Distributed Coordination in Heterogeneous Power Grids: A Fresh Model-Based Approach

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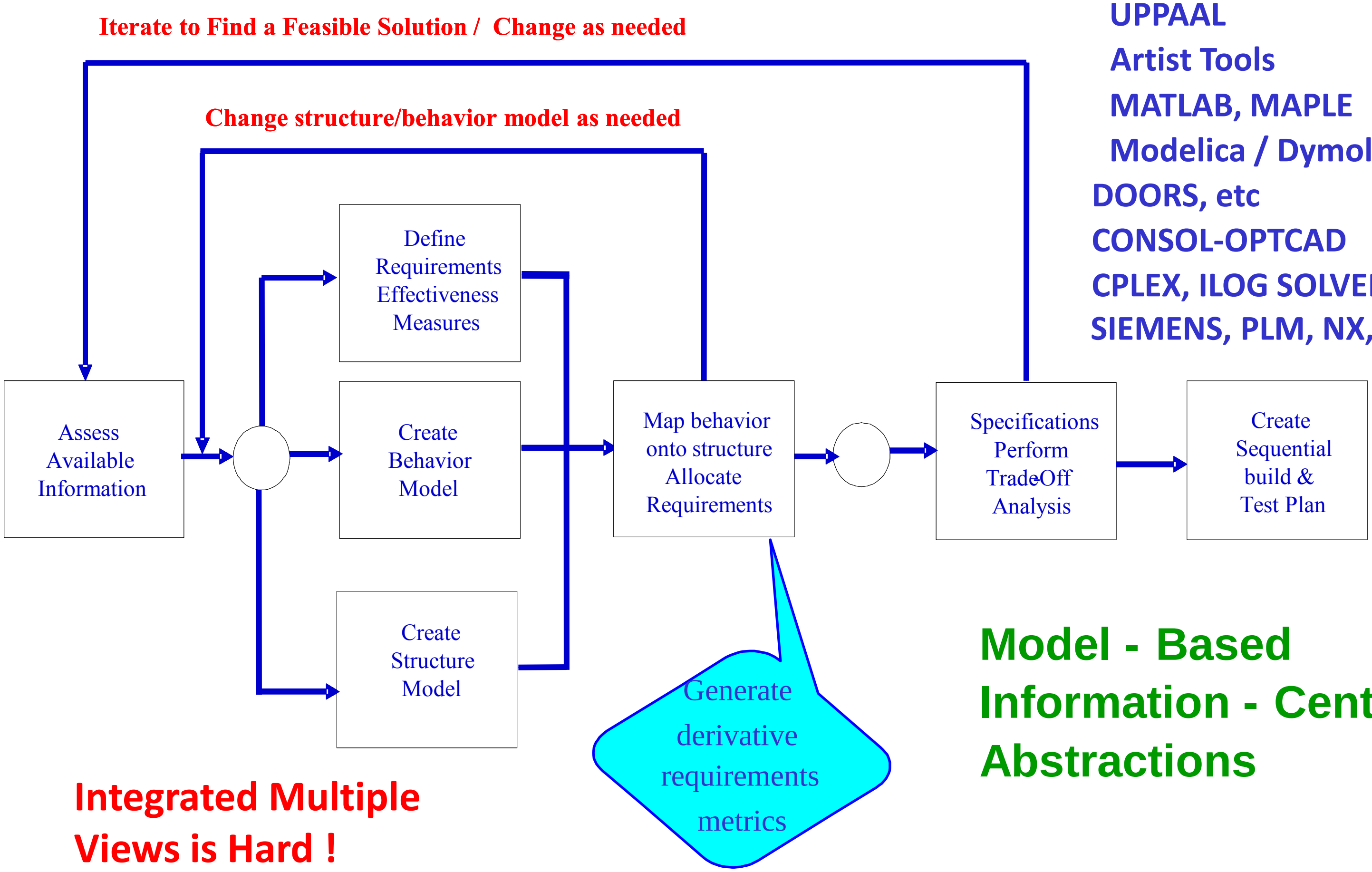
- **Sponsors: NSF, AFOSR, NIST, DARPA, SRC, Lockheed Martin**

COMPONENT- BASED SYSTEM SYNTHESIS

Integrated System Synthesis Tools -
& Environments missing

Model- - based
- **UML - SysML - GME - eMFLON**
- **Rapsody**
- **UPPAAL**
- **Artist Tools**
- **MATLAB, MAPLE**
- **Modelica / Dymola**

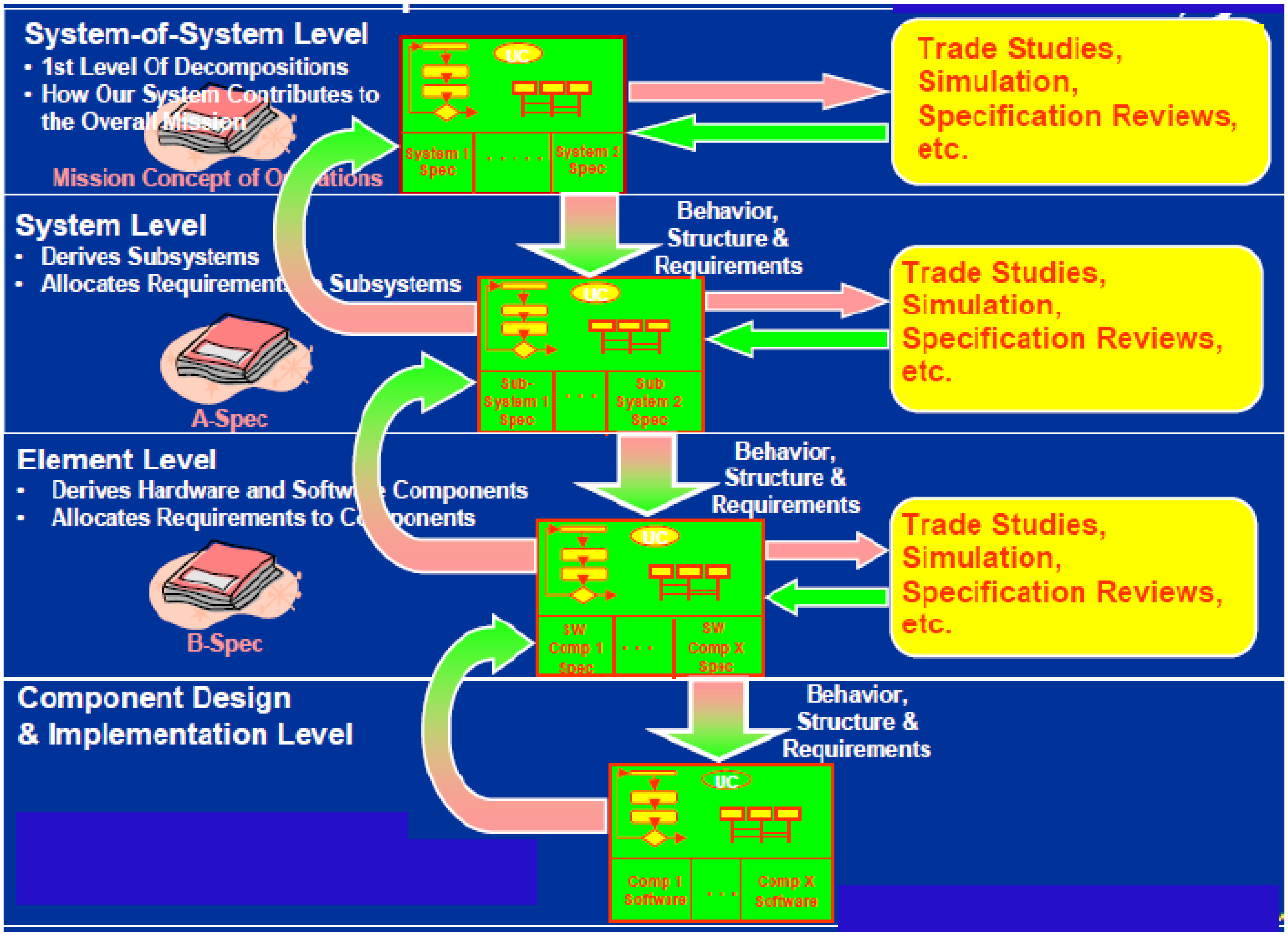
DOORS, etc
CONSOL-OPTCAD
CPLEX, ILOG SOLVER,
SIEMENS, PLM, NX, TEAM CENTER



Model - Based Information - Centric Abstractions

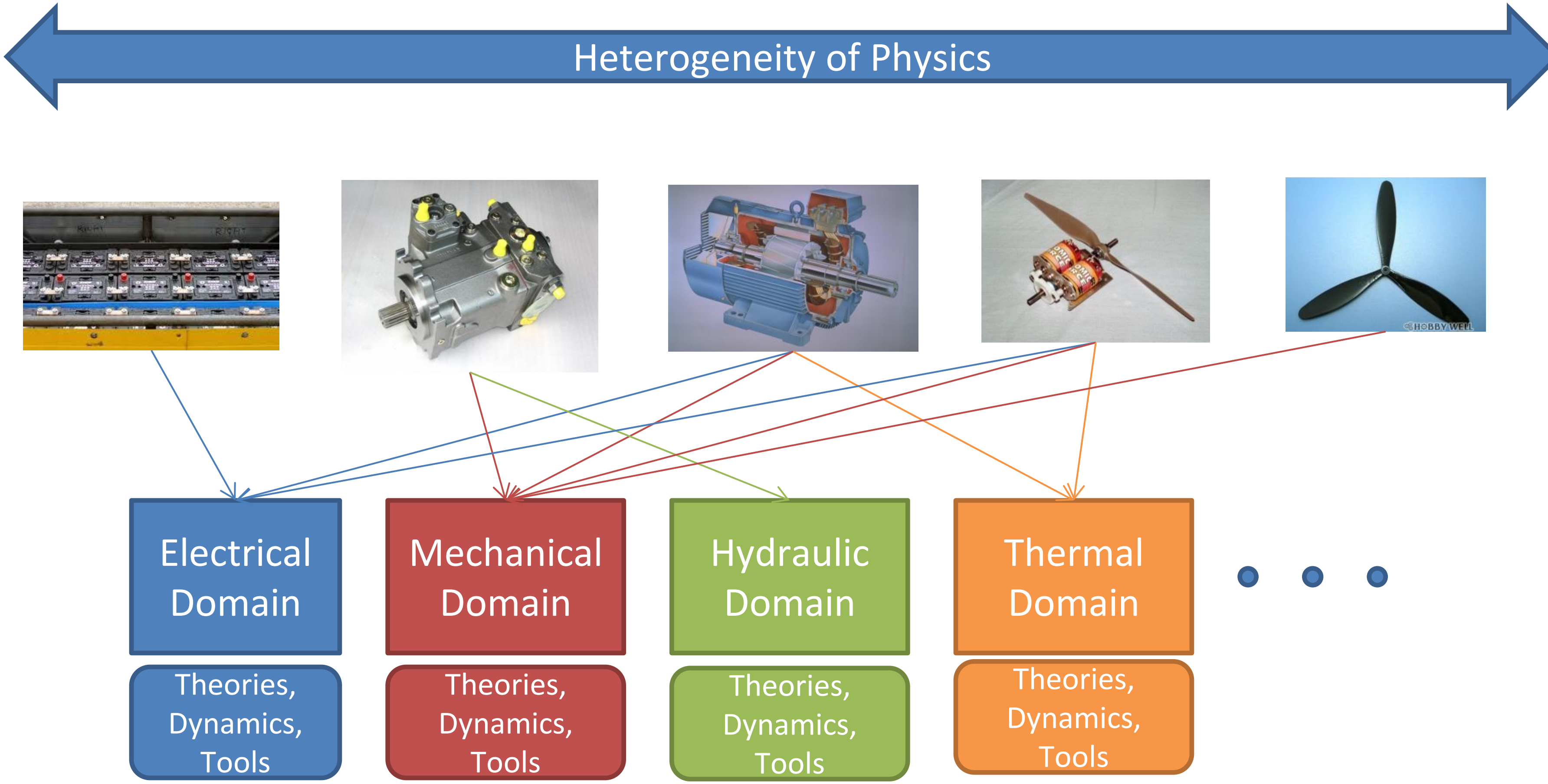
Integrated Multiple Views is Hard !

Layered MBSE -- Hierarchies



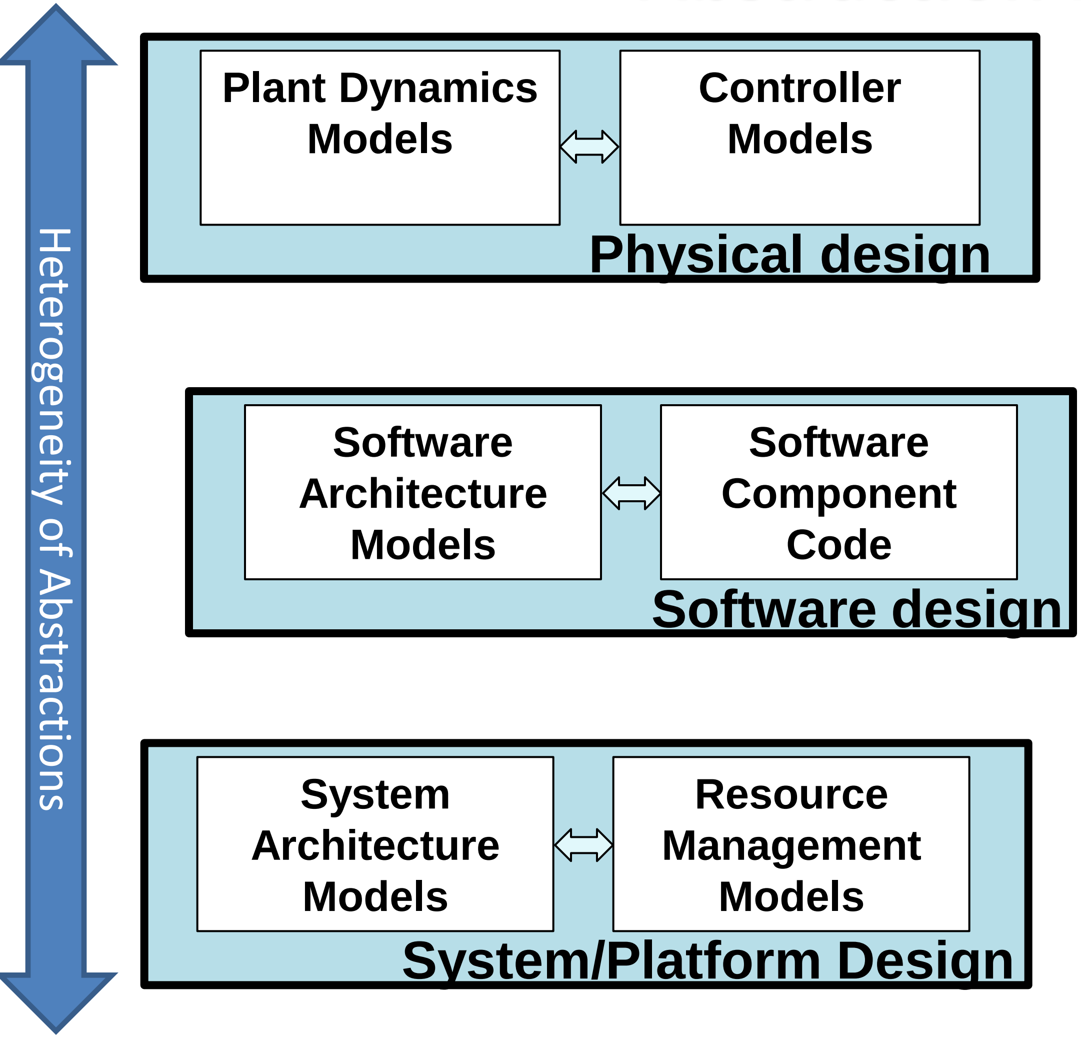
(Watson 2008, Lockheed Martin)

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

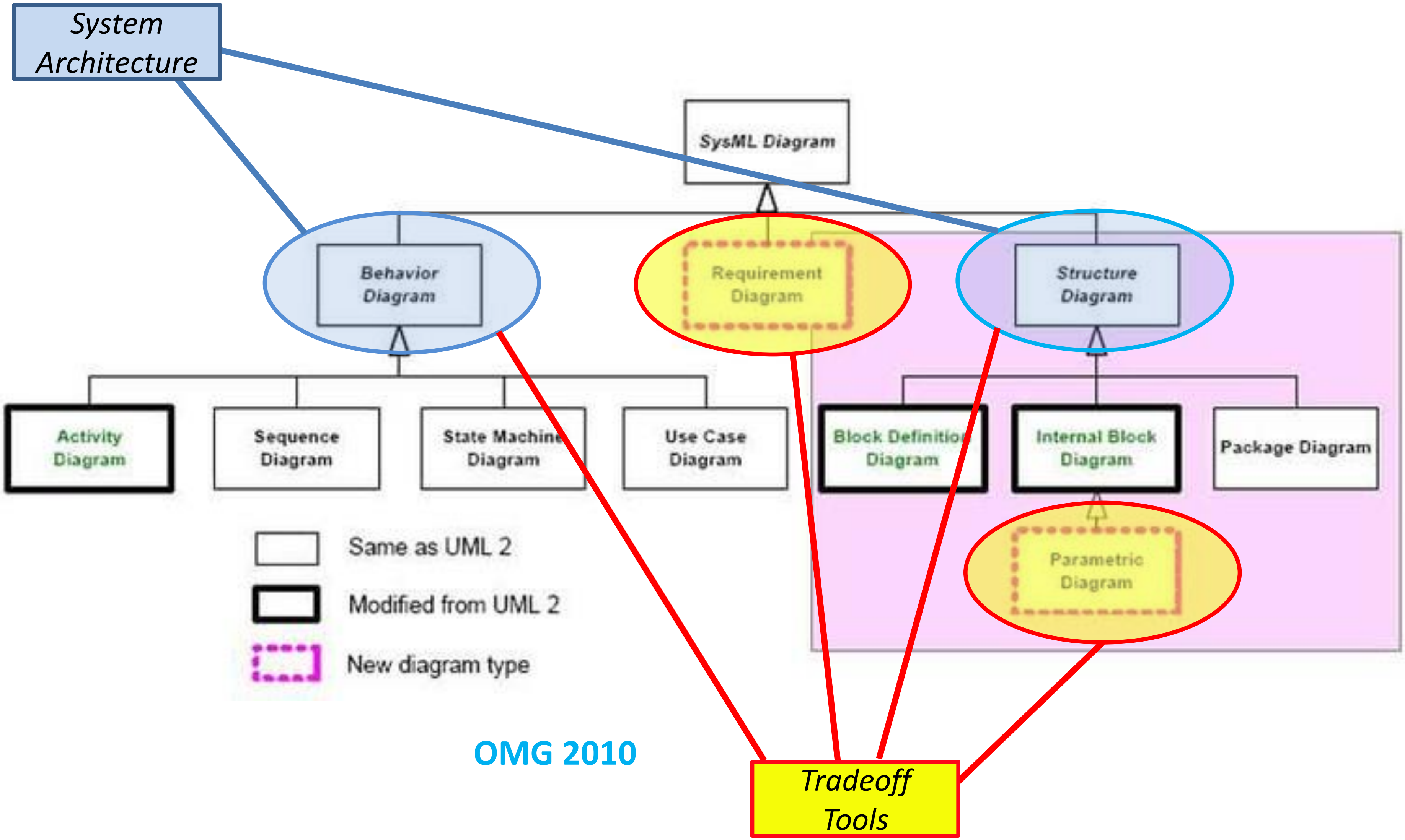
- *Properties*: deadlock, invariants, security,…
- *Abstractions*: logical-time, concurrency, atomicity, ideal communication,..

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?

