholinesterase activity → ↓ ACh

ion

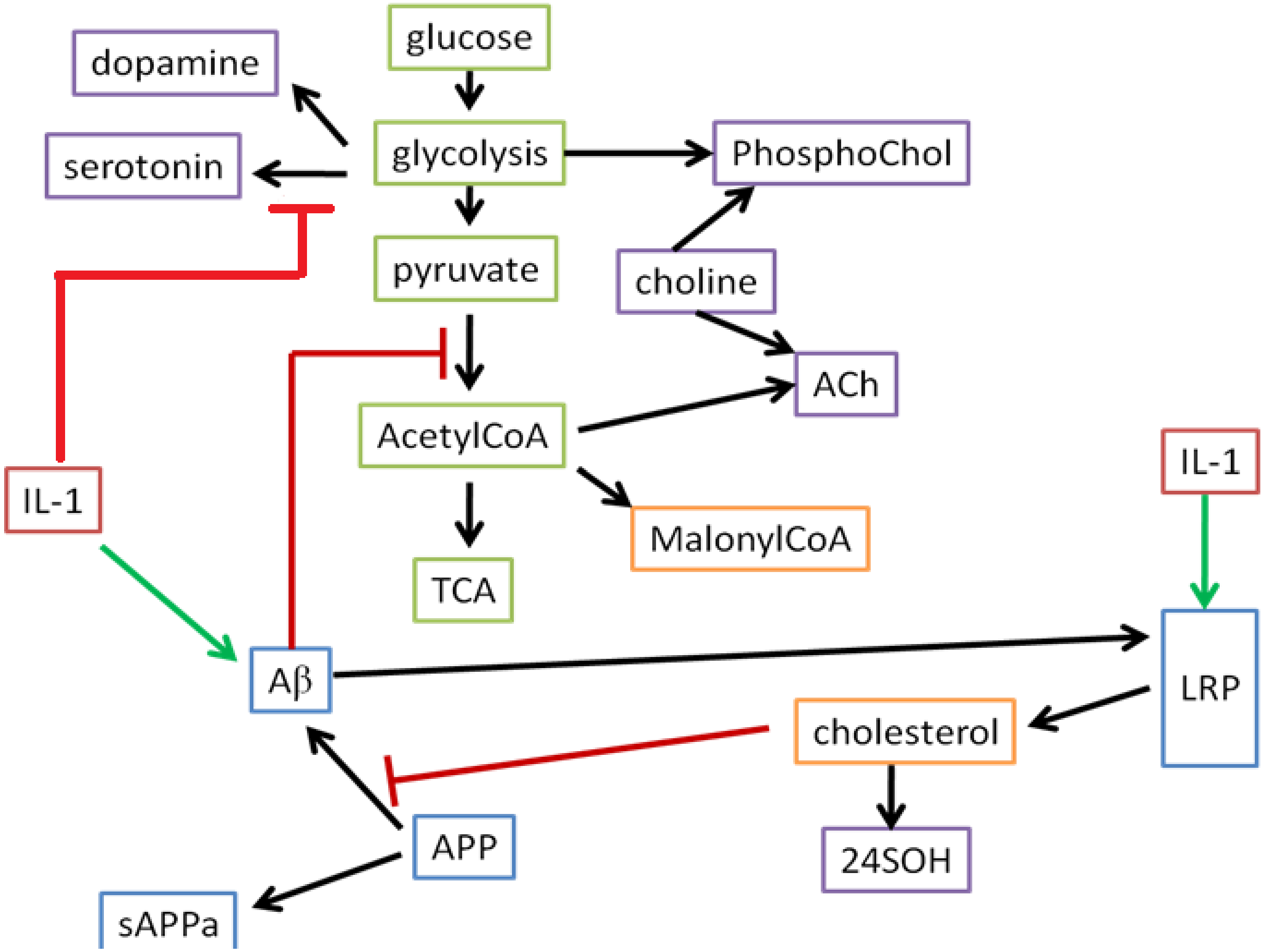
- Synapse formation
- Co-localizes w/ Aβ plaques



