# Towards a Rigorous Framework for Model-Based Systems Engineering and Applications

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The Institute for Systems Research

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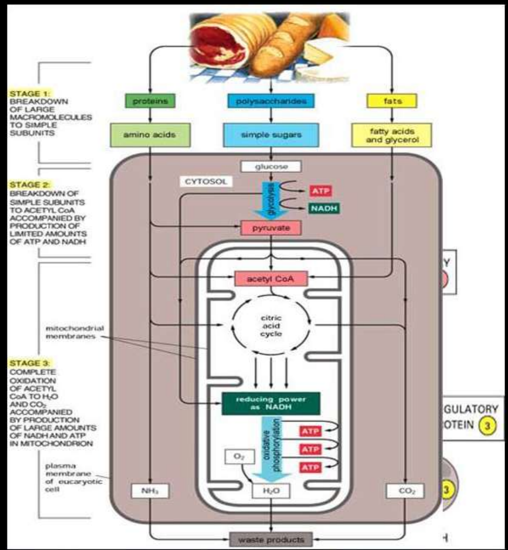
# The "Hottest" Job Market Currently

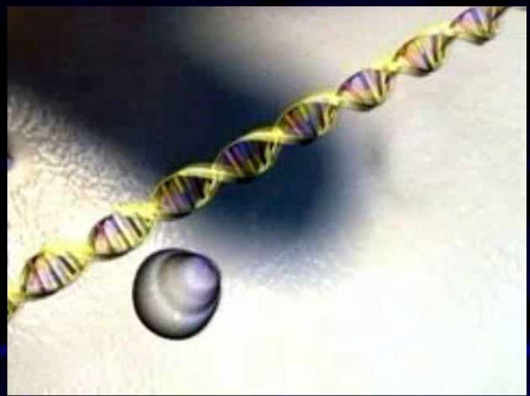
**"The Nation that has the System Engineers has the Future"**

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

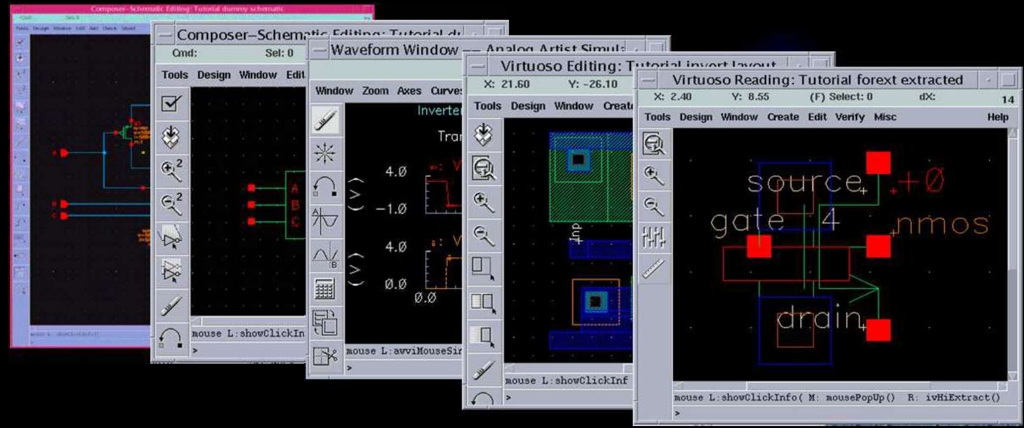
# From IT abstractions to “hardware” (Baras lecture --- 2003 White Symposium)

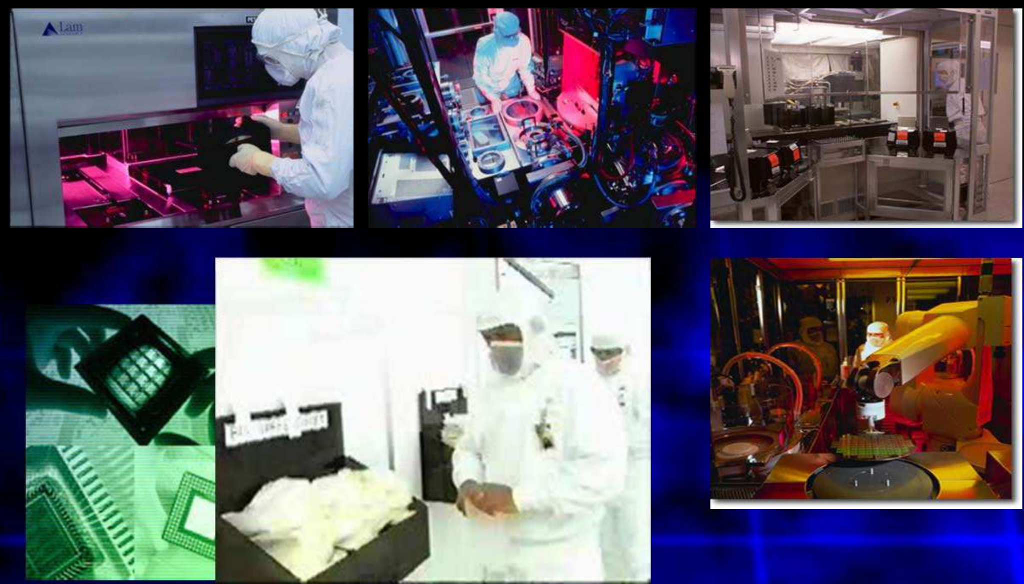
From DNA ‘programs’ to living organisms





From CAD schematics to chips



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# What has happened since then?

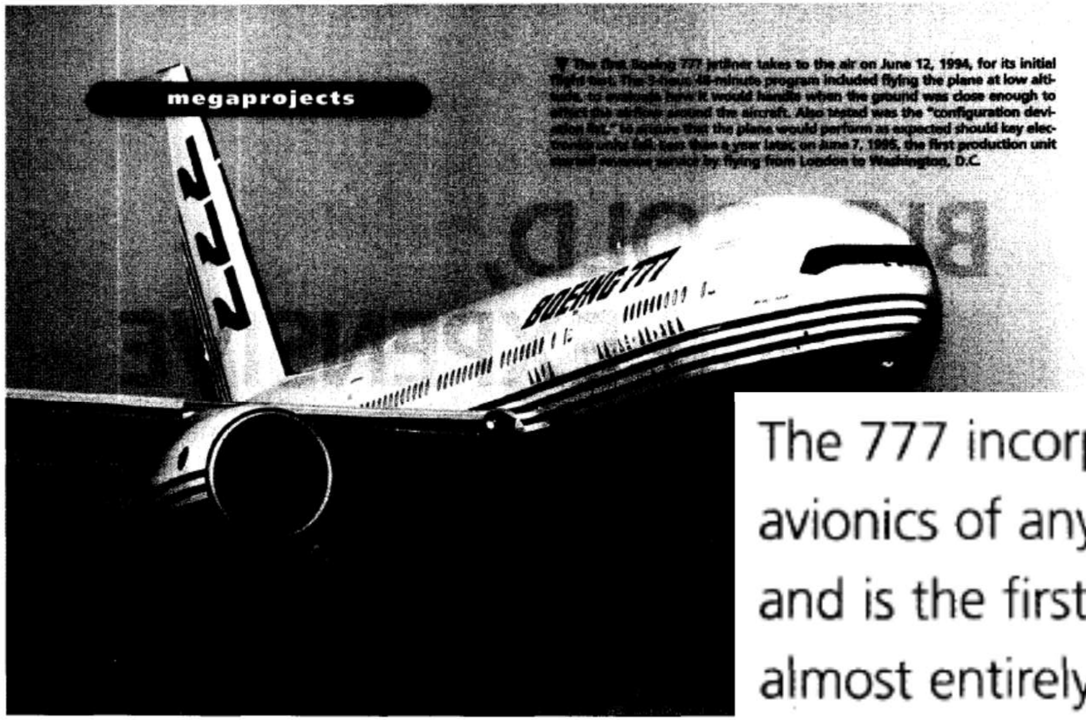
- Design and manufacturing of Boeing 777 aircraft, and then Boeing 787 aircraft …
- Humans become integral part of systems -- *iPhone*, …
- Cyber-Physical Systems (CPS) …
- Social networks over the Web mushroomed …
- Economic networks over the Web mushroomed …
- Renewable energy, smart grid …