SysML Taxonomy

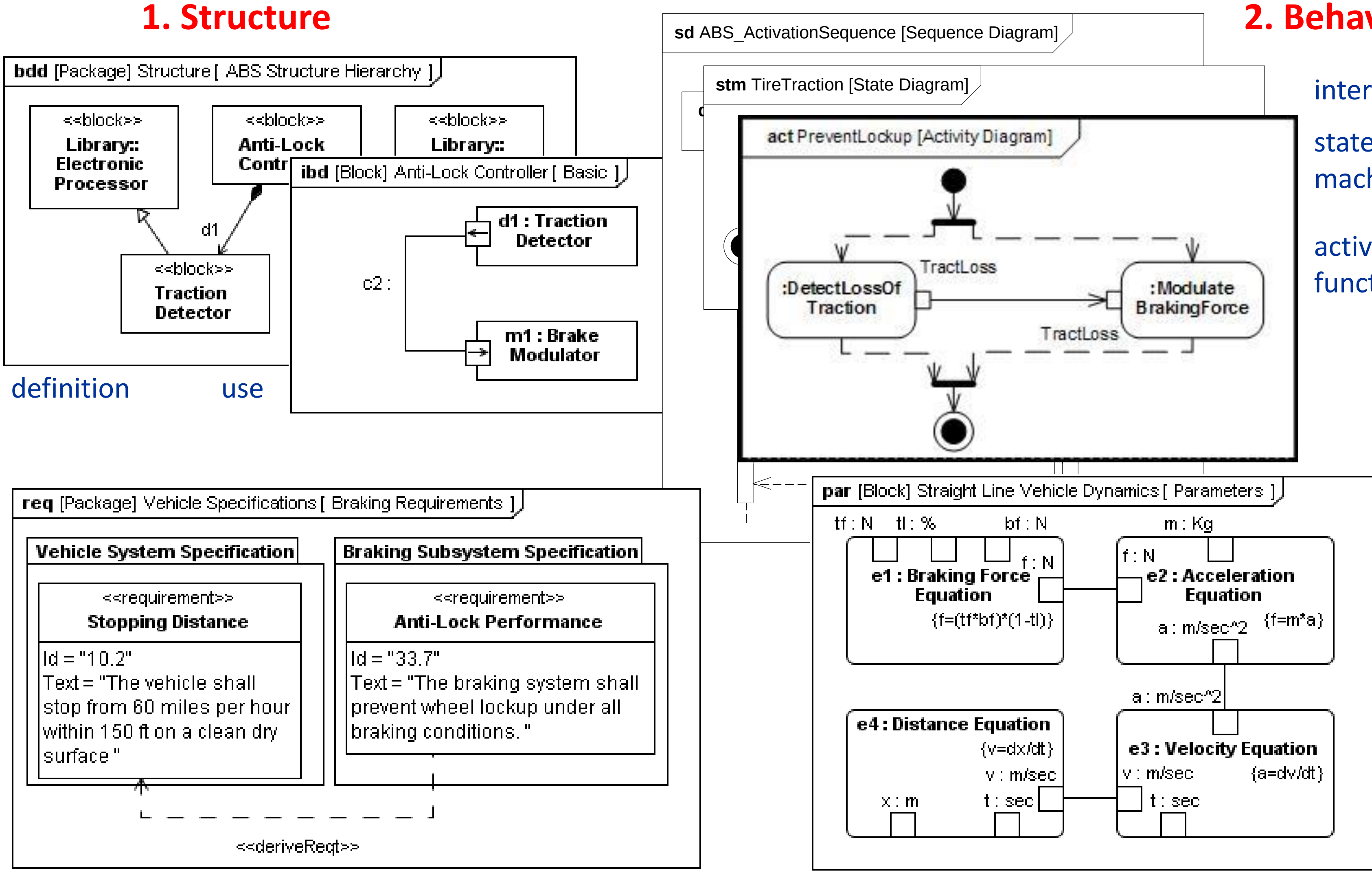


OMG 2010

FOUR PILLARS OF SYSML

1. Structure

2. Behavior



definition use

interaction

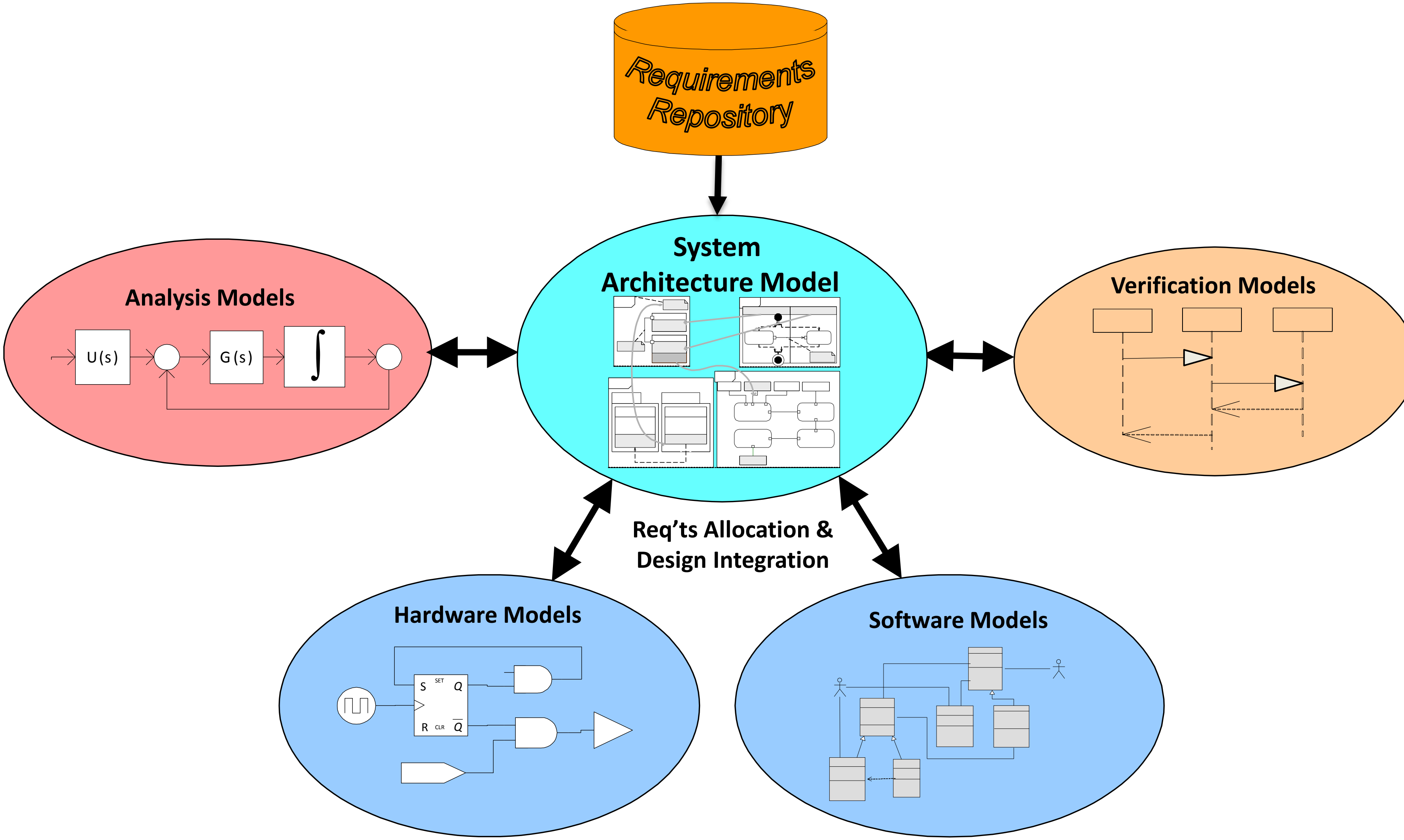
state machine

activity/ function

3. Requirements

4. Parametrics

Using *System Architecture Model* as an Integration Framework



A Rigorous Framework for Model-based Systems Engineering

The Institute for Systems Research

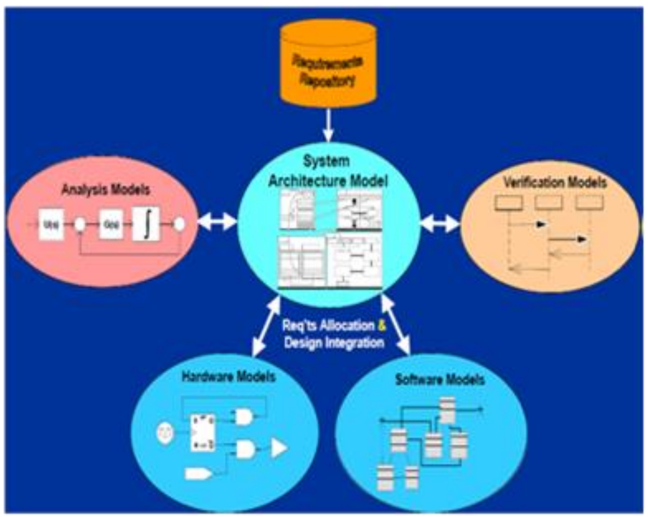
University of Maryland 1856

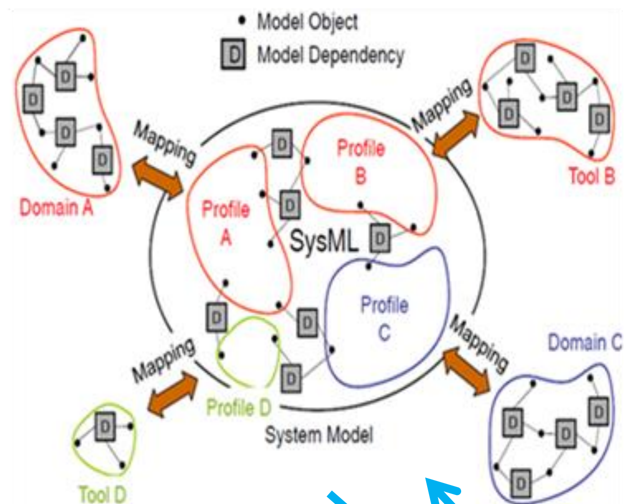
The Challenge & Need:

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**

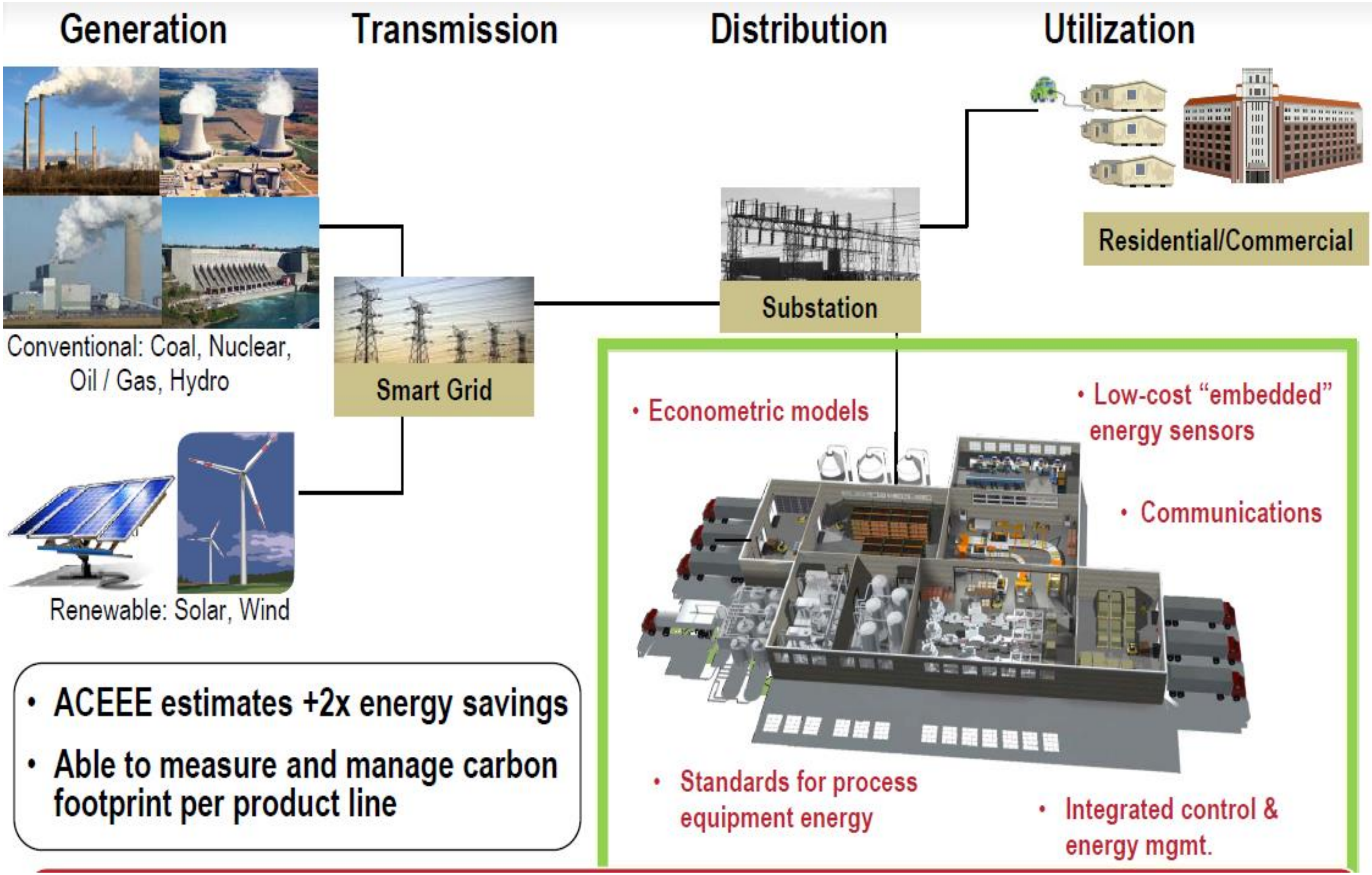
APPLICATIONS

- **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?**

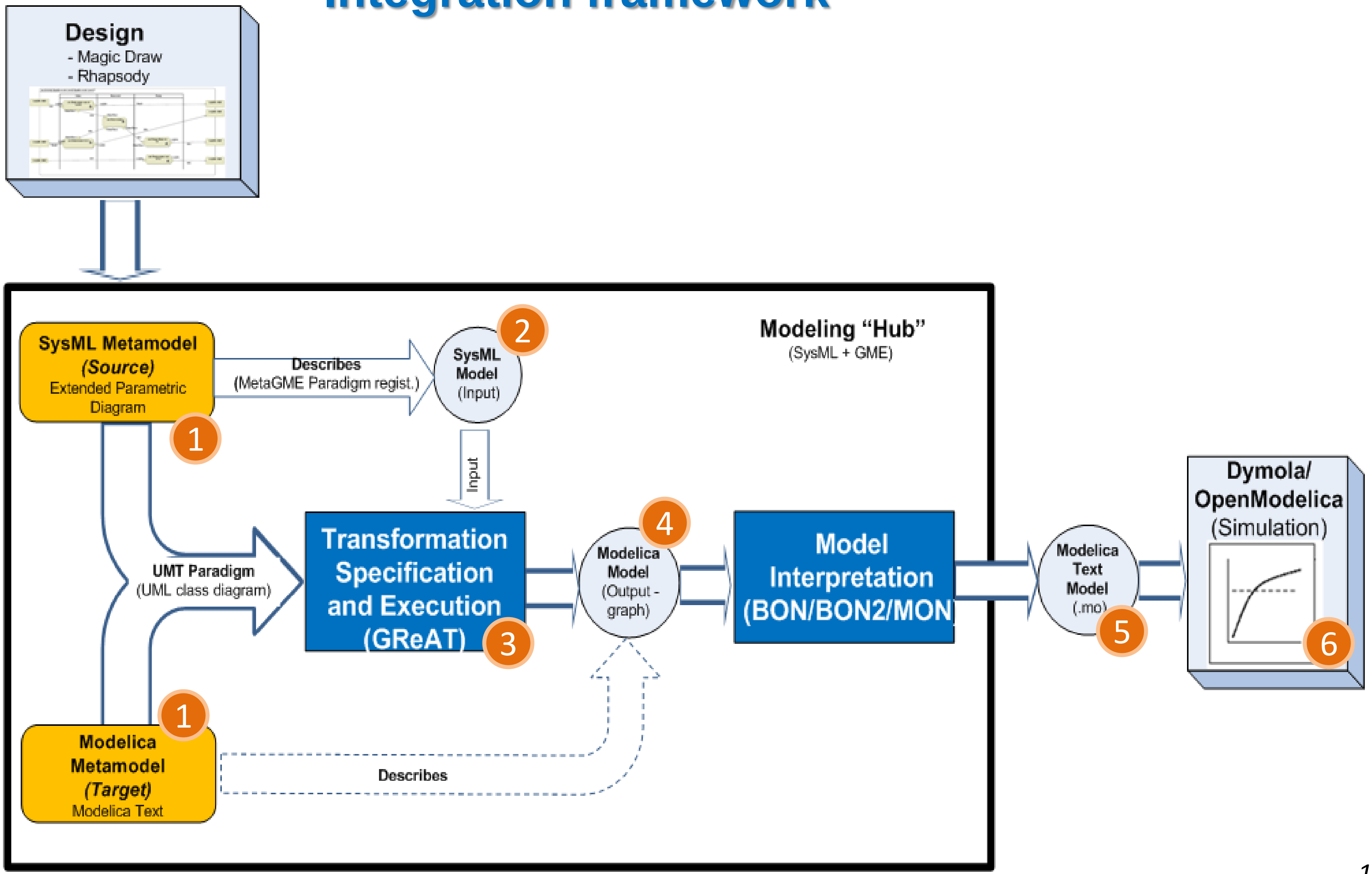
Smart Grids



- ACEEE estimates +2x energy savings
- Able to measure and manage carbon footprint per product line

Integrated Modeling Hub: SysML and Modelica Integration

Integration framework

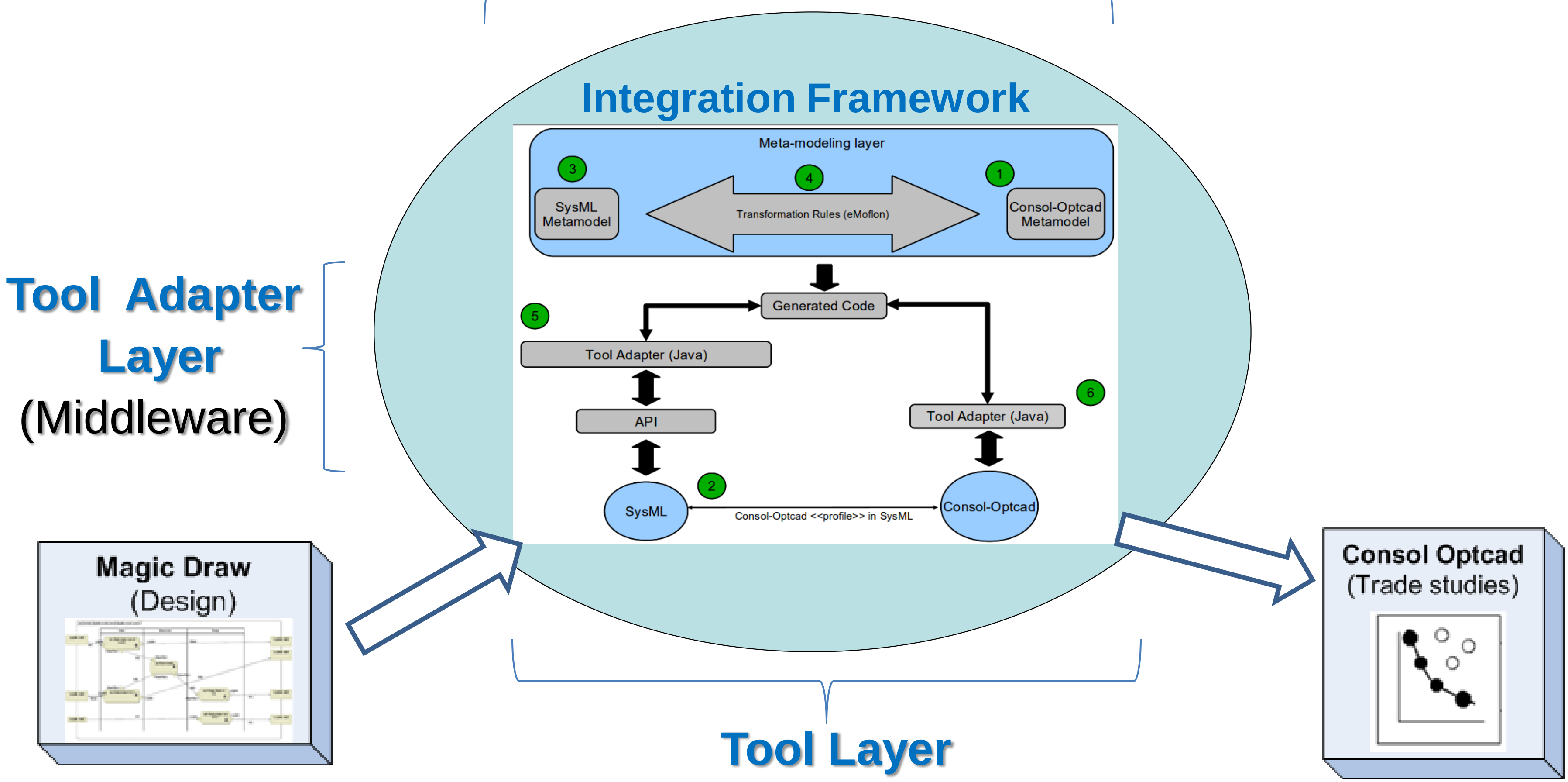


SysML and Consol-Optcad Integration

Overview

Meta-modeling Layer

(Enterprise Architect + eMoflon, Eclipse development environment)



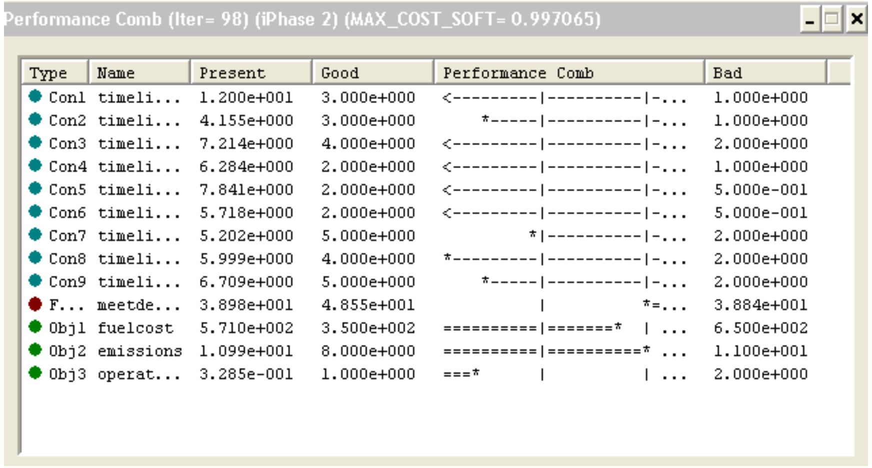
Tool Layer

(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)

