A Framework for Model-Based Systems Engineering for CPS with Emphasis on Design Space Exploration Methods and Tools

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Linköping University

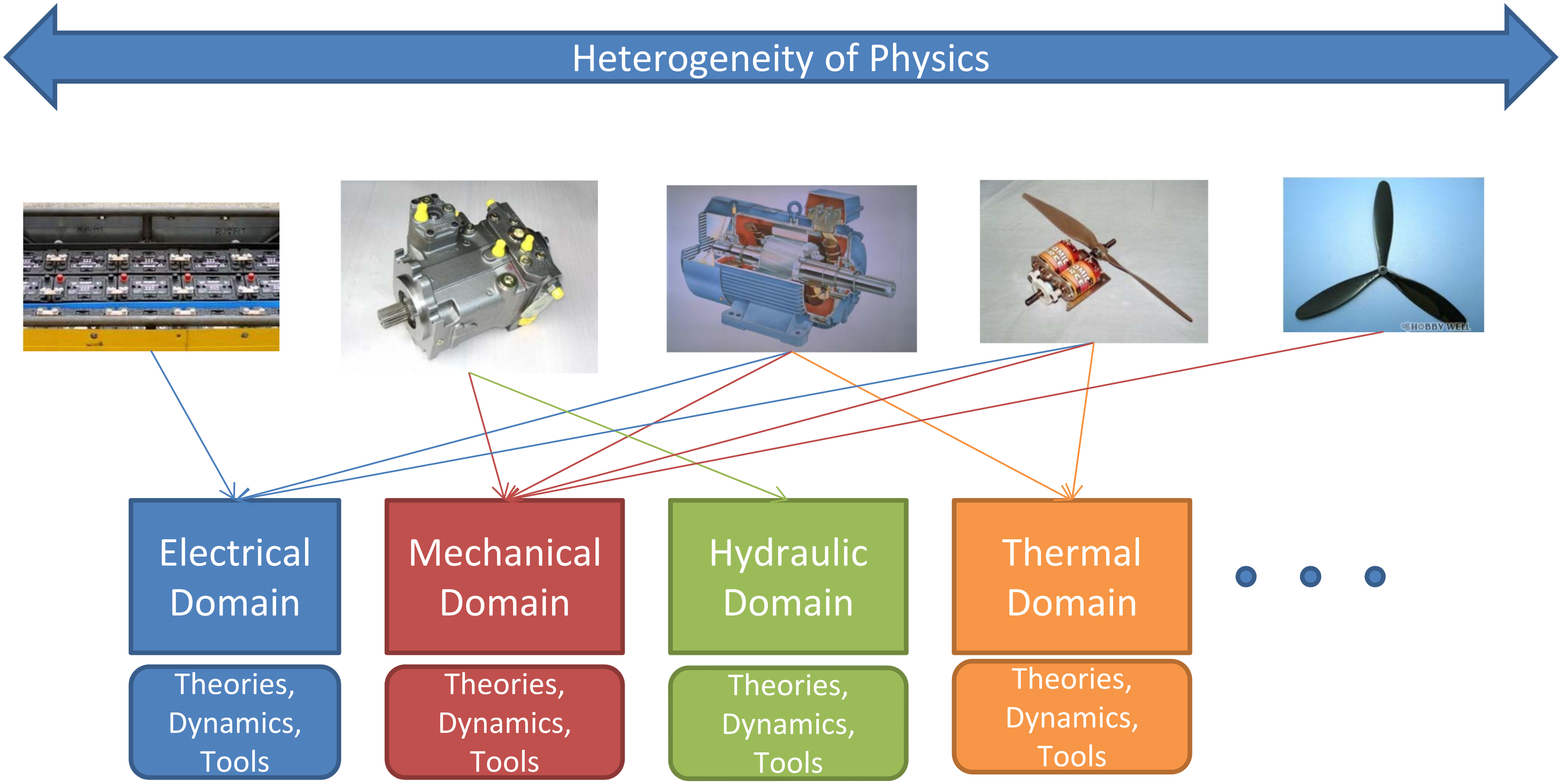
Linköping, Sweden

Acknowledgments

- **Joint work with: Mark Austin, Shah-An Yang, Dimitrios Spyropoulos, Brian Wang, Yuchen Zhou, David Daily**

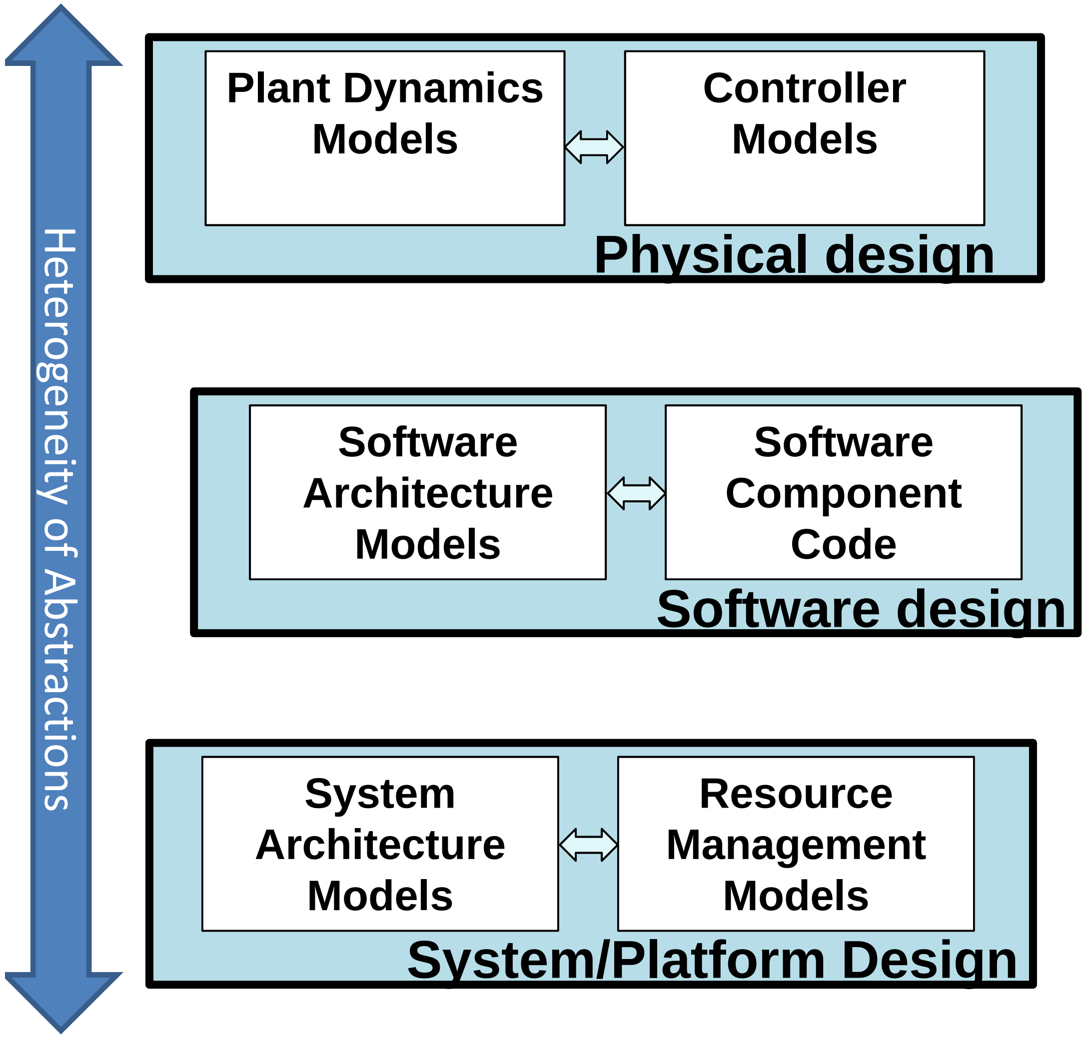
- **Sponsors: NIST, NSF, DARPA, SRC, Lockheed Martin, BAE, Northrop Grumman, Telcordia (ACS), Hughes Network Systems**

Model Integration Challenge: Physics



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

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,..

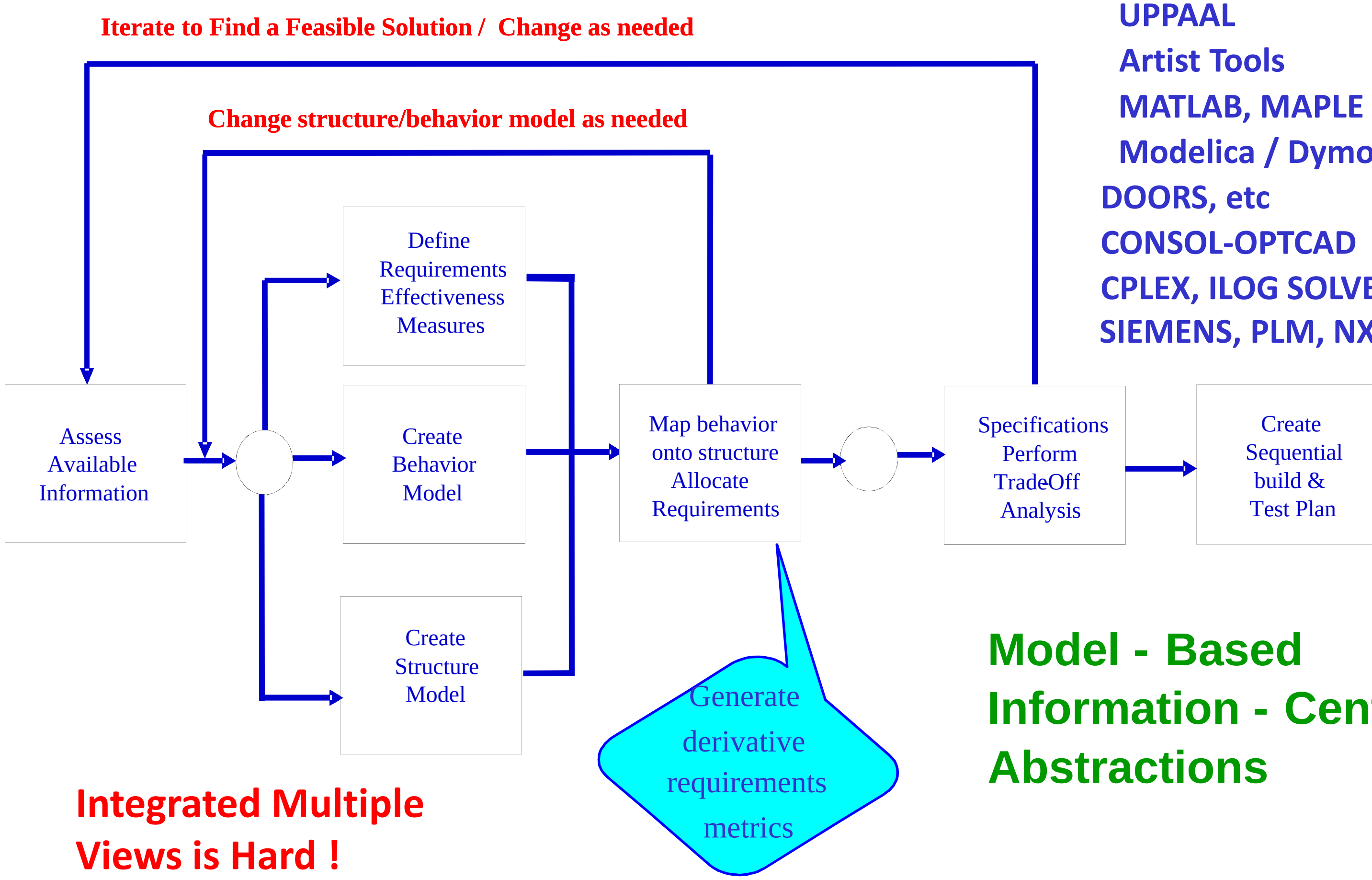
Systems : $B(t_j) = \kappa_p(B_1(t_i),\ldots,B_k(t_i))$

- *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
- UPPAAL
- Artist Tools
- MATLAB, MAPLE
- Modelica / Dymola

DOORS, etc
CONSOL-OPTCAD
CPLEX, ILOG SOLVER,
SIEMENS, PLM, NX, TEAM CENTER

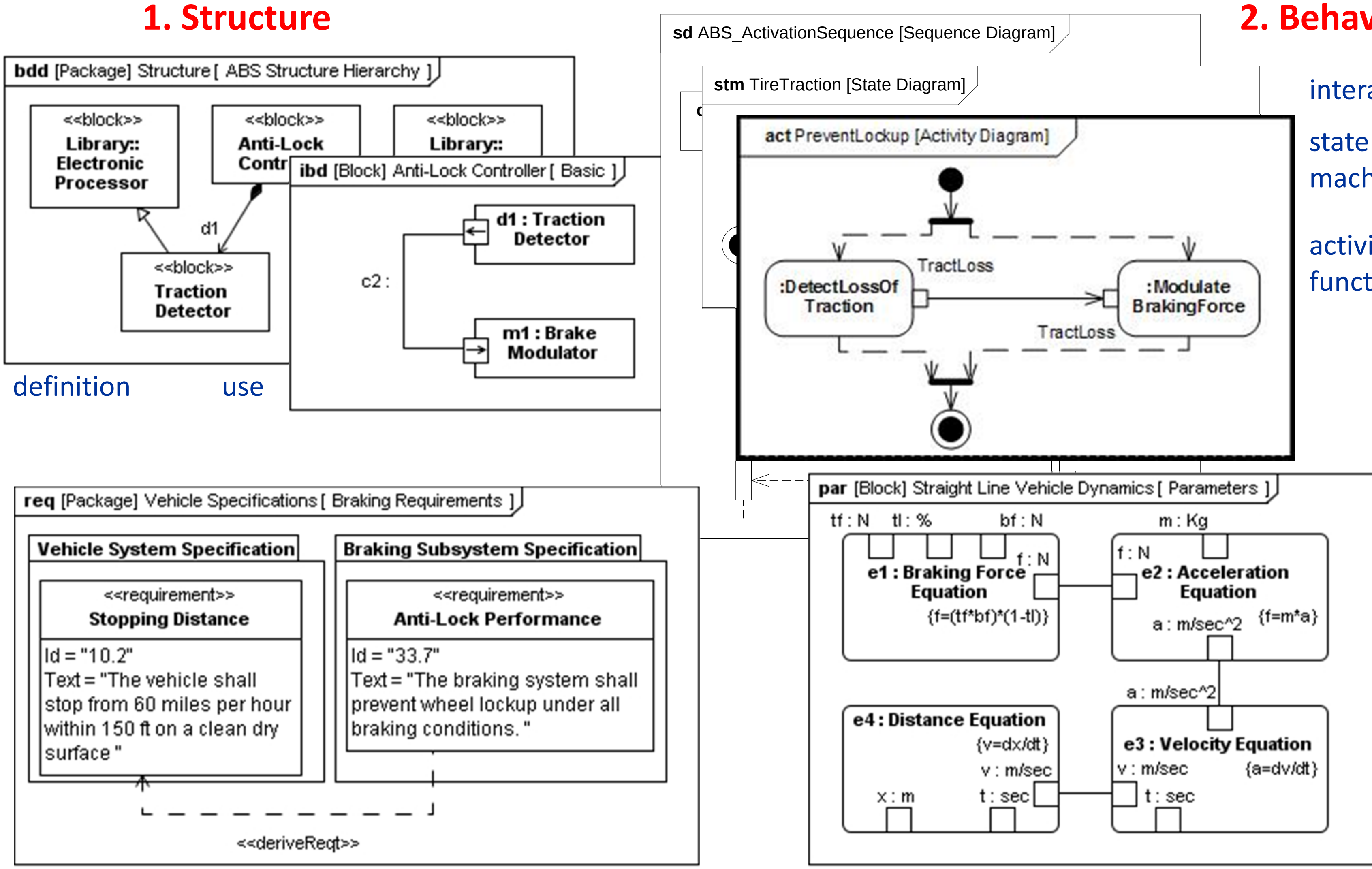
Model - Based Information - Centric Abstractions

Integrated Multiple Views is Hard !

FOUR PILLARS OF SYSML

1. Structure

2. Behavior



definition use

interaction

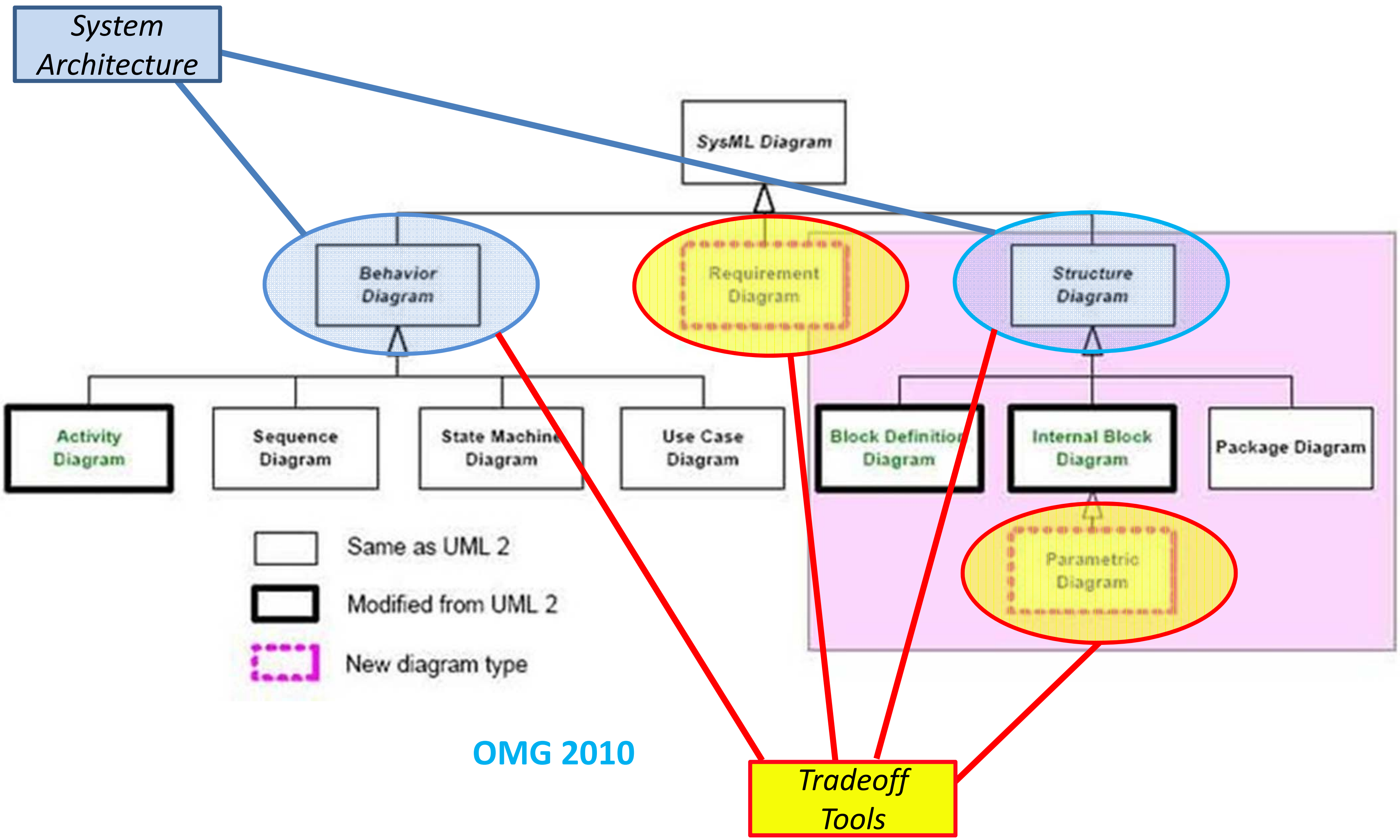
state machine

activity/ function

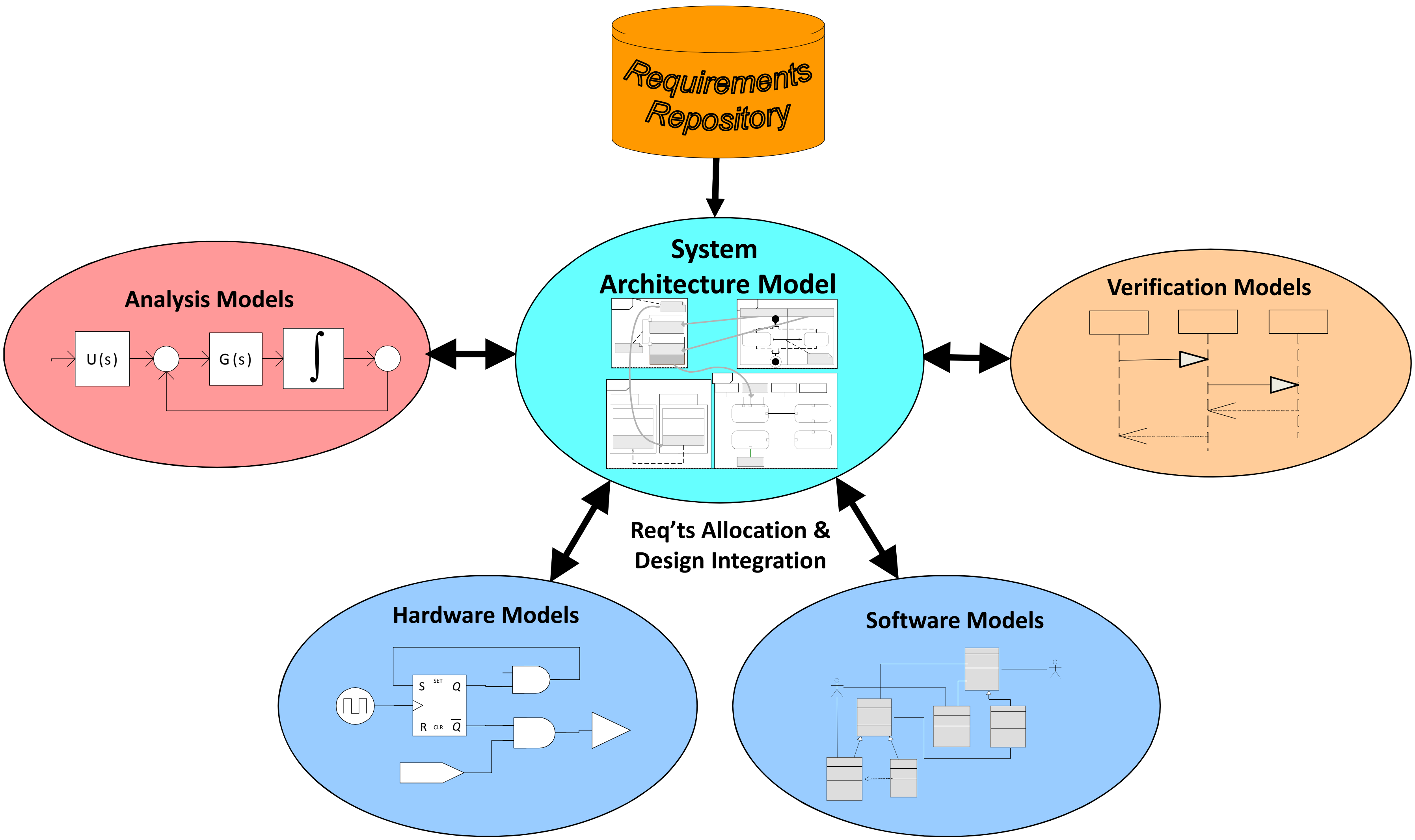
3. Requirements

4. Parametrics

SysML Taxonomy



Using *System Architecture Model* as an Integration Framework



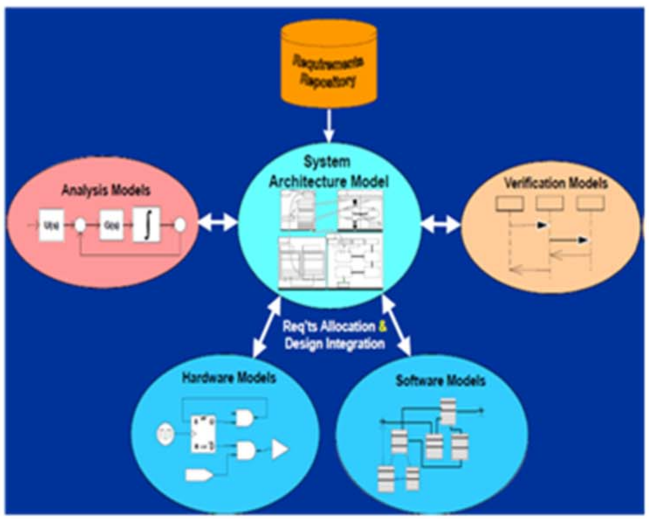
A Rigorous Framework for Model-based Systems Engineering