# What has happened since then?

- Individual human genome generation becomes fast, inexpensive …
- Multisensory environmental monitoring spreads…
- Autonomous and connected cars designed and tested …
- Cloud Computing, “Big Data”, …
- Health information technology spreads …
- “Crowd sourcing” and manufacturing …

# Boeing's Seventh Wonder

**(*IEEE Spectrum, 1995 October*)**




The 777 incorporates the most advanced avionics of any commercial U.S. aircraft and is the first plane of any kind to be almost entirely computer-designed

## BOEING'S SEVENTH WONDER

### Fresh start

The answers are in the new technology used in the 777 itself, and in the design-engineering revolution that stormed through Boeing, based in Everett, Wash., during the creation of its first all-new jetliner since the early 1980s. Advances in electronics and in computer-aided design, manufacture and simulation provided the foundation for the new technology. Using these tools and systems to an unprecedented extent, Boeing was able to start afresh with the 777, changing the way in which the company builds aircraft. The results have been so dramatic that practically every new Boeing flight product—from the new generation of the venerable 737 family and F-22 air superiority fighter to International Space Station and the proposed X-33 reusable launch vehicle—is adopting some part of the program pioneered by the 777.

GUY
Cont
E

# BOEING 787: CLEANER, QUIETER, MORE EFFICIENT

The 787 Dreamliner delivers:

20%* reduction in fuel and $CO_2$

28% below 2008 industry limits for NOx

60%* smaller noise foot print

*Relative to the 767

# iPhone -- Smartphone




A remarkably innovative systems integration

Attention to the user

# The device that can do "everything"

**Mobile wallet gains currency**

- September 14, 2011 5:56 pm

He not usually avoids carrying to fail by his wallet and reason adult a line, though a drumming also automatically adds faithfulness points to his Walgreens' faithfulness card, also stored in his phone, and can assistance him redeem any banking he competence have downloaded from a Internet.

Soon, he will be means to do a same for his favorite sandwich during Subway. McLaughlin, arch rising payments officer during Mastercard, has been one of a initial to try out a Google Wallet mobile compensate complement introduced by a Internet hulk in May in partnership with Citigroup and Mastercard Worldwide.

http://wn.com/Google_Wallet

Google Wallet


BBC NEWS

TECHNOLOGY

**19 May 2011** Last updated at 20:47 ET

## Mobile wallet offered to UK shoppers

GOOGLE, CITI, MASTERCARD, FIRST DATA AND SPRINT TEAM UP TO MAKE YOUR PHONE YOUR WALLET

Google Wallet will enable consumers to tap, pay and save with their phones

NEW YORK, May 26, 2011 /CNW/ – At an event today, Google, Citi, MasterCard, First Data and Sprint announced and demonstrated Google Wallet, an app that will make your phone your wallet so you can tap, pay and save money and time while you shop. For businesses, Google Wallet is an opportunity to strengthen customer relationships by offering a faster, easier shopping experience with relevant deals, promotions and loyalty rewards.

## Mobile Wallets: Security and Privacy Questions Raised By New Google App


First Posted: 9/20/11 07:32 PM ET Updated: 9/20/11 07:32 PM ET

React

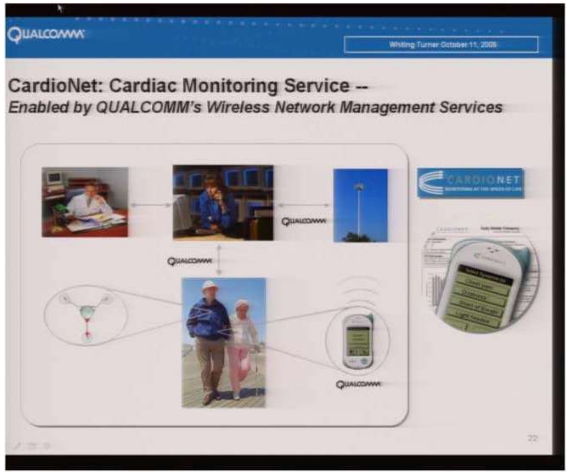
It is billed as the future of commerce: swiping a smartphone at the checkout counter instead of a credit card.

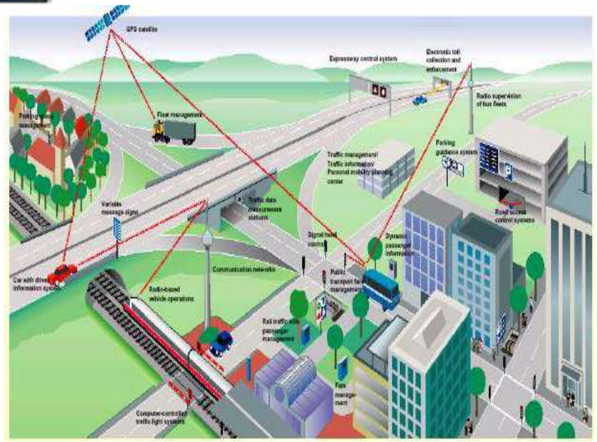
On Monday, Google made its foray into the budding market of mobile payment systems by launching Google Wallet, an app that stores users' credit card information on their phones, allowing them to purchase goods by swiping their phones at stores.

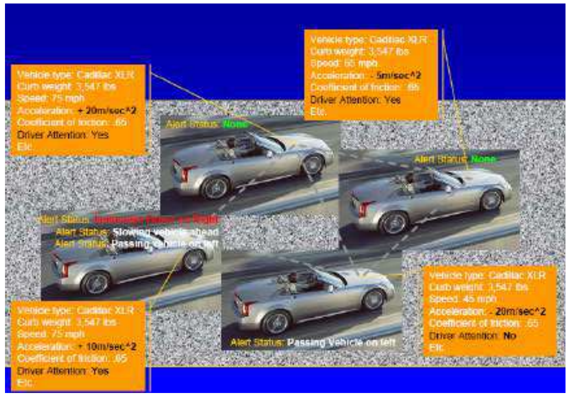
# Future “Smart” Homes and Cities

- UI for “Everything”
  - Devices with Computing Capabilities & Interfaces
- Network Communication
  - Devices Connected to Home Network
- Media: Physical to Digital
  - MP3, Netflix, Kindle eBooks, Flickr Photos
- Smart Phones
  - Universal Controller in a Smart Home
- Smart Meters & Grids
  - Demand/Response System for “Power Grid”
- Wireless Medical Devices
  - Portable & Wireless for Real-Time Monitoring

# Wireless and Networked Embedded Systems: Ubiquitous Presence



# A Network Immersed World

A complex collection of sensors, controllers, compute nodes, and actuators that work together to improve our daily lives

- From very small: Ubiquitous, Pervasive, Disappearing, Perceptive, Ambient
- To very large: Always Connectable, Reliable, Scalable, Adaptive, Flexible