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

Fig. 1: Pcomb

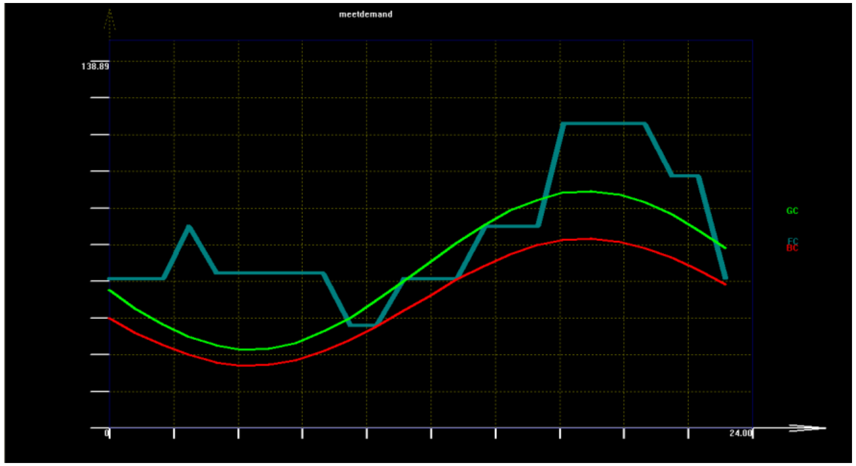


Fig. 2: Example of a functional constraint

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

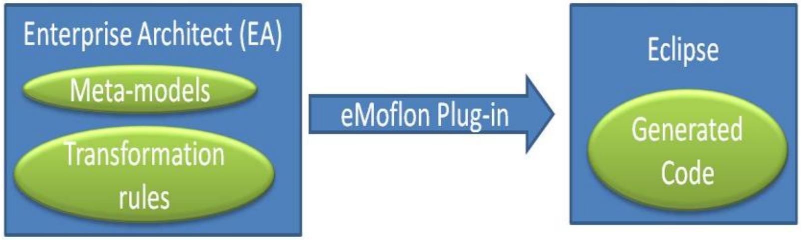


Fig. 3: eMoflon high-level architecture

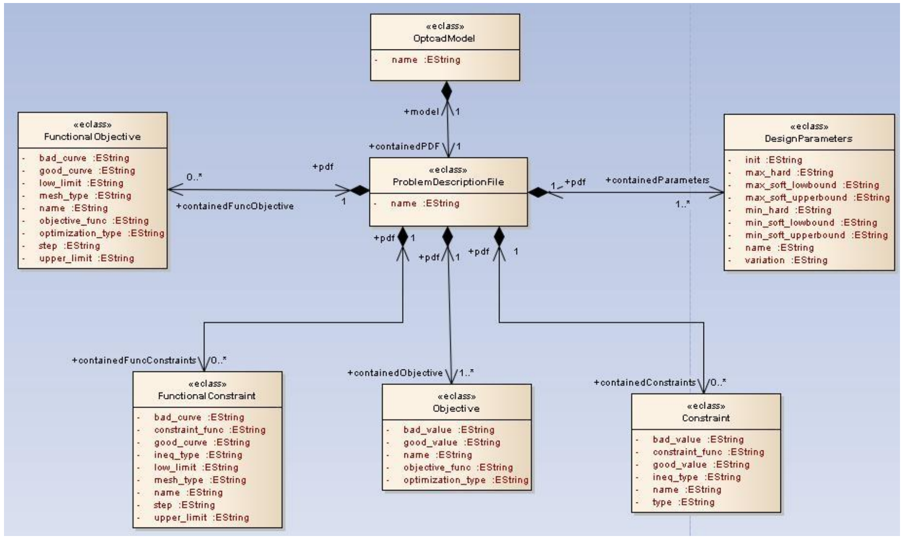


Fig. 4: Consol-Optcad metamodel

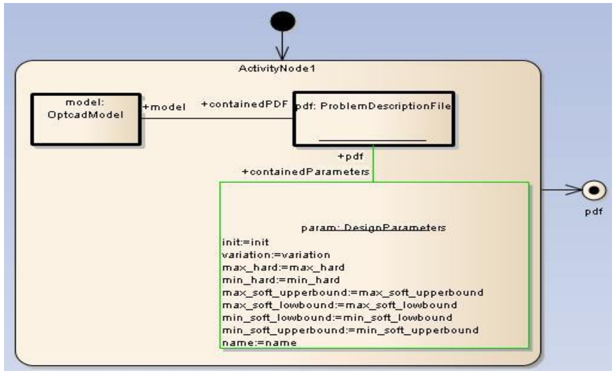


Fig. 5: Story diagram

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

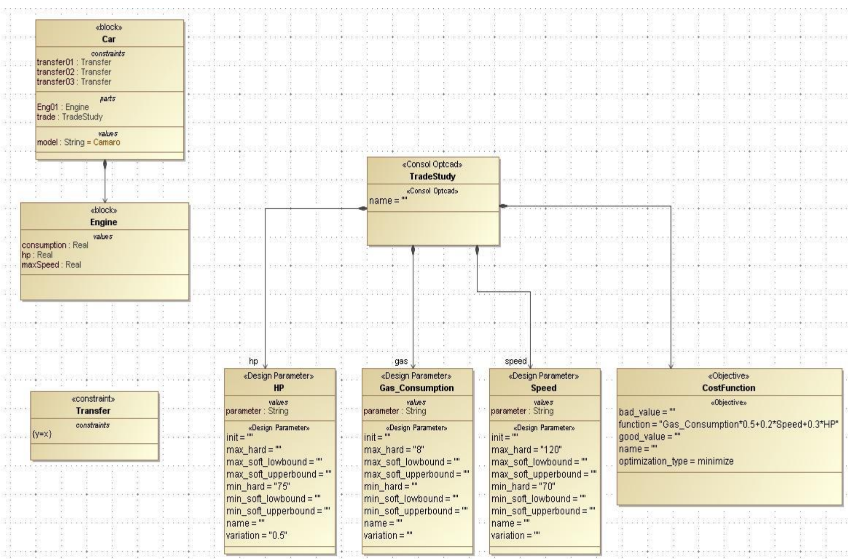


Fig. 6: Using constructs of Consol-Optcad profile in MagicDraw environment

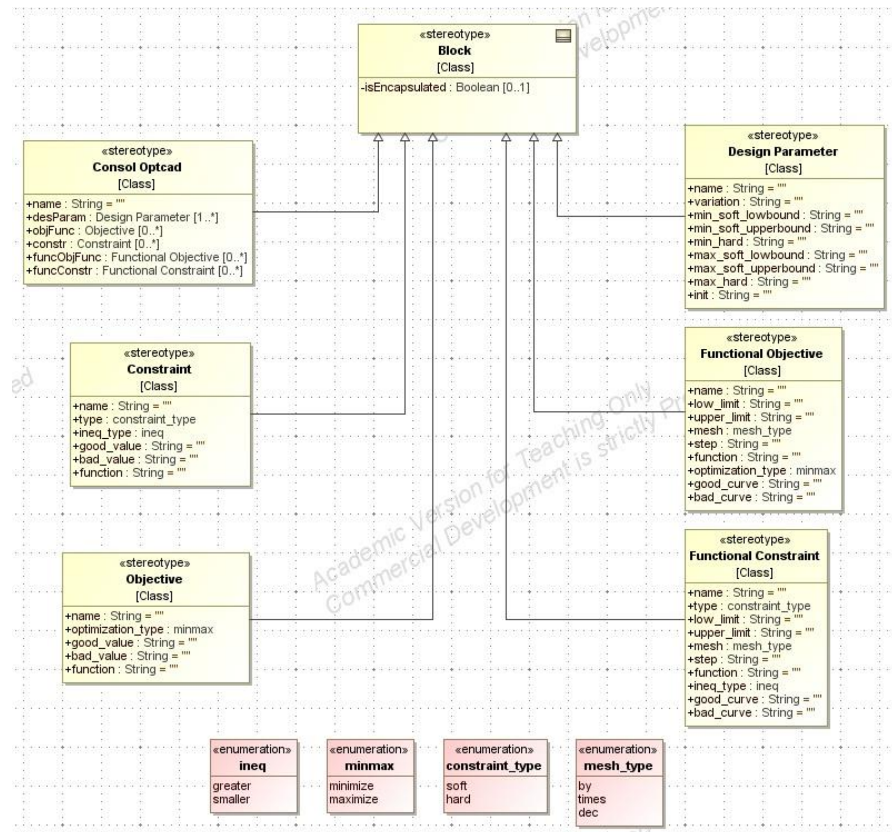


Fig. 7: Consol-Optcad profile in SysML

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

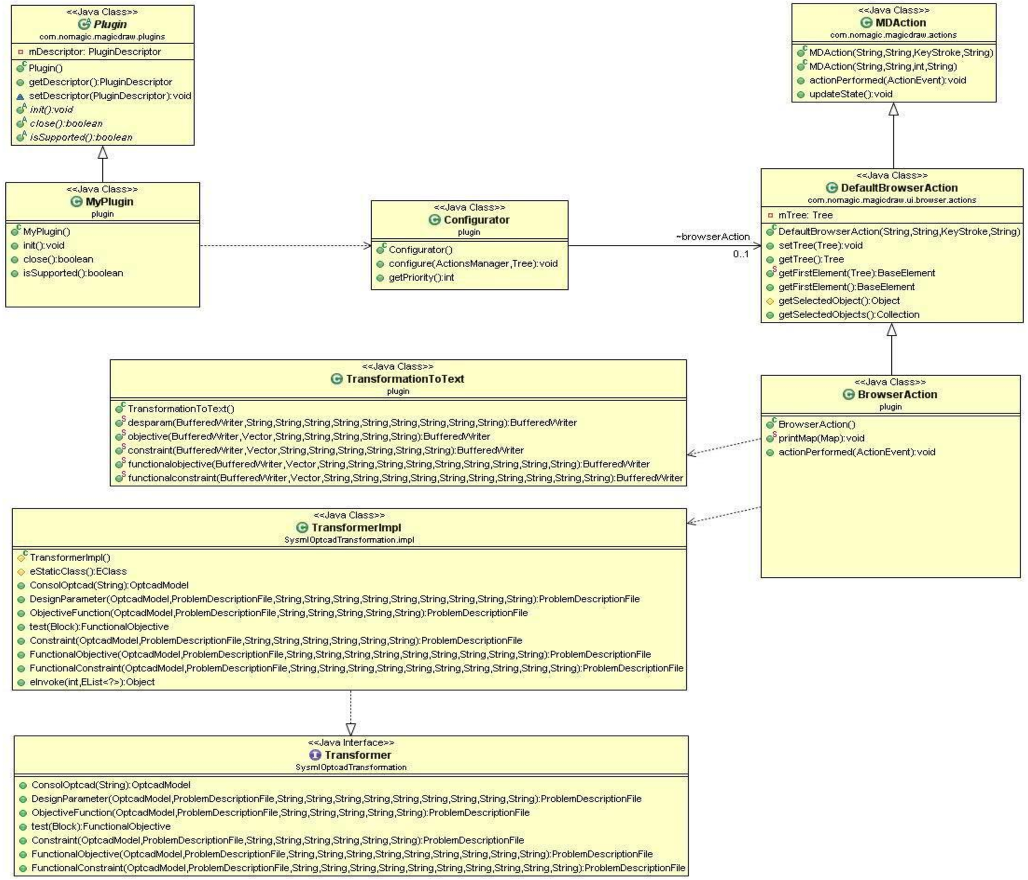


Fig. 8: Consol-Optcad MagicDraw plug-in class diagram

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

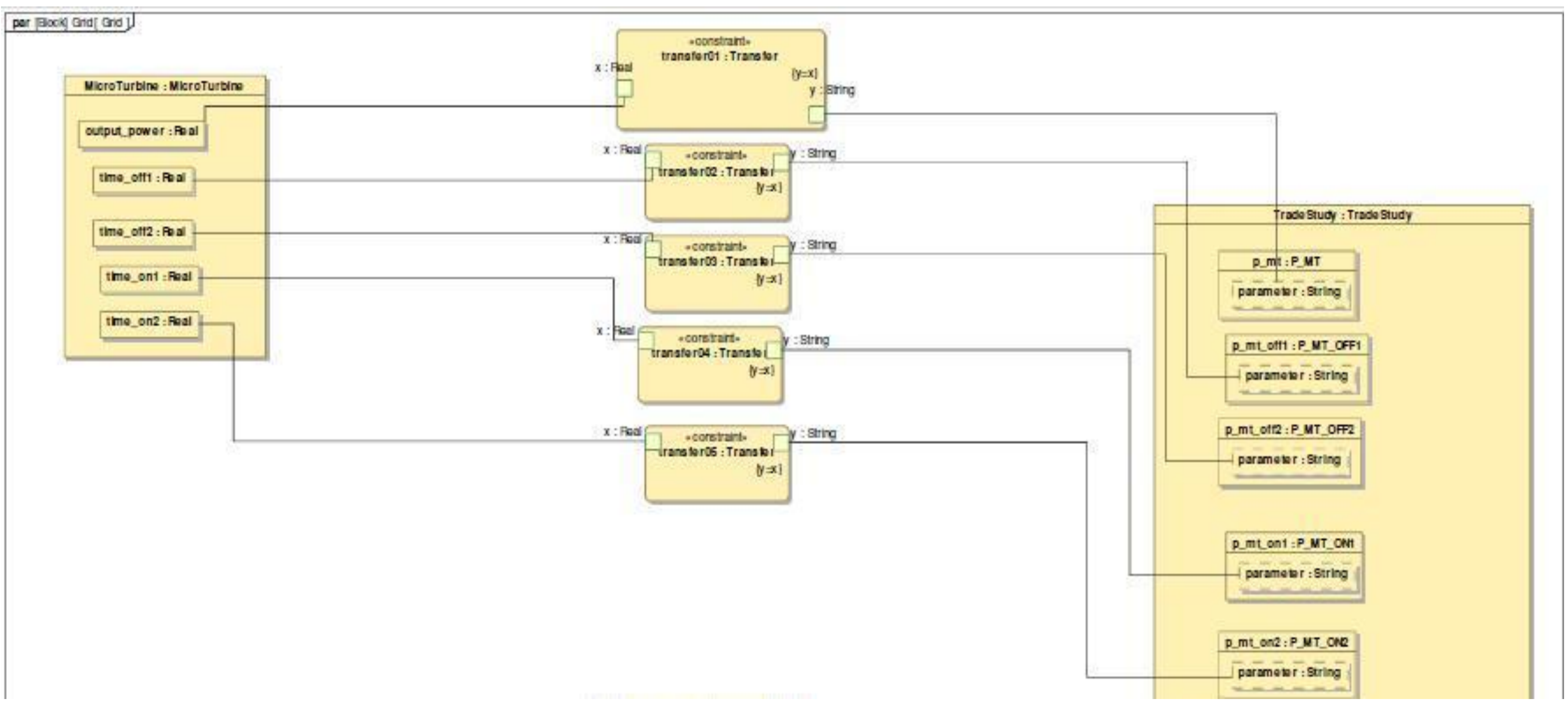


Fig. 9: Parametric diagram

IMH and Consol-Optcad Integration

Working Example

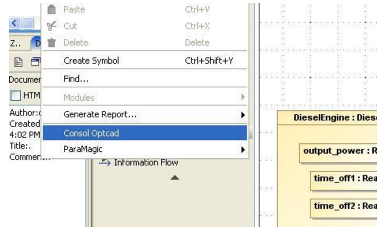


Fig. 11: Initiate transformation

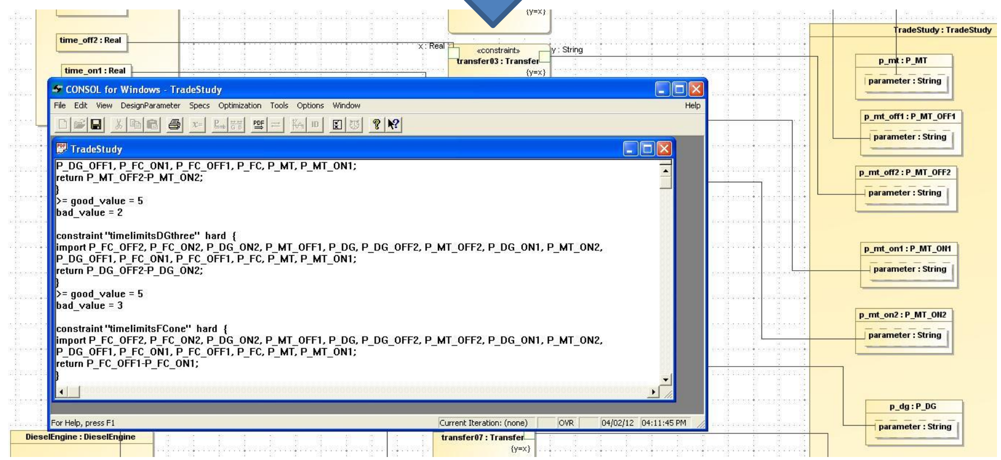


Fig. 12: Consol-Optcad environment

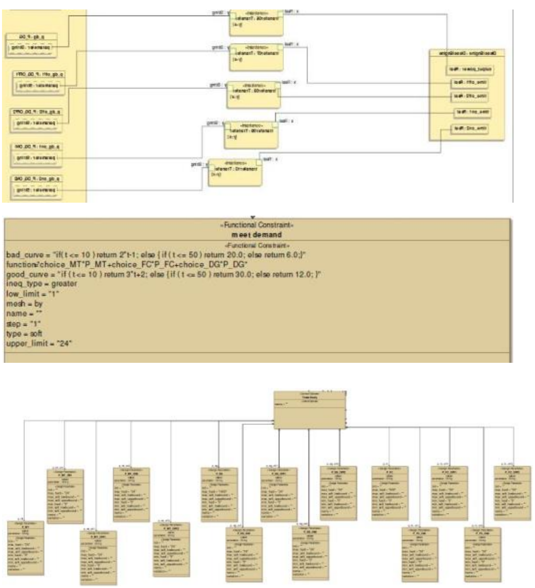


Fig. 10: Models in SysML

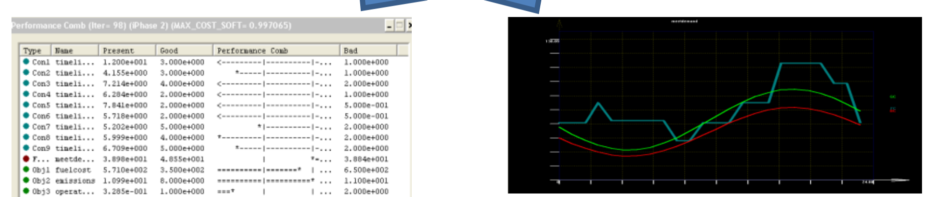


Fig.13: Perform trade-off analysis in Consol-Optcad

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

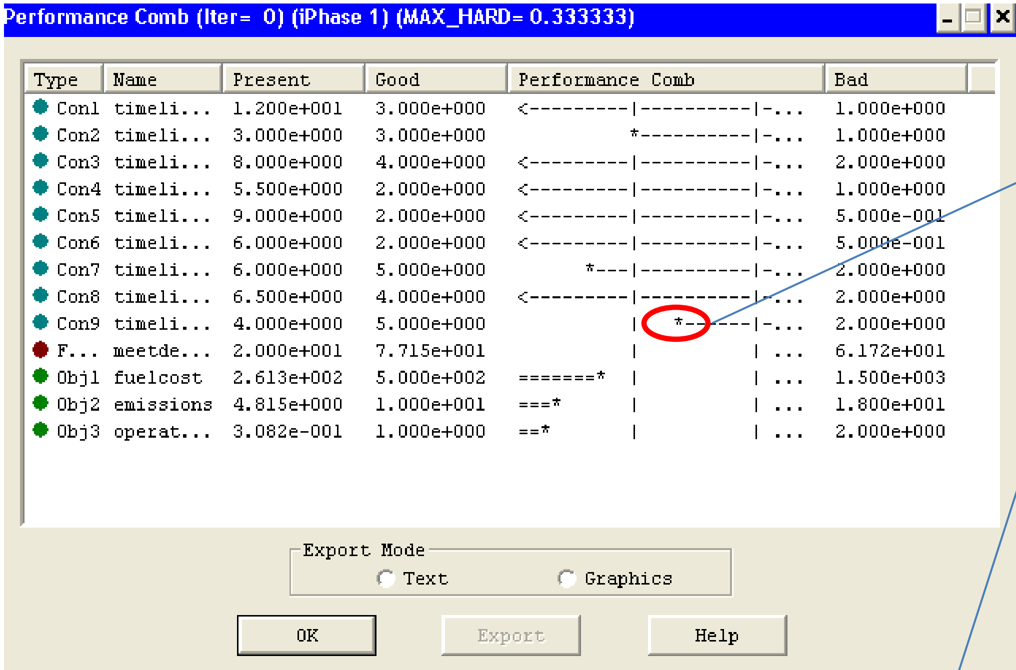
  Functional constraint and shall be met for all values of the free parameter *t*
- Each power source should turn on and off only 2 times during the day

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: $t_{i\_off1} - t_{i\_on1} \geq x_i$ and $t_{i\_off2} - t_{i\_on2} \geq x_i, \quad i = 1,2,...N$
- Each generating unit should remain turned off for at least a period y_i defined by the specifications: $t_{i\_on2} - t_{i\_off1} \geq y_i, \quad i = 1,2,...N$

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

Tradeoff Study in Consol-Optcad


Performance Comb (Iter= 0) (iPhase 1) (MAX_HARD= 0.333333)

<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>3.000e+000</td><td>3.000e+000</td><td>*----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con3</td><td>timeli...</td><td>8.000e+000</td><td>4.000e+000</td><td><----------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con4</td><td>timeli...</td><td>5.500e+000</td><td>2.000e+000</td><td><----------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con5</td><td>timeli...</td><td>9.000e+000</td><td>2.000e+000</td><td><----------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con6</td><td>timeli...</td><td>6.000e+000</td><td>2.000e+000</td><td><----------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con7</td><td>timeli...</td><td>6.000e+000</td><td>5.000e+000</td><td>*---|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con8</td><td>timeli...</td><td>6.500e+000</td><td>4.000e+000</td><td><----------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con9</td><td>timeli...</td><td>4.000e+000</td><td>5.000e+000</td><td>| *-------|-...</td><td>2.000e+000</td></tr>
<tr><td>F...</td><td>meetde...</td><td>2.000e+001</td><td>7.715e+001</td><td>| | ...</td><td>6.172e+001</td></tr>
<tr><td>Obj1</td><td>fuelcost</td><td>2.613e+002</td><td>5.000e+002</td><td>=======* | | ...</td><td>1.500e+003</td></tr>
<tr><td>Obj2</td><td>emissions</td><td>4.815e+000</td><td>1.000e+001</td><td>===* | | ...</td><td>1.800e+001</td></tr>
<tr><td>Obj3</td><td>operat...</td><td>3.082e-001</td><td>1.000e+000</td><td>==* | | ...</td><td>2.000e+000</td></tr>
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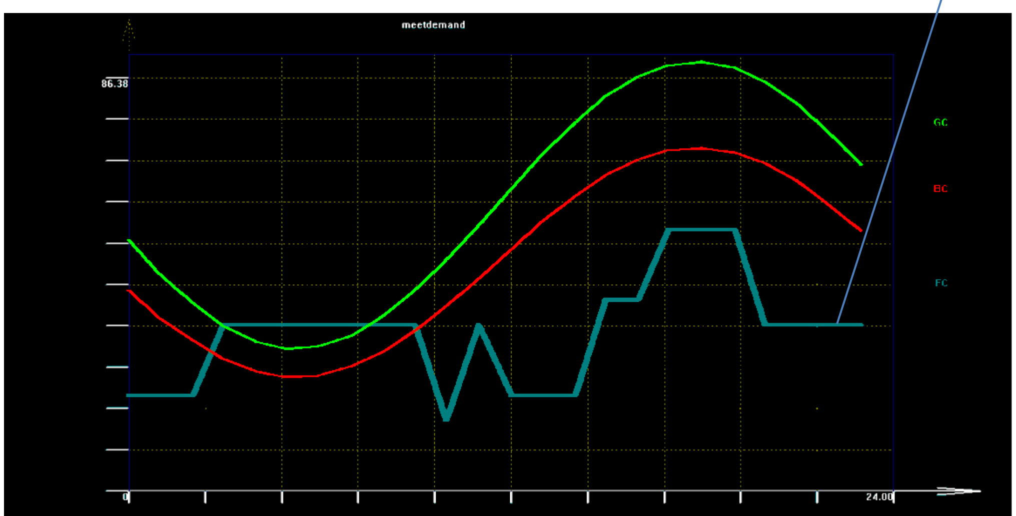
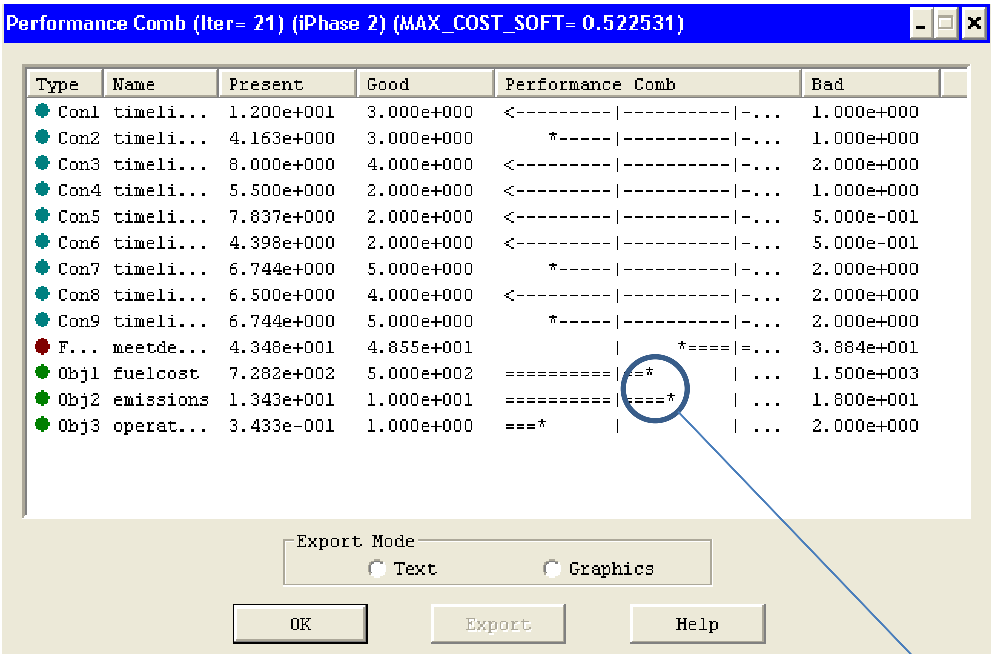


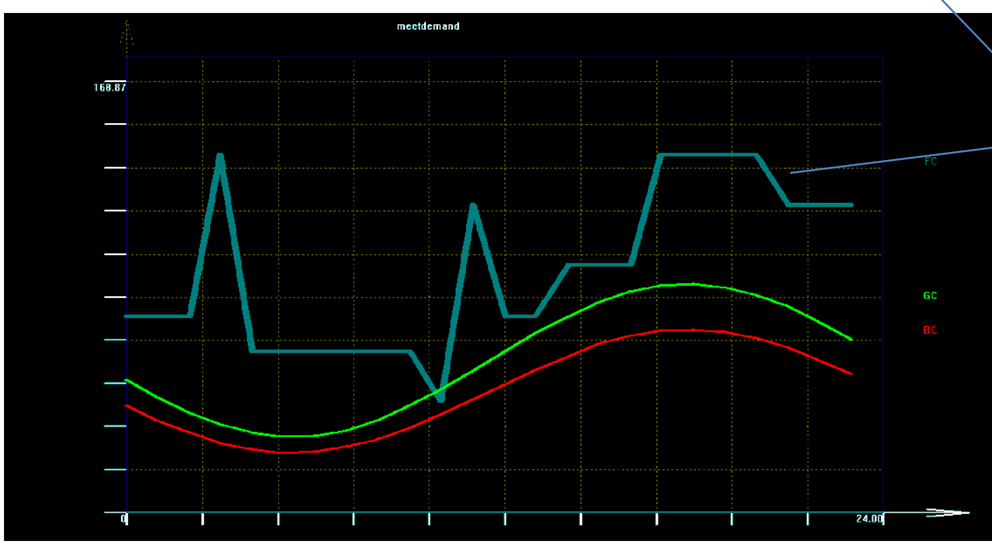
Iteration 1 (Initial Stage)

- ✓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



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



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)