The Institute for Systems Research

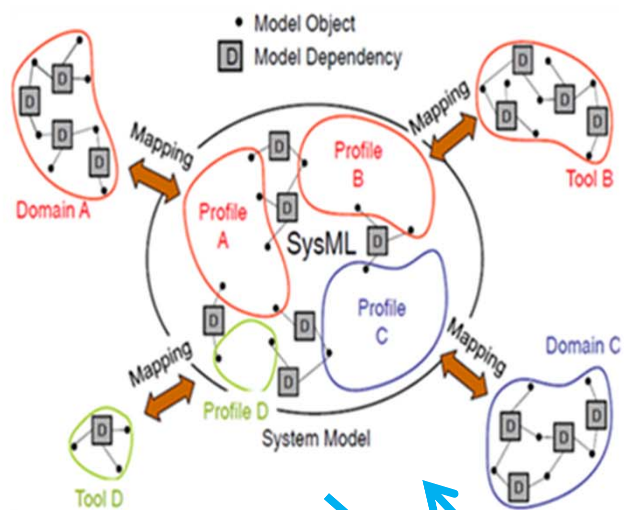
The Challenge & Need:

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

ADD & INTEGRATE

Multiple domain modeling tools

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

DB of system components and models

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**

Requirements Engineering

- **How to represent requirements?**
  - Automata, Timed-Automata, Timed Petri-Nets
  - Dependence-Influence graphs for traceability
  - Set-valued systems, reachability, … for the continuous parts
  - Constraint – rule consistency across resolution levels
- **How to automatically allocate requirements to components?**
- **How to automatically check requirements?**
  - **Approach**: Integrate contract-based design, model-checking, automatic theorem proving
- **How to integrate automatic and experimental verification?**
- **How to do V&V at various granularities and progressively as the design proceeds – not at the end?**
- **The front-end challenge: Make it easy to the broad engineering user?**

Framework for MBSE for CPS: Key Challenges Addressed

- Methodology to develop integrated modeling hubs (IMH) for CPS – multi-physics and cyber
- Methodology to link IMHs with design space exploration via multi-criteria tradeoff methods and tools
- Linkage to component databases
- Working on the last remaining challenge: requirements management
- Developed new methods and tools to handle complexity in design space exploration

BOEING 787: CLEANER, QUIETER, MORE EFFICIENT

The 787 Dreamliner delivers:

*Relative to the 767

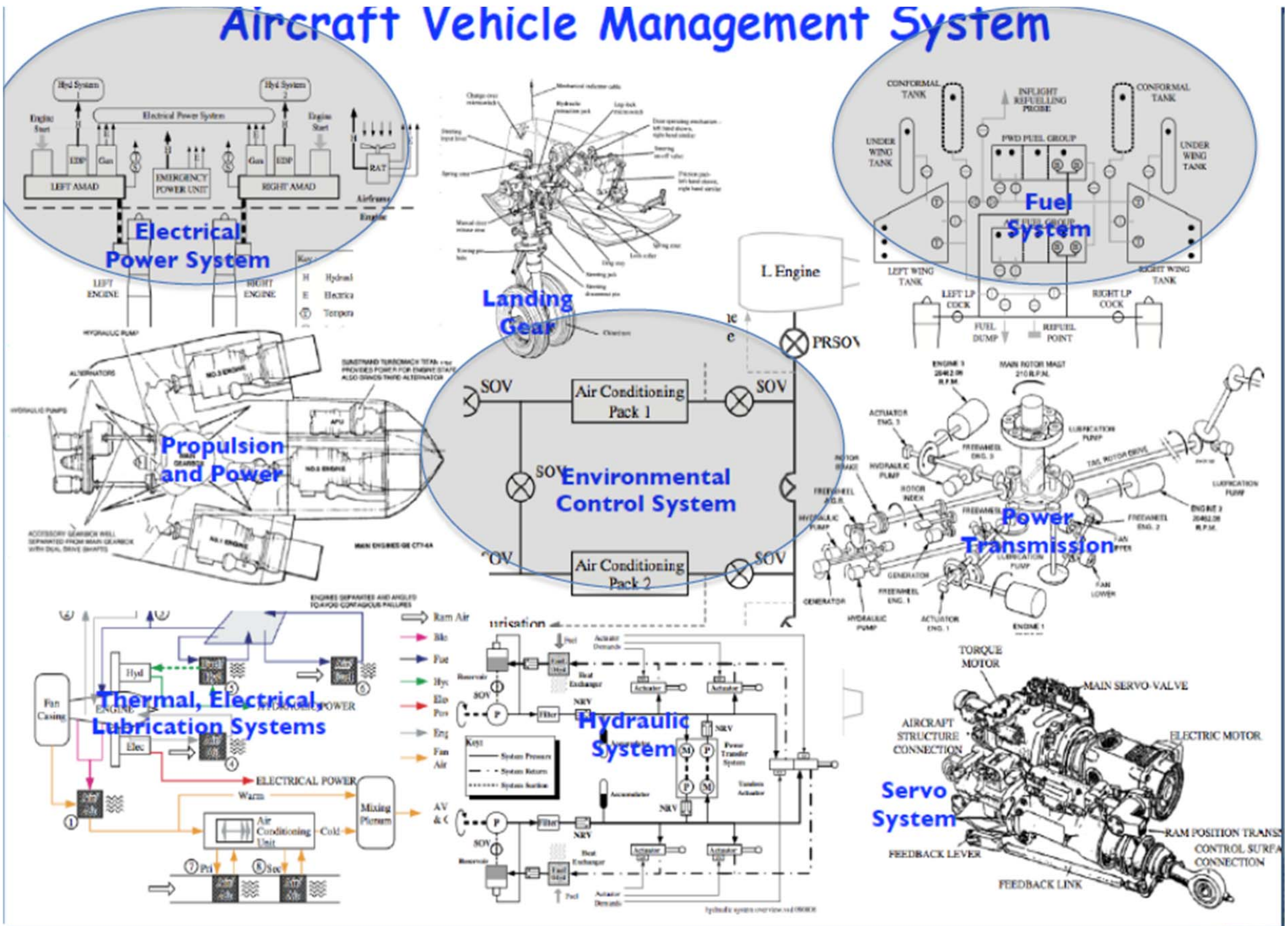
20%* reduction in fuel and CO_2

28% below 2008 industry limits for NOx

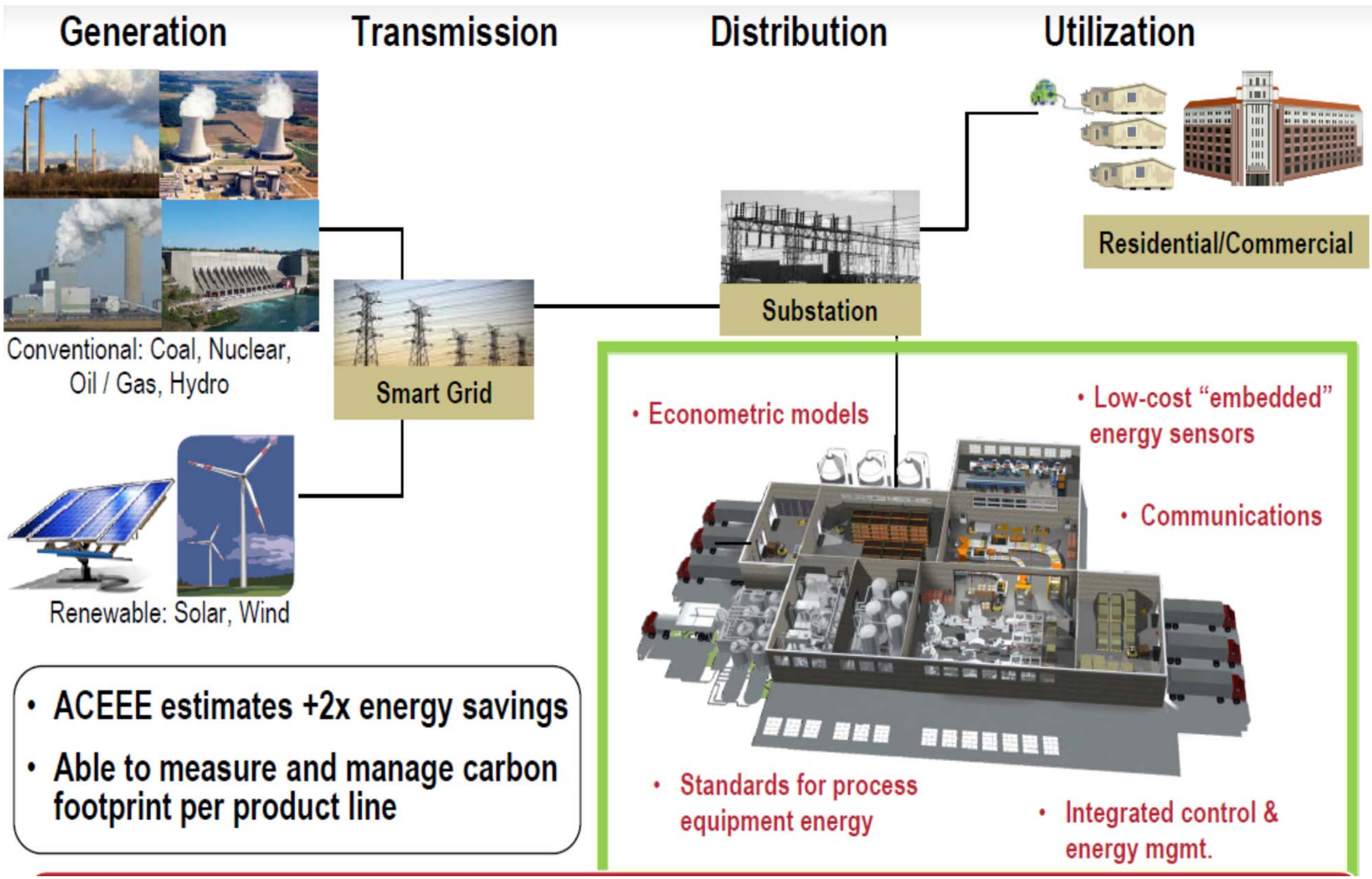
60%* smaller noise foot print

Boeing

Aircraft Vehicle Management System

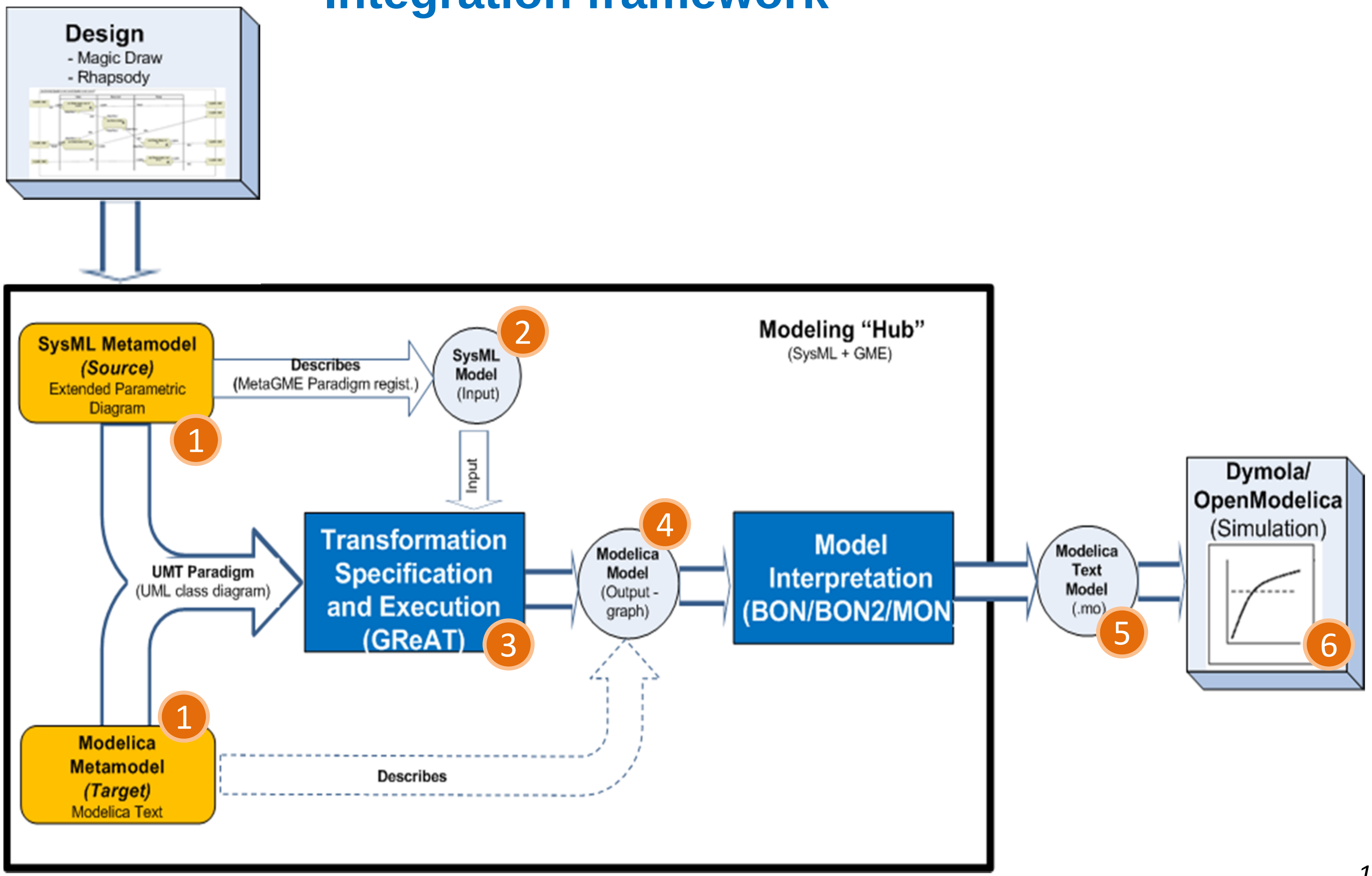


Smart Grids in a Network Immersed World



SysML and Modelica Integration

Integration framework



SysML and Consol-Optcad Integration

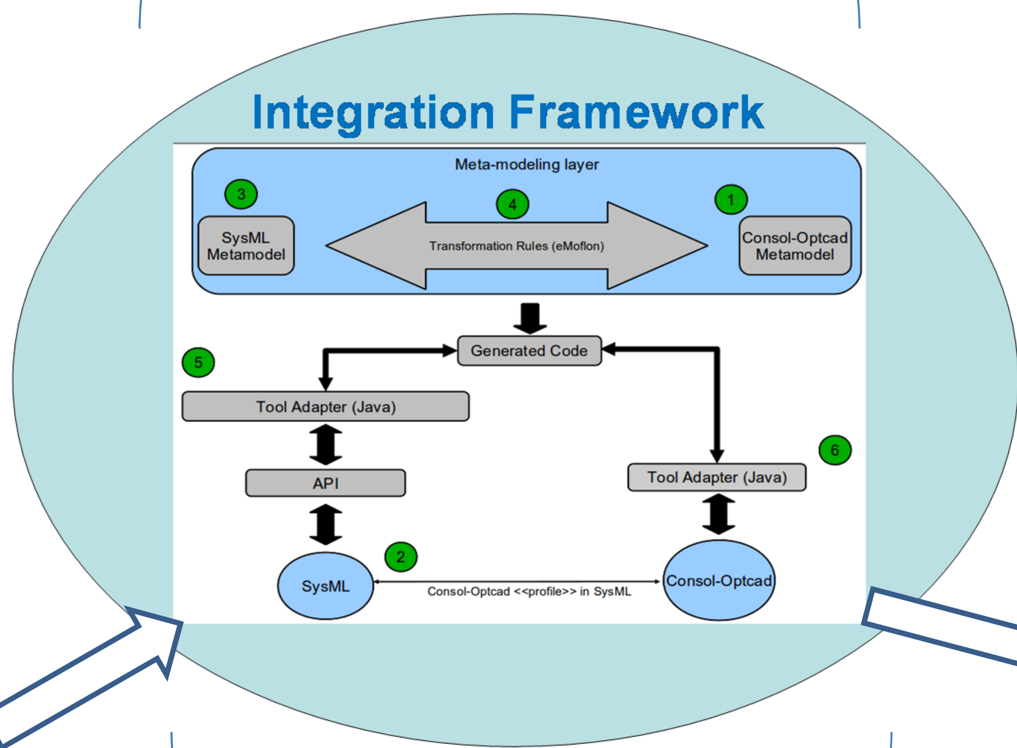
Overview

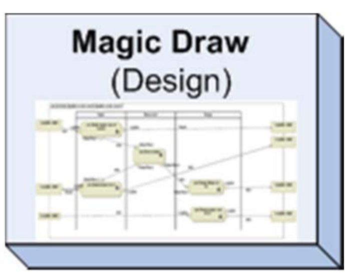
Meta-modeling Layer

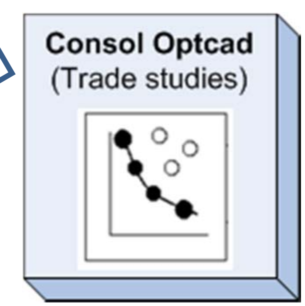
(Enterprise Architect + eMoflon, Eclipse development environment)

Tool Adapter Layer

(Middleware)







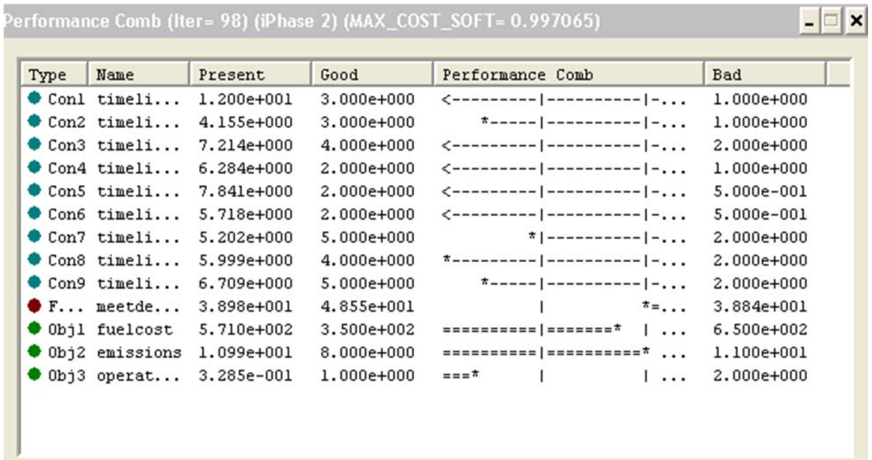
Tool Layer

(Magic Draw, Consol Optcad)