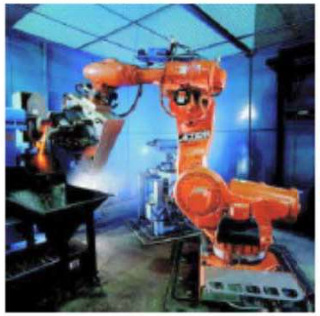
Emerging Service Models

- Building energy management
- Automotive safety and control
- Management of metropolitan traffic flows
- Distributed health monitoring
- Smart Grid

# CYBER-PHYSICAL SYSTEMS


Automotive


Aeronautics



Industrial automation

Robotics

Elevators

Building automation

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# Fundamental Challenges

**Our research identified the following fundamental challenges for the modeling, design, synthesis and manufacturing of CPS:**

- Framework for developing cross-domain **integrated modeling hubs** for complex systems;
- Framework for linking these integrated modeling hubs with tradeoff analysis methods and tools for **design space exploration**;
- Framework of linking these integrated synthesis environments with **databases of modular component and process** (manufacturing) models, backwards compatible with legacy systems;
- Framework for translating textual requirements to mathematical representations as constraints, rules, metrics involving both logical and numerical variables, **allocation of specifications** to components, to enable automatic **traceability** and **verification**.

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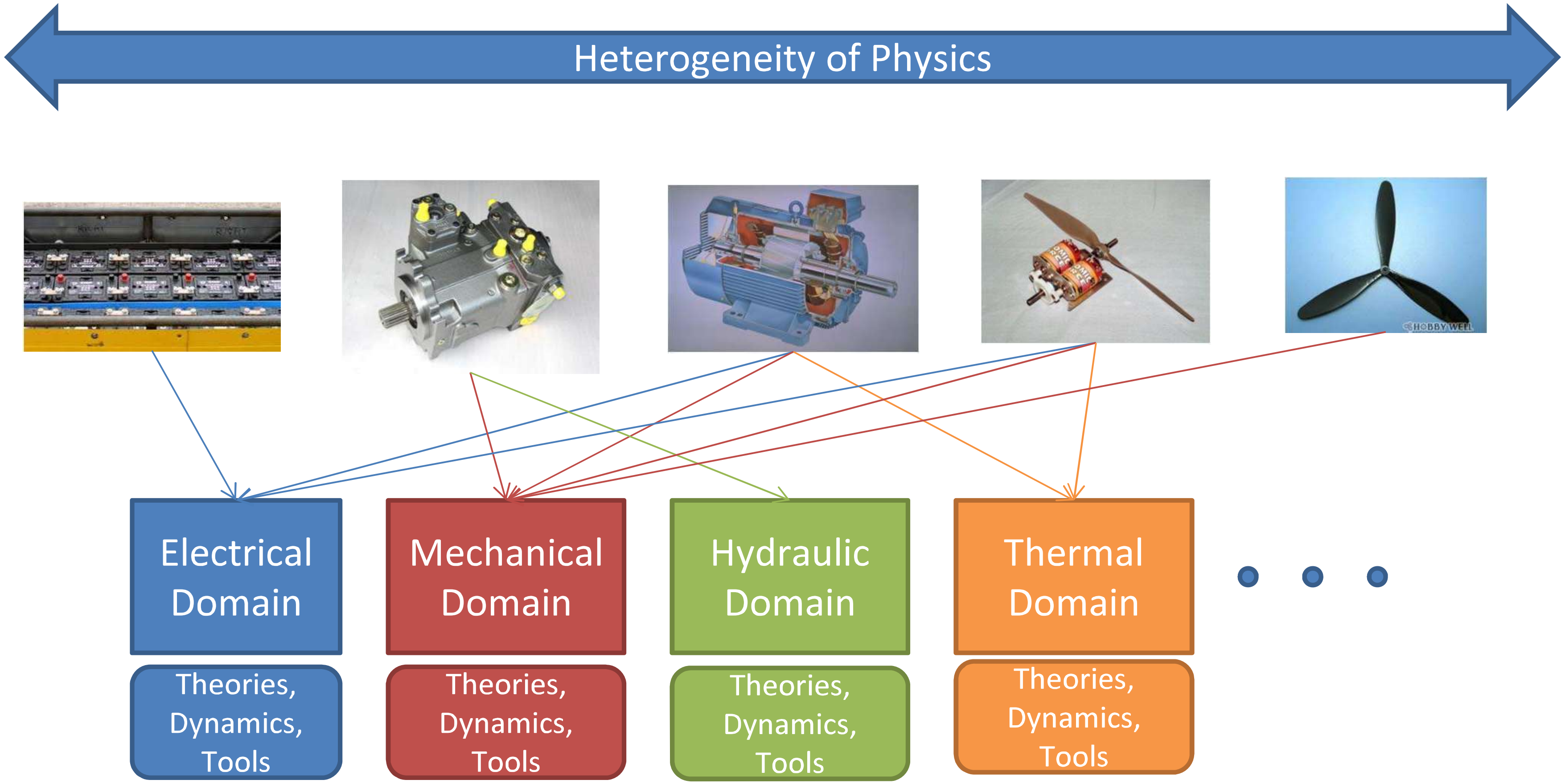
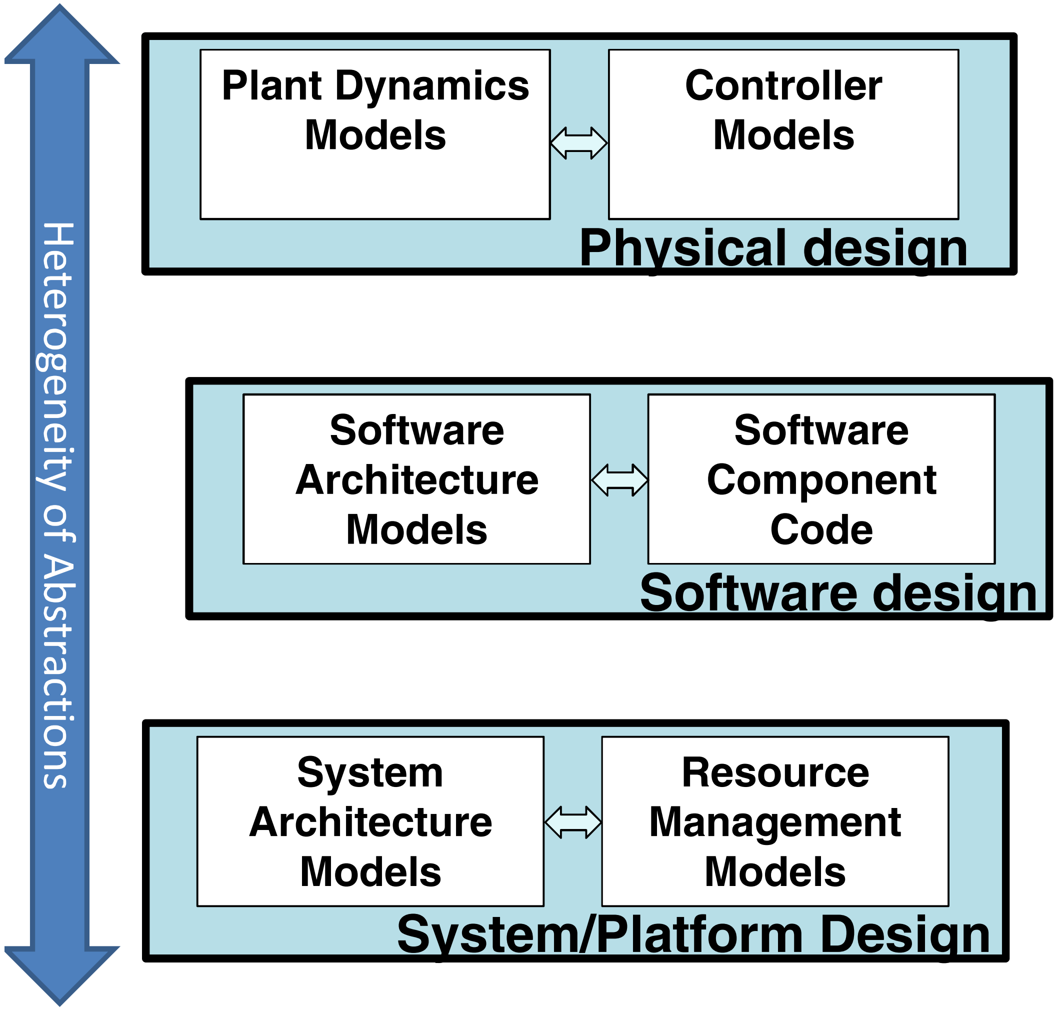
# Model Integration Challenge: Physics