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<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>
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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>
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<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>
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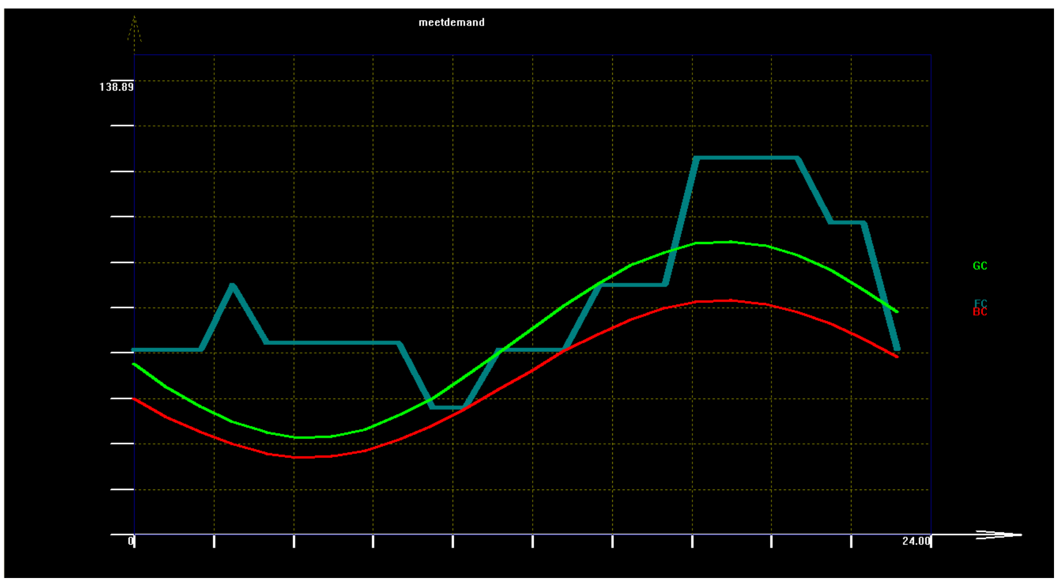
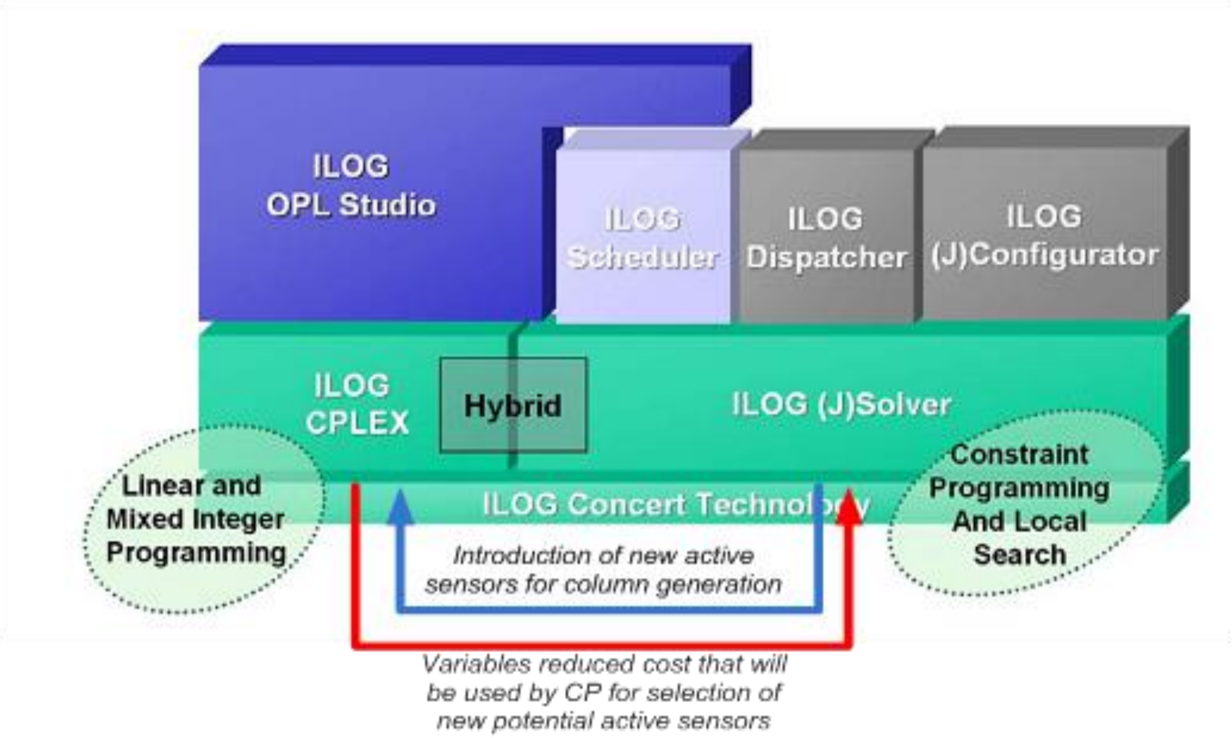


Iteration 95 (Final Solution)

- ✓ 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

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



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

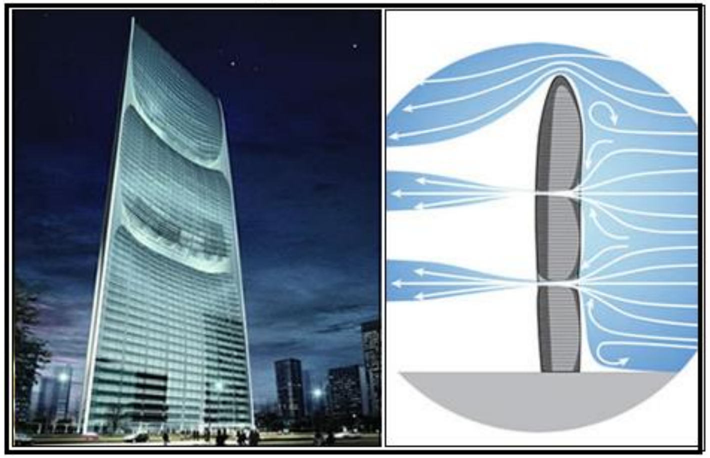
Power Delivery and Demand Response

Building Materials, Misc. Equipment

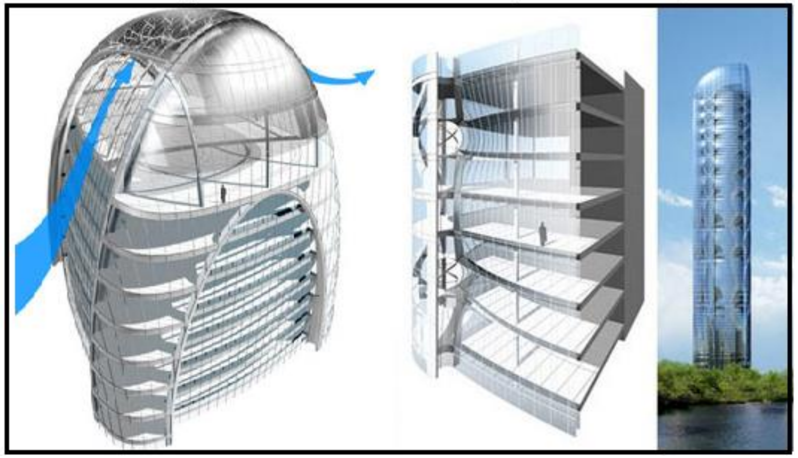
Buildings as Cyber-Physical Systems

- **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)

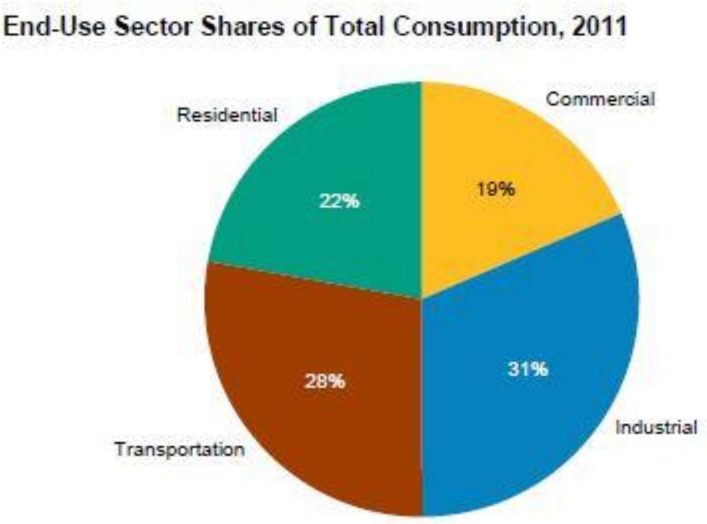
Net-Zero Energy

Net Zero Energy

- Net-Zero: when a building produces the same amount of energy than it consumes annually
- Net-Positive: when a building produces *more* energy than it consumes annually

Impact

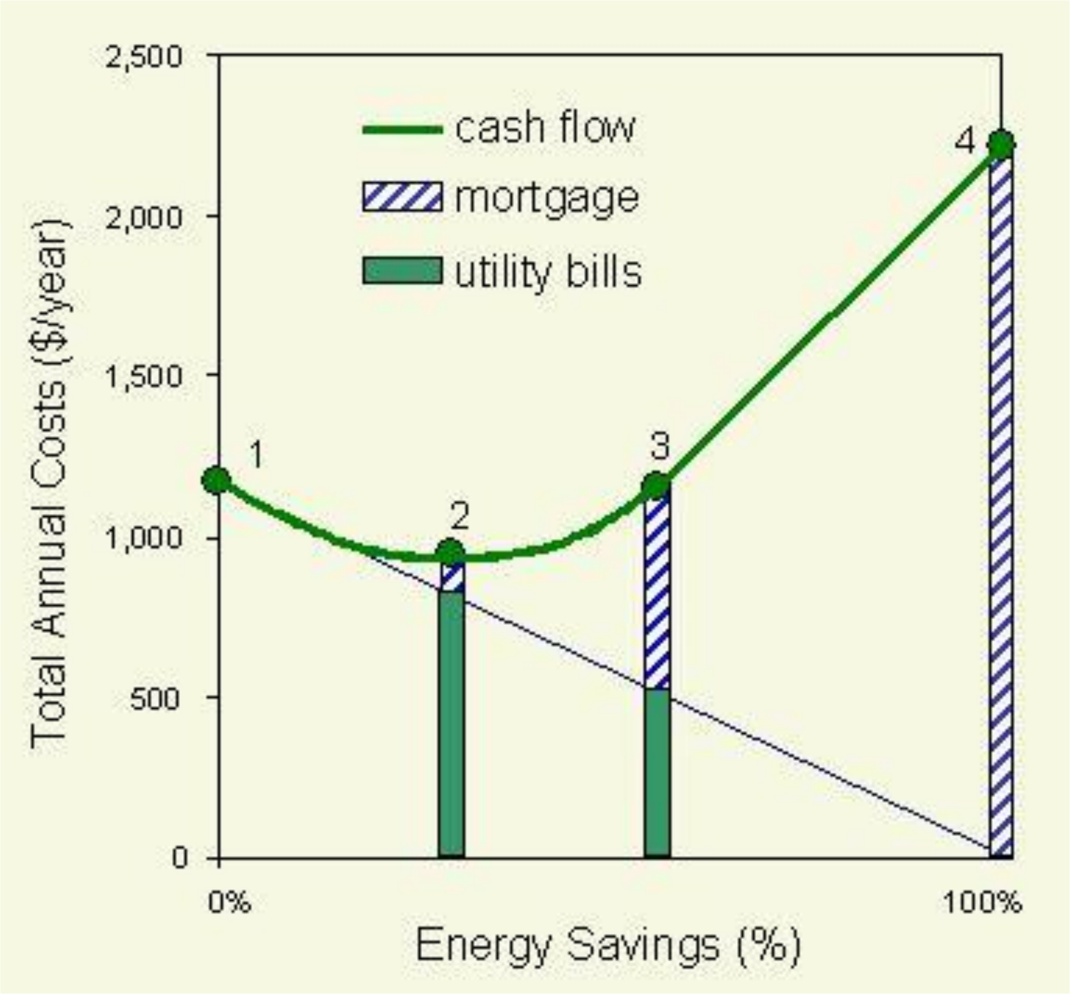
- Over 22% of all energy produced in US is consumed by residential sources
- Huge potential for savings with energy efficiency:
  - Reducing loads
  - Increasing grid stability
  - Reducing transmission losses
- Many tools and techniques can be applied to commercial sector as well



Courtesy of EIA (2011)

NET-zero Energy

Path to NZE

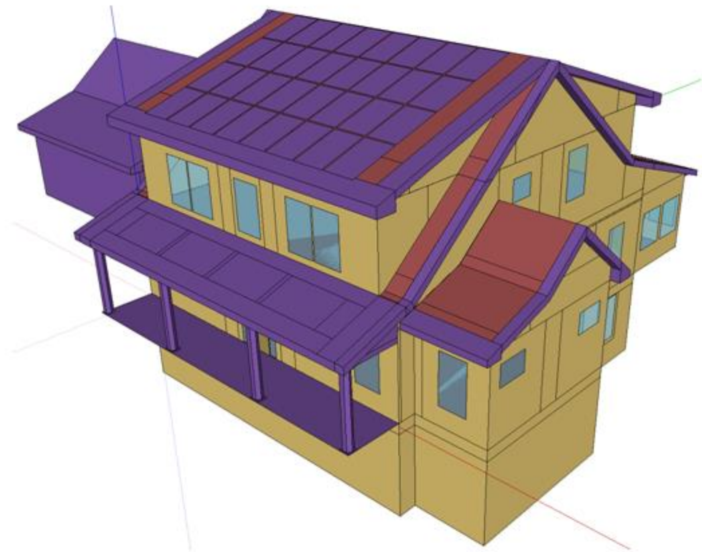


Courtesy BEopt

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)

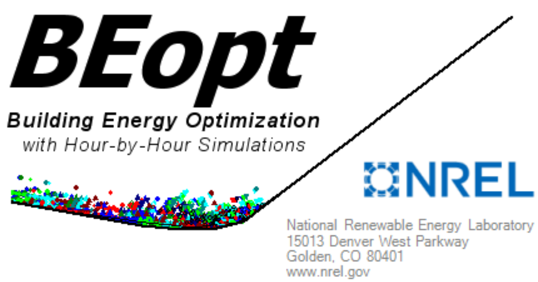
CURRENT CAPABILITIES AND SOFTWARE

BEopt – Building Energy Optimization

- Developed by NREL
- Software that couples with EnergyPlus (and DOE2) that acts as an optimized simulation controller and provides easy analytic capabilities
- Extends functionality of EnergyPlus

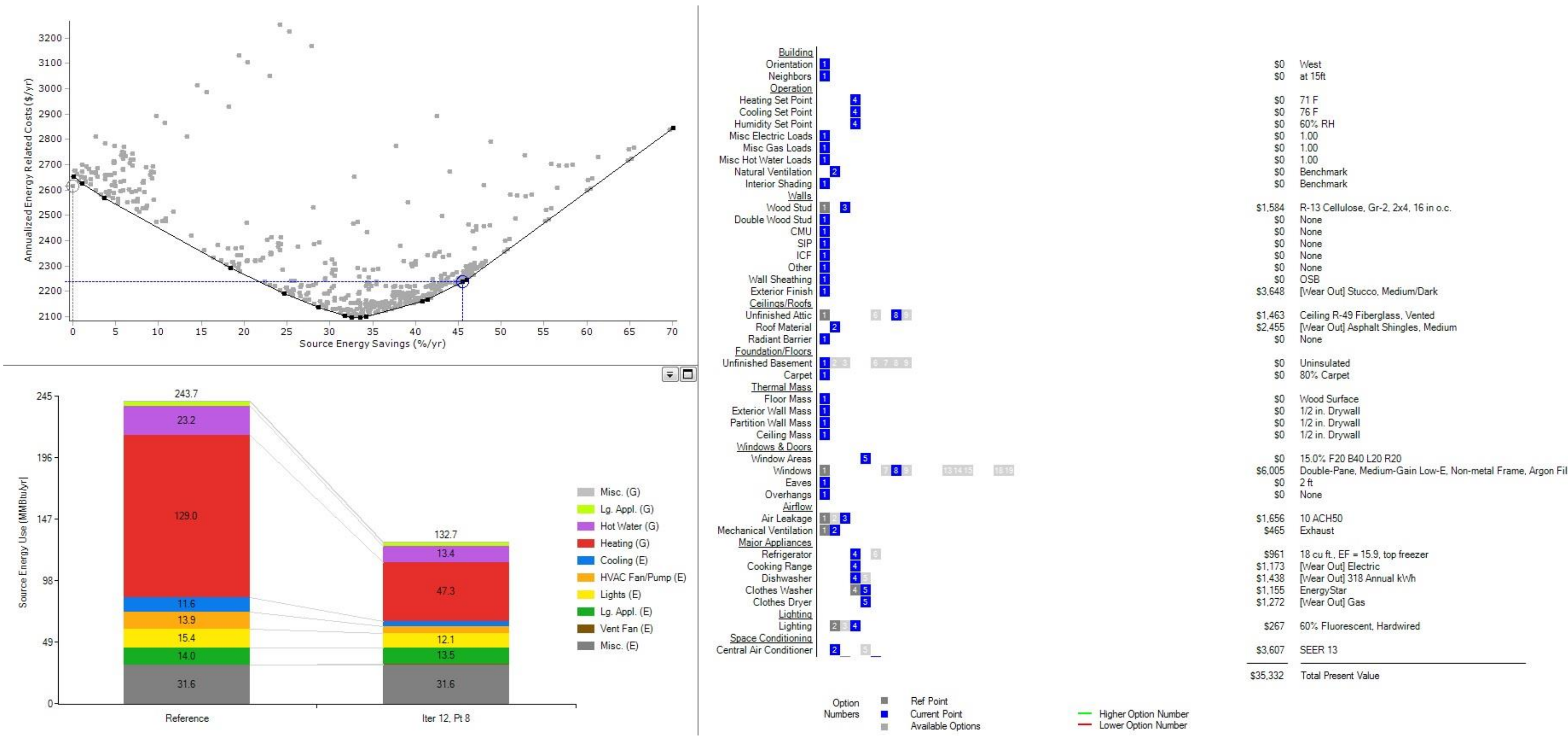
BEopt – Pros

- Decreases time per simulation by simplifying scope of energy model
- Uses sequential search algorithm to reduce number of necessary simulations
- Lists discrete options for parameters
- Includes model dependencies between parameters
- Finds optimal designs for Bi-Objective Optimization of Life Cycle Cost vs Energy Savings



CURRENT CAPABILITIES AND SOFTWARE

BEopt



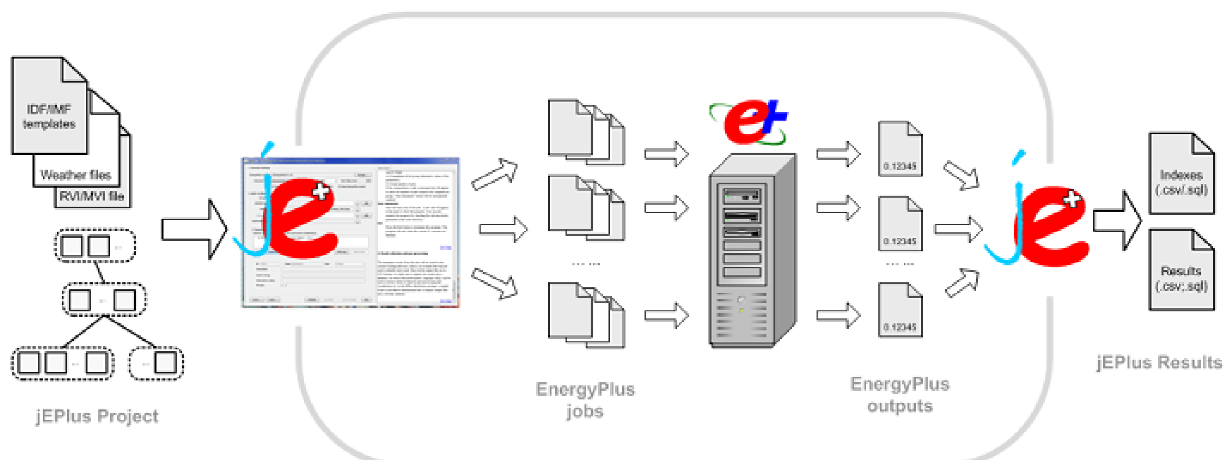
CURRENT CAPABILITIES AND SOFTWARE

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

BEOPT AND ENERGYPLUS METHOD

Concept

- BEopt greatly reduces the time necessary for simulations and has a search algorithm for finding optimal solutions to a bi-objective problem

- EnergyPlus can produce significantly more detailed results, however takes much longer

- Use BEopt to reduce state space and remove dominated solutions

- Translate BEopt model solutions to EnergyPlus and run further parametric analysis with greater model detail and new parameters

- Near-Optimal to True-Optimal

BEOPT AND ENERGYPLUS METHOD

Setup

- Full State Space

Design Variable	Parameter Values				
Exterior Wall Interior Insulation	19	21			
Exterior Wall Exterior Insulation	0	6	12	18	24
Basement Wall Interior Insulation	0	6	12		
Roof Exterior Insulation	6	12	18	24	30
Windows	.35/.35	.26/.65	.17/.25		
Infiltration Rate	3	2	1	.5	
High-Efficiency Lighting	75%	85%	95%	100%	
Heat Pump	13/7.7	14/8	15/8.5	16/9	
Mechanical Ventilator	Min. Outdoor Air	HRV	ERV		
Water Heater Tank	Electric	Heat Pump			
Solar Thermal	0	1	2		
Array Capacity	0	2.5	5.5	7.6	10.2

- ~2.6 million simulations/20,000 simulations per day = 129 days
- This is why detailed DSE is infeasible!