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)

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<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
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<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

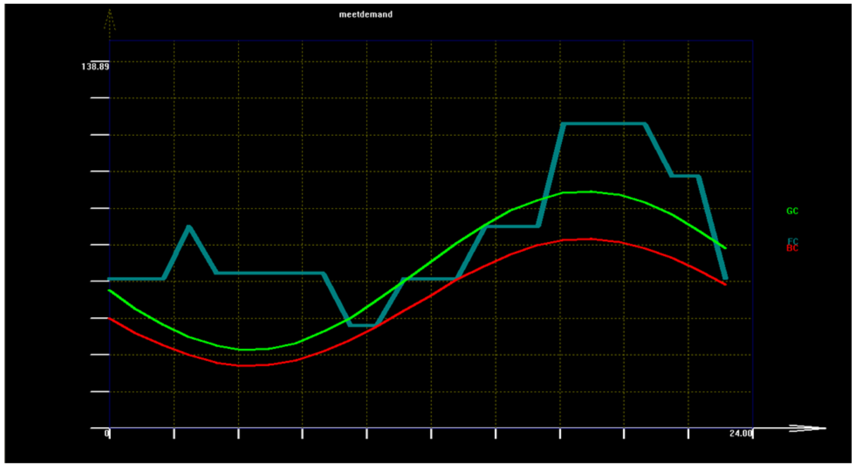


Fig. 2: Example of a functional constraint

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

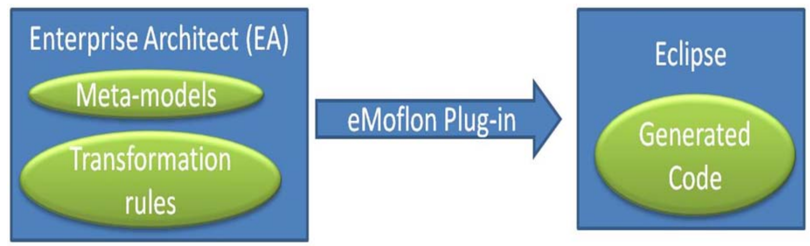


Fig. 3: eMoflon high-level architecture

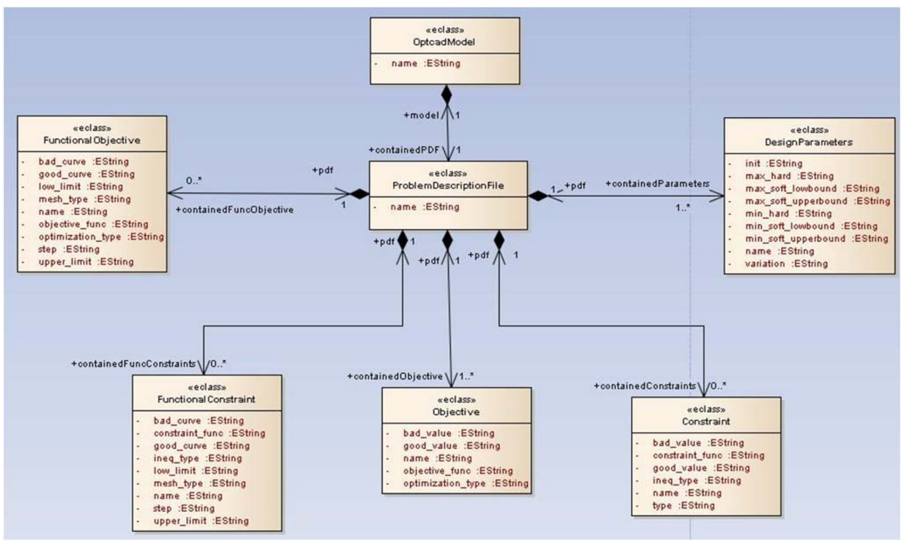


Fig. 4: Consol-Optcad metamodel

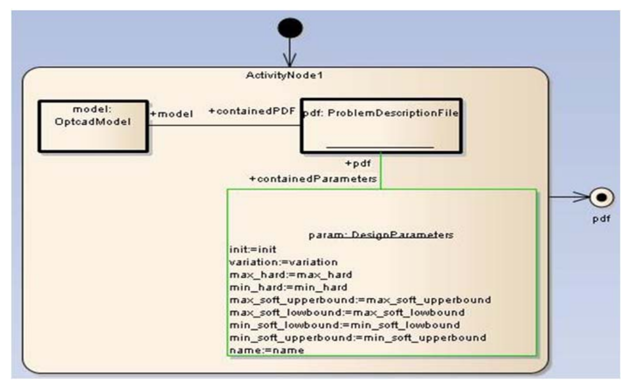


Fig. 5: Story diagram

IMH and Consol-Optcad Integration

Working Example

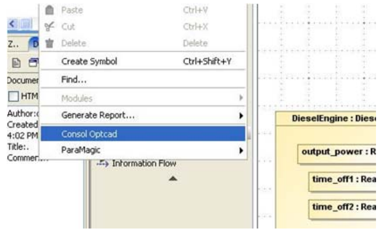


Fig. 11: Initiate transformation

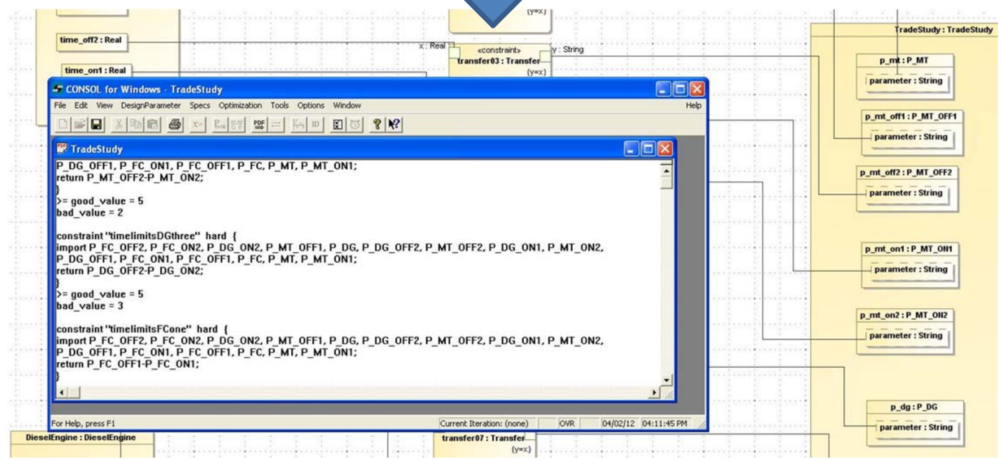


Fig. 12: Consol-Optcad environment

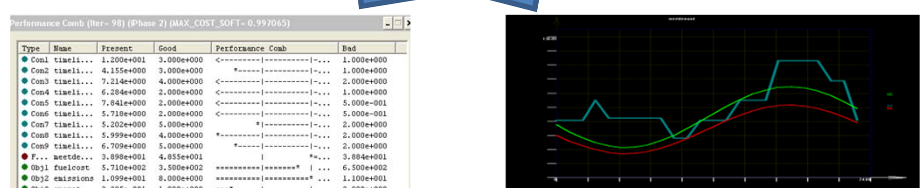


Fig.13: Perform trade-off analysis in Consol-Optcad

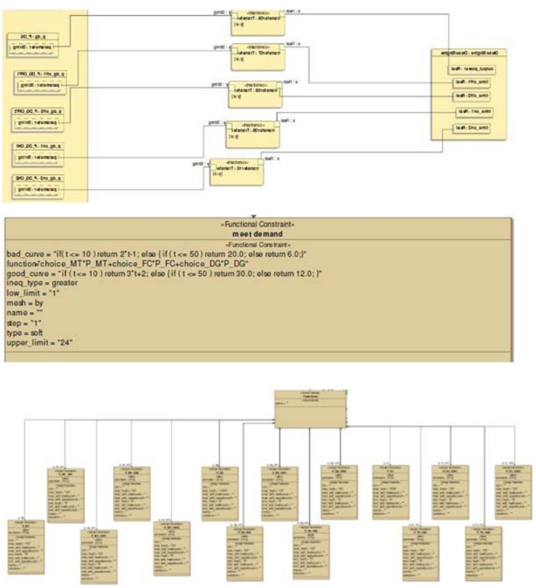


Fig. 10: Models in SysML

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

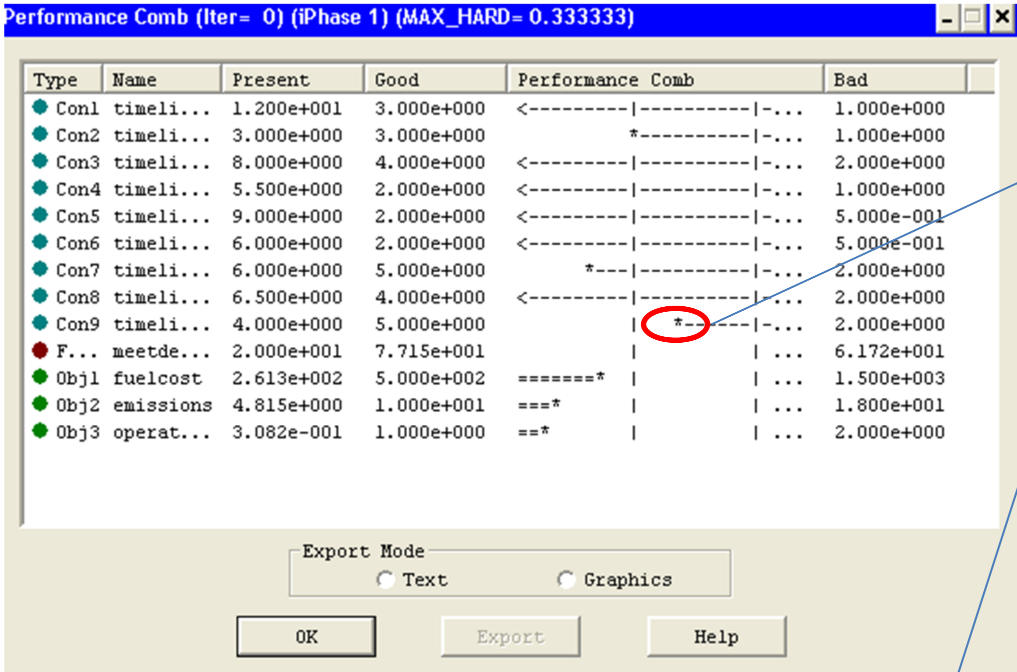
Constraints for correct operation of the generation unit

- 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 $t_{i\_off\,2} - t_{i\_on2} \geq x_i, \quad i = 1,2,\ldots N$

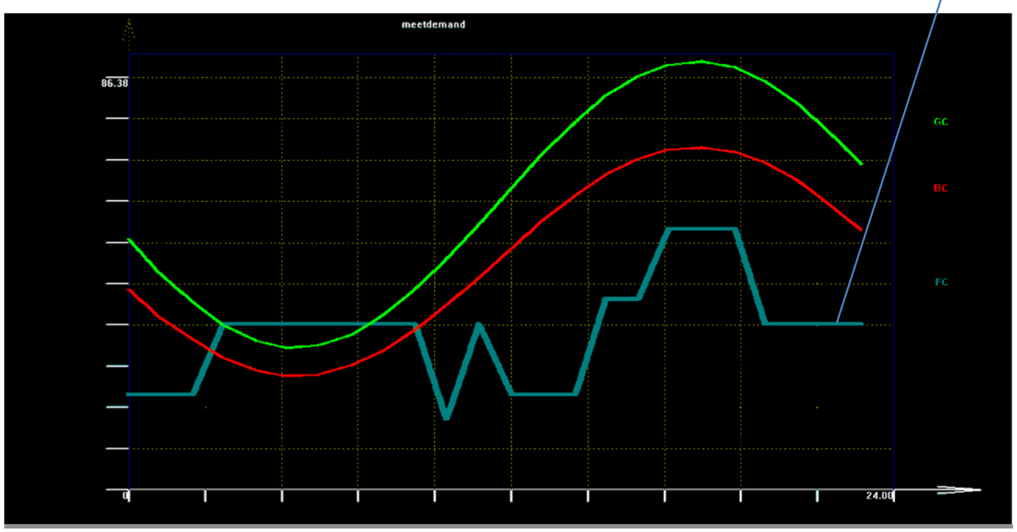
- Each generating unit should remain turned off for at least a period y_i defined by the specifications: $t_{i\_on2} - t_{i\_off1} \geq y_i, \quad i = 1,2,\ldots N$

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

Tradeoff Study in Consol-Optcad



Type	Name	Present	Good	Performance Comb	Bad
Con1	timeli...	1.200e+001	3.000e+000	<---------|----------|-...	1.000e+000
Con2	timeli...	3.000e+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...	9.000e+000	2.000e+000	<---------|----------|-...	5.000e-001
Con6	timeli...	6.000e+000	2.000e+000	<---------|----------|-...	5.000e-001
Con7	timeli...	6.000e+000	5.000e+000	*---|----------|-...	2.000e+000
Con8	timeli...	6.500e+000	4.000e+000	<---------|----------|-...	2.000e+000
Con9	timeli...	4.000e+000	5.000e+000	| *------|-...	2.000e+000
F...	meetde...	2.000e+001	7.715e+001	| | ...	6.172e+001
Obj1	fuelcost	2.613e+002	5.000e+002	=======* | | ...	1.500e+003
Obj2	emissions	4.815e+000	1.000e+001	===* | | ...	1.800e+001
Obj3	operat...	3.082e-001	1.000e+000	==* | | ...	2.000e+000

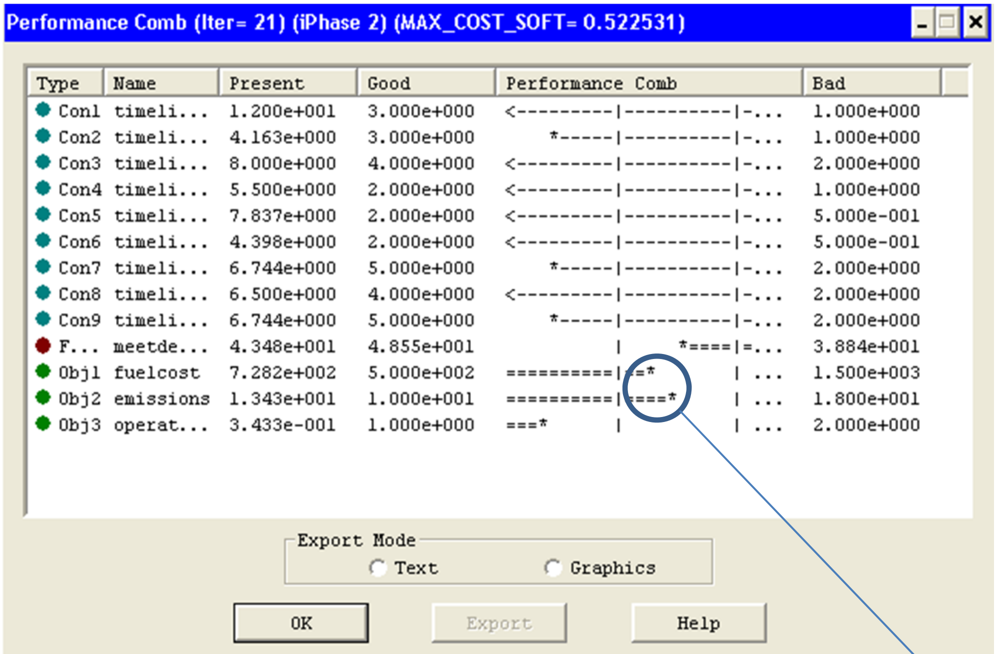


Iteration 1 (Initial Stage)

- ✓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

The Institute for Systems Research

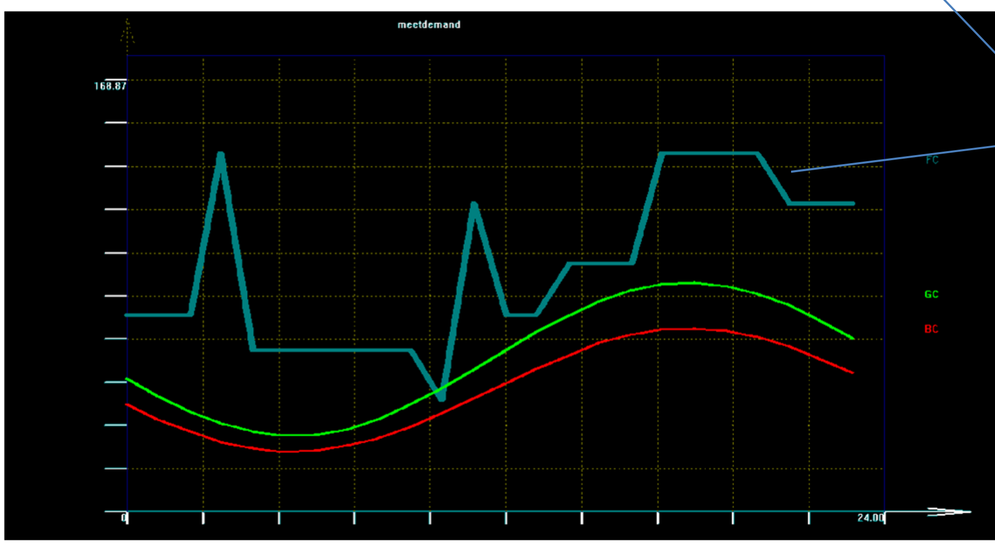


Performance Comb (Iter= 21) (iPhase 2) (MAX_COST_SOFT= 0.522531)

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

Export Mode
Text Graphics

OK Export Help



Iteration 28 (User Interaction)

✓All hard constraints are satisfied

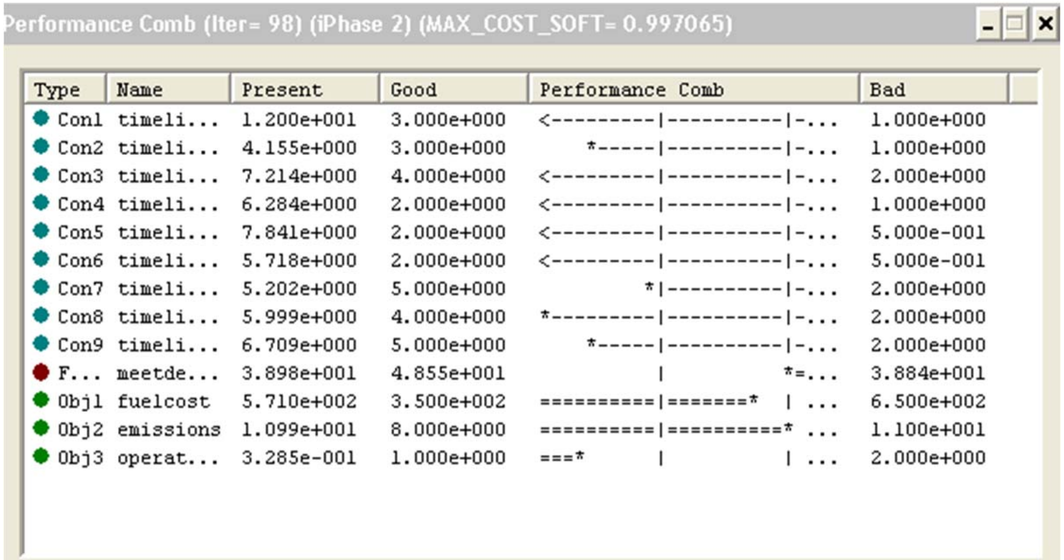
✓ Functional Constraint meets the specified demand. Goes below the good curve only for a small period of time but as a soft constraint is considered satisfied

✓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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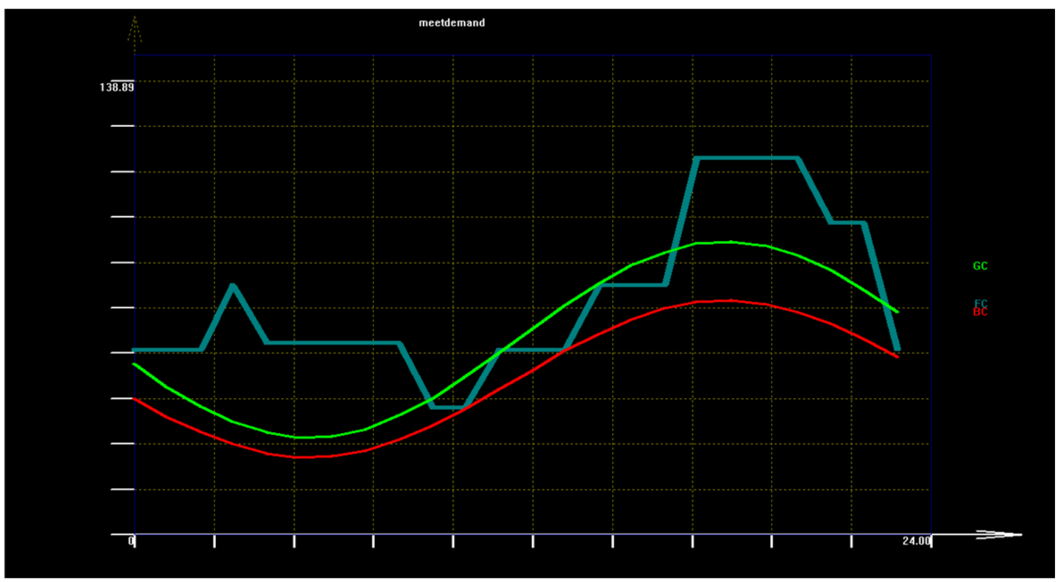
<tr><td>Obj1</td><td>fuelcost</td><td>5.710e+002</td><td>3.500e+002</td><td>==========|=======* | ...</td><td>6.500e+002</td></tr>
<tr><td>Obj2</td><td>emissions</td><td>1.099e+001</td><td>8.000e+000</td><td>==========|==========* ...</td><td>1.100e+001</td></tr>
<tr><td>Obj3</td><td>operat...</td><td>3.285e-001</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