**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?**

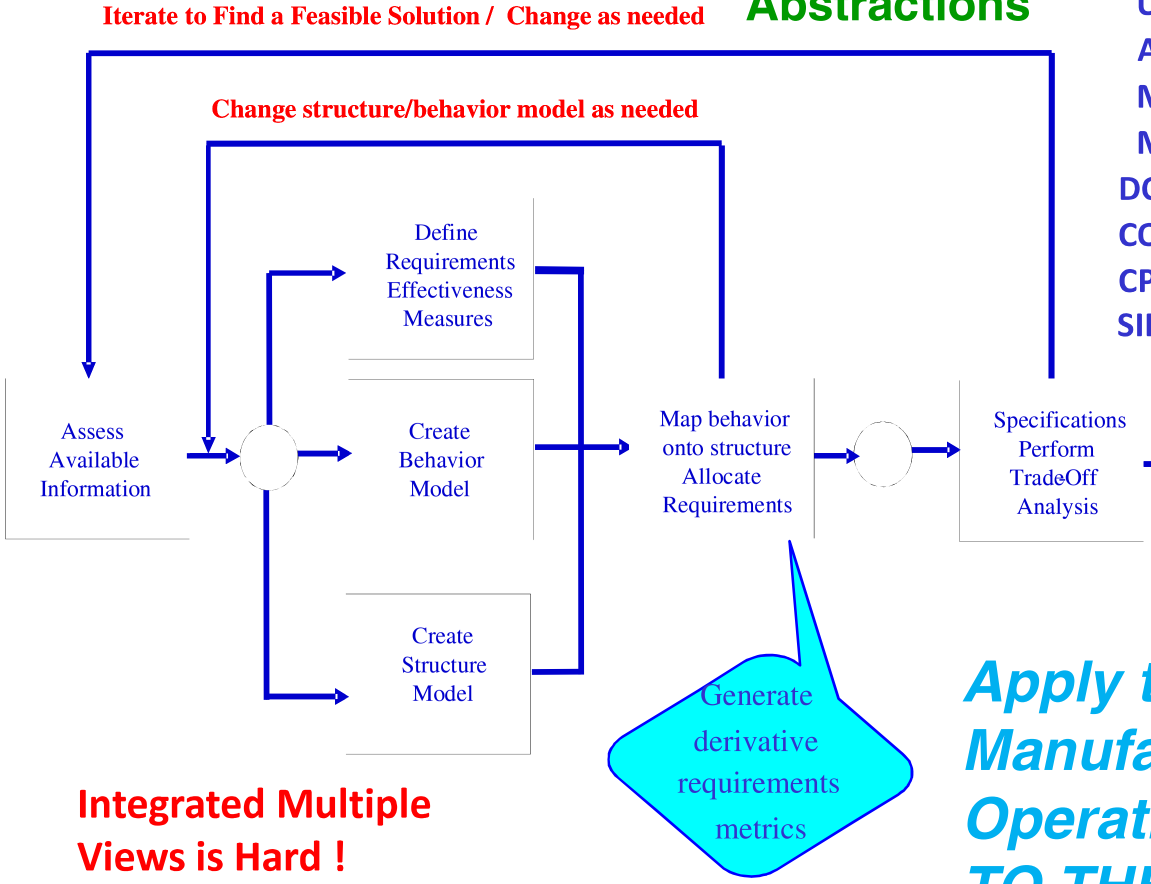
# MODEL BASED SYSTEMS ENGINEERING

**Integrated System Synthesis Tools & Environments missing**

**Model - Based Information – Centric Abstractions**

**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**