BEOPT AND ENERGYPLUS METHOD

Setup

- Reduced State Space

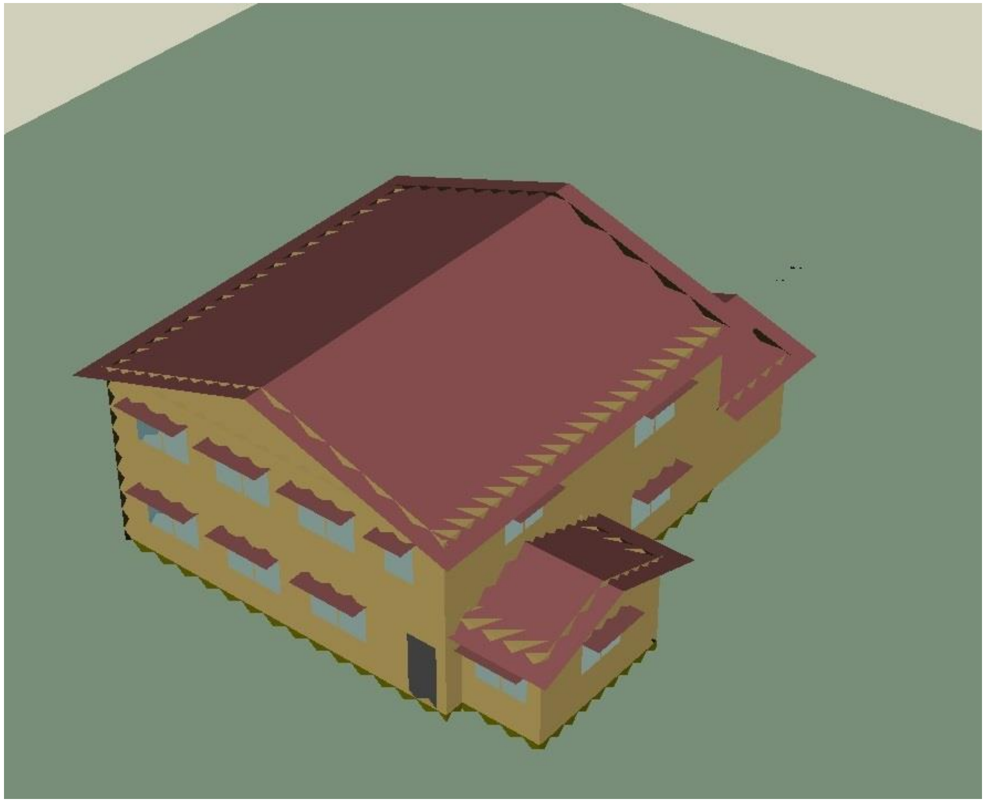
Design Variable	Parameter Values		
Exterior Wall Interior Insulation	19	21	
Exterior Wall Exterior Insulation	0	12	24
Basement Wall Interior Insulation	0	6	12
Roof Exterior Insulation	4	12	30
Windows	.35/.35	.3/.3	.2/.25
Infiltration Rate	3	2	.6
High-Efficiency Lighting	100%		
Heat Pump	15/9.05		
Mechanical Ventilator	HRV		
Water Heater Tank	Heat Pump		
Solar Thermal	0	1	2
Array Capacity	0	5.5	10.2

- ~13,000 simulations, 11 computer running 60 parallel simulations = 1.8 days

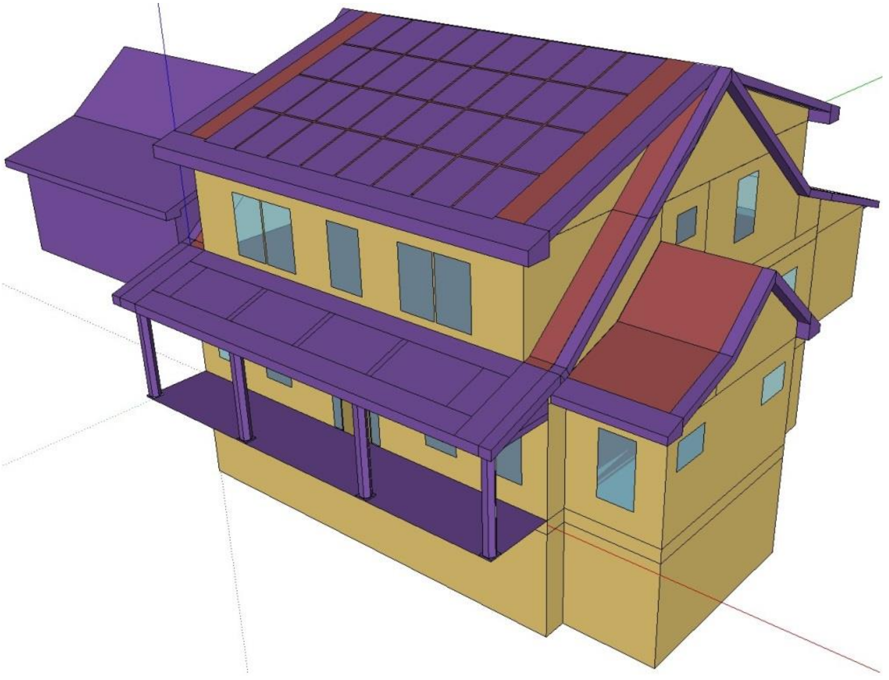
BEOPT AND ENERGYPLUS METHOD

Setup

BEopt Model

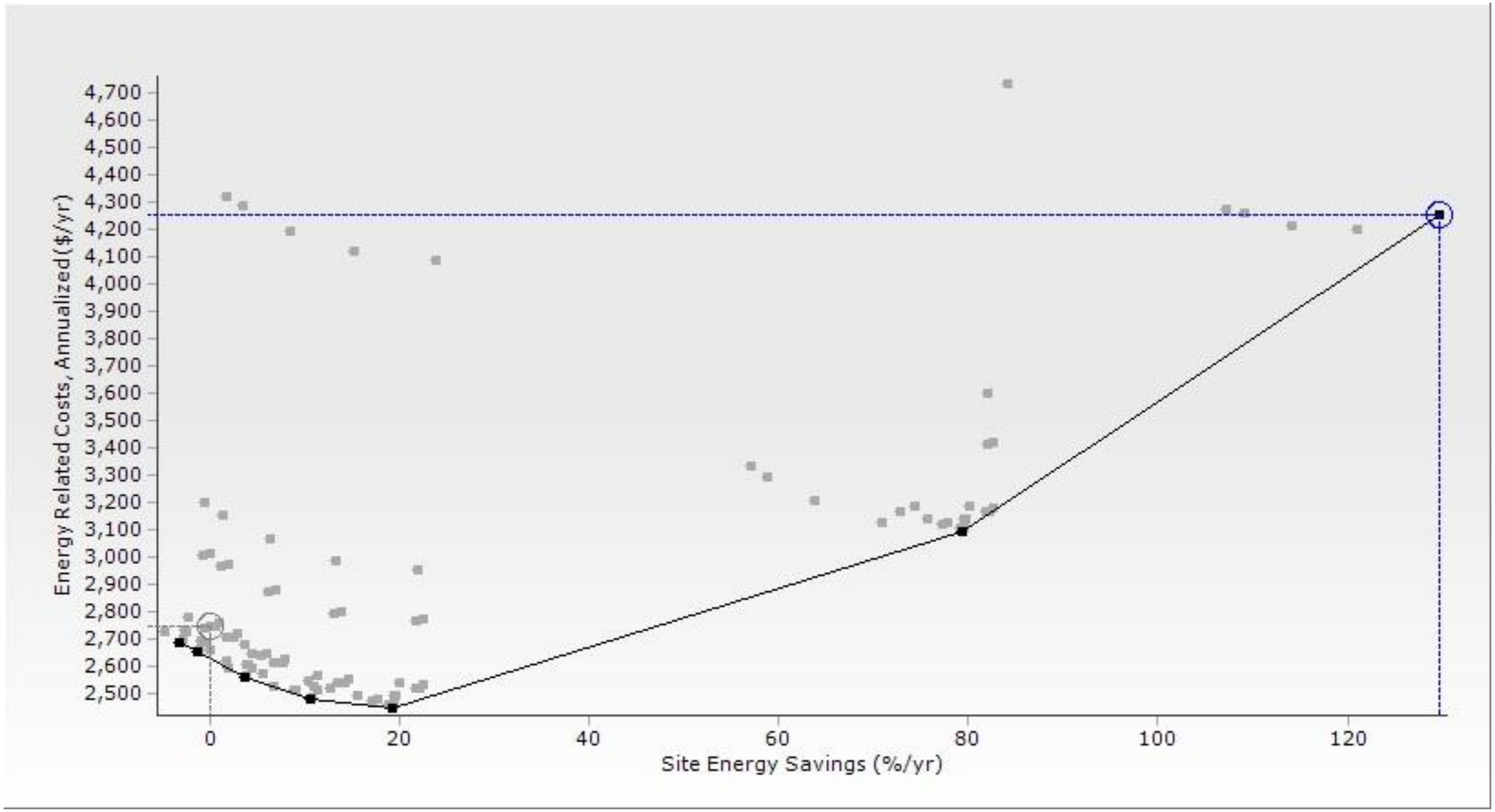


EnergyPlus Model



BEOPT AND ENERGYPLUS METHOD

BEopt Results



BEOPT AND ENERGYPLUS METHOD

BEopt Results

Design Variable	Optimal 1	Optimal 2	Optimal 3	Optimal 4	Optimal 5	Optimal 6	Optimal 7
Exterior Wall Interior Insulation	19	19	19	21	19	21	21
Exterior Wall Exterior Insulation	0	24	24	24	24	24	24
Basement Wall Interior Insulation	0	0	12	12	12	12	12
Roof Exterior Insulation	4	4	30	30	30	30	30
Windows	.35/.35	.35/.35	.35/.35	.35/.35	.35/.35	.35/.35	.35/.35
Infiltration Rate	3	0.6	0.6	0.6	0.6	0.6	0.6
Array Capacity	0	0	0	0	0	5	10
Solar Thermal	0	0	0	0	0	0	0
Energy Management	1	1	1	1	1	1	1

- ~108 simulations, 1 computer running 8 parallel simulations = 45 minutes

BEOPT AND ENERGYPLUS METHOD

Conclusions

- BEopt can *significantly* reduce the time necessary for simulations and provide great insight into near-optimal configurations.
- While a direct connection of the cost models could not be validated between the two programs, the performance was.
- Further refinement of the cost model for EnergyPlus is necessary.
- There was a sizeable different in final optimal points between the BEopt and EnergyPlus's detailed model indicating that, when dealing with NZE and DSE, building models must include significant detail in order to capture the entire scope of building behavior.
- This methods progression of detail does coincide well with the building design process since multiple models must be created. Conceptual Design to Detailed Design to Construction Documents

MULTI-OBJECTIVE OPTIMIZATION

Concept

- BEopt achieves great improvements in speed, but is limited to LCC vs Energy Savings
- Buildings have significantly more objectives that require attention and trade-off in the design process
- A better solution would be one that can handle true multi-objective optimization
- Utilizes our work done in 2012 on multi-objective optimization of micro grids with Consol-Optcad, a powerful multi-objective optimization tool
- Consol-Optcad uses an FSQP algorithm that guarantees feasibility for all following iterations after it is found
  - Also has the benefit of using functional constraints and allows for free parameter varying constraints

MULTI-OBJECTIVE OPTIMIZATION

Problem Formulation

Design Parameters	Description	Constraint	Initial	Unit
x_1	Exterior Wall Insulation (R-Value)	$19 \leq x_1 \leq 44$	$x_1 = 19$	$\frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$
x_2	Roof Insulation (R-Value)	$50 \leq x_2 \leq 75$	$x_2 = 50$	$\frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$
x_3	Window (U-Value)	$0.2 \leq x_3 \leq 0.35$	$x_3 = 0.35$	$\frac{Btu}{ft^2 \cdot {}^\circ F \cdot hr}$
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

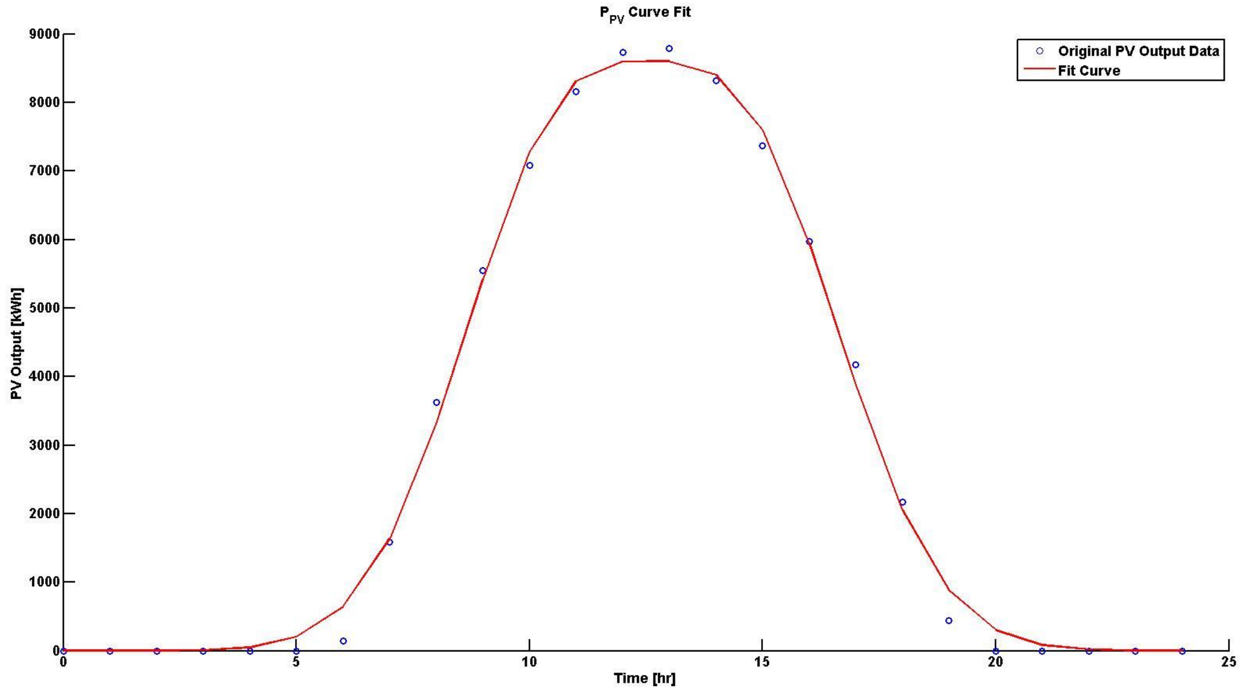
$$EU = \sum_{t=0}^{24} \frac{(P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op})}{60000}$$

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

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

Energy Use Objective Function

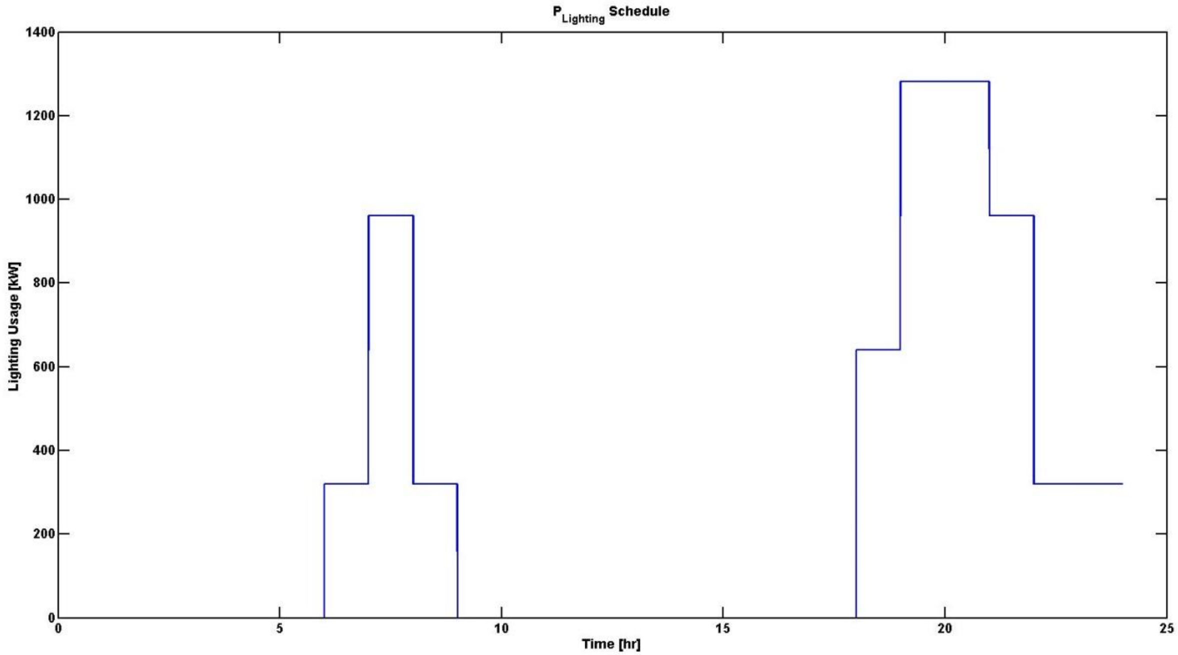
$$P_{PV}(t) = \frac{-x_8}{10240}\left(6970\mathrm{e}^{-\left(\frac{t-14.66}{3.014}\right)^2} + 6870\mathrm{e}^{-\left(\frac{t-10.55}{2.954}\right)^2}\right)$$



MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

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



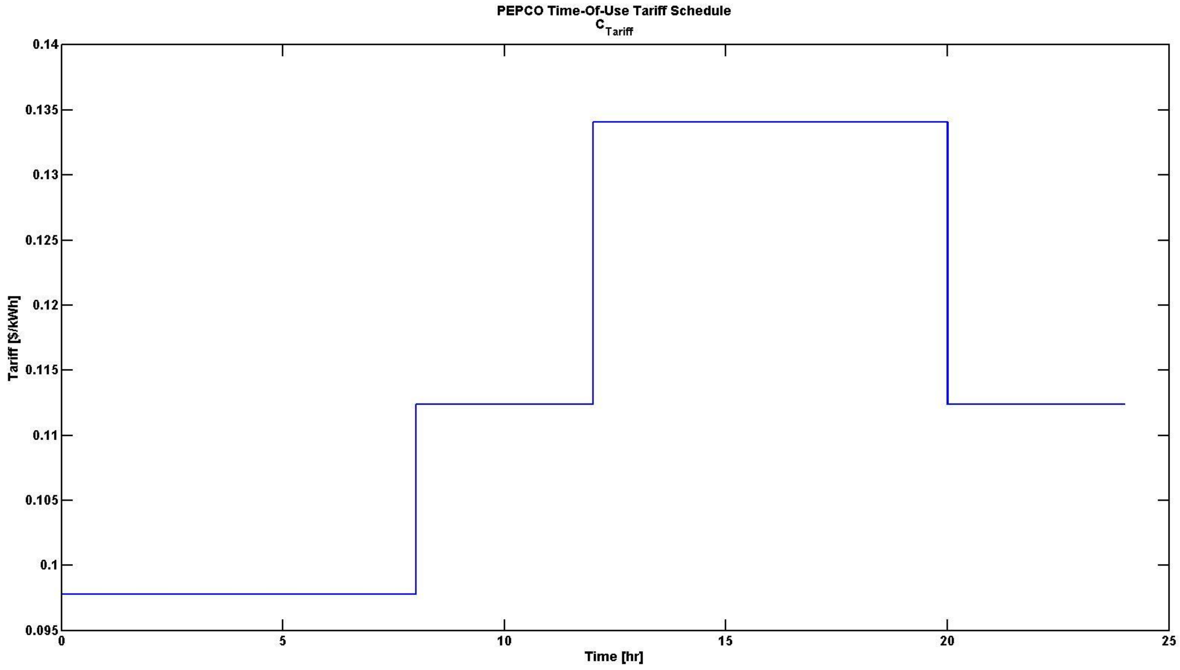
Operational Cost Objective Function

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

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



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

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

Heat Transfer Equations

$$T_{room}[t] = \frac{Q_{net,t-1}}{C_p \cdot \rho \cdot V_{room}} + T_{room}[t-1]$$

$$C_p = 0.24 \; \frac{\text{Btu}}{{}^\circ\text{F} \cdot \text{lb}_\text{m}}$$

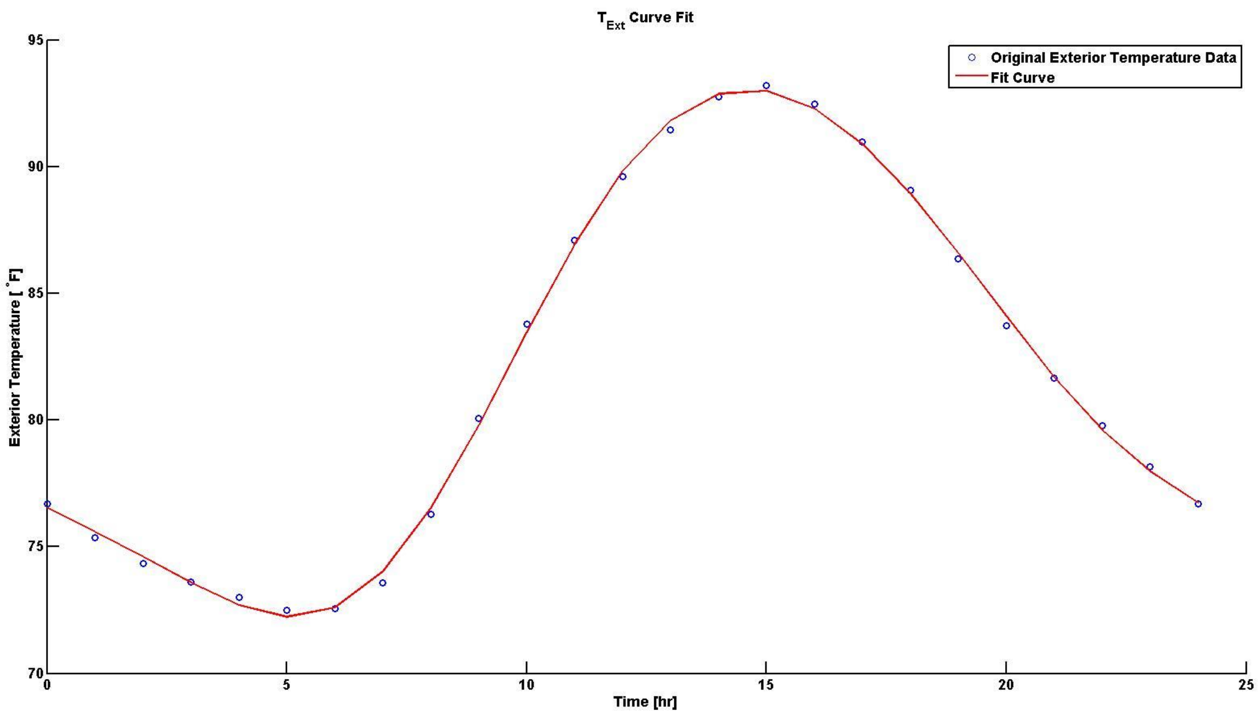
$$\rho = 0.075 \; \frac{\text{lb}_\text{m}}{\text{ft}^2}$$

$$V_{room} = 12800 \; \text{ft}^3$$

MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

$$
\begin{aligned}
T_{ext}(t) = 81.96 &- 6.614\cos(0.2594t) - 7.6\sin(0.2594t) \\
&+ 1.347\cos(0.5188t) + 1.306\sin(0.5188t) \\
&- 0.1291\cos(0.7702t) + 0.3703\sin(0.7702t)
\end{aligned}
$$



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

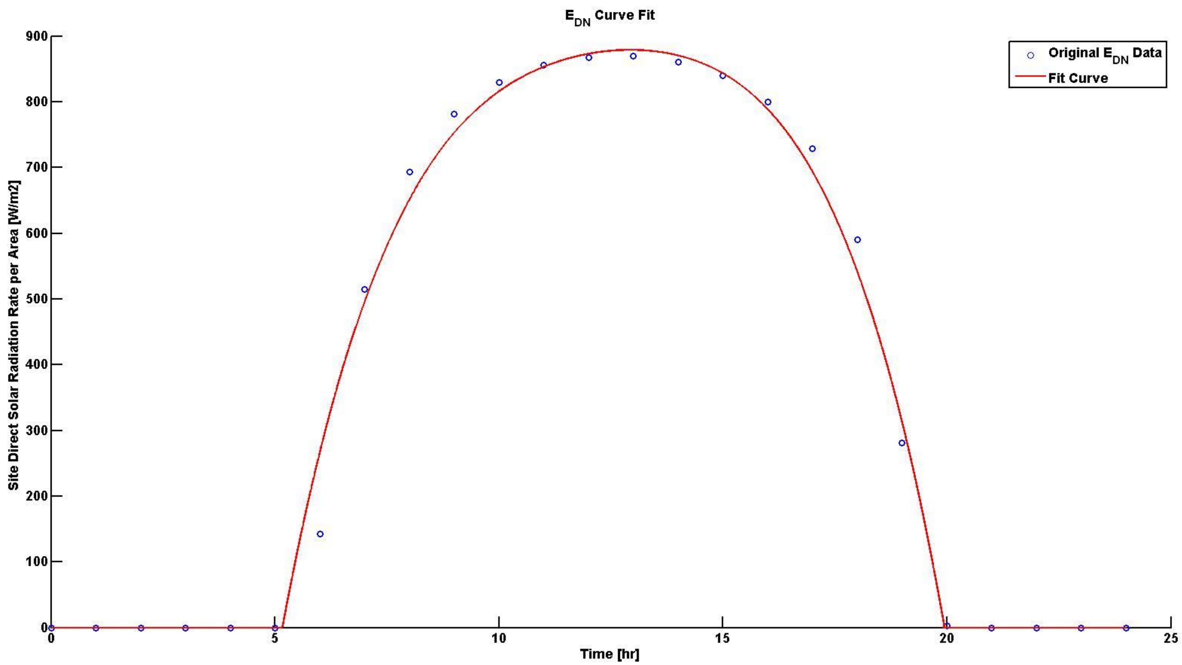
$$Q_{win} = A_{win}\, x_3 \left(T_{ext}(t) - T_{room}[t]\right)$$

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

Heat Transfer Equations

$$Q_{winrad} = \frac{A_{win}\, E_{DN}(t)\, x_4\ \cos\theta}{3.15}$$

$$E_{DN}(t) = \begin{cases} -0.1729t^4 + 8.591t^3 - 166.7t^2 + 1497t - 4346, & \text{for } 5.17 < t < 19.93 \\ 0, & \text{otherwise} \end{cases}$$



MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

$$Q_{inf} = \rho\, C_p\, x_5\, (T_{ext}(t) - T_{room}[t])$$

$$Q_{vent} = 60\, \dot{V}_{vent}\, \rho\, C_p\, (1 - x_6)\, (T_{ext}(t) - T_{room}[t])$$