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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

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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

```
========================================
  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
```

Iteration 29 (Final Solution)

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

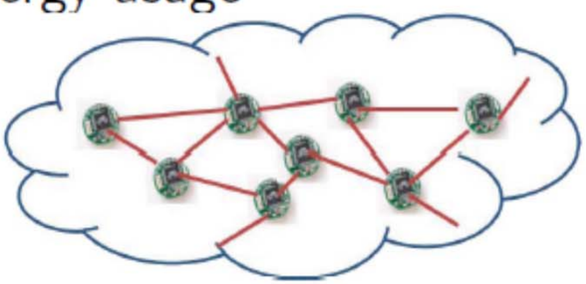
Results

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

Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

- Environmental systems
- Structural health
- Construction projects
- Energy usage



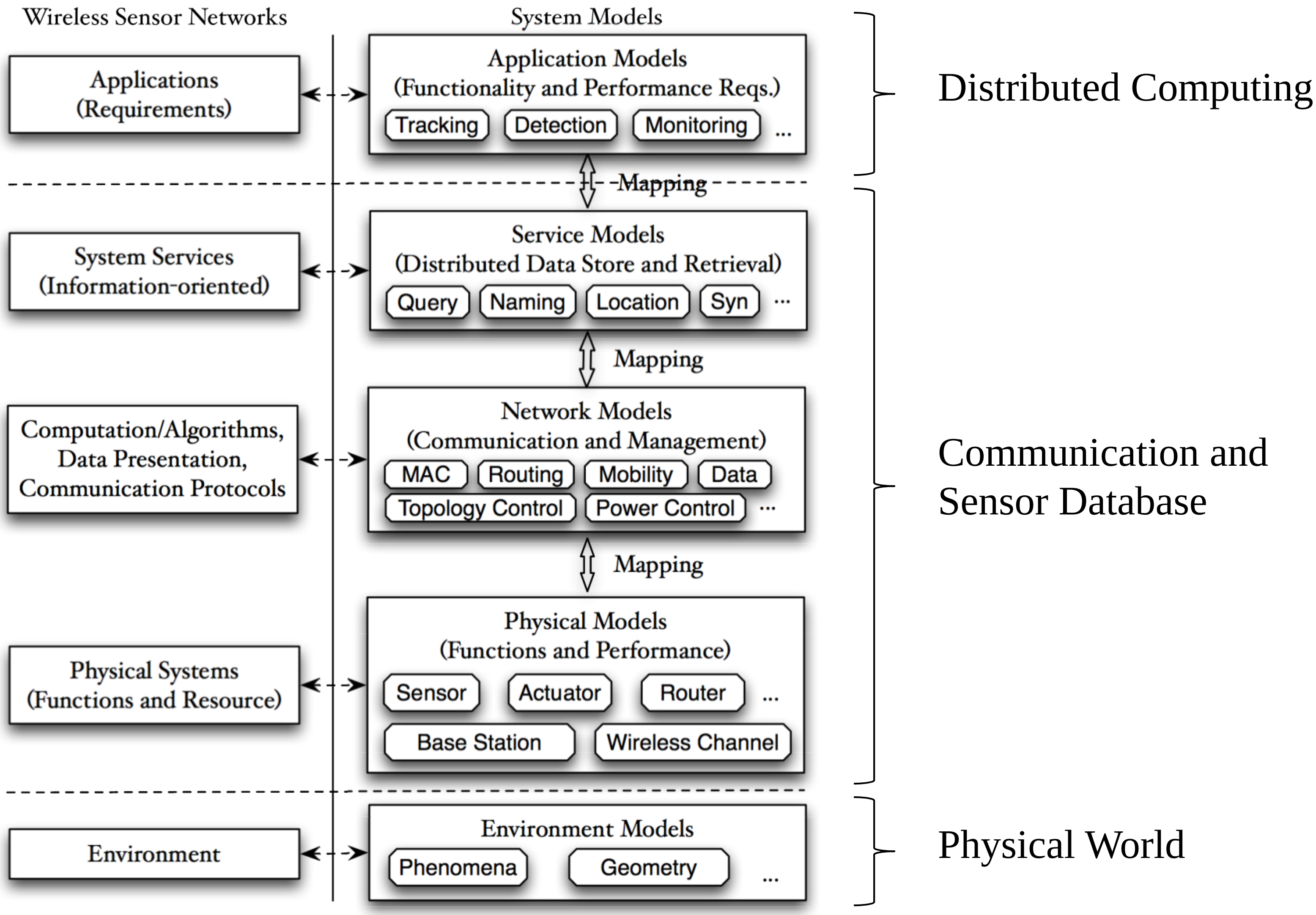
MBSE for Wireless Sensor Networks: Contributions

- Developed a model-based system design framework for WSNs
  - Integrate both event-triggered and continuous-time dynamics
  - Provide a hierarchy of system model libraries
- Developed 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

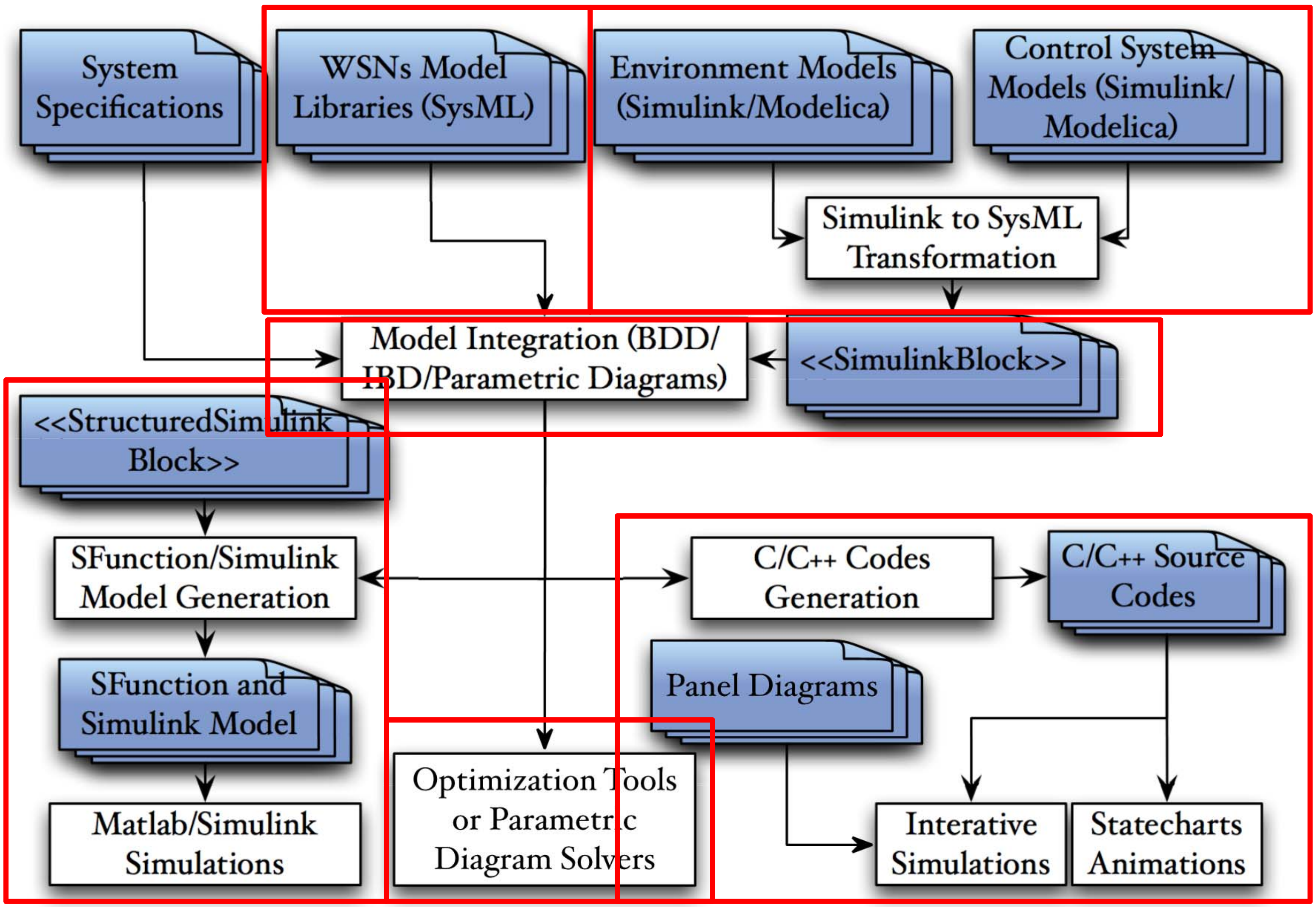
System Framework

- 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



MBSE for Sensor Networks



Component Based Networking: Network MBSE for MANET

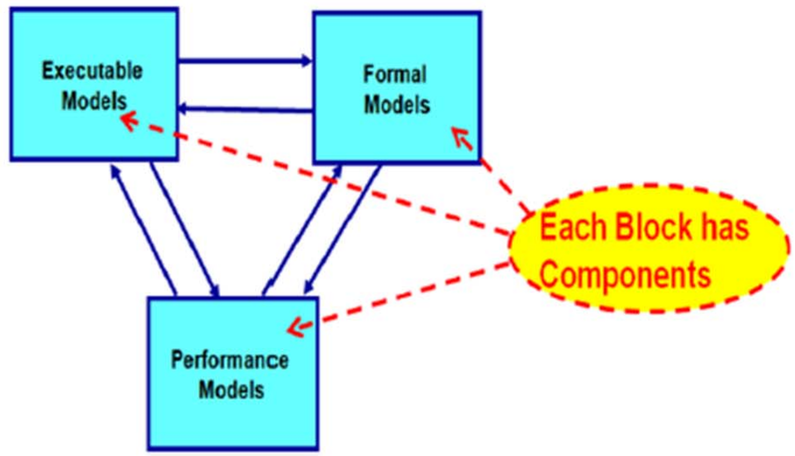
The Challenge & Need:
Design DoD and Commercial MANET Adaptive to Dynamic Mission Requirements

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



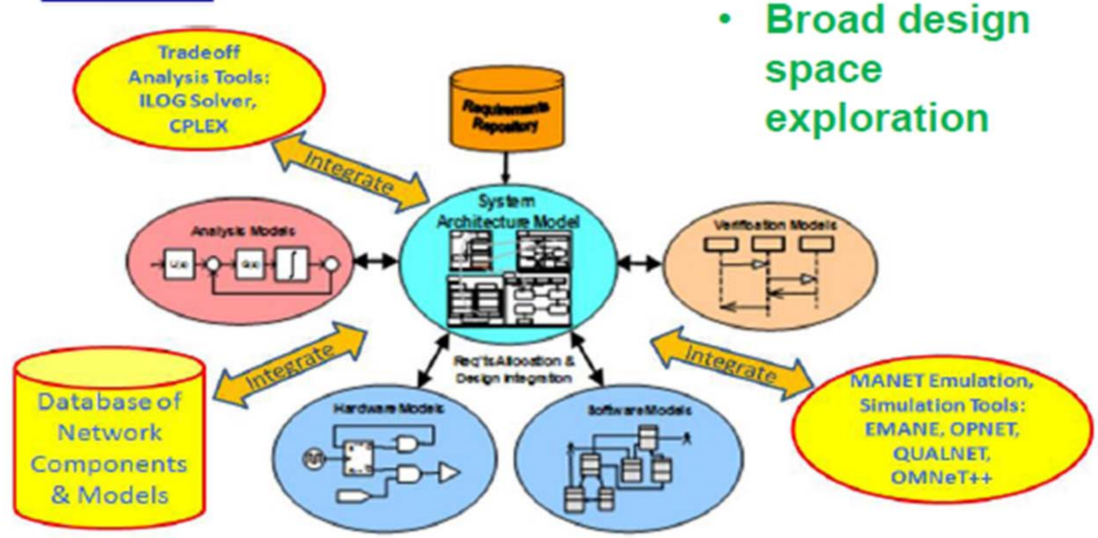


Fig. 3: Network MBSE Toolset : integrating **SysML** Architecture Model with DB of network models, emulation-simulation models, tradeoff tools

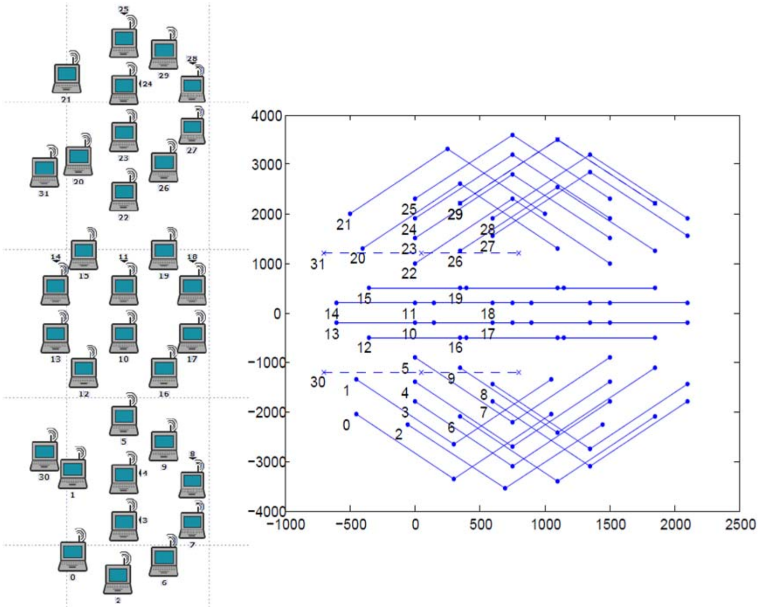
BENEFITS

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

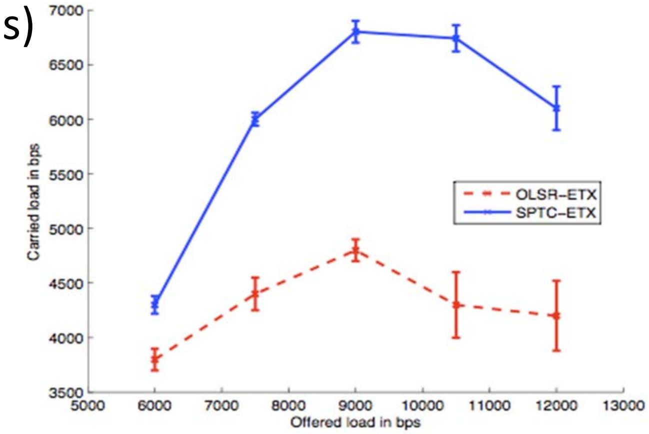
Components for Routing Protocols

- Neighborhood Discovery Component (NDC)
  - Status of nodes that are close to me (2-hop neighborhood)
- Selector of Topology Information to Disseminate Component (STIDC)
  - What information should be broadcasted in the network
- Topology Information Dissemination Component (TDC)
  - How the information is shared
- Route Selection Component
  - Path selection Criteria

3 Platoon Mobility Scenario



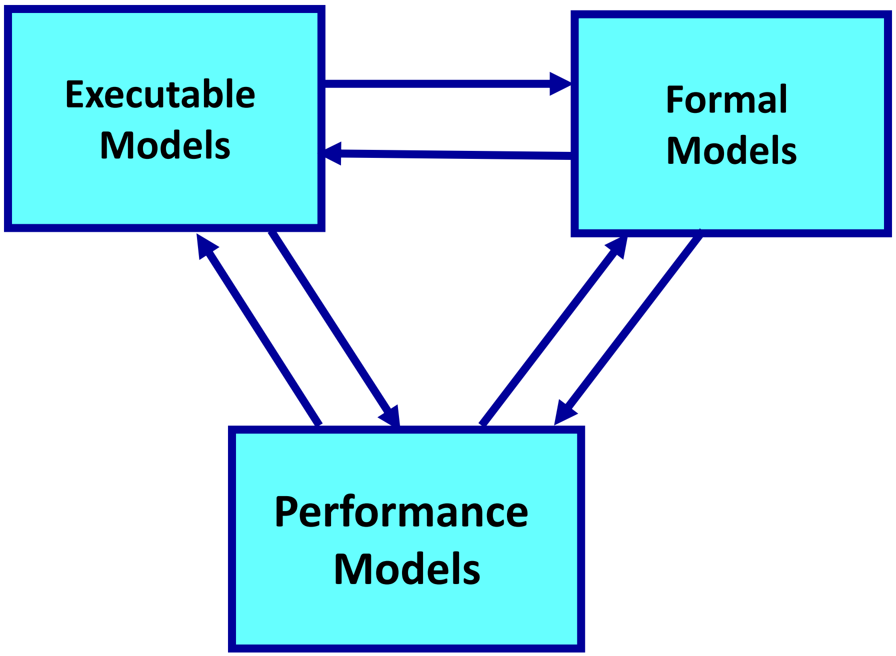
Long connection from 20 to 0 (platoon heads)



	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

Component-base Networks and Composable 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**

Universally Composable Security (UCS)

Results todate (Canetti, Lindell, …) :

- When there is a clear majority of well behaving nodes (i.e.2/3) **almost any functionality is secure under UCS**
- When there is no clear majority then UCS is **impossible** to achieve unless there are pre-conditions – typically some short of trust mechanism
- Introducing **special structure in the network** (e.g. overlay structure, small subset of absolutely trusted nodes) helps substantially in establishing UCS, even without preconditions
- **Many applications:** military networks, health care networks, sensor networks, SCADA and energy cyber networks
- **The challenge and the hope: Use "tamper proof hardware" (physical layer schemes, TPM etc.) even on a small subset of nodes to provably (validation) establish UCS – role of fingerprints and physical layer techniques.**
- **Establish it and demonstrate it?**

Latest: Adaptive Component-Based MANET Security

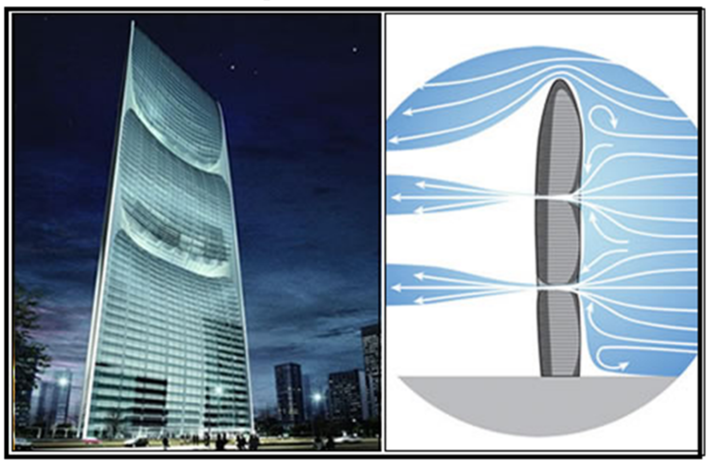
- **Components of MANET Routing Protocols**
- Neighborhood Discovery Component (NDC)
  - Status of nodes that are close to me (2-hop neighborhood)
- Selector of Topology Information to Disseminate Component (STIDC)
  - What information should be broadcasted in the network
- Topology Information Dissemination Component (TDC)
  - How the information is shared
- Route Selection Component
  - Path selection Criteria

- **Cross-layer – MAC and Routing**
- **Detect attacks – mitigation strategies – adaptively change protocol component parameters and structure**
- **Distributed trust an integral part**
- **Treat it as a Feedback Control System!**
- **Part of the DARPA WND program**

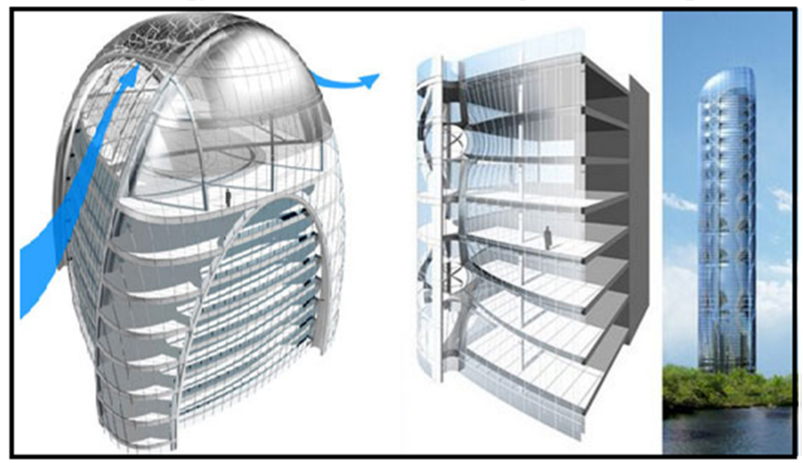
Buildings as Cyber-Physical Systems

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

Pearl River Tower Complex



Green Technology Tower –– Architectural Proposal for Chicago



NET-zero Energy

NIST Net Zero Energy Residential Test Facility

Courtesy J. Kneifel (2012)