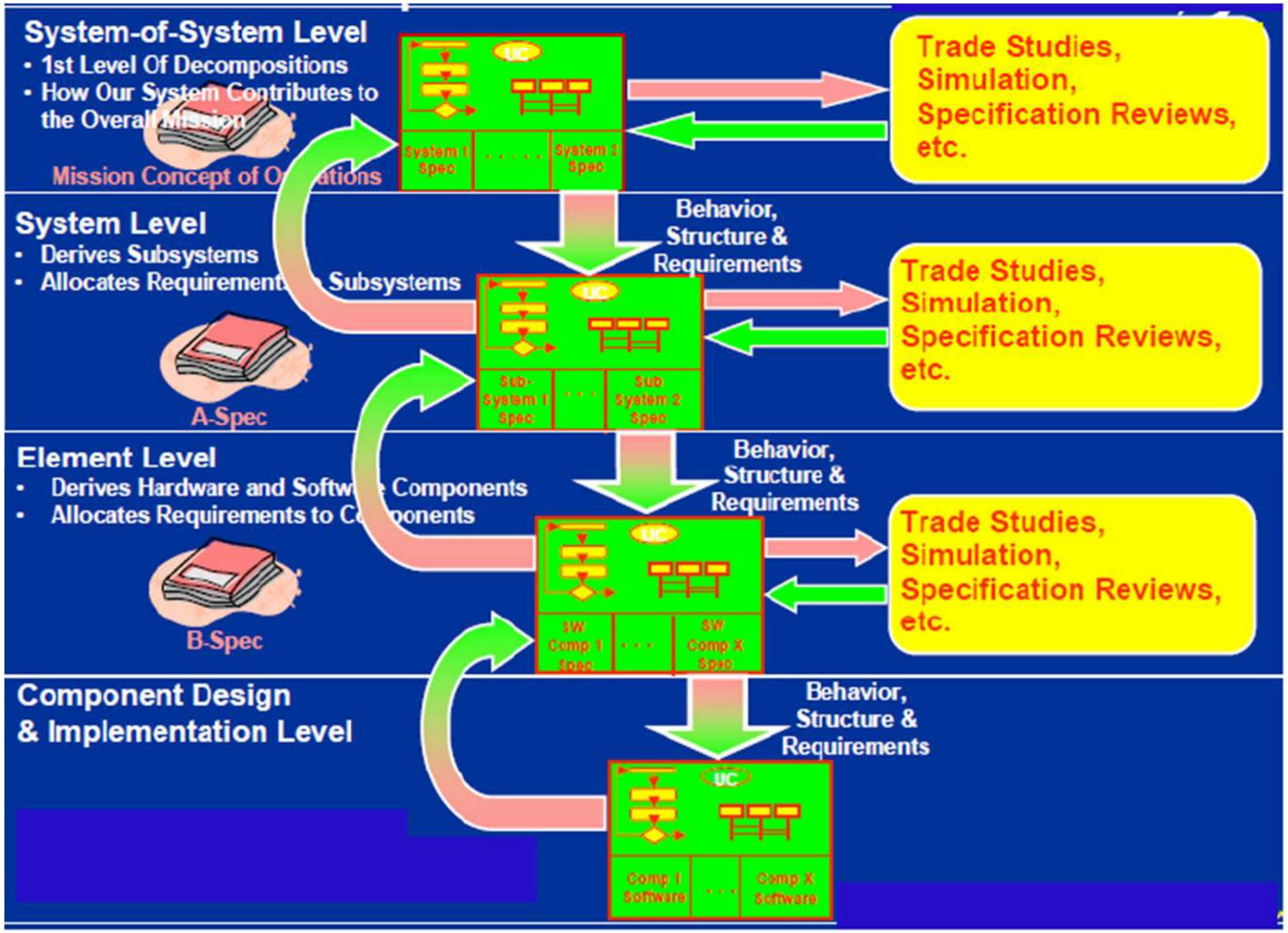



**Integrated Multiple Views is Hard !**

***Apply this to: Design, Manufacturing, Operations and Management TO THE WHOLE LIFE-CYCLE***

# Layered MBSE -- Hierarchies



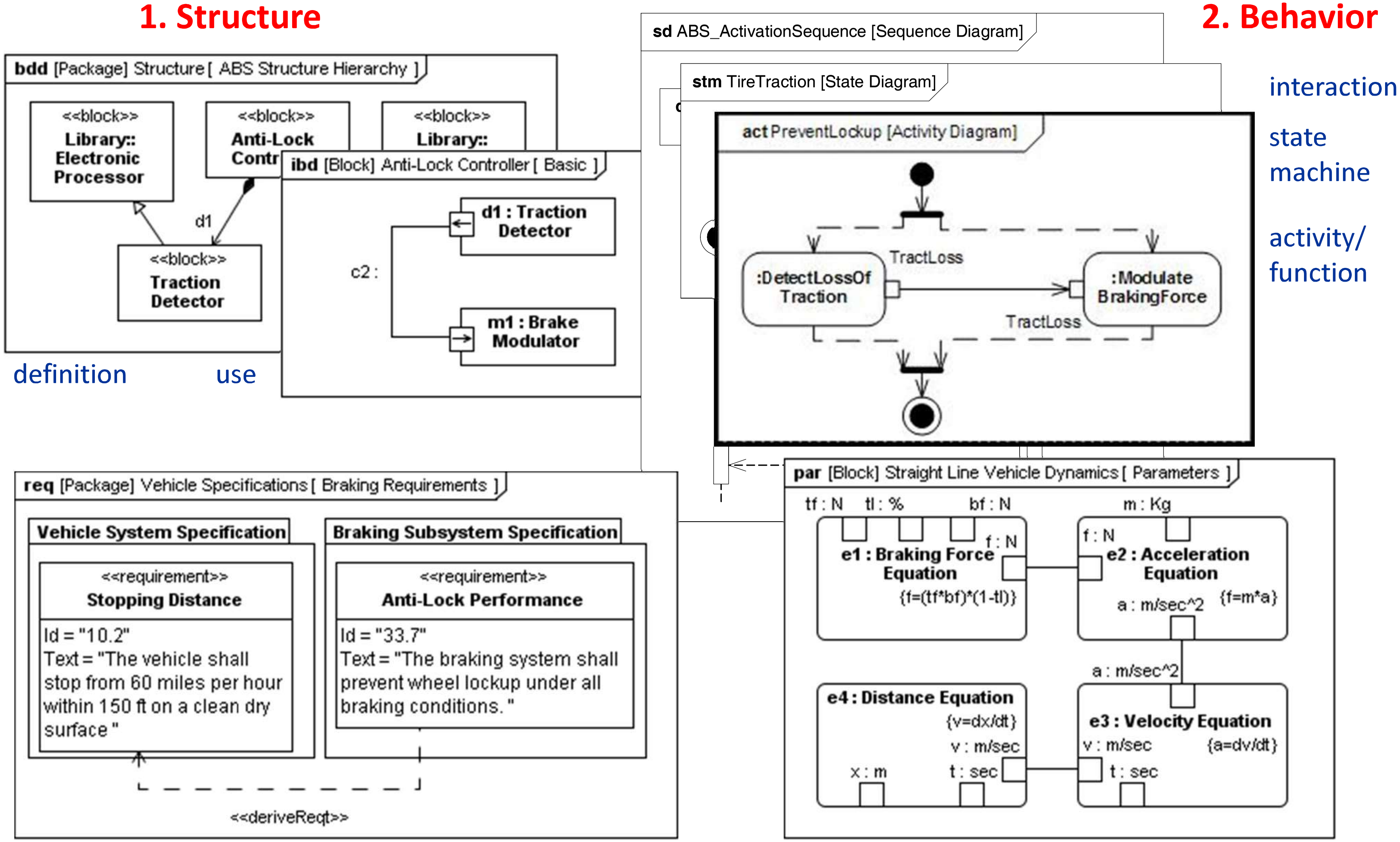



(Watson 2008, Lockheed Martin)