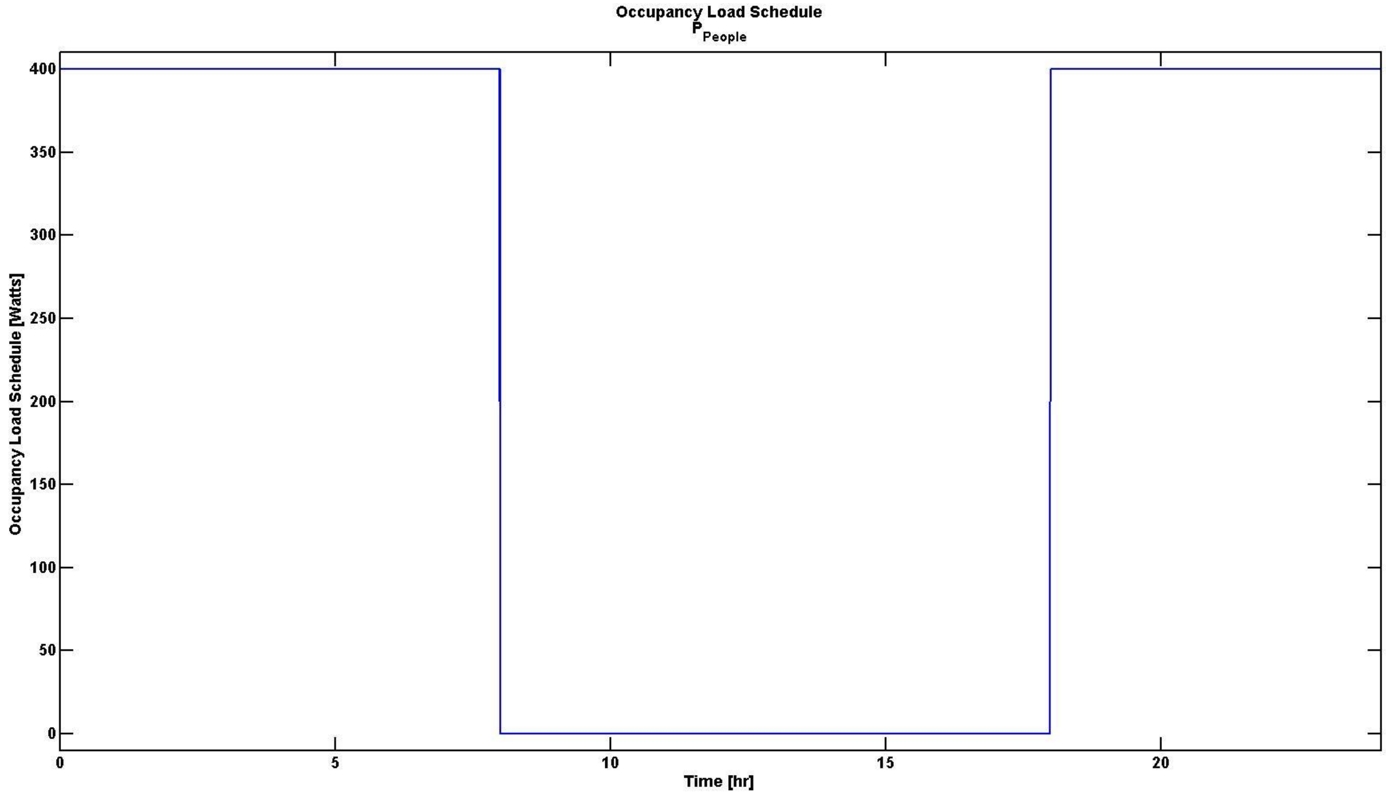
$$Q_{int} = \frac{(P_{People} + P_{Lighitng})}{3.412}$$

$$Q_{HVAC} = \frac{3500\ beta_t}{3.412}$$

$$\text{where } \dot{\mathrm{V}}_{\mathrm{vent}} = 42.32\ \mathrm{CFM}$$

Heat Transfer Equations

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



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

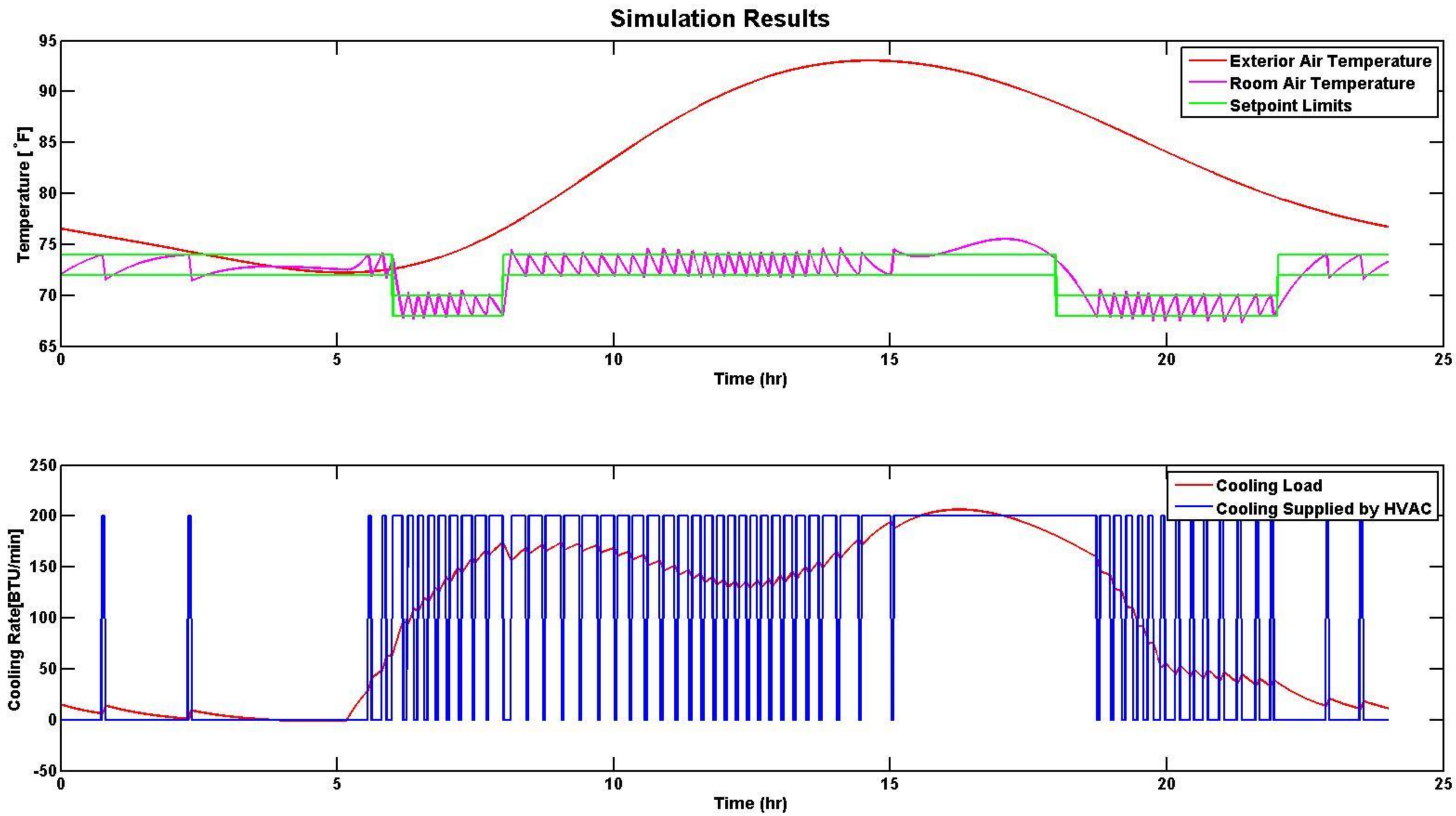
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

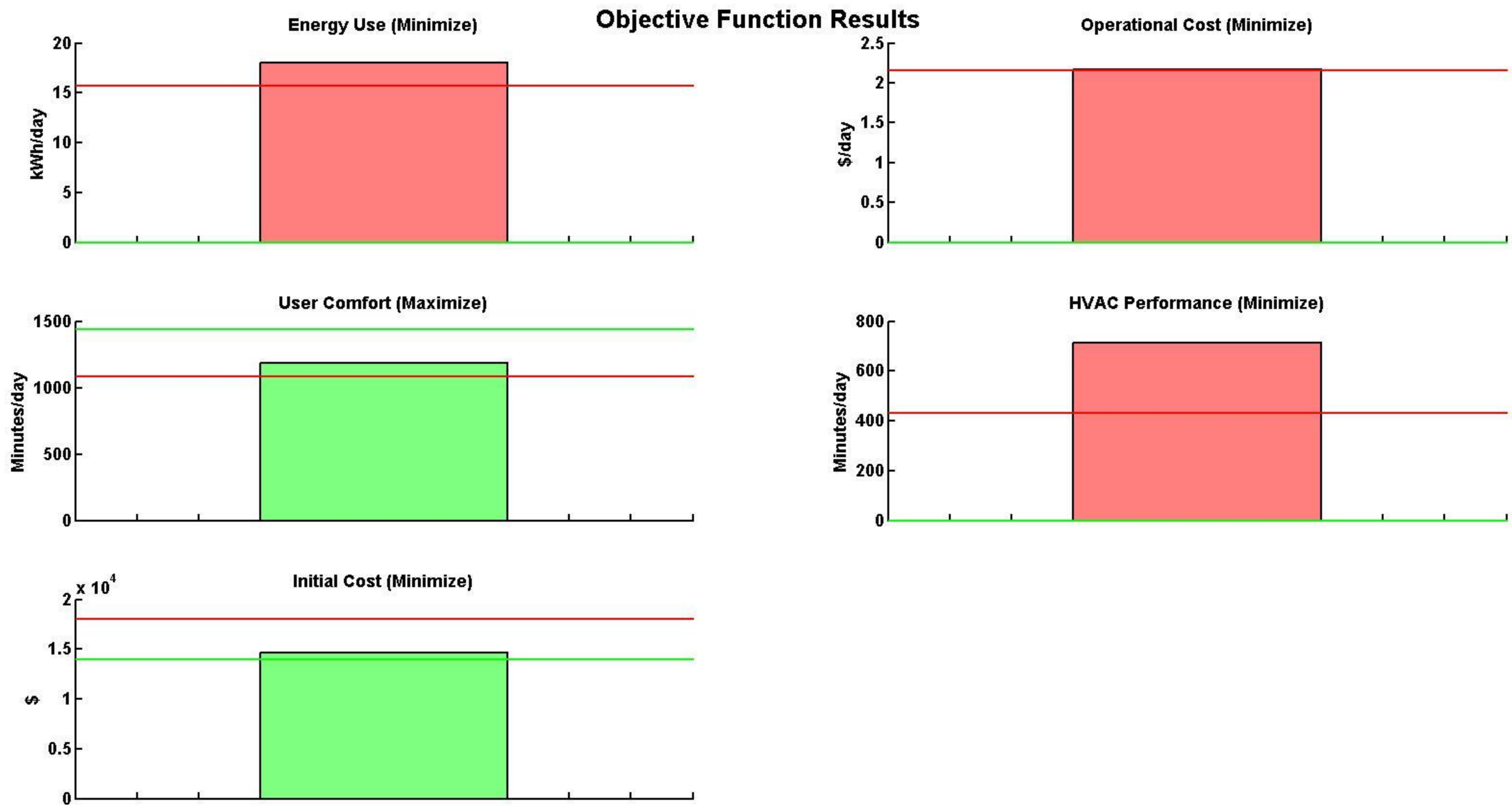
MULTI-OBJECTIVE OPTIMIZATION

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

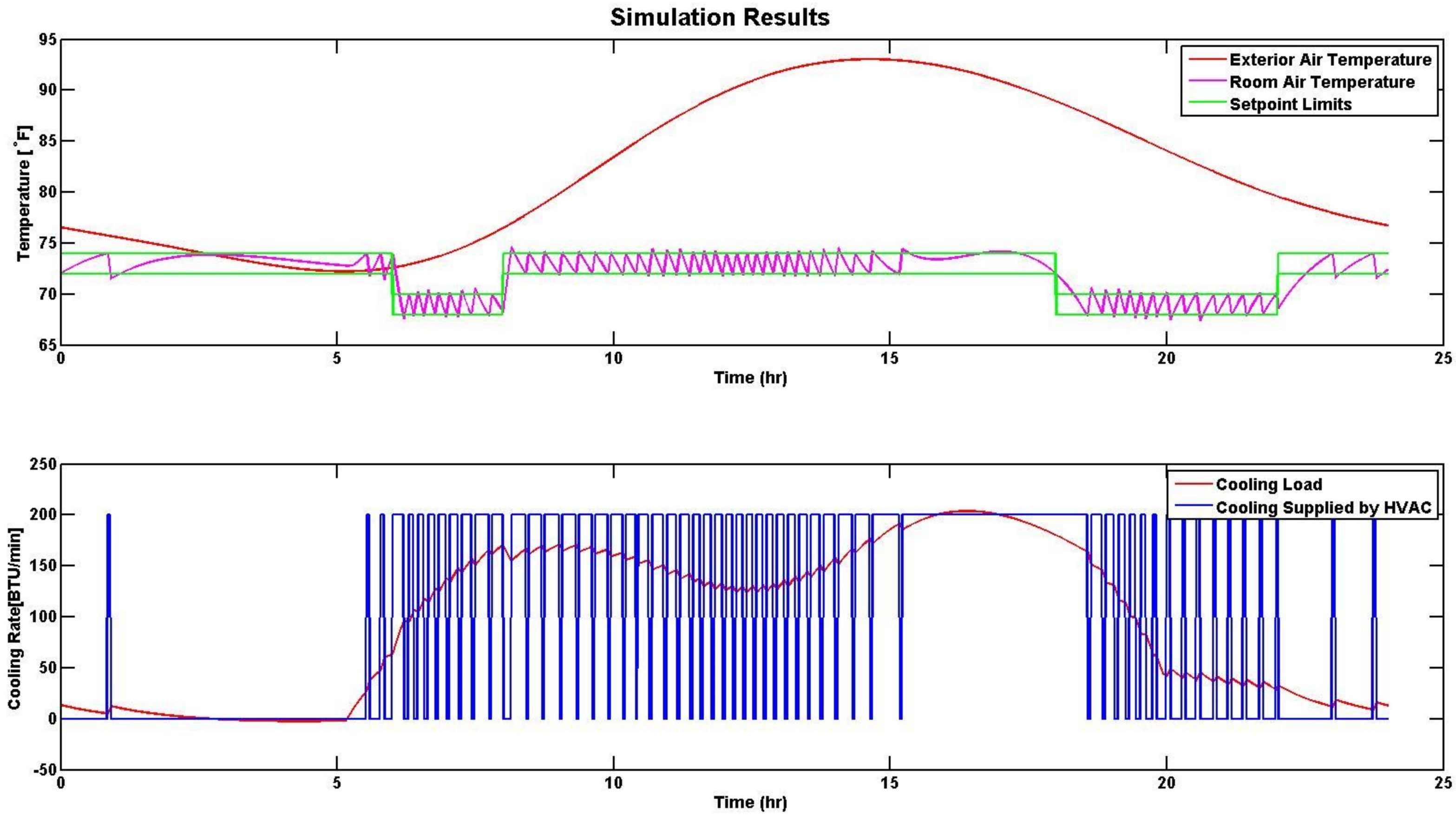
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

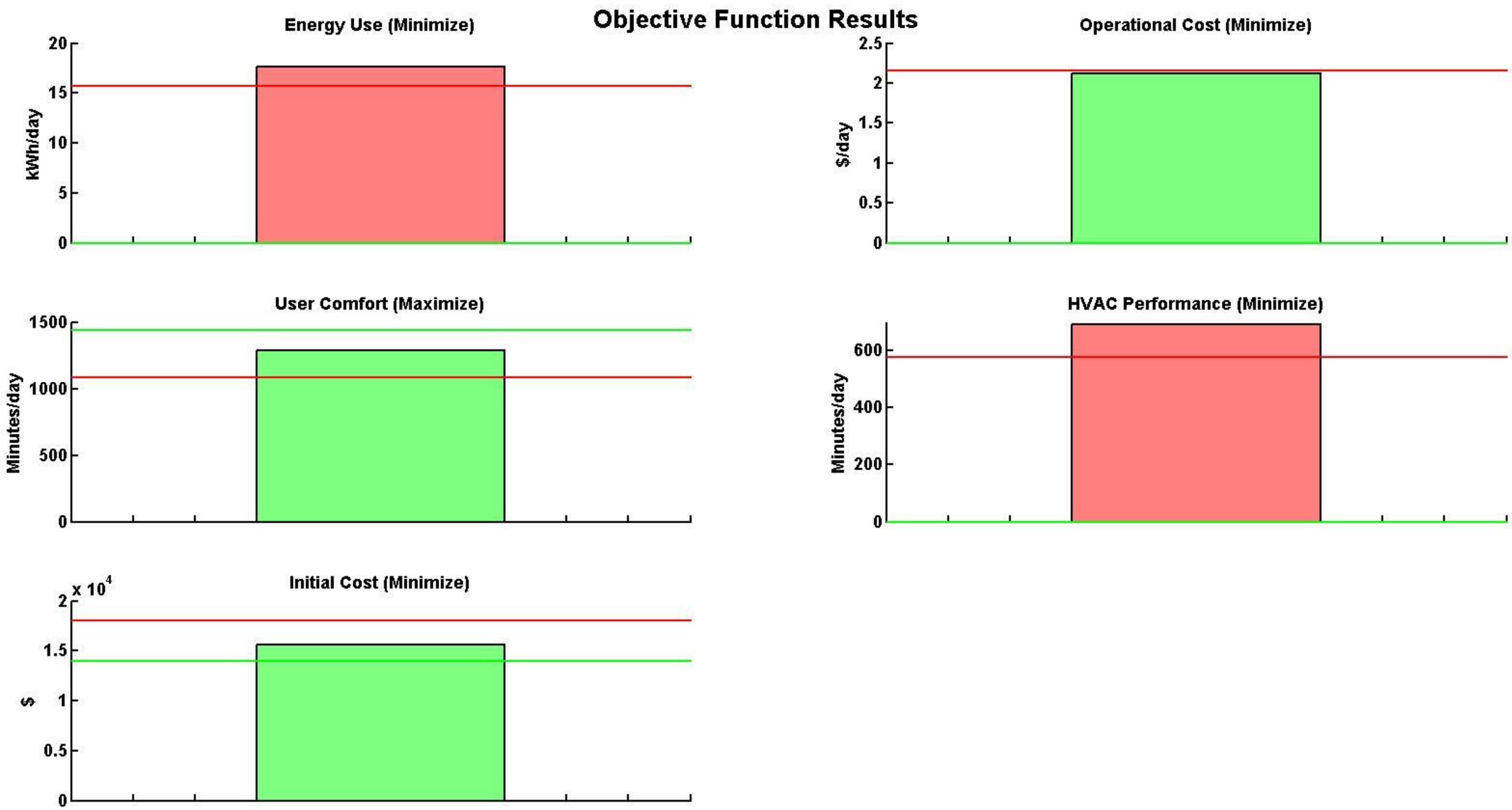
MULTI-OBJECTIVE OPTIMIZATION

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

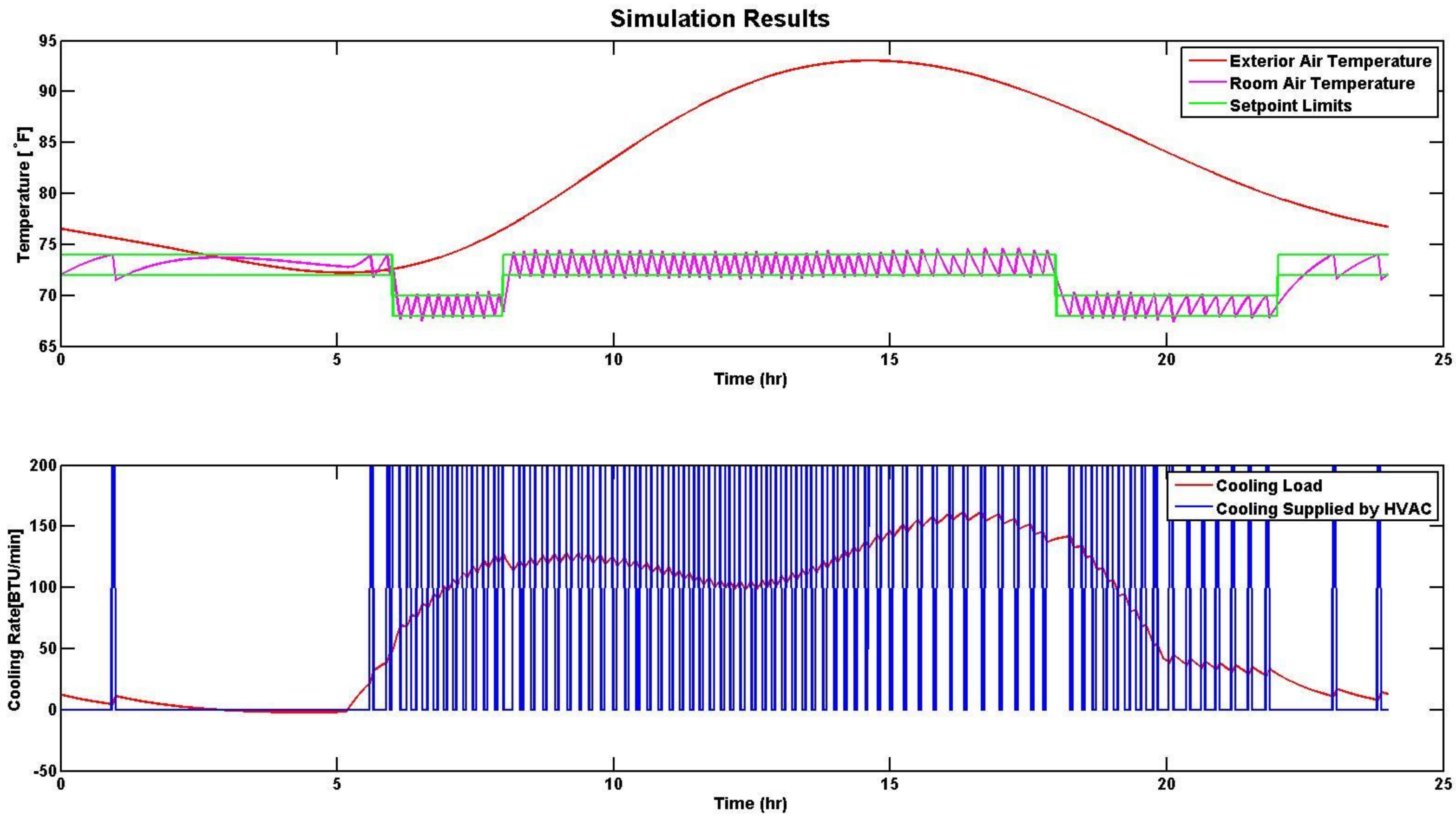
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