CURRENT CAPABILITIES AND SOFTWARE

EnergyPlus

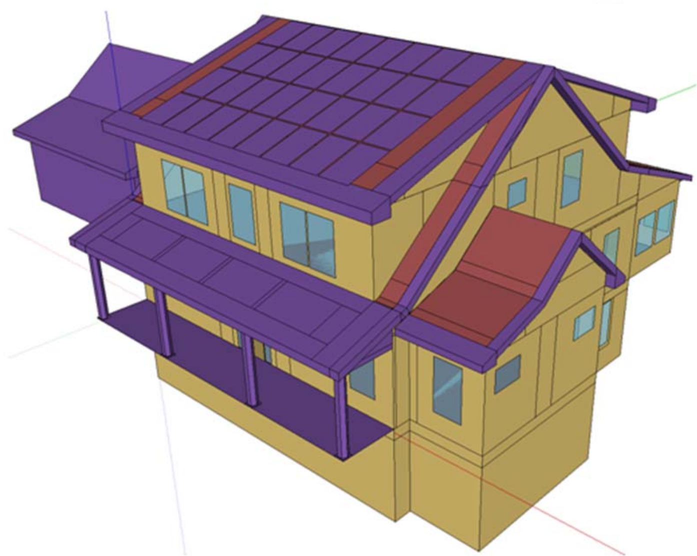
- Developed in 2001 by DOE and LBNL, currently v8.1
- Whole Building Energy Simulator – Weather, HVAC, Electrical, Thermal, Shading, Renewables, Water, Green Roof
- Steady state simulation down to 1 minute time intervals
- Reporting on built-in, component or system level properties.
  - Reports can vary in frequency: Annual, Monthly, Daily, Timestep
- Includes EML for HVAC controls (see MLE+)

EnergyPlus - Pros

- Highly detailed models for realistic as-builts
- Captures many of the complex physical interactions that outside and within a building
- Active and wide community and support

EnergyPlus – Cons

- Models can have long development time and steep learning curve



Courtesy EnergyPlus, J. Kneifel (2012)

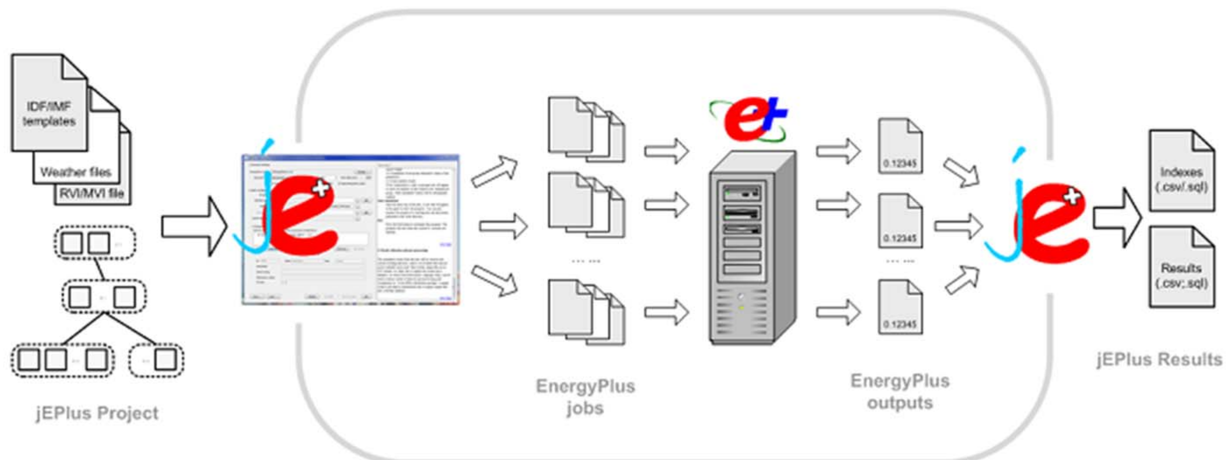
CURRENT CAPABILITIES AND SOFTWARE

jEPlus

- Developed by Yi Zhang and Ivan Korolija at De Montfort University, UK
- Java wrapper for EnergyPlus that simplifies parametric analysis
- Extends functionality of EnergyPlus

jEPlus– Pros

- Greatly enhances parametric analysis across all platforms
- Parametric tagging system makes it much easier to code for large state spaces



Courtesy Y. Zhang

MULTI-OBJECTIVE OPTIMIZATION

Problem Formulation

Design Parameters	Description	Constraint	Initial	Unit
x_1	Exterior Wall Insulation (R-Value)	$19 \leq x_1 \leq 44$	$x_1 = 19$	$\frac{\text{ft}^2 \cdot {}^\circ\text{F} \cdot \text{hr}}{\text{Btu}}$
x_2	Roof Insulation (R-Value)	$50 \leq x_2 \leq 75$	$x_2 = 50$	$\frac{\text{ft}^2 \cdot {}^\circ\text{F} \cdot \text{hr}}{\text{Btu}}$
x_3	Window (U-Value)	$0.2 \leq x_3 \leq 0.35$	$x_3 = 0.35$	$\frac{\text{Btu}}{\text{ft}^2 \cdot {}^\circ\text{F} \cdot \text{hr}}$
x_4	Window (SHGC)	$0.25 \leq x_4 \leq 0.35$	$x_4 = 0.35$	Unit-less
x_5	Infiltration (ACH)	$0.6 \leq x_5 \leq 3$	$x_5 = 3$	ACH
x_6	HRV/Ventilation (% Energy Recovered)	$0\% \leq x_6 \leq 85\%$	$x_6 = 0\%$	%
x_7	Lighting (% Efficient Lighting)	$75\% \leq x_7 \leq 100\%$	$x_7 = 75\%$	%
x_8	PV (Capacity)	$0 \leq x_8 \leq 10240$	$x_8 = 0$	W

MULTI-OBJECTIVE OPTIMIZATION

Initial Cost Objective Function

Minimize

$$IC = \sum (IC_{Wall} + IC_{Roof} + IC_{Win} + IC_{Inf} + IC_{Vent} + IC_{Light} + IC_{PV}$$

where

$$\begin{aligned}
IC_{Wall} &= A_{Wall}\ (.0666\ (x_1 - 19) + 0.7) \\
IC_{Roof} &= A_{Roof}\ (0.1\ (x_2 - 49) + 2.5) \\
IC_{Win} &= A_{Win}\ (456.2 - 2633\ x_3 - 216.6\ x_4 + 3863\ x_3^2 + 942\ x_3\ x_4 \\
IC_{Inf} &= \frac{V_{room}}{8}\ (0.52\ x_5^{-0.7462}) \\
IC_{Vent} &= 42(8.571\ x_6^2 + 0.8571\ x_6) + 1300 \\
IC_{Light} &= 0.2237\ (1281 - (-2676\ x_7 + 3288)) \\
IC_{PV} &= 2.6\ x_8;
\end{aligned}$$

MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

Minimize

$$EU = \sum_{t=0}^{24} \frac{(P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op})}{60000}$$

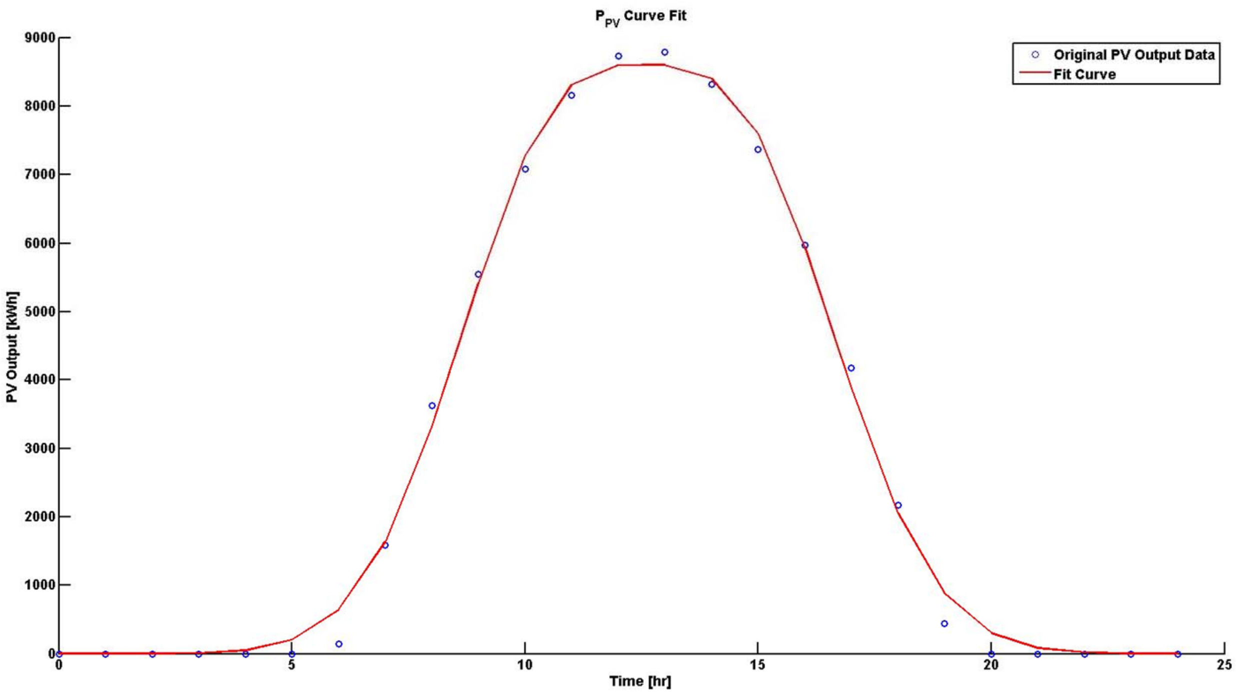
β_t is the On/Off factor for the HVAC unit at timestep t

$P_{HVAC}^{op} = 1000$

MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

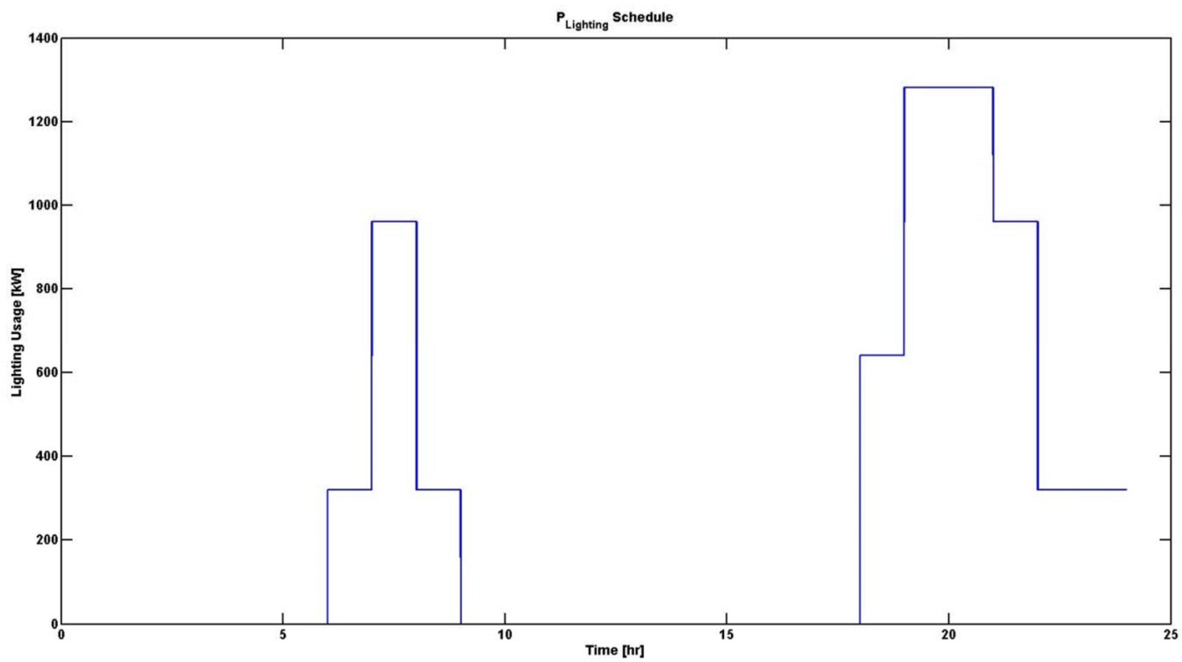
$$P_{PV}(t) = \frac{-x_8}{10240}\left(6970\mathrm{e}^{-\left(\frac{t-14.66}{3.014}\right)^2} + 6870\mathrm{e}^{-\left(\frac{t-10.55}{2.954}\right)^2}\right)$$



MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

$$P_{Lighting}(t) = \begin{cases} 0 & \text{for } 0 \le t < 6 \ \& \ 8 \le t < 18 \\ (0.25)(-2676\, x_7 + 3288), & \text{for } 6 \le t < 7 \ \& \ 22 \le t \le 24 \\ (0.5)(-2676\, x_7 + 3288), & \text{for } 18 \le t < 19 \\ (0.75)(-2676\, x_7 + 3288), & \text{for } 7 \le t < 8 \ \& \ 21 \le t < 22 \\ (-2676\, x_7 + 3288), & \text{for } 19 \le t < 21 \end{cases}$$



MULTI-OBJECTIVE OPTIMIZATION

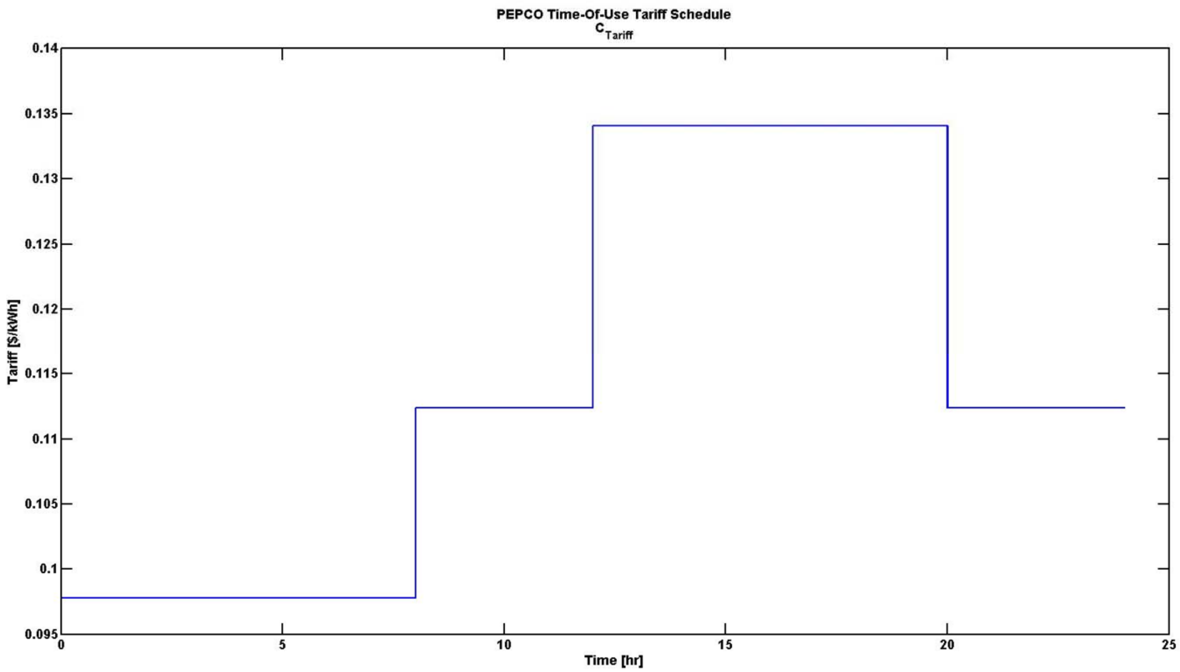
Operational Cost Objective Function

Minimize

$$OC = \sum_{t=0}^{24} \frac{C_{tariff}(t)[P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op}]}{60000}$$

Operational Cost Objective Function

$$C_{tariff}(t) = \begin{cases} 0.0978, & \text{for } 0 \le t < 8 \\ 0.1124, & \text{for } 8 \le t < 12 \ \& \ 20 \le t \le 24 \\ 0.1341, & \text{for } 12 \le t < 20 \end{cases}$$



MULTI-OBJECTIVE OPTIMIZATION

User Comfort Objective Function

Maximize

$$UC = \sum_{t=0}^{24} \gamma_t$$

where

$$\gamma = \begin{cases} 1, & \text{for } T_{room,t} < T_{thresh} \\ 0, & \text{for } T_{room,t} \geq T_{thresh} \end{cases}$$

Home Performance Objective Function

Minimize

$$HP = \sum_{t=0}^{24} \beta_t$$

MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

$$Q_{net} = Q_{wall} + Q_{roof} + Q_{win} + Q_{winrad} + Q_{infil} + Q_{vent} + Q_{int} + Q_{HVAC}$$

$$Q_{wall} = \frac{A_{wall}}{x_1} \left(T_{ext}(t) - T_{room}[t]\right)$$

where $A_{wall} = 1280\text{ft}^2$

$$Q_{roof} = \frac{A_{roof}}{x_2} \left(T_{ext}(t) - T_{room}[t]\right)$$

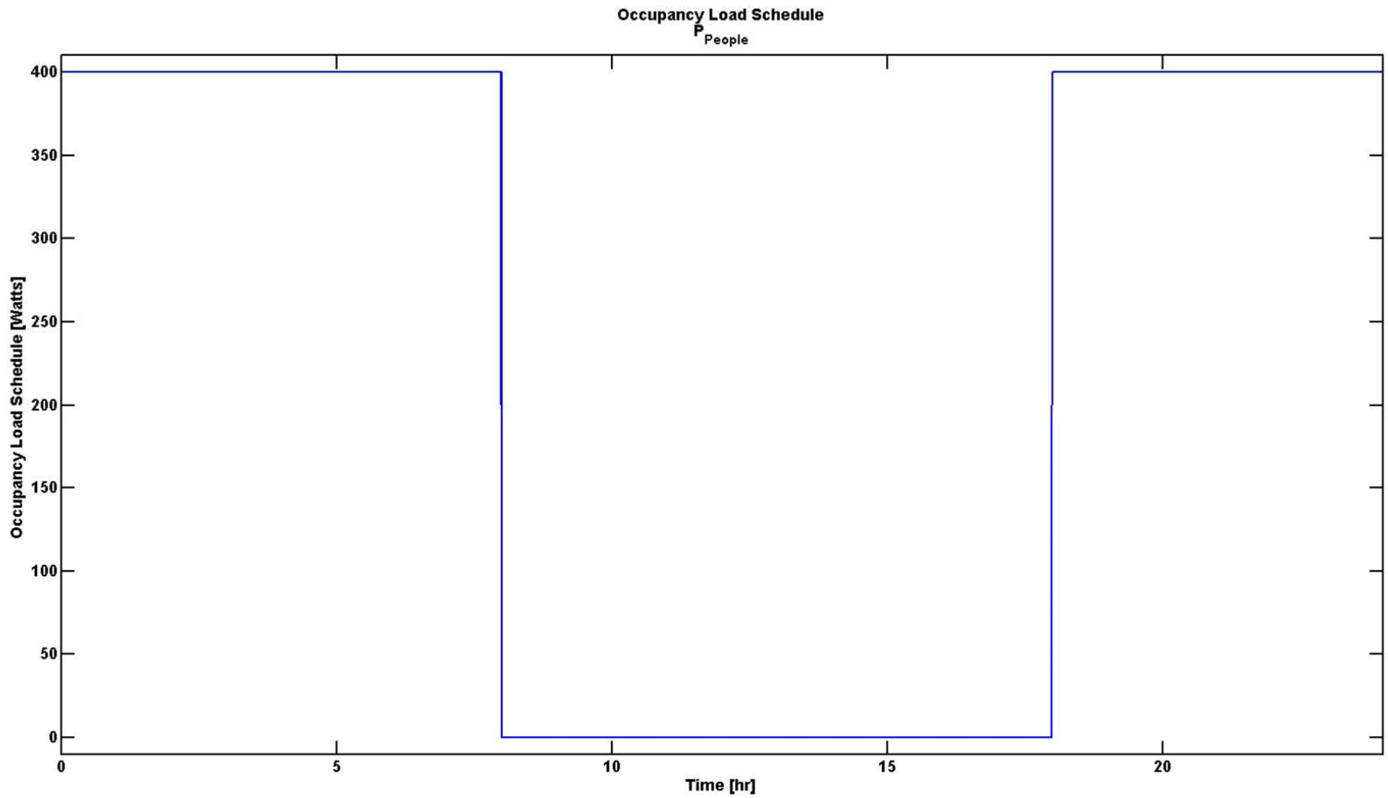
where $A_{roof} = 2240\text{ft}^2$

$$Q_{win} = A_{win}\, x_3 \left(T_{ext}(t) - T_{room}[t]\right)$$

where $A_{win} = 137.5\text{ft}^2$

Heat Transfer Equations

$$P_{People}(t) = \begin{cases} 400, & \text{for } 0 \leq t < 8 \ \& \ 18 \leq t \leq 24 \\ 0, & \text{for } 8 \leq t < 18 \end{cases}$$