# FOUR PILLARS OF SYSML

1. Structure

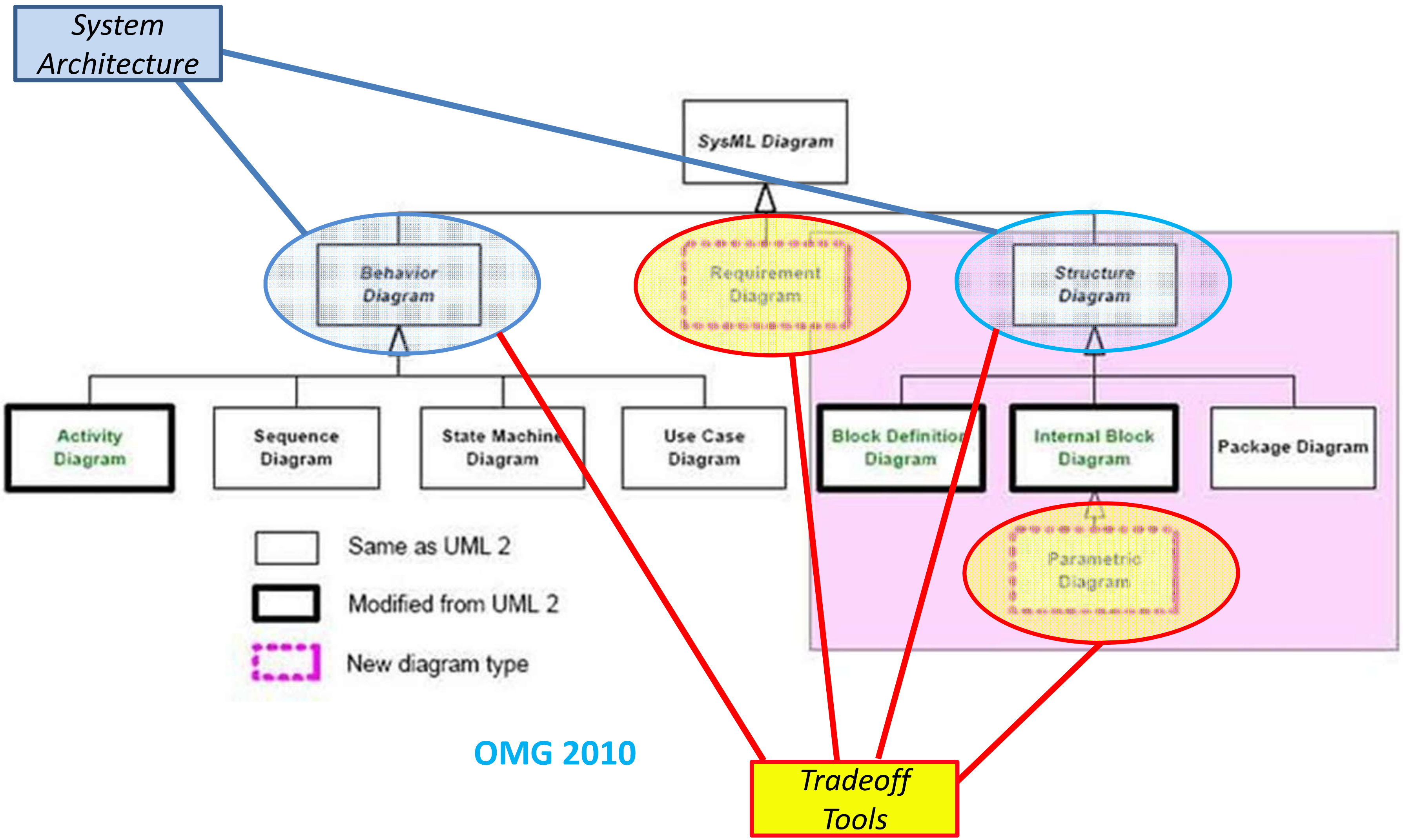
2. Behavior



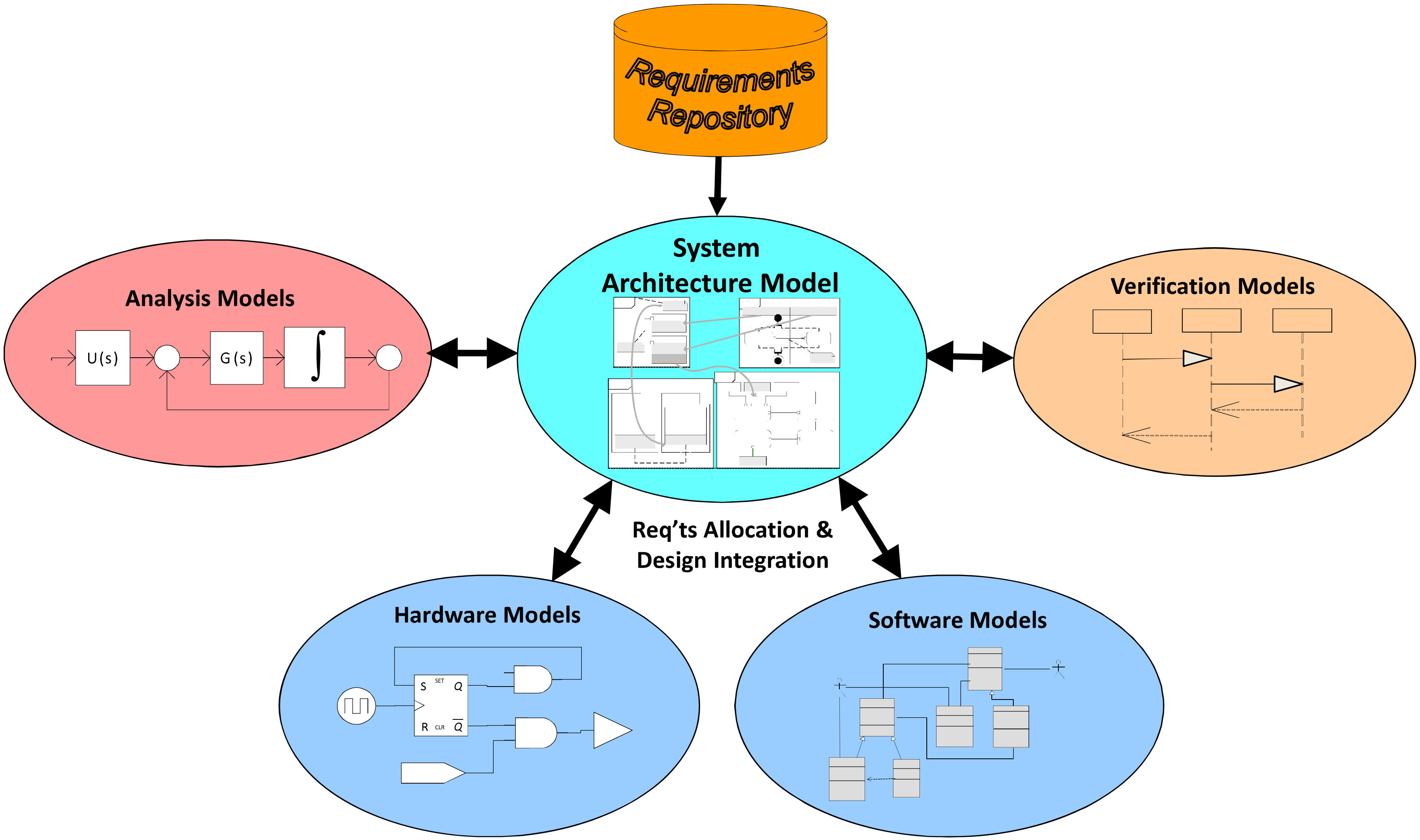

3. Requirements

4. Parametrics

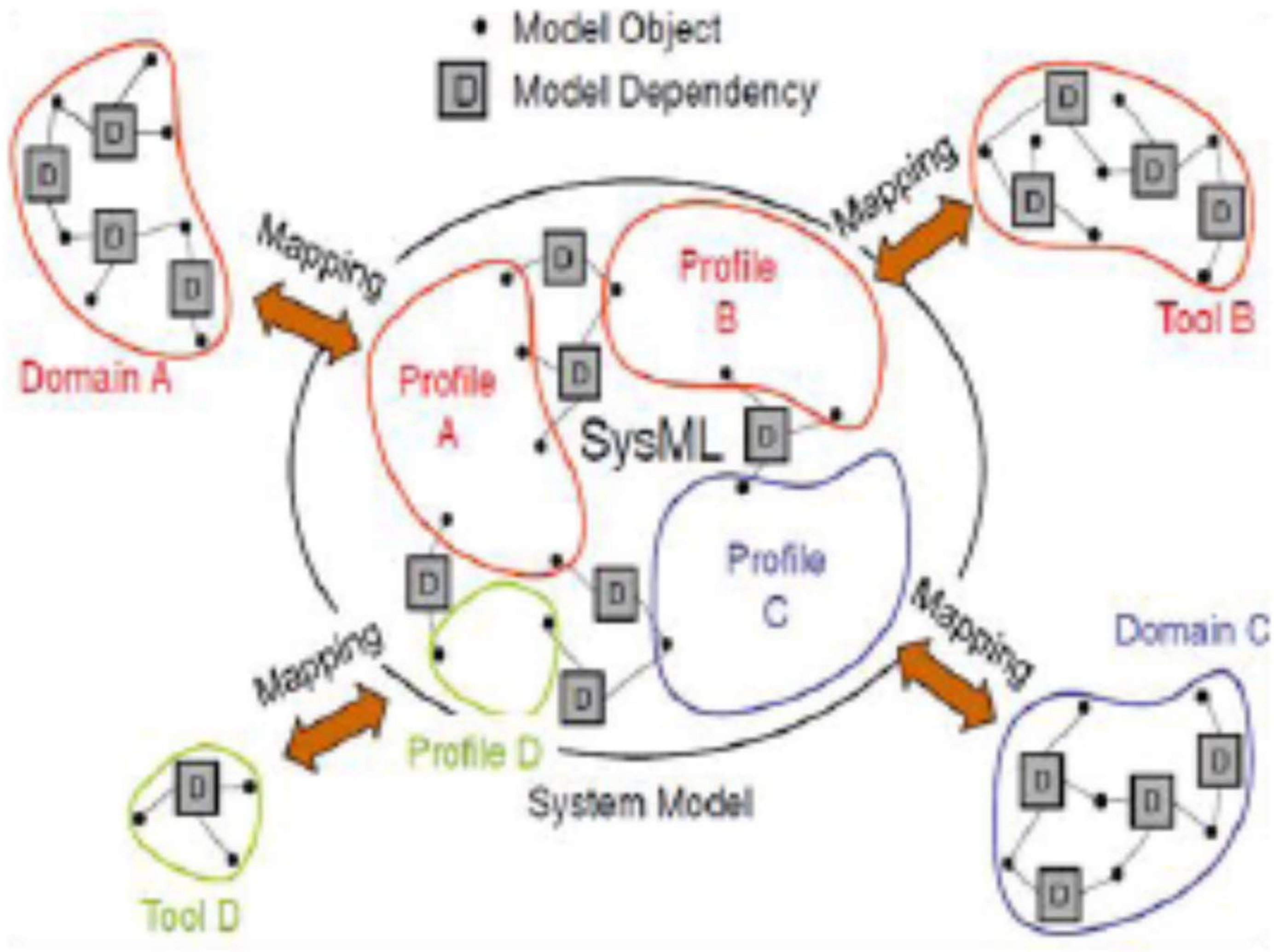
# SysML Taxonomy



# Using *System Architecture Model* as an Integration Framework



# System Modeling Transformations--Metamodeling (Models of Models)

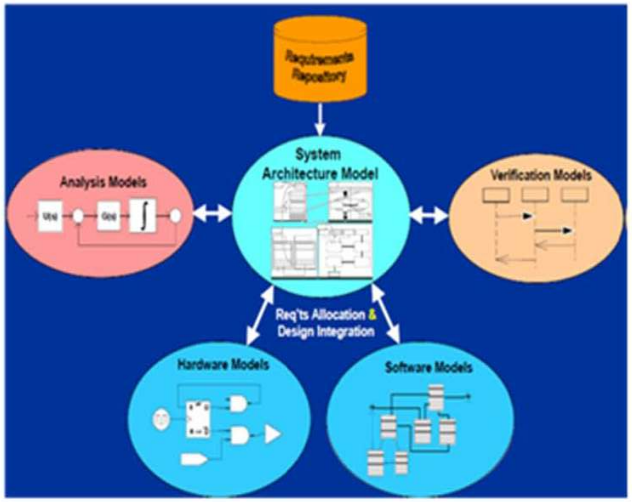