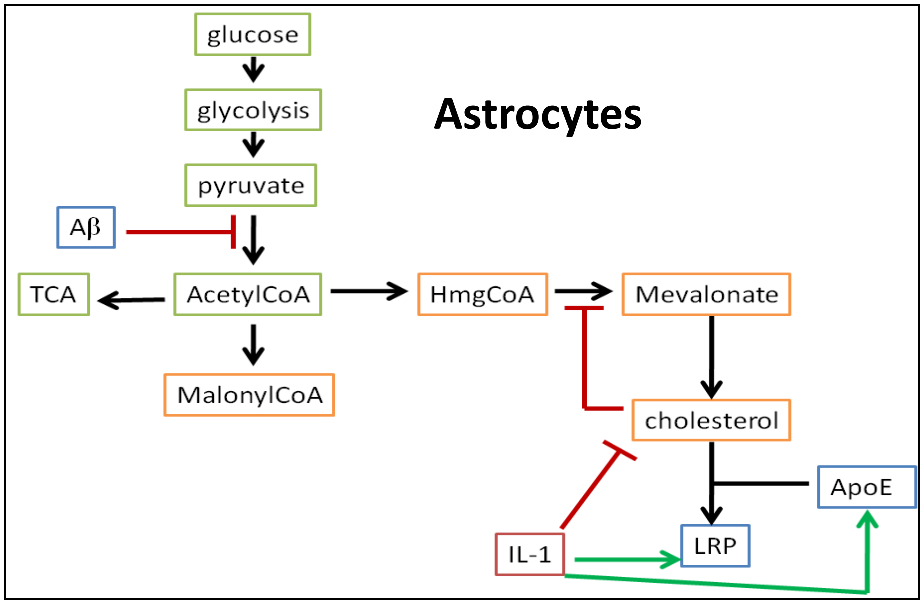
LRP-1:
- Transport of Aβ to blood
- Transfer of cholesterol to neurons & other CNS cells via apoE carrier binding