MULTI-OBJECTIVE OPTIMIZATION

Simulation

Initial Values

Design Parameters:

x1 - Exterior Wall Insulation [R] = 19.00

x2 - Roof Insulation [R] = 50.00

x3 - Window U-Value [U] = 0.35

x4 - Window SHGC [SHGC] = 0.35

x5 - Infiltration [ACH] = 3.00

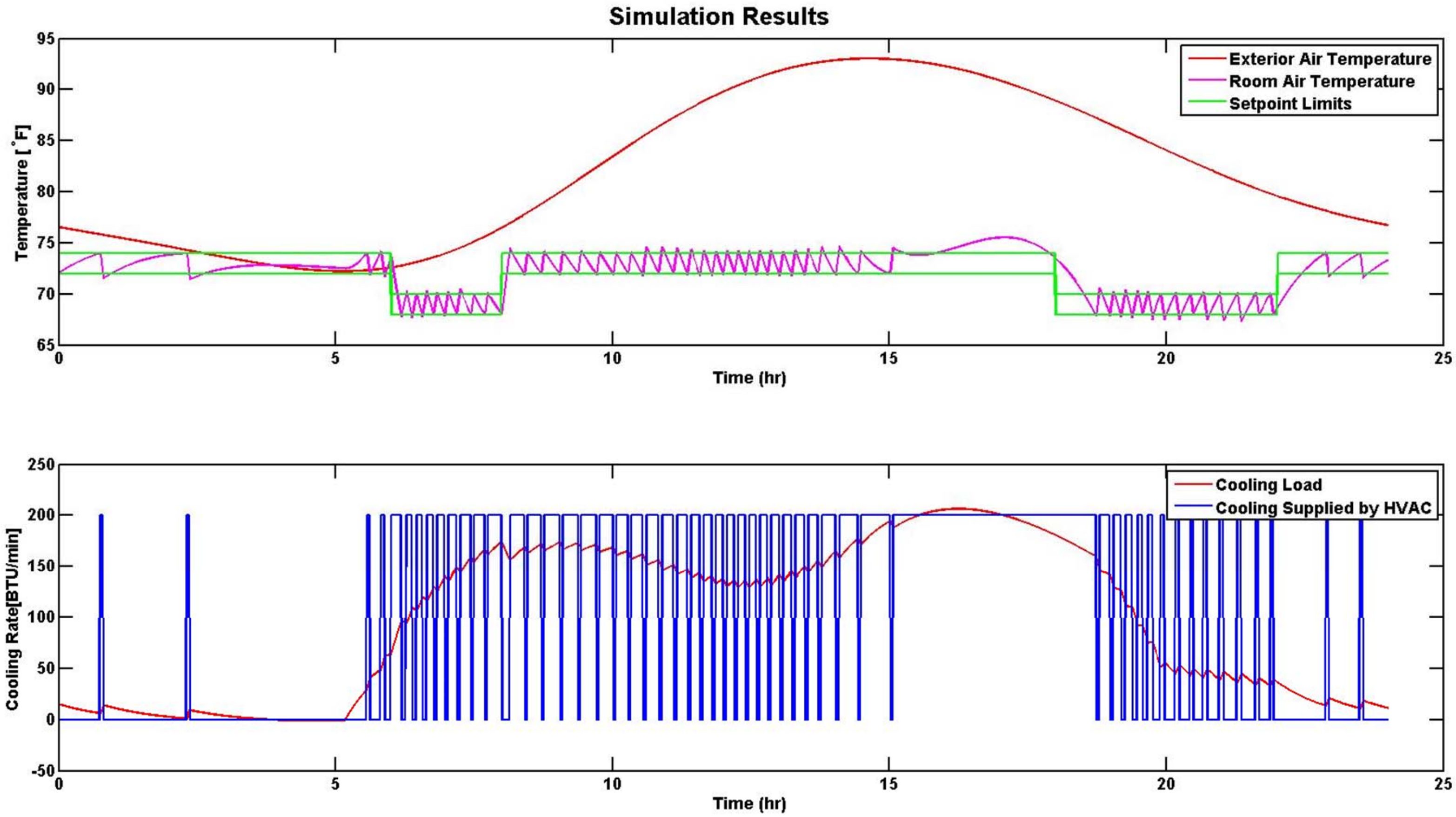
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

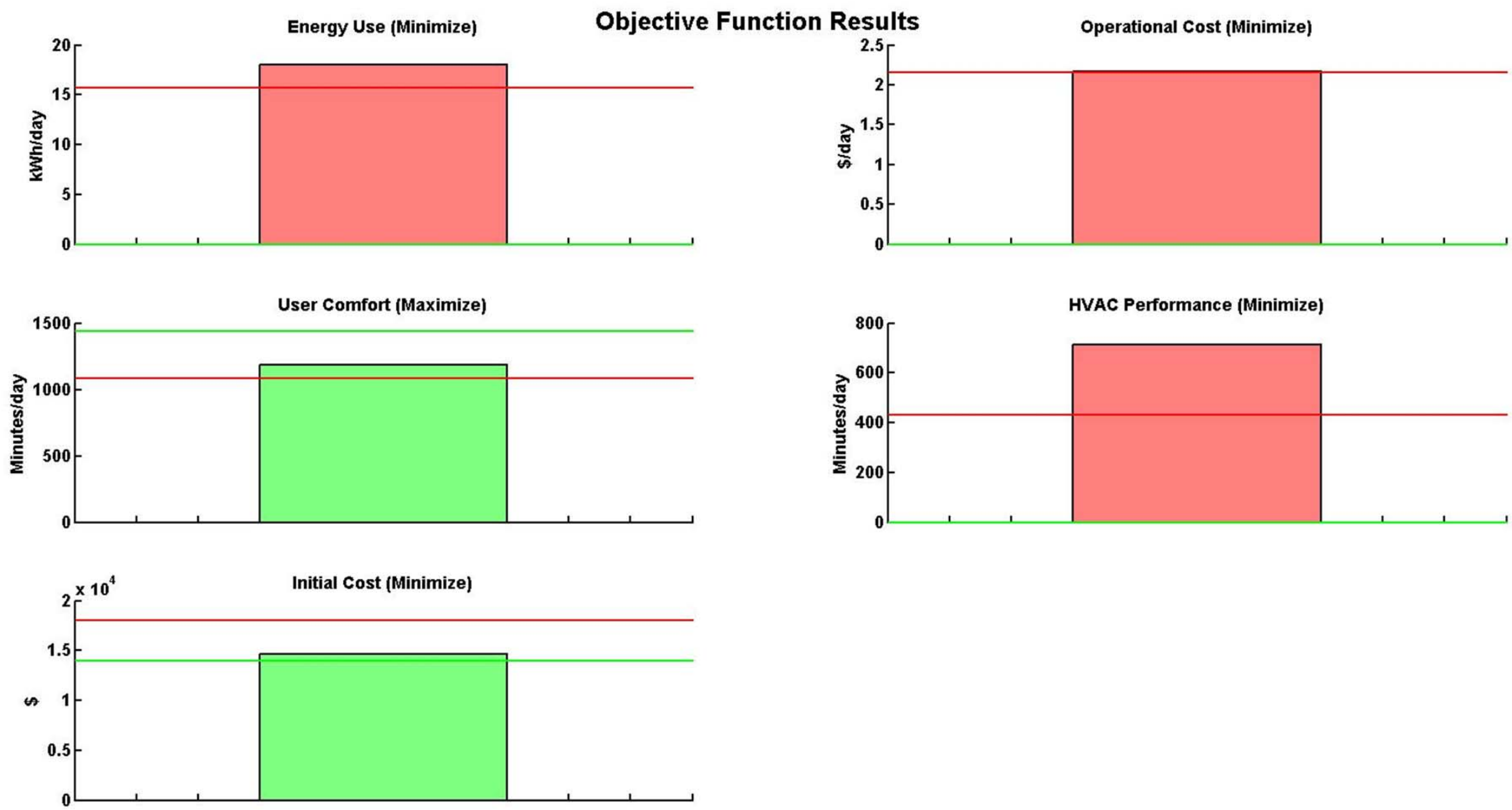
MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation

Next Iteration

Design Parameters:

x1 - Exterior Wall Insulation [R] = **30.00**

x2 - Roof Insulation [R] = 50.00

x3 - Window U-Value [U] = 0.35

x4 - Window SHGC [SHGC] = 0.35

x5 - Infiltration [ACH] = 3.00

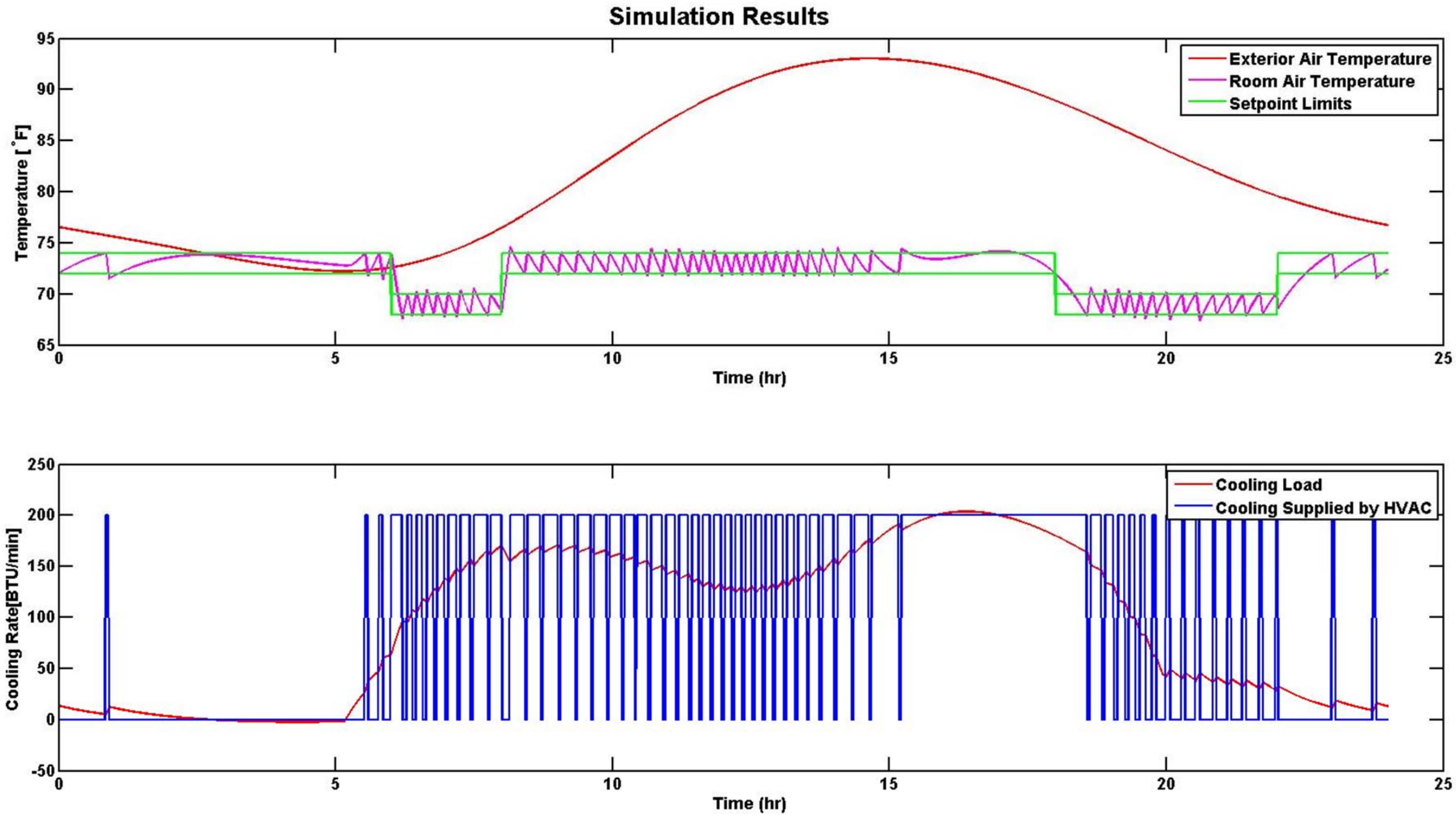
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

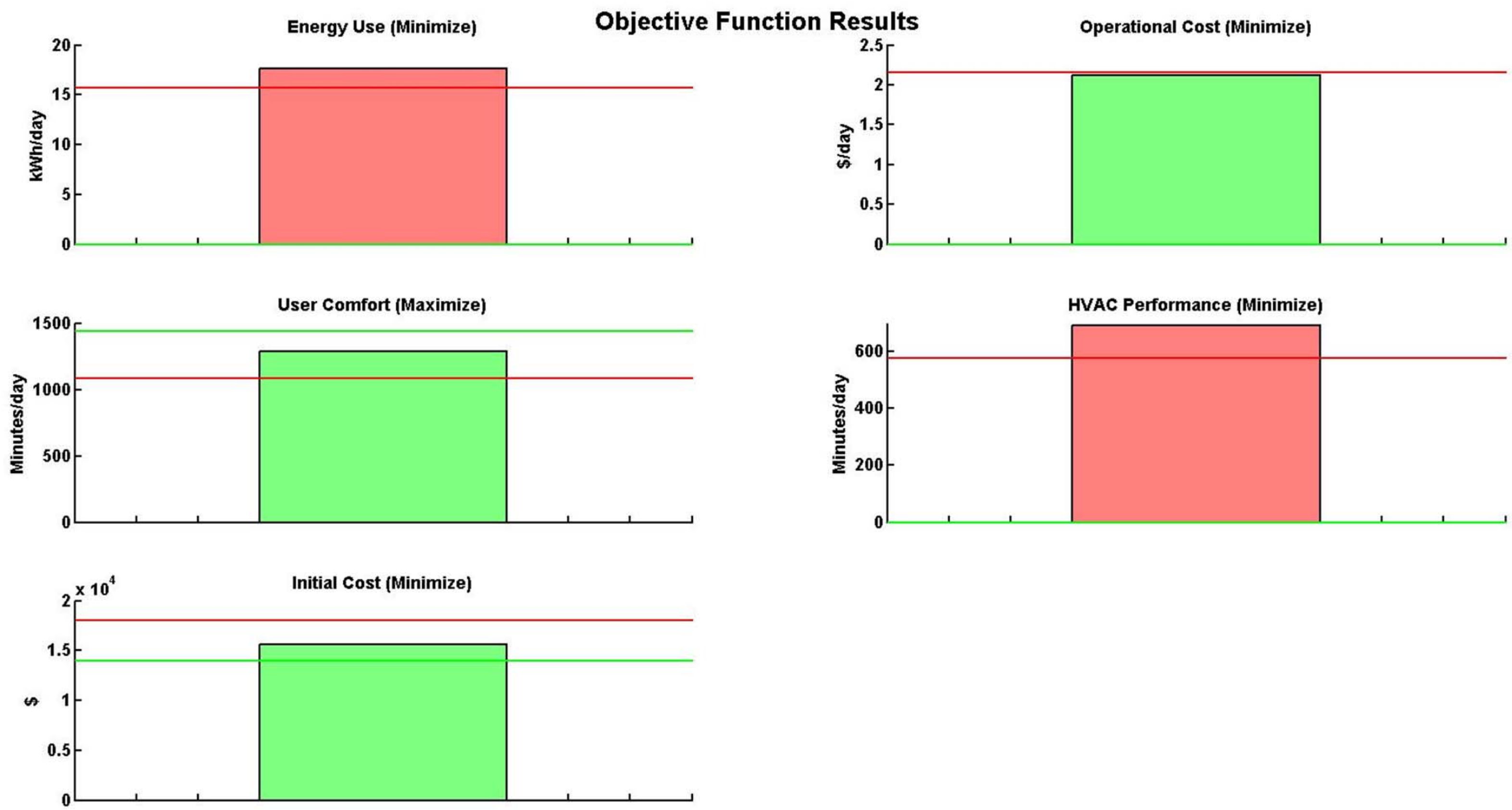
MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation

Next Iteration

Design Parameters:

x1 - Exterior Wall Insulation [R] = **30.00**

x2 - Roof Insulation [R] = 50.00

x3 - Window U-Value [U] = **0.25**

x4 - Window SHGC [SHGC] = **0.25**

x5 - Infiltration [ACH] = 3.00

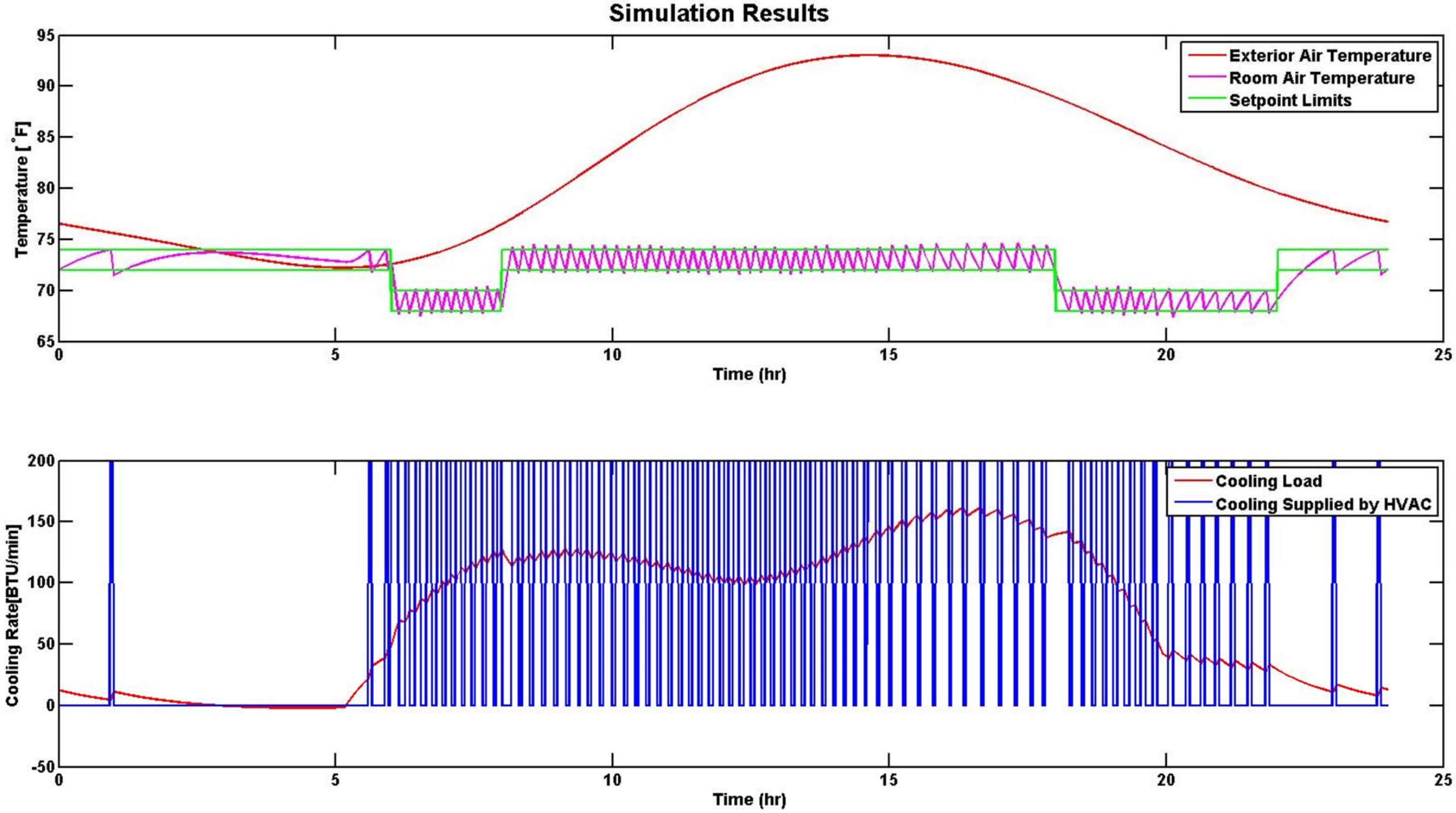
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