# A Rigorous Framework for Model-based Systems Engineering

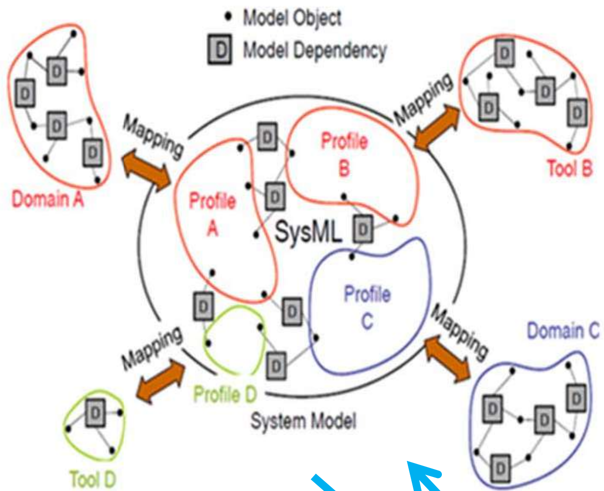
**The Challenge & Need:**

**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**

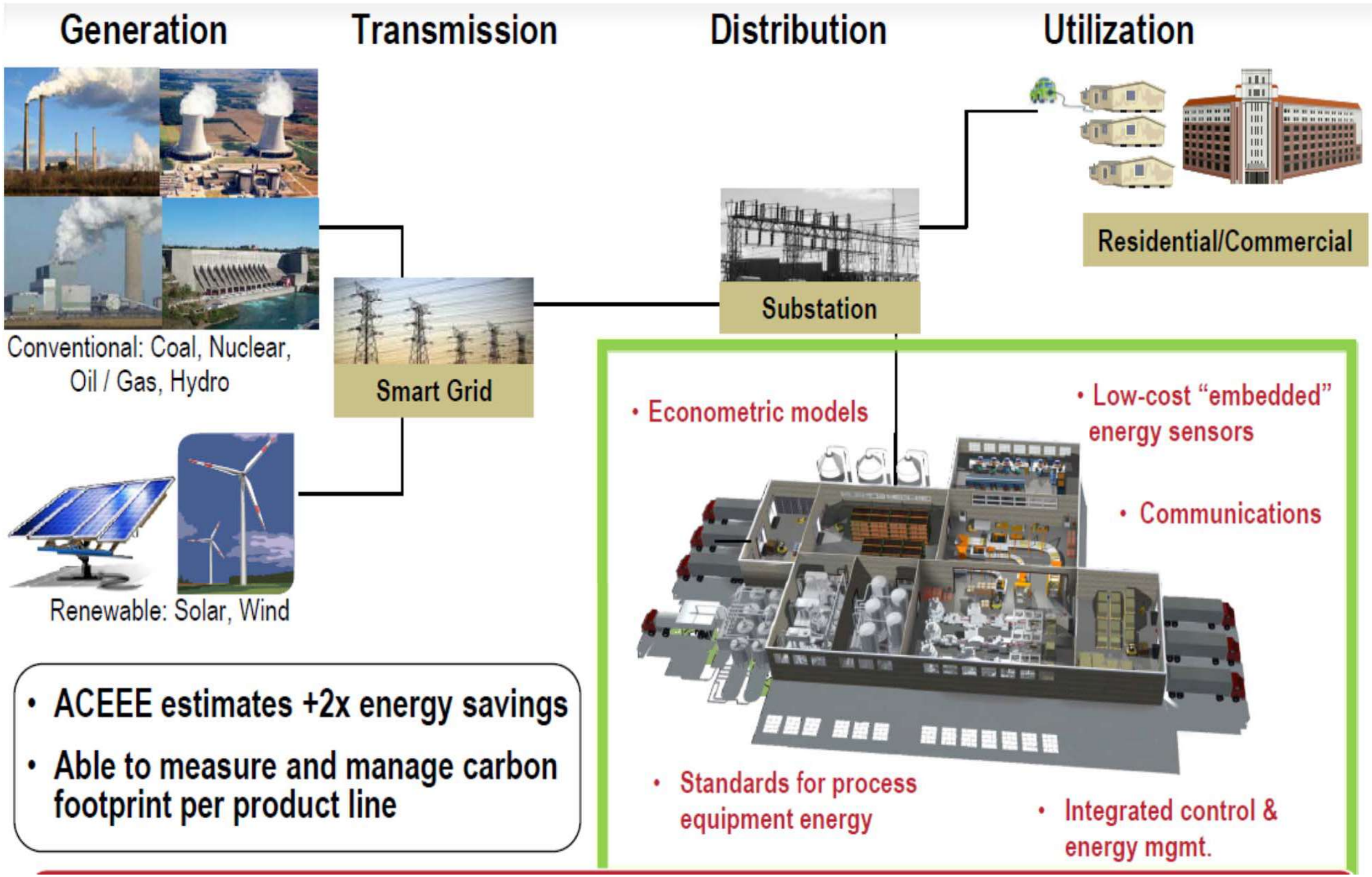
**APPLICATIONS**

- **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?**

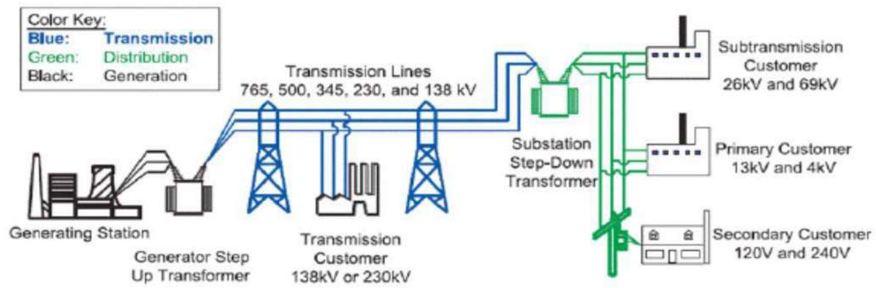
# Smart Grids in a Network Immersed World