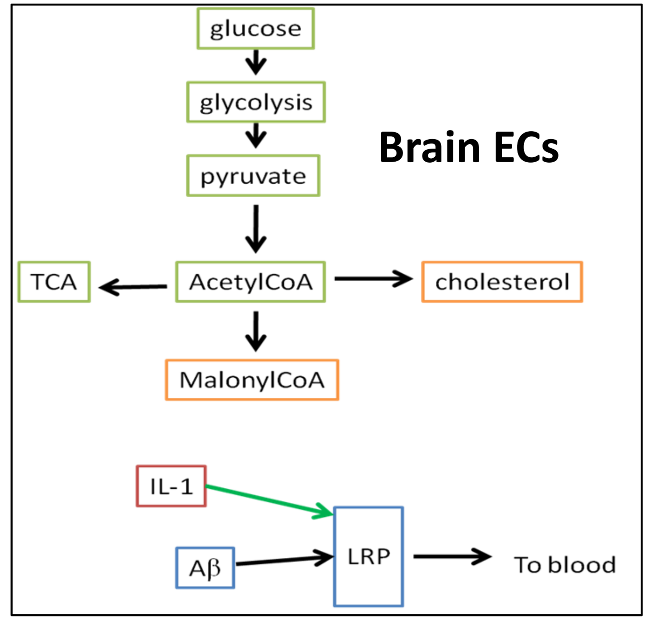
Aβ Cholesterol ApoE

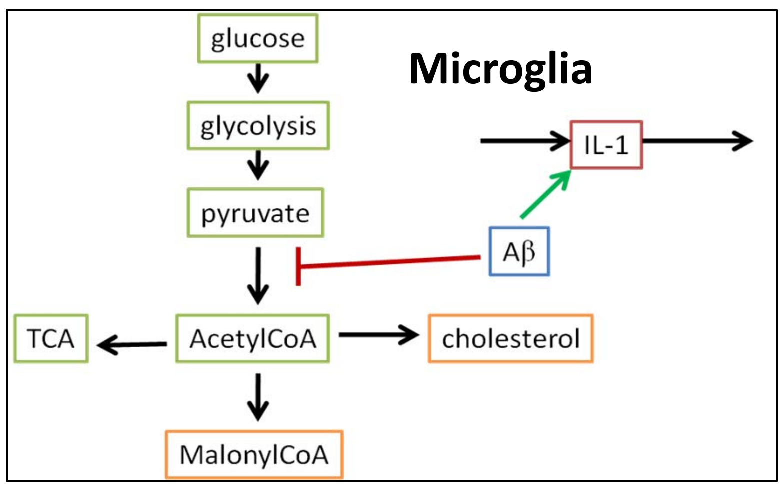
Directed Graph for Neurons



Directed Graph for Astrocytes, Microglia & Brain ECs





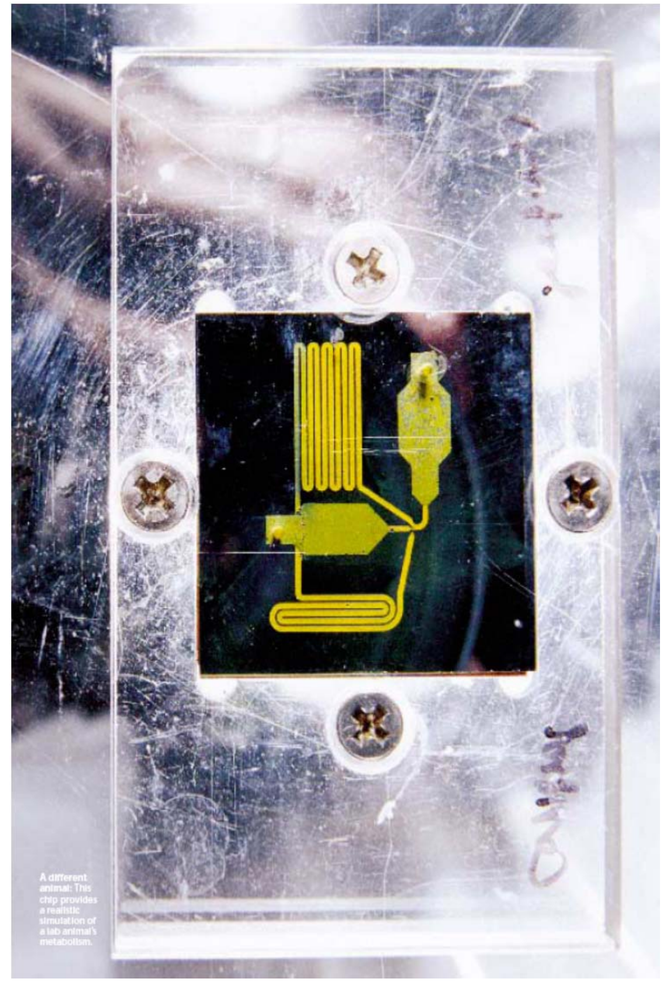


Lab-on-a-chip for Drug Testing

the silicon guinea pig

Pharmaceutical companies anxious to see if experimental drugs have toxic side effects may soon turn to a thumbnail-sized silicon chip, packed with live cells, that mimics the metabolism of a lab animal. Such "animal on a chip" devices could help to quickly and cheaply spot toxic compounds, sparing companies years and millions of dollars in the drug discovery process.