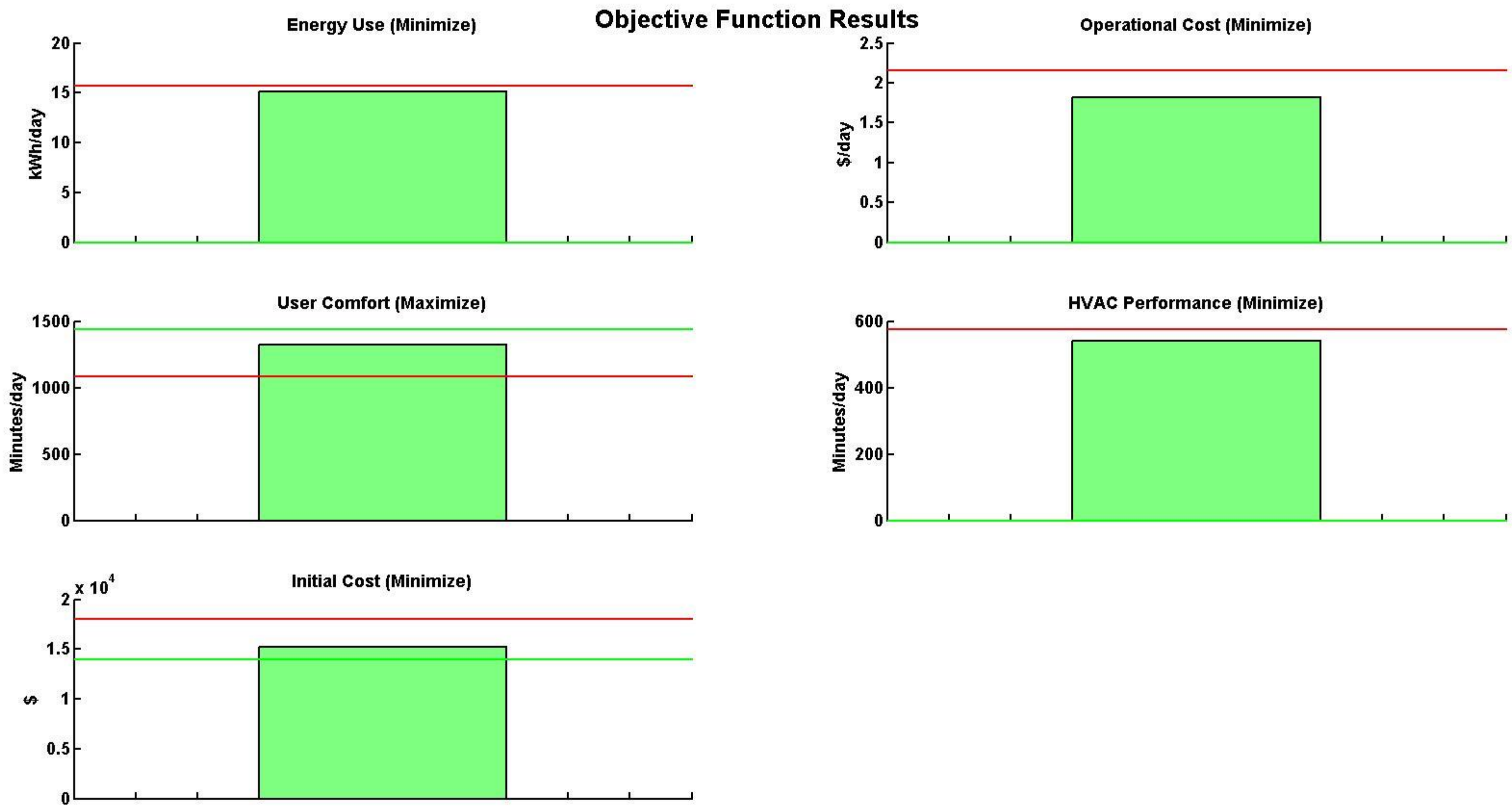
MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation

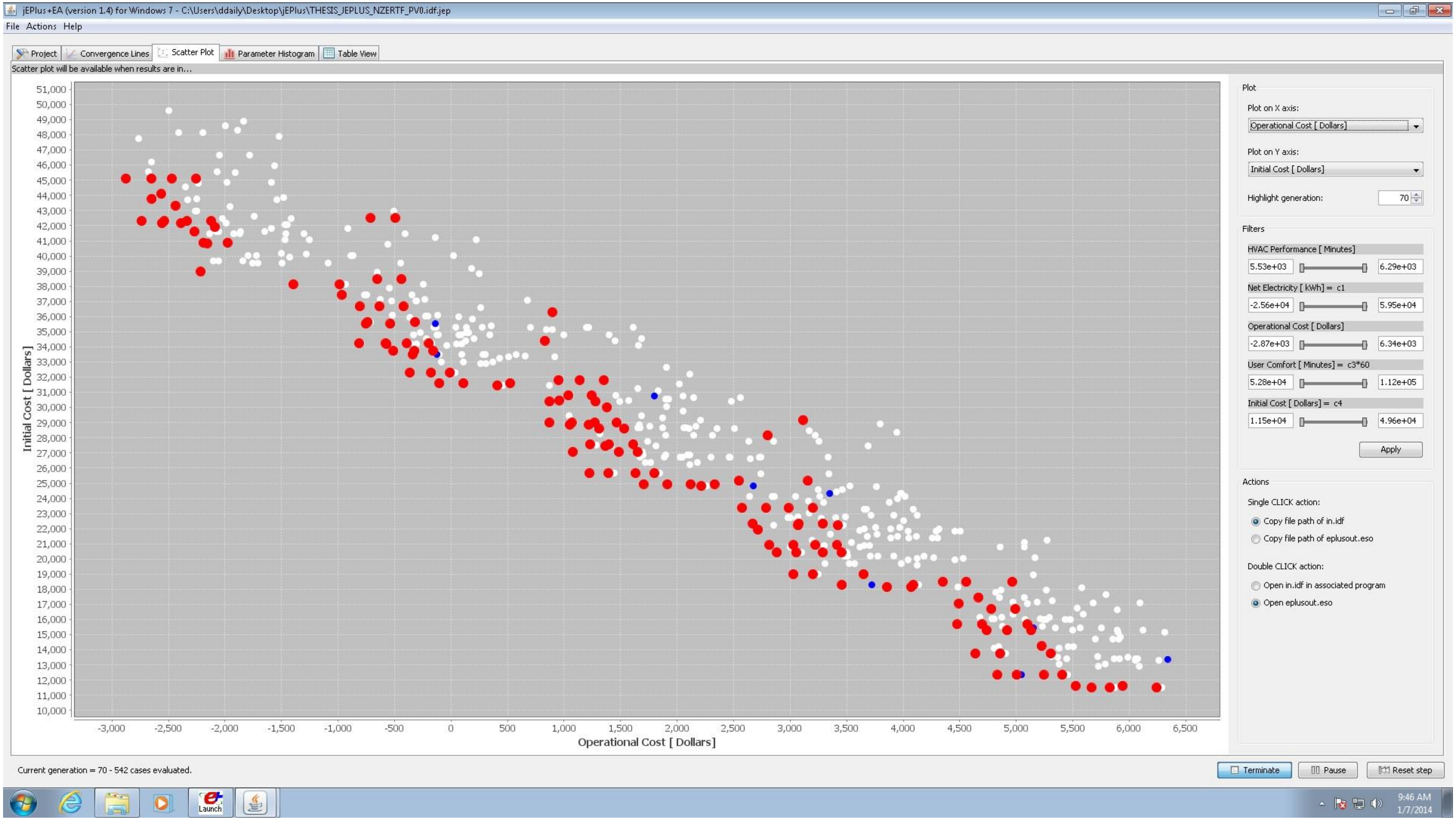


Conclusions

- Multi-Objective Optimization for DSE is a helpful tool for a designer
- Consol Optcad's FSQP solver can provide multiple feasible designs and effectively inform the designer the impact of the design across multiple objectives
- This problem should be scaled up in size and complexity in order to test its effectiveness, but the strengths are demonstrated and highlighted by this example
- The method's strength lies in its speed and multi-objective optimization capabilities, however, the model is very basic in its current state. We would like to have a tool that has all three properties.

JEPLUS+EA OPTIMIZATION

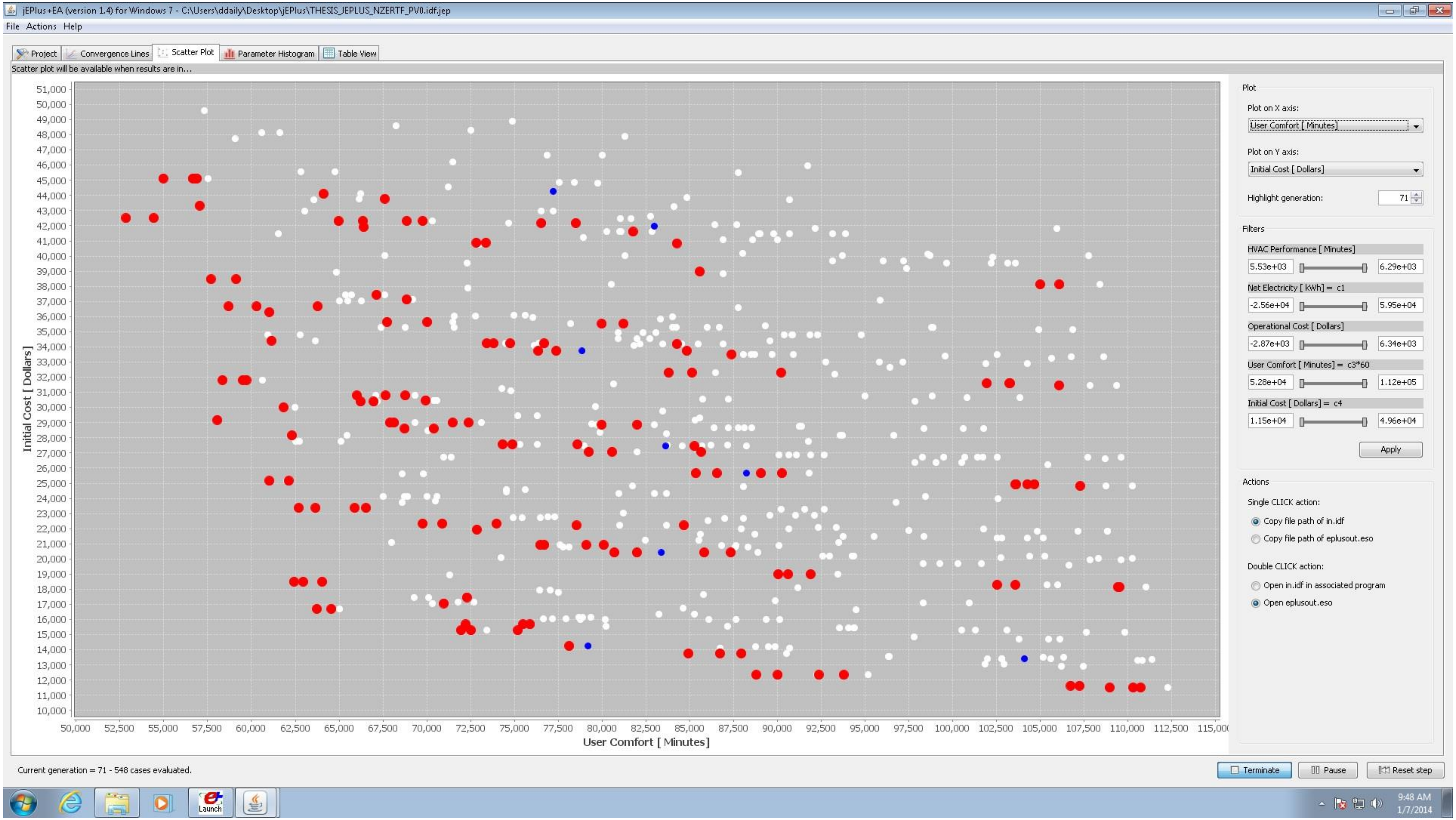
Simulation



The Institute for Systems Research

JEPLUS+EA OPTIMIZATION

Simulation



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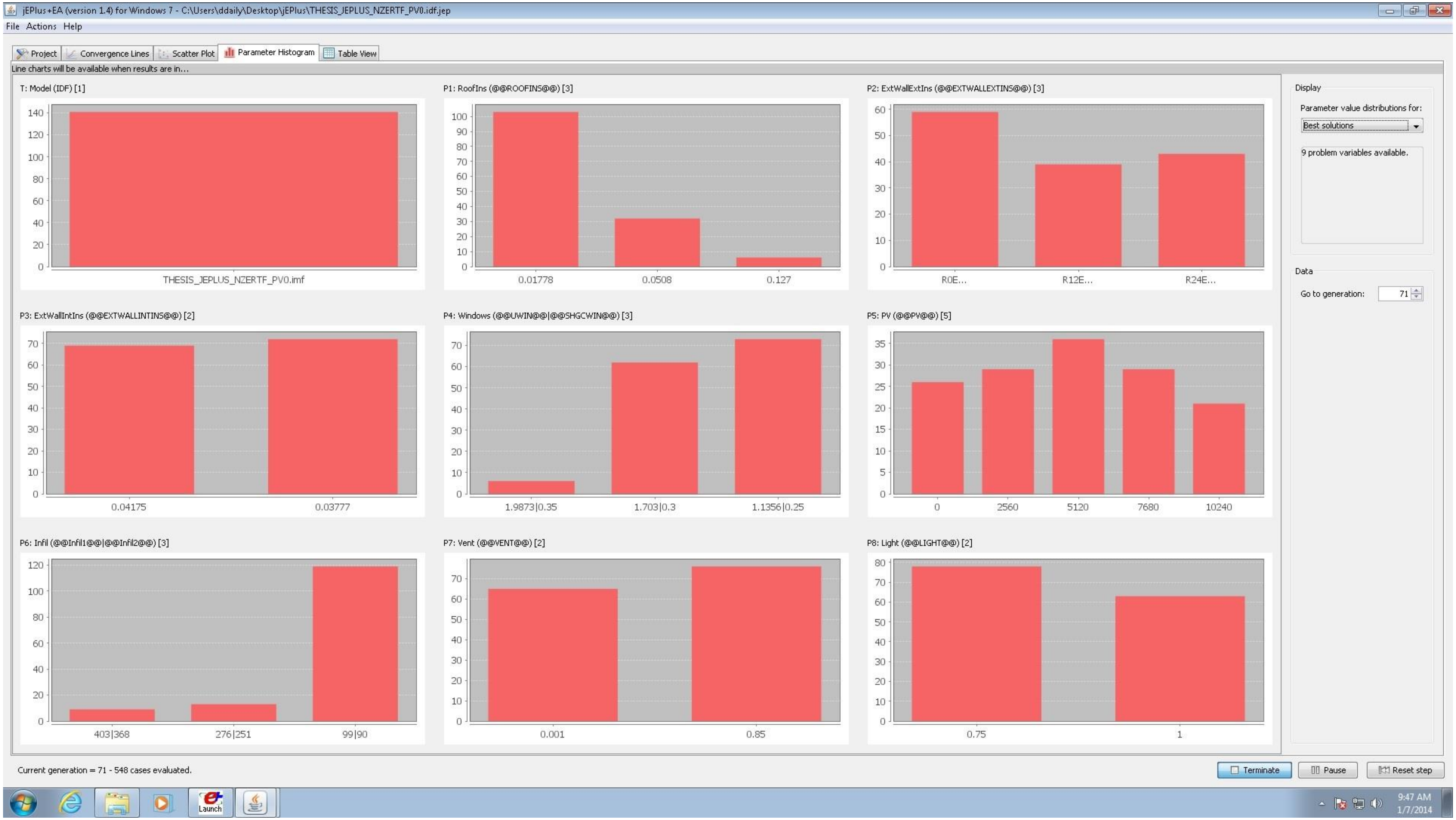


MBSE FOR ENERGY EFFICIENT BUILDINGS: CONCLUSIONS

Conclusions

- Detailed, Simulation-Based DSE Exploration is necessary when trying to design retrofits for energy efficient buildings.
- There exist programs that reduce the time necessary for a detailed DSE by:
  - reducing the time it takes to perform a simulation
  - reducing the number of simulations required through the use of optimization
- BEopt's model is abstracted to the point that its results should be considered near-optimal
- Consol Optcad is a powerful solver but is not designed specifically for buildings unlike the other two programs
- jEPlus is currently the best tool through its use of Evolutionary Algorithms to reduce the number of simulations necessary; however, the other two methods still provide insight into what the next generation of tools will include.

MBSE FOR ENERGY EFFICIENT BUILDINGS: CONCLUSIONS

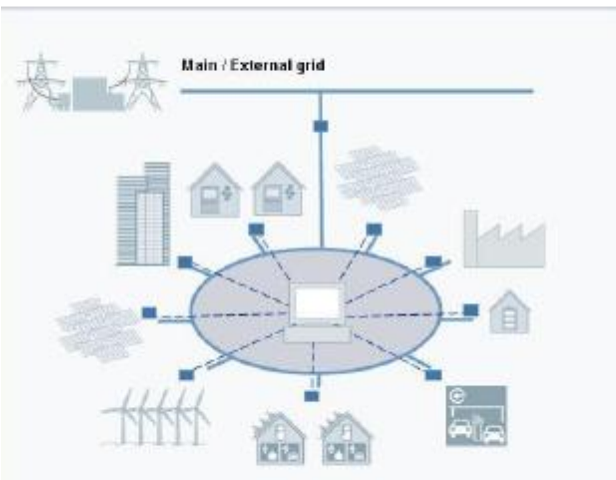
- Consol Optcad allows for real time interaction with the simulator. This gives the designer the ability to adjust parameters of the optimization problem as the problem is progressing. Functionality like this gives the designer an opportunity to alter the path of convergence to global optima more suited to the homeowner's needs. jEPlus allows for EA properties to be changed (like population or max generations) mid optimization, however, this does not change the properties of the system being simulated and does not have the same effect. Such dynamic functionality will enhance the capabilities of the designer.

- EnergyPlus is the main, free building simulator in the industry but it is limited in its capability since it is a steady state approximation. An improved model could reduce simulation times while capturing a wider scope of effects such as transients. All of this could be performed without sacrificing accuracy or detail. EnergyPlus is working with Modelon to rewrite EnergyPlus in Modelica which will be a good step in improving the model.

- Current multi-objective optimization tools do not integrate complex controllers very well into the energy model. MLE+ is a new tool that allows for MATLAB controllers to be written for EnergyPlus components and co-simulated. Not only does this bring the capabilities of MATLAB for controller design, but it allows for component level optimization *inside* the simulation with MATLAB Optimization Toolbox. Up until now, we have been optimizing the way the simulations are run rather than the simulation itself. Currently, jEPlus, BEopt, and MLE+ are not compatible, however, it will be necessary to merge these capabilities, especially as more complex systems are develop in and around the home.

Integrating Siemens PLM Tools for MBSE in Energy Efficiency

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

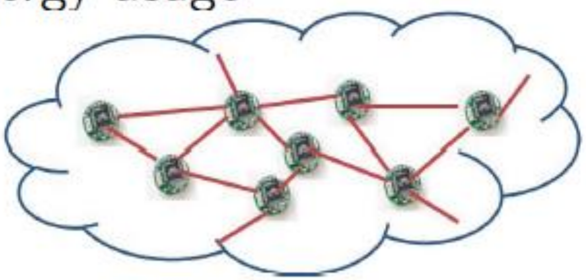


- Smart-grids at various scales from a few houses to neighborhoods to regions
- Retrofit design of existing houses for improved energy efficiency
- Zero or positive energy houses by design
- Partitions and design elements (4GD)
- Manufacturing (read Construction) process management
- Collaborative design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

Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

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



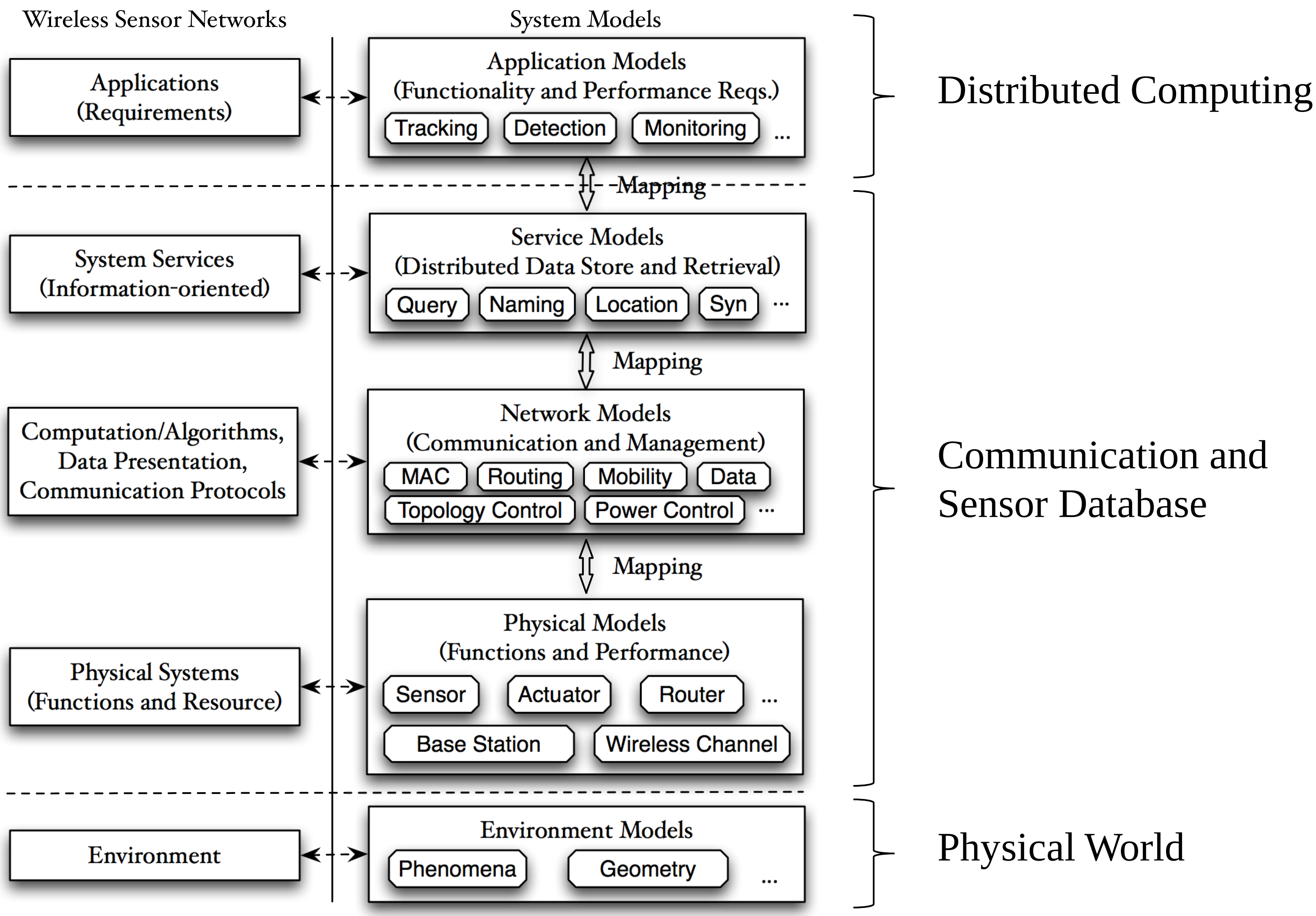
MBSE for Wireless Sensor Networks: Contributions