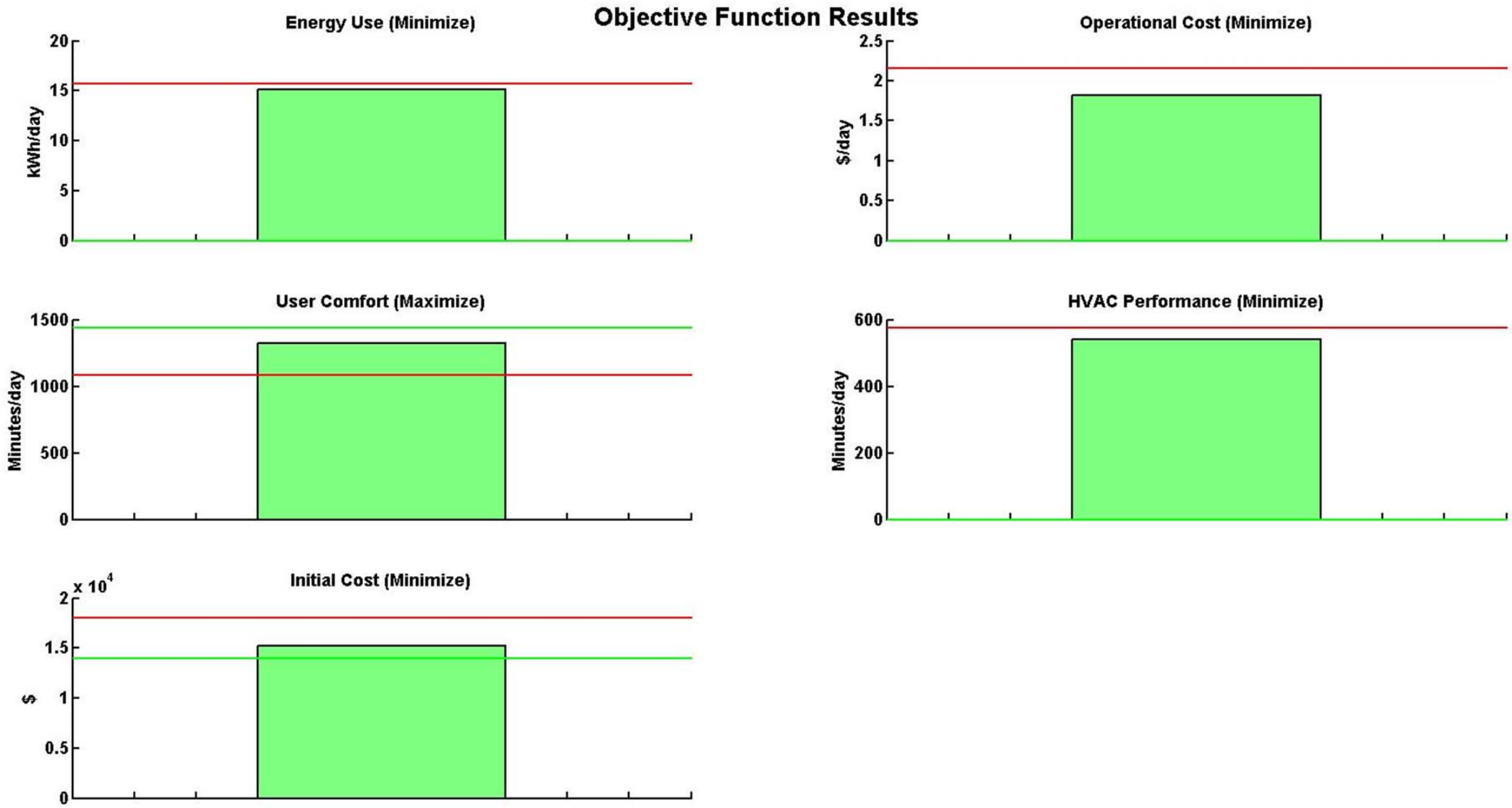
MULTI-OBJECTIVE OPTIMIZATION

Simulation



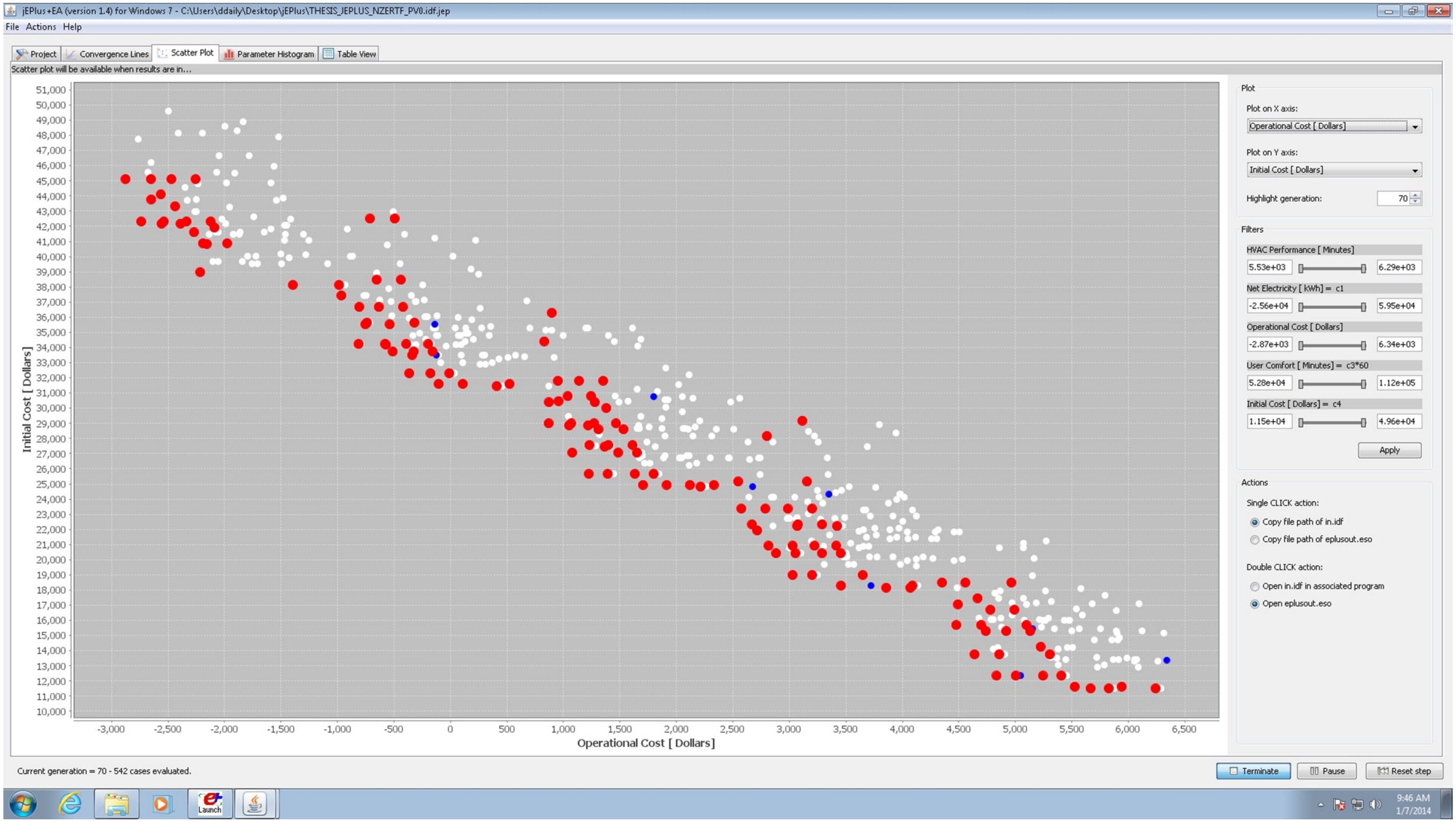
MULTI-OBJECTIVE OPTIMIZATION

Simulation



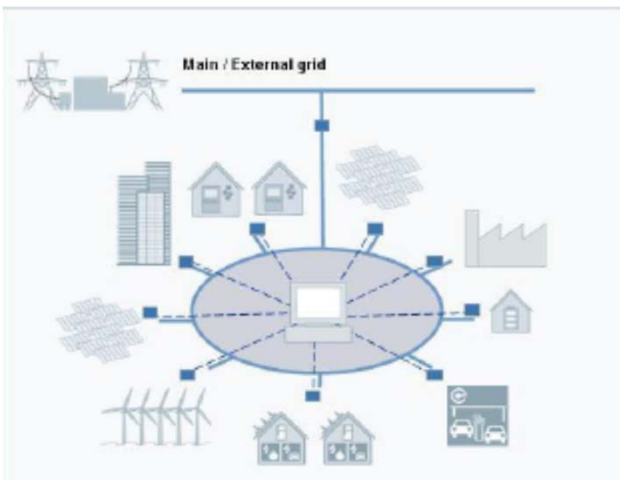
JEPLUS+EA OPTIMIZATION

Simulation



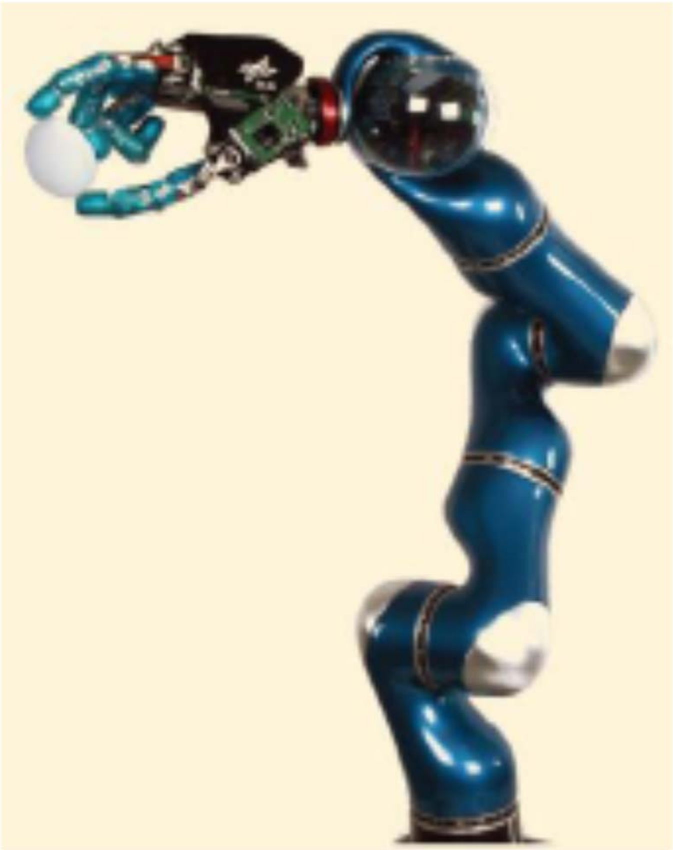
Integrating Siemens PLM Tools for MBSE in Energy Efficiency

- Teamcenter, 4GD, NX CAD, PLM elements like Cost



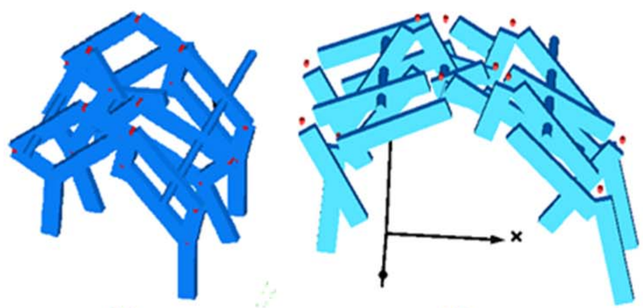
- Smart-grids at various scales from a few houses to neighborhoods to regions
- Retrofit design of existing houses for improved energy efficiency
- Zero or positive energy houses by design
- Partitions and design elements (4GD)
- Manufacturing (read Construction) process management
- Collaborative design and requirements management (Teamcenter)
- Linking Teamcenter, NX CAD, 4GD, with our MBSE framework suite; especially with our advanced tradeoff and design space exploration tools

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

Application to Microrobotics

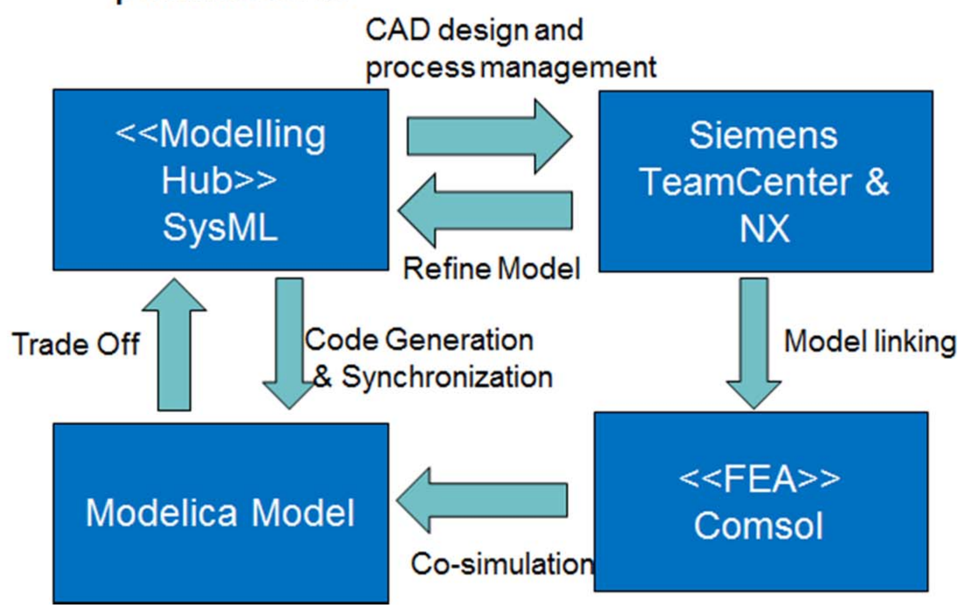


(a) (b)

- Micro-robots design and manufacturing require control algorithm and physical layer (material and geometry) co-design.
- This insect-like robot is modeled in Modelica language using Differential Algebraic Equation.
- We are working on a Model-Based Systems Engineering approach to perform analysis, modeling and tradeoff for robotics and its material and control parameters.

Siemens Tools Utilization

- Design and analysis CAD model at the design phase
- Guide requirement to implementation from CAD design to physical simulation



Kinematics

- Coordinate transformations

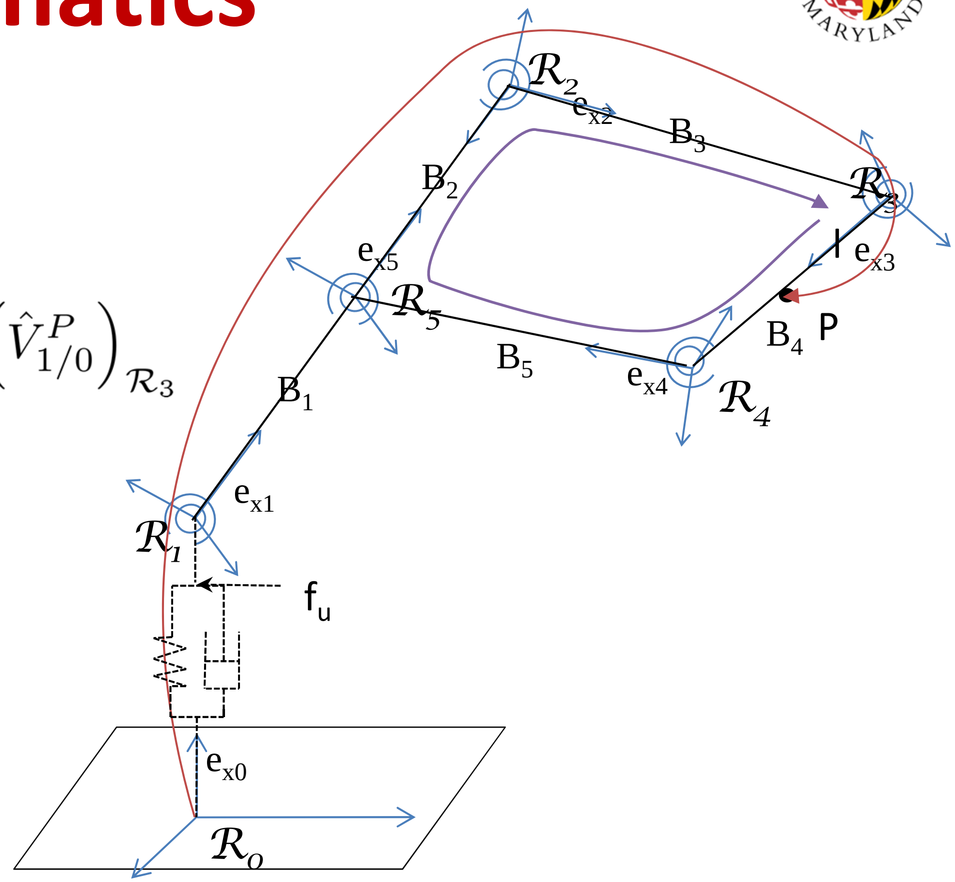
$$\left(\hat{V}^{P}_{3/0}\right)_{\mathcal{R}_3} = \left(\hat{V}^{P}_{3/2}\right)_{\mathcal{R}_3} + \left(\hat{V}^{P}_{2/1}\right)_{\mathcal{R}_3} + \left(\hat{V}^{P}_{1/0}\right)_{\mathcal{R}_3}$$

- Direct Kinematics

$$\left(\hat{V}^{P}_{3/2}\right)_{\mathcal{R}_3} = \begin{pmatrix} \dot{\theta}_3 e_z^3 \\ l e_x^3 \times \dot{\theta}_3 e_z^3 \end{pmatrix}$$

$$\left(\hat{V}^{P}_{2/1}\right)_{\mathcal{R}_3} = \begin{pmatrix} \dot{\theta}_2 e_z^2 \\ (l_2 e_x^2 + l e_x^3) \times \dot{\theta}_2 e_z^2 \end{pmatrix}$$

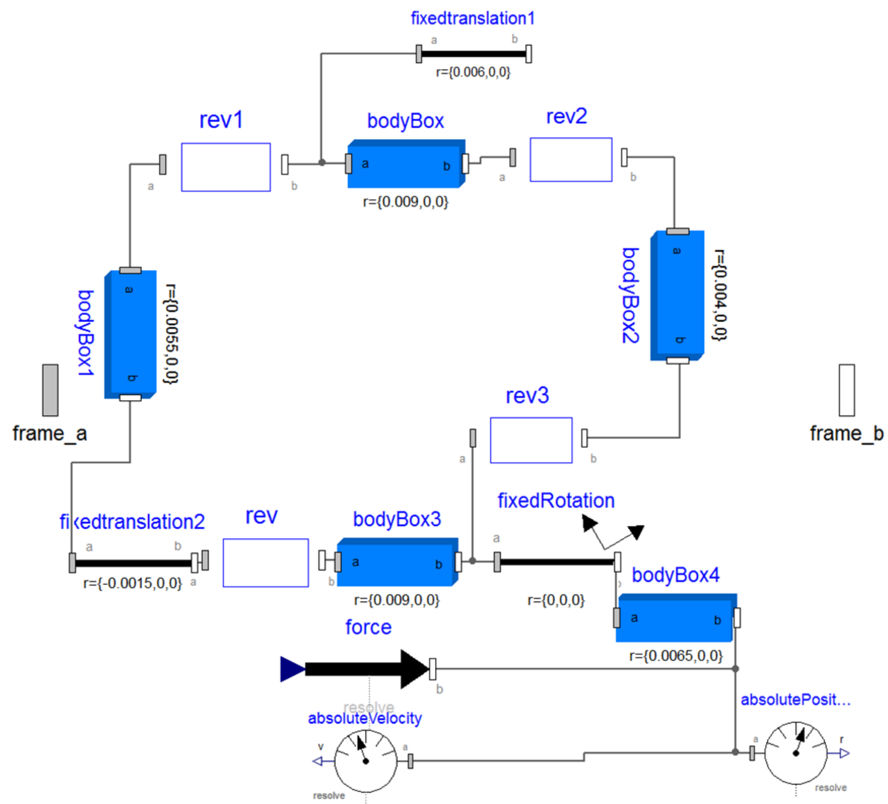
$$\left(\hat{V}^{P}_{1/0}\right)_{\mathcal{R}_3} = \begin{pmatrix} \dot{\theta}_1 e_z^1 \\ (l_1 e_x^1 + l_2 e_x^2 + l e_x^3) \times \dot{\theta}_1 e_z^1 \end{pmatrix}$$



Mechanical model of one single leg. One can express the motion of point P in terms of generalized coordinates and its derivatives using a coordinates transformation.

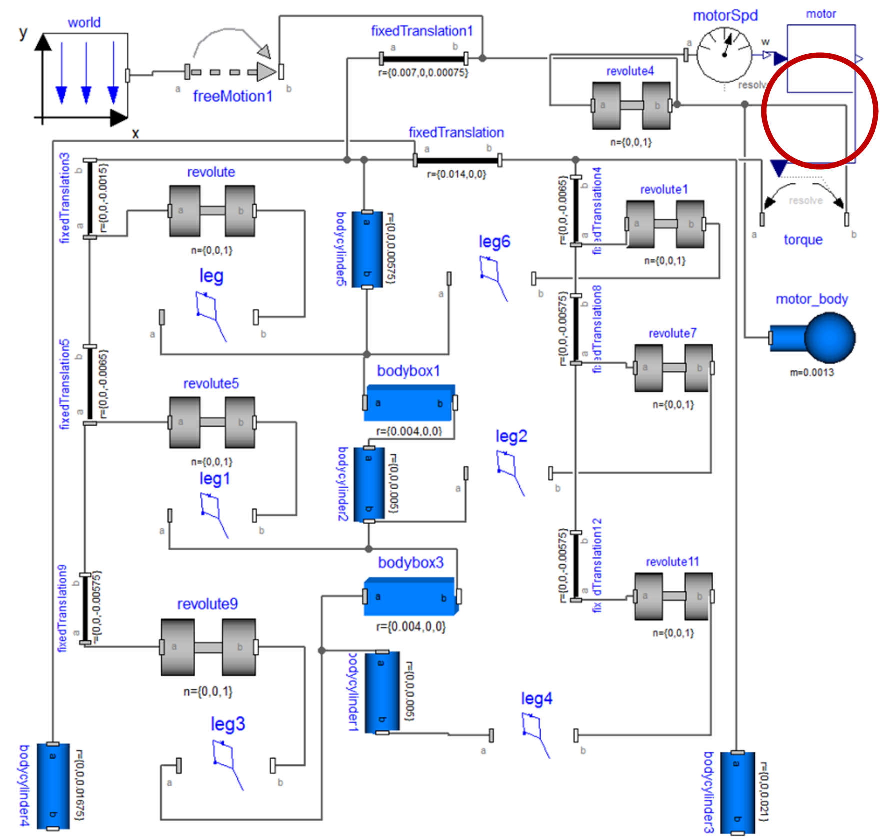
Modelica Model

- Leg Model



Structure of the leg model in Modelica block diagram. The joints rev, rev1, rev2 and rev3 are the joints with flexible material.

- Overall Model



Simplified structure of the robot using the leg submodel. Highlighted submodel is an electrical motor model, includes a Pulse Width Modulation controller, which is the Cyber part of the robot.