BY DAVID H. FREEDMAN | PHOTOGRAPHS BY DAVID BARRY

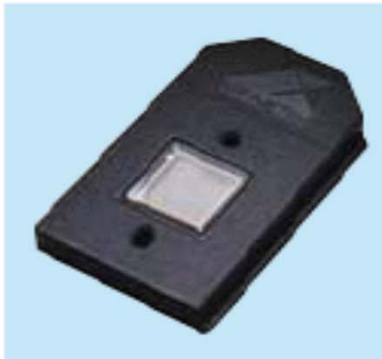


A different animal: This chip provides a realistic simulation of a lab animal's metabolism.

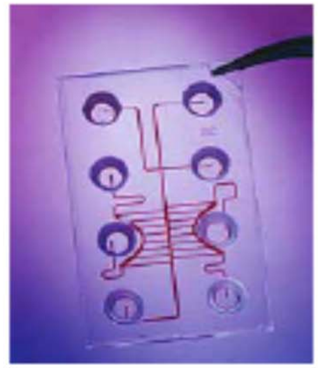
HYBRID LOC -- BIOCHIPS

Biochips are currently emerging with different form factors and technologies for applications in research, pharma and healthcare

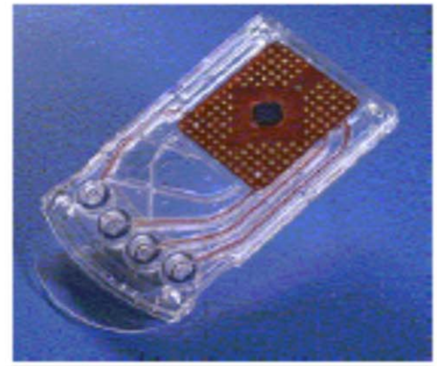
All biochip concepts are disposables



DNA µArray



µfluidic chip



µfluidic chip
+
DNA µArray

Applications:

- Basic research
- Pharma R&D / Drug development
- Healthcare

"Red Biotech"

- Agriculture and environment — "Green Biotech"
- Industrial and process control — "Grey Biotech"

REVOLUTIONIZING DRUG TESTING

- **Rapidly approaching untenable situation in human health -- Blockbuster drugs, which cure major diseases afflicting huge populations, are being pulled from the shelves (e.g., Vioxx) for unforeseen side-effects.**
- **They are being replaced by drugs that have smaller market potential and more localized impact (subpopulations, e.g., FluMist).**
- **Current cost of developing a drug and getting it to market exceeds $1B and process takes over ten years**
- **These competing forces cannot be resolved without truly transformational changes in the way drugs are discovered, developed, and approved.**
- **This need is exacerbated by the emergence of personalized medicine – a natural outcome of high throughput sequencing technologies.**

THE ISR SE PROGRAMS IN BRIEF

MSSE

DEGREE REQUIREMENTS

The following courses are required:

Systems Engineering Core

ENSE 621 Systems Engineering Principles
ENSE 622 System Modeling and Analysis
ENSE 623 Systems Engineering Design Project
ENSE 624 Human Factors in Systems Engineering

Management Core

ENSE 626 Systems Life Cycle Cost Estimation
ENSE 627 Quality Management in Systems

Those choosing the thesis option also take ENSE 799 Master's Thesis (for six credits) as well as an additional four electives. Those choosing the non-thesis option take an additional six electives.

Both Supplemented by Technical Electives form many Technical Areas

ENPM-SE

DEGREE REQUIREMENTS

The ENPM Systems Option requires four courses from the systems engineering core, three courses from the management core, and four electives. The courses are identical to the MSSE curriculum.

Systems Engineering Core

ENPM 641 Systems Engineering Principles
ENPM 642 System Modeling and Analysis
ENPM 643 Systems Engineering Design Project
ENPM 644 Human Factors in Systems Engineering

Management Core

ENPM 646 Systems Life Cycle Cost Estimation
ENPM 647 Quality Management in Systems

A Bold Experiment

Starting early in the education chain

Undergraduates working with industry and government mentors on SE projects

Thank you!

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Questions?