- 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

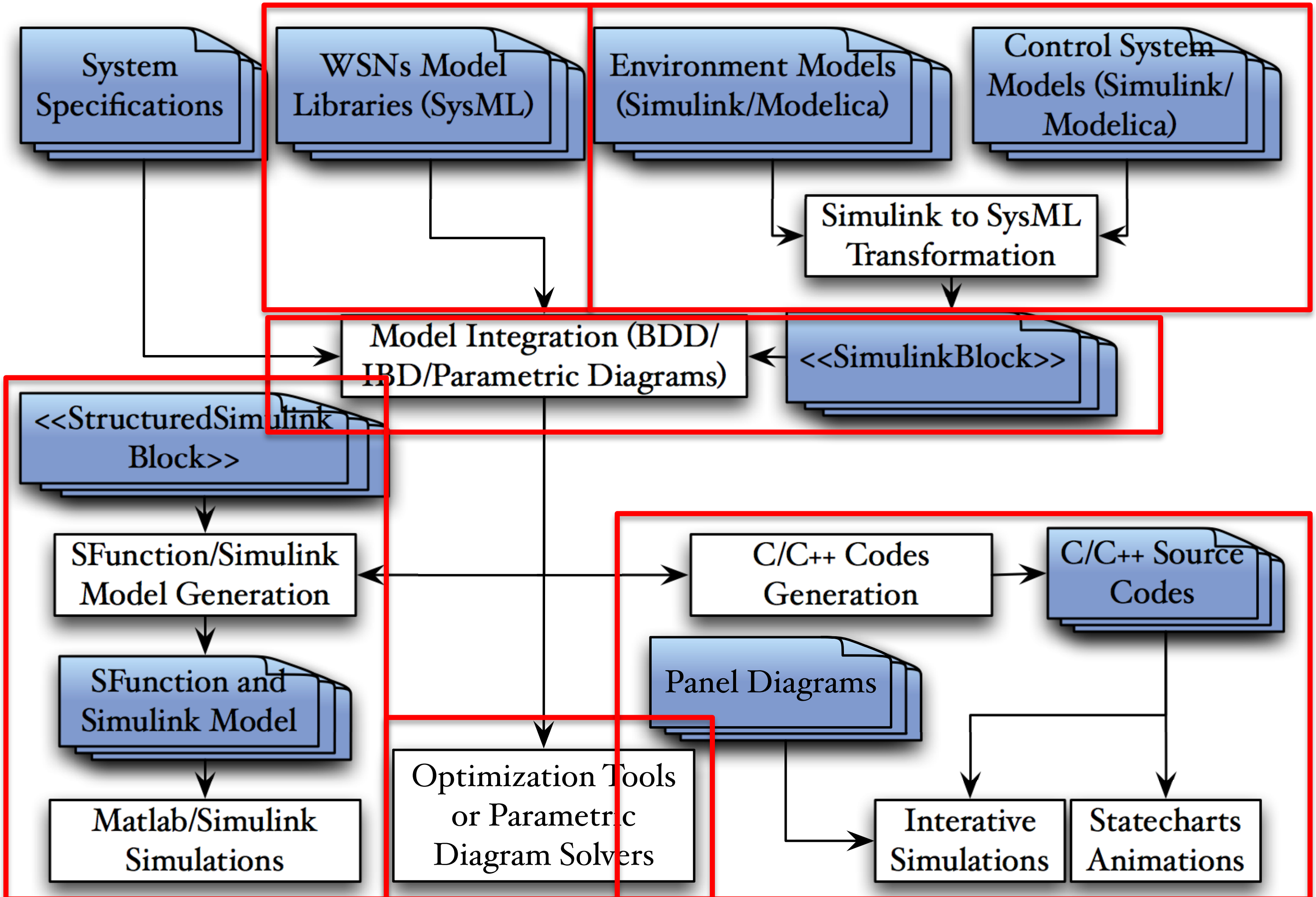
System Framework

- 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

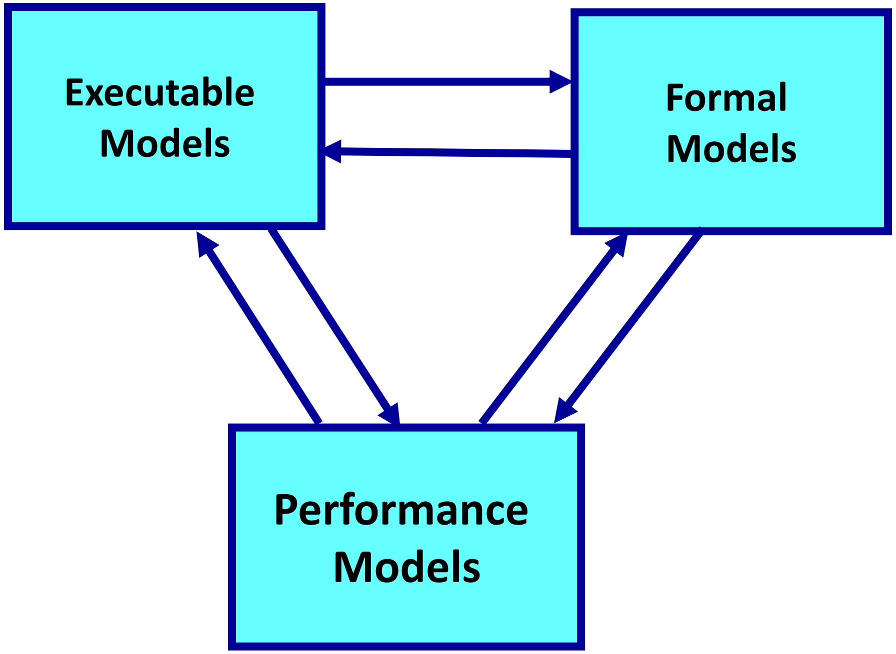
System Framework



MBSE for Sensor Networks



Component-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 :

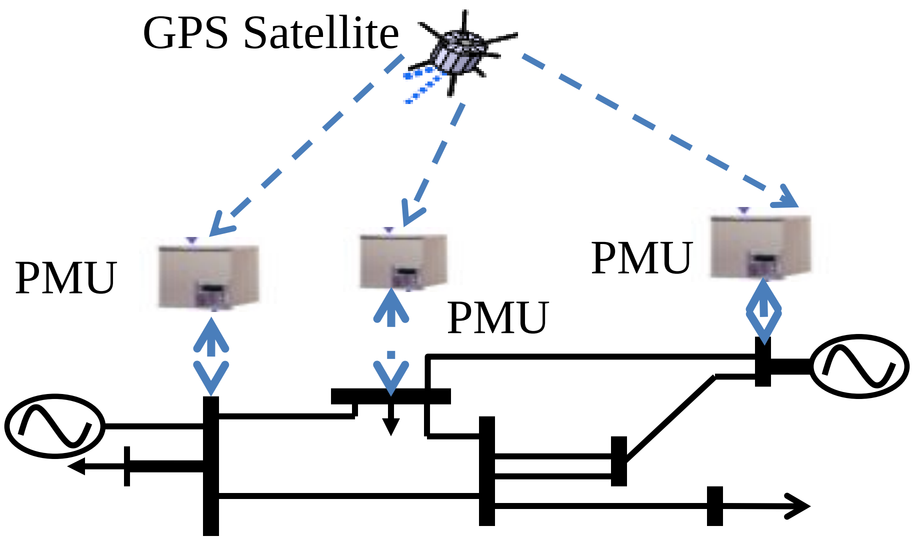
- **Under what conditions can the composition of these protocols be provably secure?**
- **Investigate time and resource requirements for achieving this**

Power Grid Cyber-security

- Inter-area oscillations (modes)
  - Associated with large inter-connected power networks between clusters of generators
  - Critical in system **stability**
  - Requiring **on-line** observation and control

- Automatic estimation of modes
  - Using currents, voltages and angle differences measured by PMUs (Power Management Units) that are distributed throughout the power system

Distributed Estimation



N multiple recording sites (PMUs) to measure the output signals

- To compute an accurate estimate of the state *x* (*k*), using:
  - **local measurements** $y_j(k)$;
  - information received from the PMUs in its **communication neighborhood**;
  - confidence in the information received from other PMUs provided by the **trust model**

Problem Formulation

- We assume that some agents can become faulty or under the control of non-authorized entities that can cause the respective agents to spread false data on the power grid to the other agents.

- Our goal is to propose a strategy aimed at limiting the effect of false data injection on the state estimate computation, based on the notion of *trust*.

Trust Model

- To each information flow (link) $j \rightarrow i$, we attach a positive value T_{ij}, which represents the **trust** PMU i has in the information received from PMU j;

- Trust interpretation:
  - *Accuracy*
  - *Reliability*

- **Goal:** Each PMU has to compute ***accurate estimates*** of the state, by ***intelligently*** combining the measurements and the information from neighboring PMUs

Trust-based Multi-agent State Estimation

Algorithm 1: Distributed Filtering

Input: μ_0, P_0

1 Initialization: $\hat{x}_i = \mu_0$, $P_i = P_0$

2 **while** new data exists

3 Compute the filtering gain L_i

4 Compute the intermediate estimate of the state:

$$\varphi_i = \hat{x}_i + L_i(y_i - C_i \hat{x}_i)$$

5 Estimate the state after a Consensus step:

$$\xi_i = \sum_{j \in \mathcal{N}_i} w_{ij} \varphi_j$$

6 Update the state of the local filter:

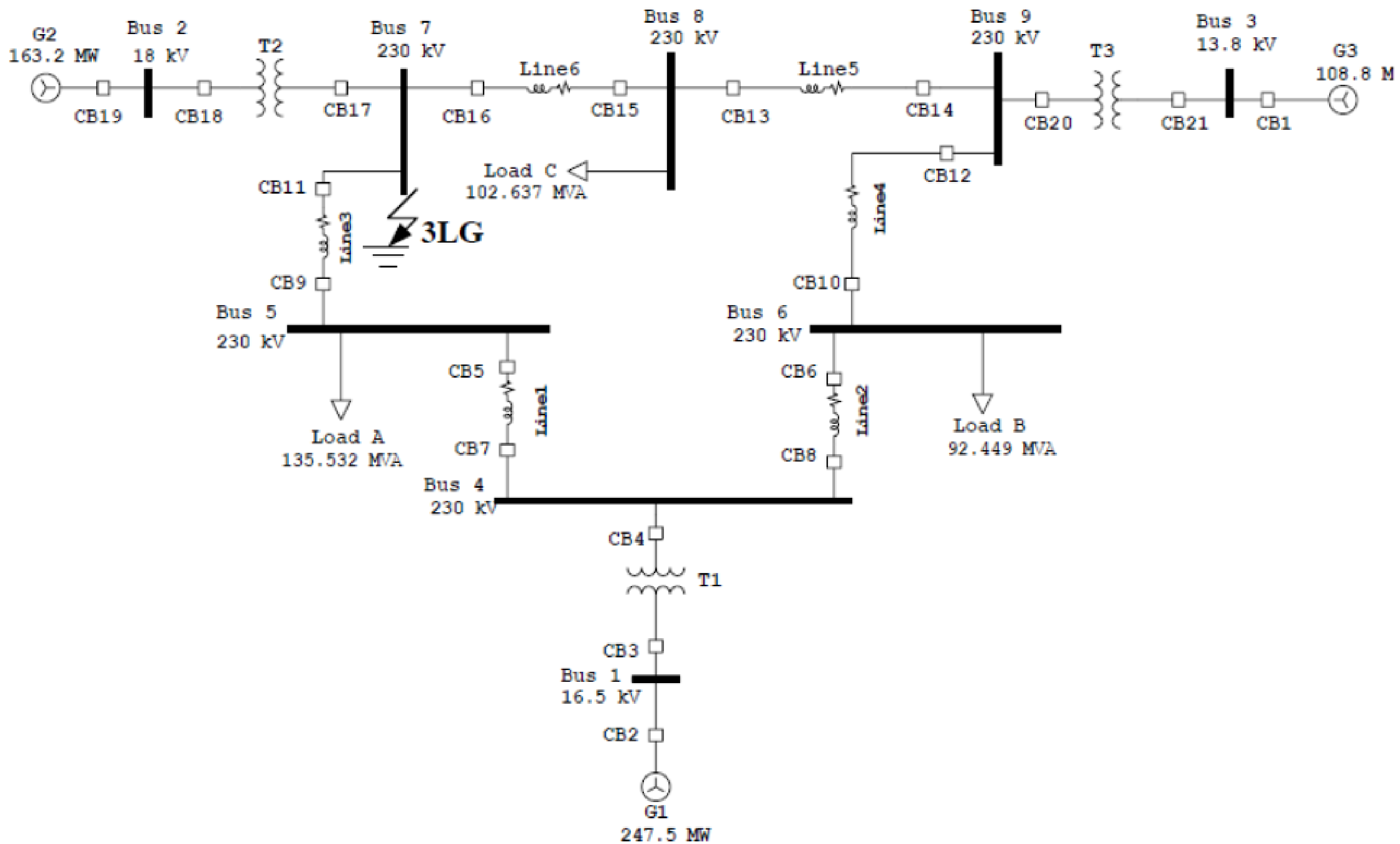
$$\hat{x}_i = A \xi_i$$

- Does not require global information about the power grid topology
- Ensures greater robustness in computing the state estimate

- **Main idea:** pick the weights w_{ij} to be trust dependent

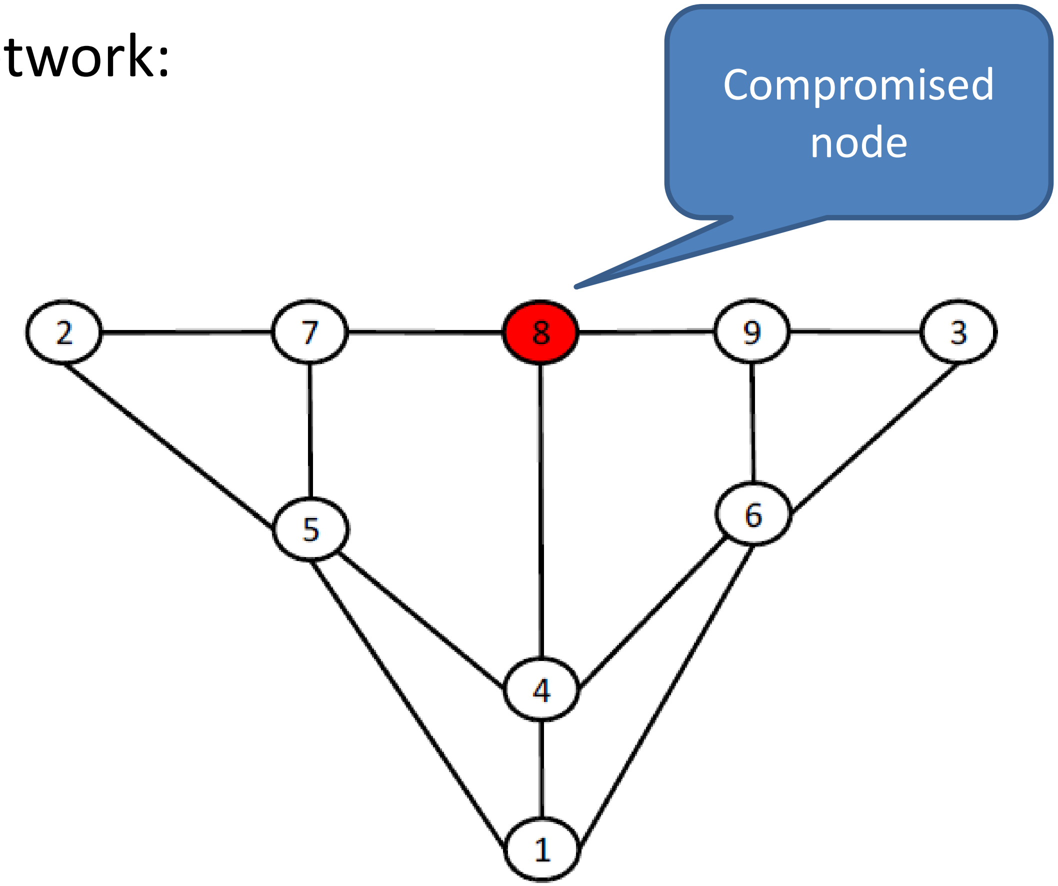
Numerical Example

- 3-generators, 9-bus system:

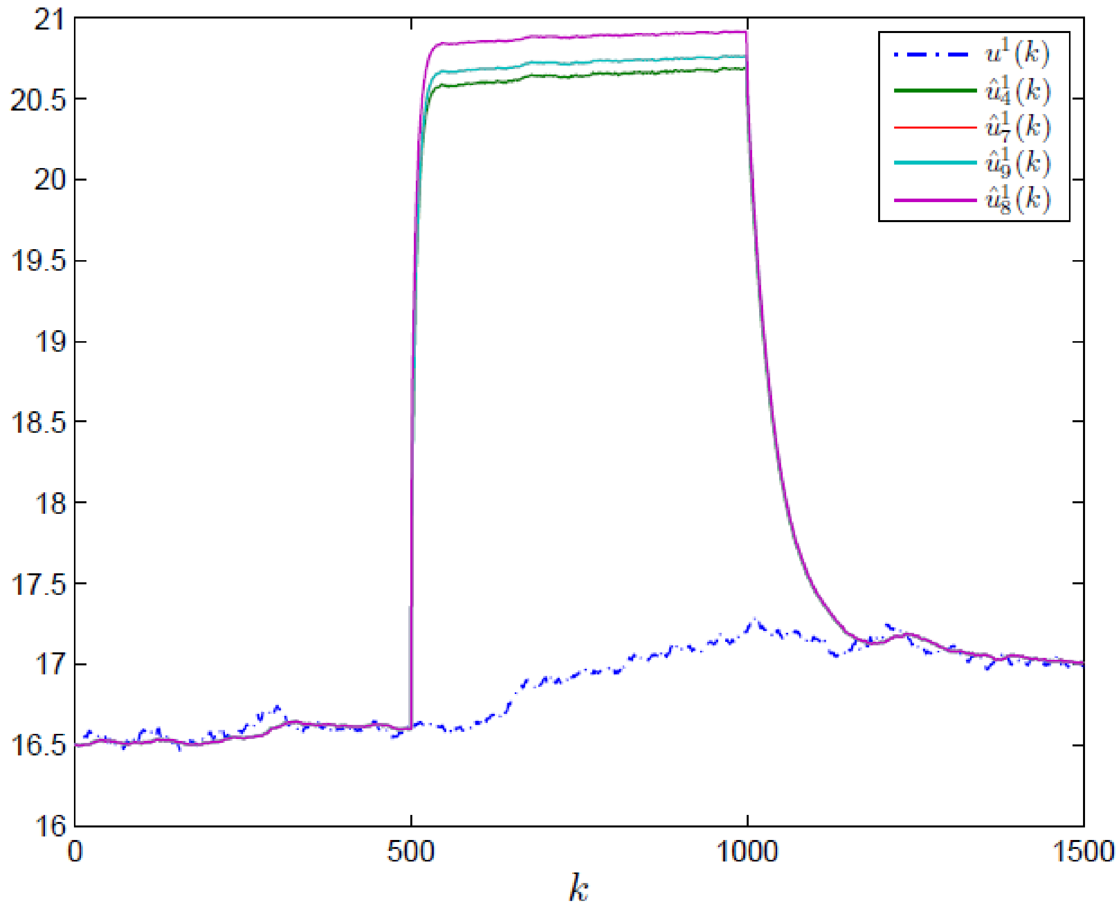


Numerical Example (cont.)

- PMU network:

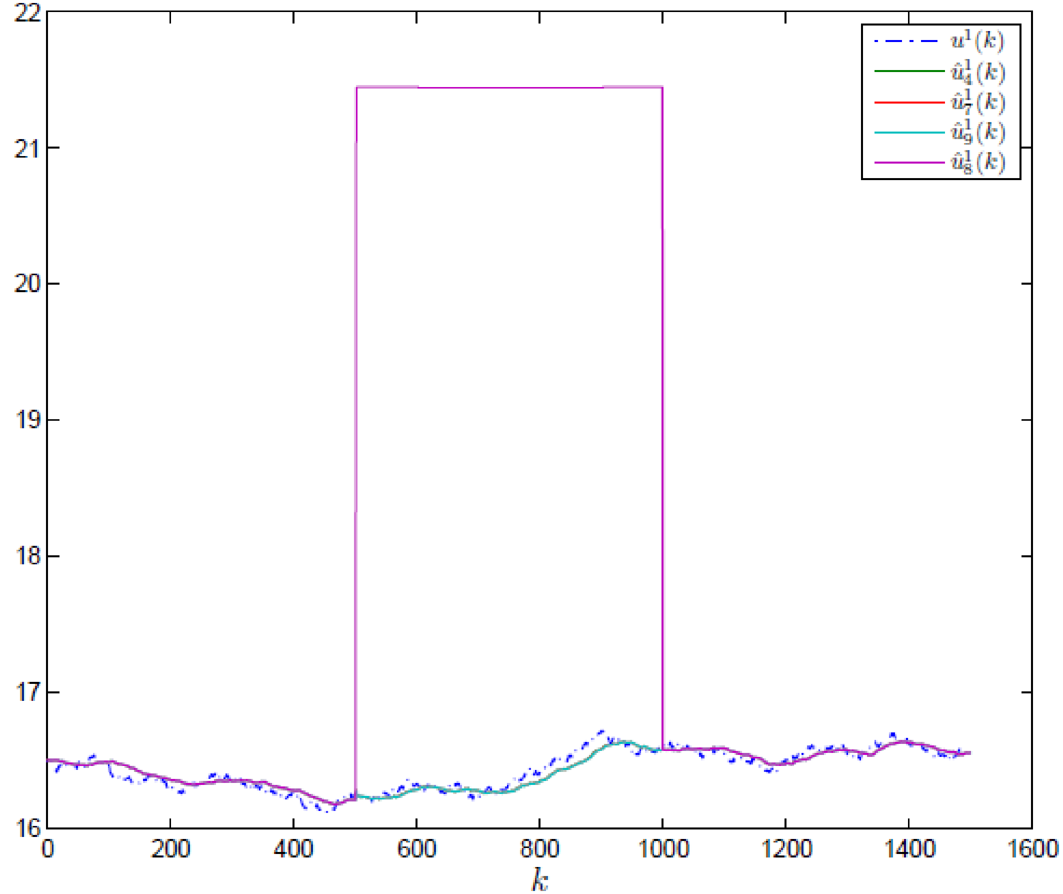


Numerical Example (cont.)



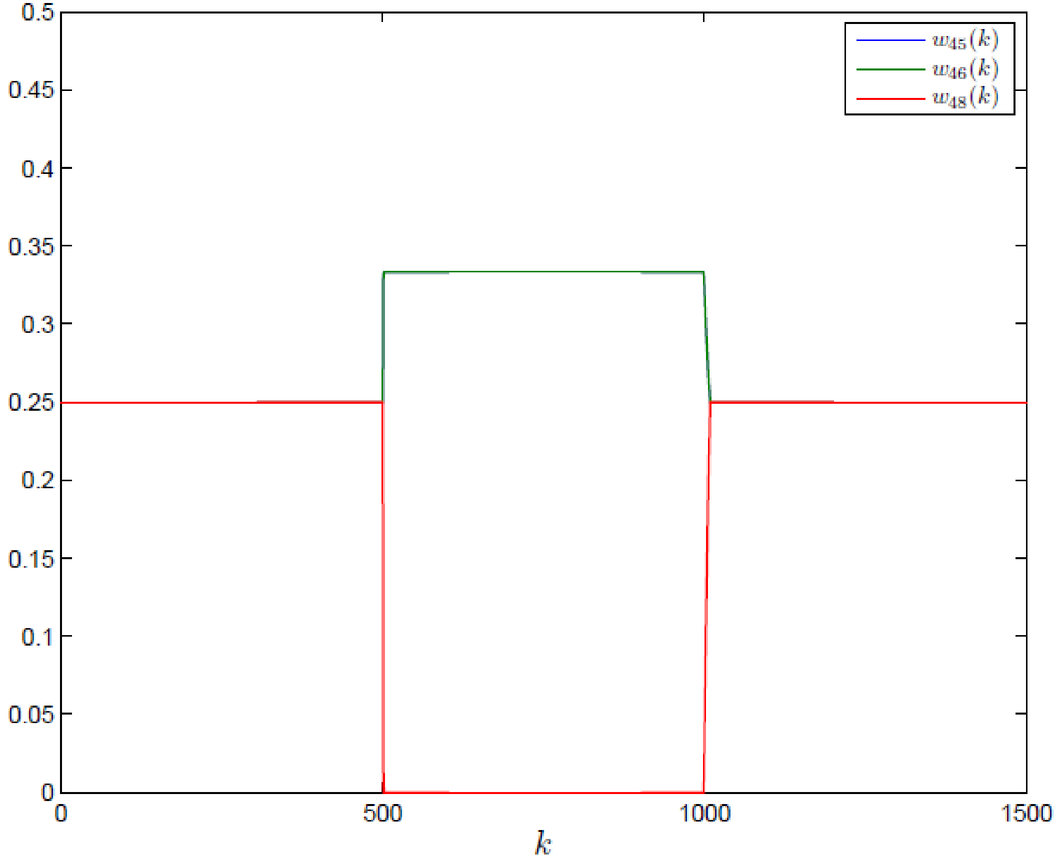
- Estimates of the voltage at bus 1 using Algorithm 1, with agent 8 injecting false data

Numerical Example (cont.)



- Estimates of the voltage at bus 1 using Algorithm 3, with agent 8 injecting false data

Numerical Example (cont.)



- The evolution of agent 4's weights

Thank you!

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Questions?