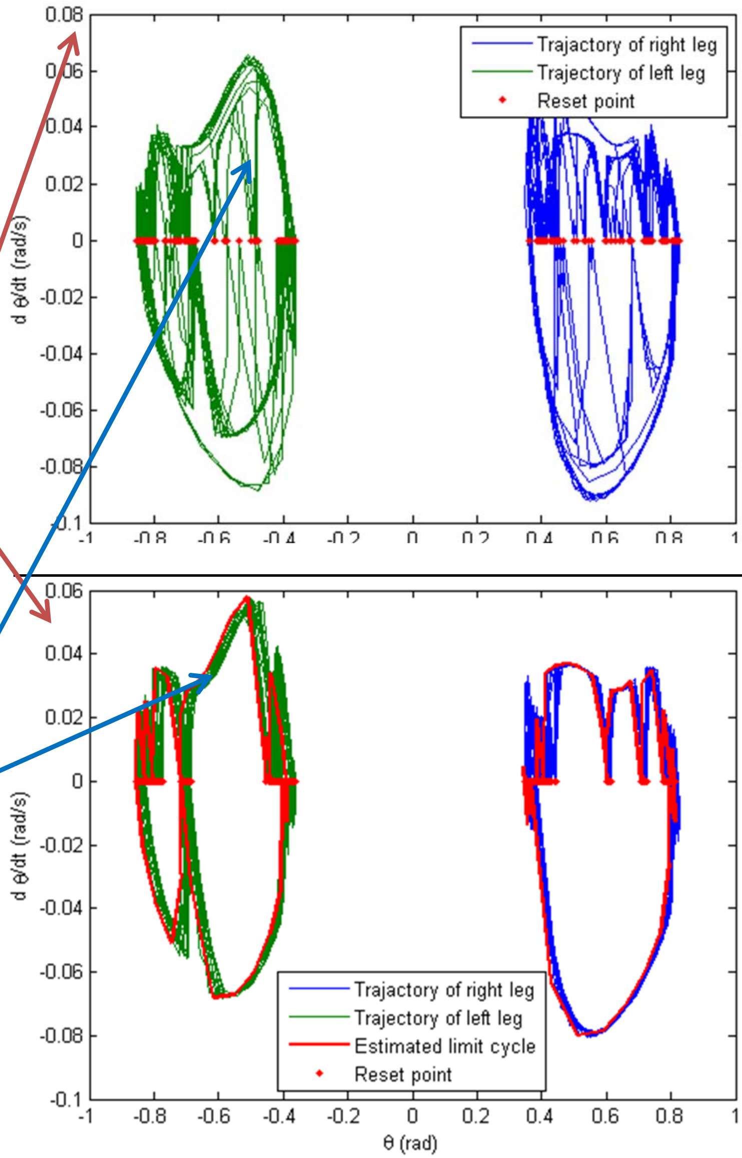
The Institute for Systems Research

Limit Cycle Analysis and Adding PWM

- New geometry alters the problem dramatically.
  - Although the new joint dimension should improve stability, it is hard to verify.
  - Howev… used, t… able to… high te… joints, unless motor output is increased dramatically. So no comparison is given here.
  - By che… we find th… helpfu… jumpi…

Note decreases in limit cycle size in derivative direction

Note changes in reset points of limit cycles

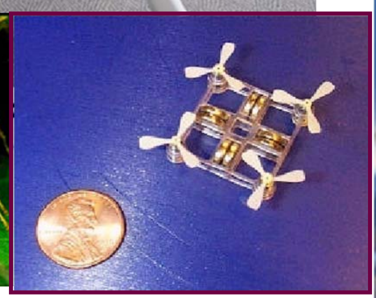


Before adding PWM

After adding PWM

Autonomous Swarms – Networked Control

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



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

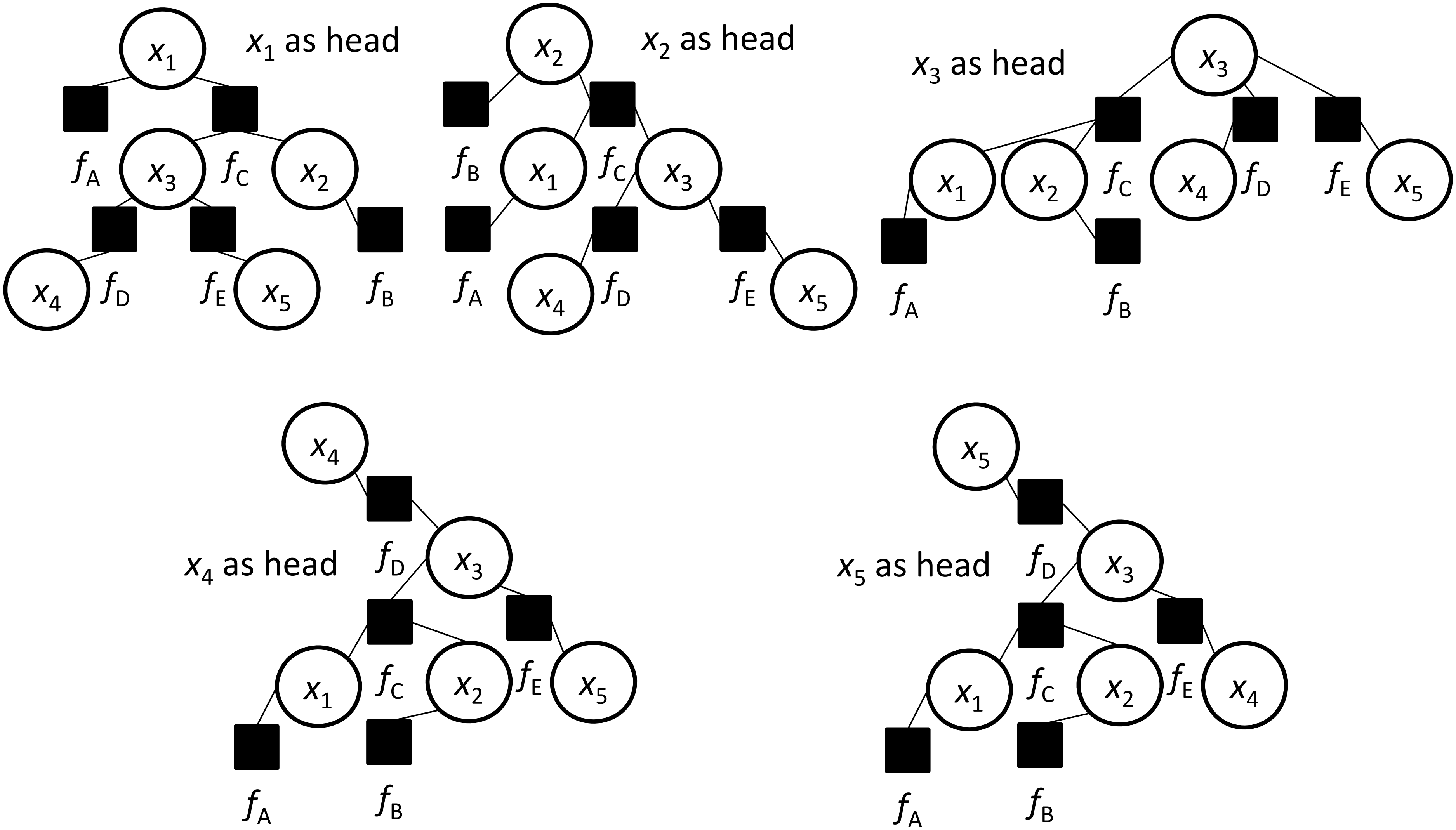
- To perform **tradeoff analysis at system level**, of complex systems a simplified view of the underlying components must be available
- **Challenge**: create an abstract, tractable component representation
- **Hypothesis**: Although components are not perfectly decoupled, structure provides useful 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**

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*

Query Induced Hierarchies



Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph

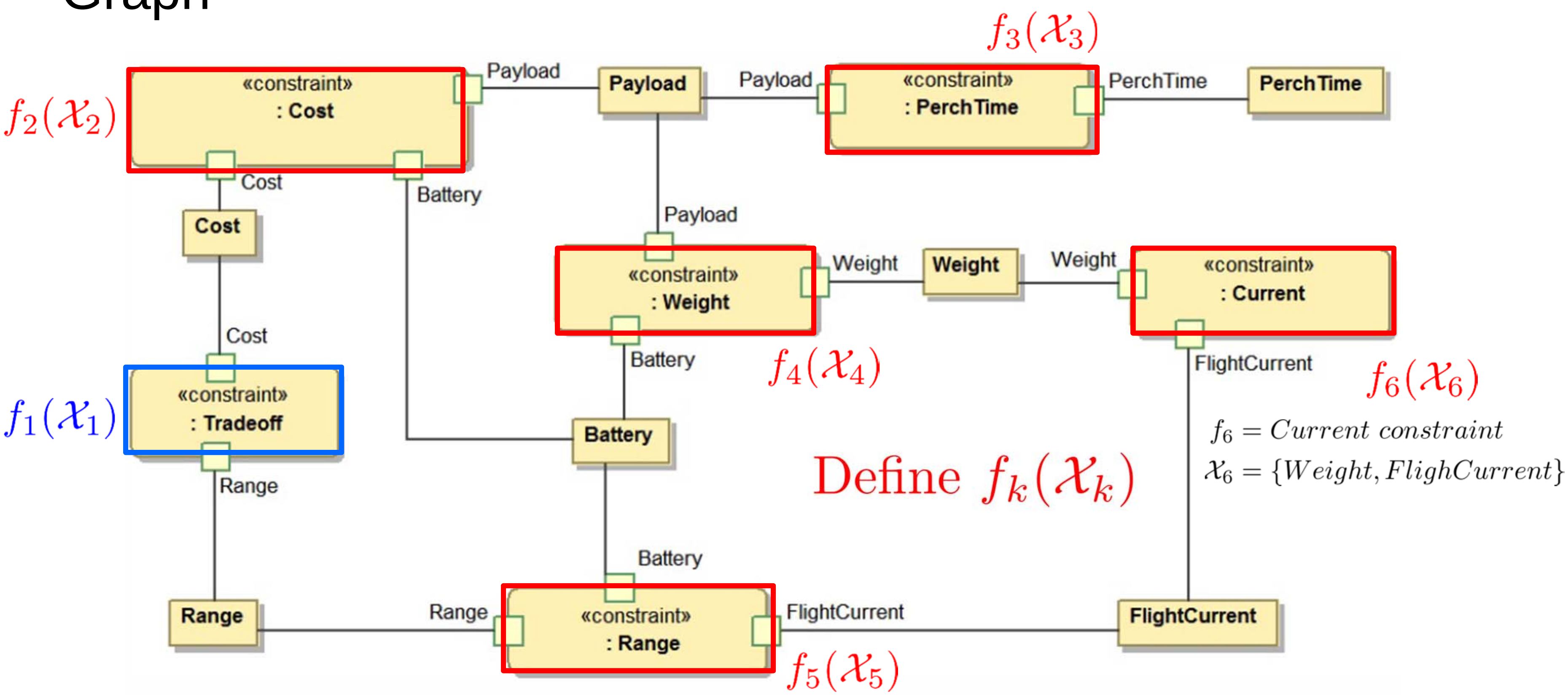


Figure: SysML Parametric Diagram (Factor Graph)

Example: Quadrotor

SysML Parametric Diagram ➔ **Functional Dependence Graph** ➔ Join Tree

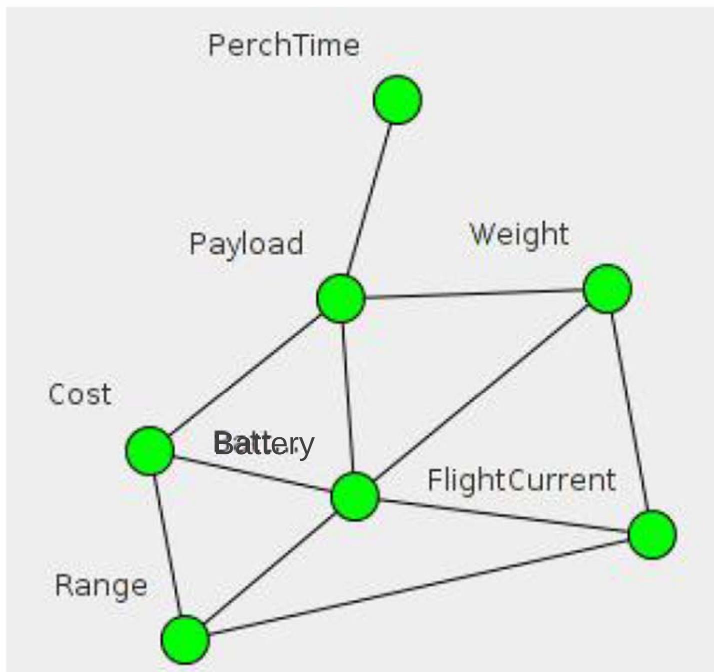


Figure: Functional Dependence Graph (step 1)

Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph ➔ **Join Tree** ➔ Factor Join Tree

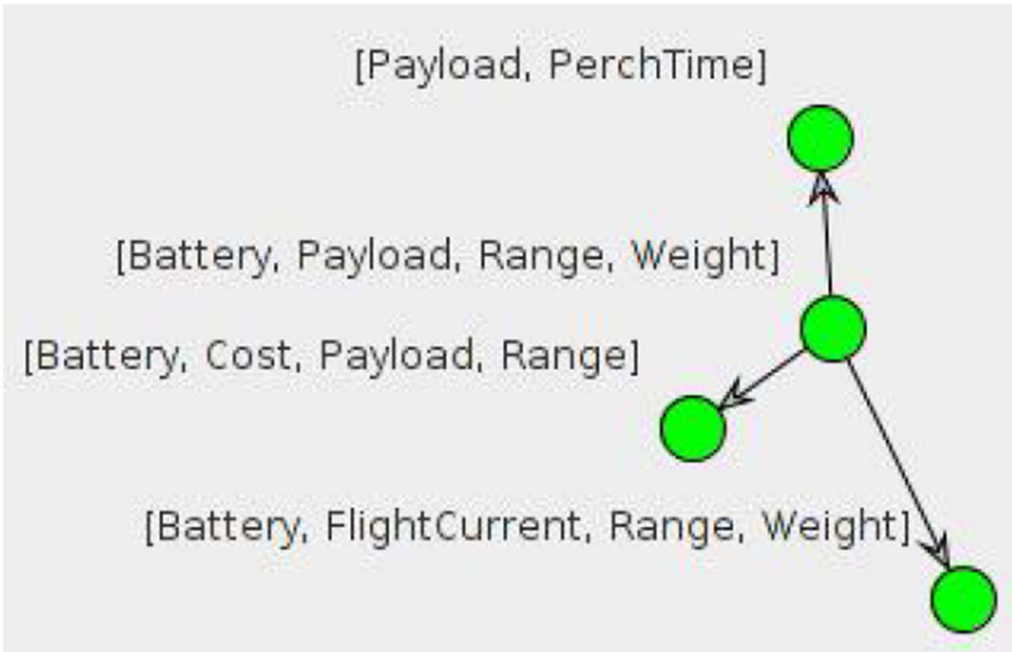


Figure: Join Tree (step 2)

Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph ➔ Join Tree ➔ Factor Join Tree ➔ **Summary Propagation**

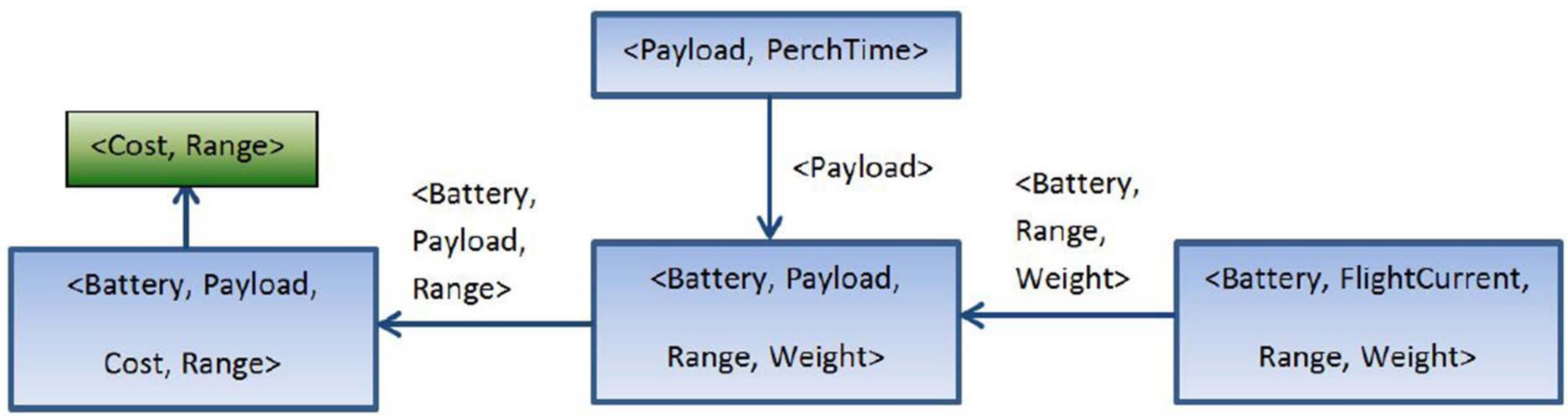
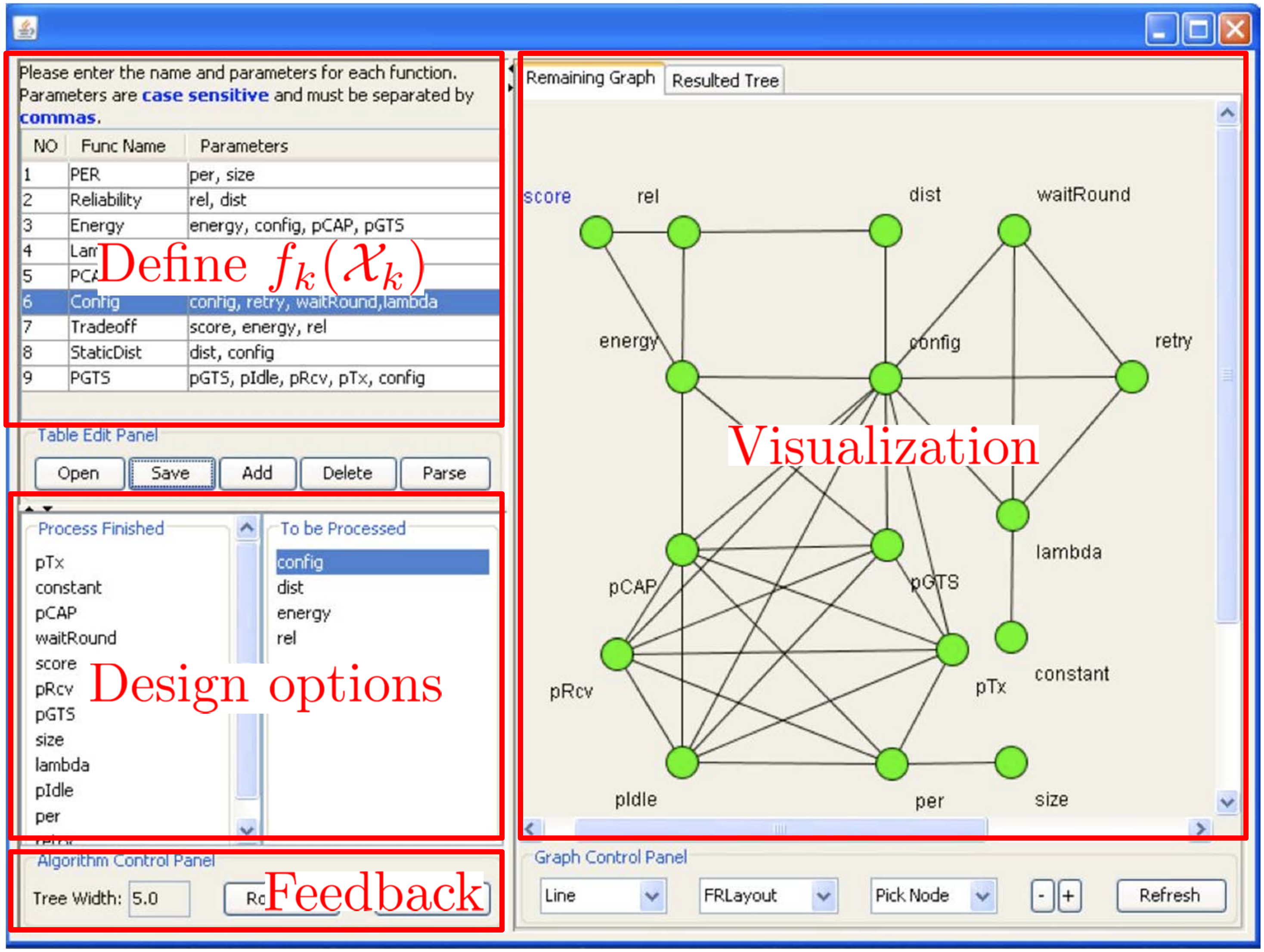


Figure: Summary Propagation (step 4): $\langle \oplus = \mathit{Projection}, \otimes = \mathit{Intersecion} \rangle$

Complexity of system analysis: reduced from D^7 to $3D^4 + D^2$

GUI



Please enter the name and parameters for each function. Parameters are case sensitive and must be separated by commas.
NO
Func Name
Parameters
1 PER per, size
2 Reliability rel, dist
3 Energy energy, config, pCAP, pGTS
6 Config config, retry, waitRound,lambda
7 Tradeoff score, energy, rel
8 StaticDist dist, config
9 PGTS pGTS, pIdle, pRcv, pTx, config
Define $f_k(\mathcal{X}_k)$
Table Edit Panel
Open
Save
Add
Delete
Parse
Process Finished
pTx
constant
pCAP
waitRound
score
pRcv
pGTS
size
lambda
pIdle
per
To be Processed
config
dist
energy
rel
Design options
Algorithm Control Panel
Tree Width: 5.0
Feedback
Remaining Graph
Resulted Tree
score
rel
dist
waitRound
energy
config
retry
Visualization
lambda
pCAP
pGTS
constant
pRcv
pTx
pIdle
per
size
Graph Control Panel
Line
FRLayout
Pick Node
Refresh

How to Use It?

- Input constraints of SysML Parametric Diagrams
- Interact with our tool to generate a factor join tree
- Roll back if necessary
- Create SysML Block Diagrams
- Revise the original SysML Parametric Diagrams
- Analyze the system using summary propagation

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Thank you!

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Questions?