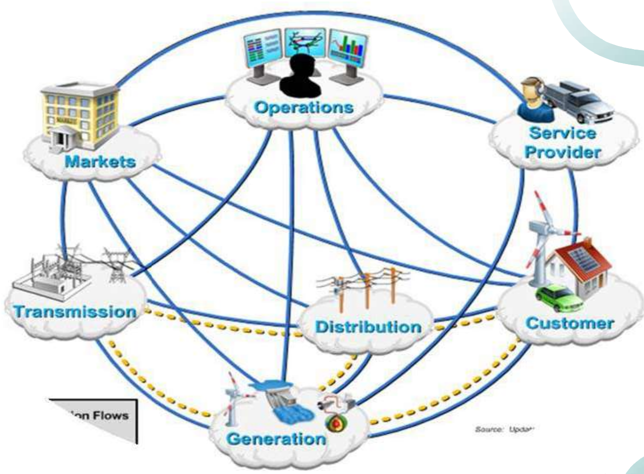



Rockwell

# Smart Grid – Micrograids Architecture

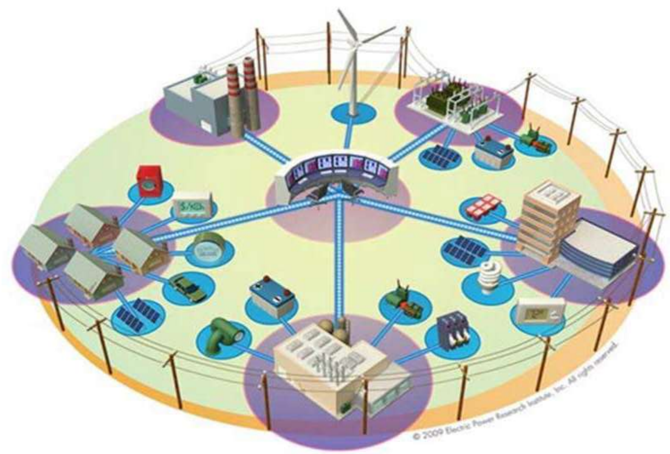
Grid 1.0
Legacy Grid




Grid 2.0
Smart Grid

Grid 3.0
Future Grid



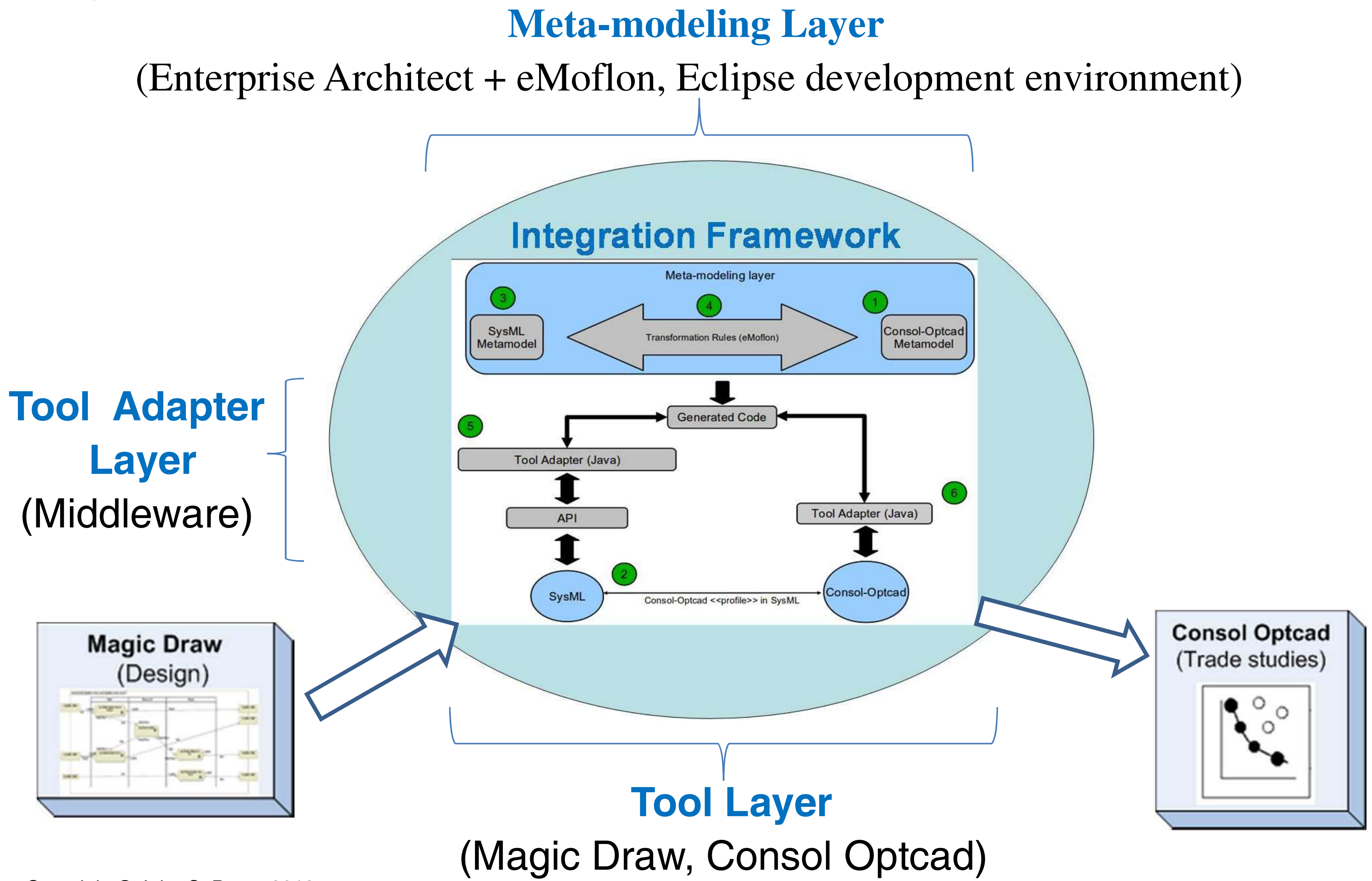
NIST-EPRI

# Differences from Other Approaches

- Clear framework for integrating SysML with external tools
- Consol-Optcad can perform sophisticated trade-off studies based on FSQP algorithm
- Allows interaction with the user while the optimization is in process
- Consol-Optcad allows for design space exploration
- eMoflon Metamodeling tool-suite was used for the first time for such an integration

# SysML and Consol-Optcad Integration

## Overview



# Meta-modeling Layer - eMoflon

## Characteristics

- ✓ Meta-models are following the Ecore format
- ✓ Story Diagrams are used to express the transformation rules
- ✓ Graph transformations is the underlying theory
- ✓ It generates Java code for the transformations

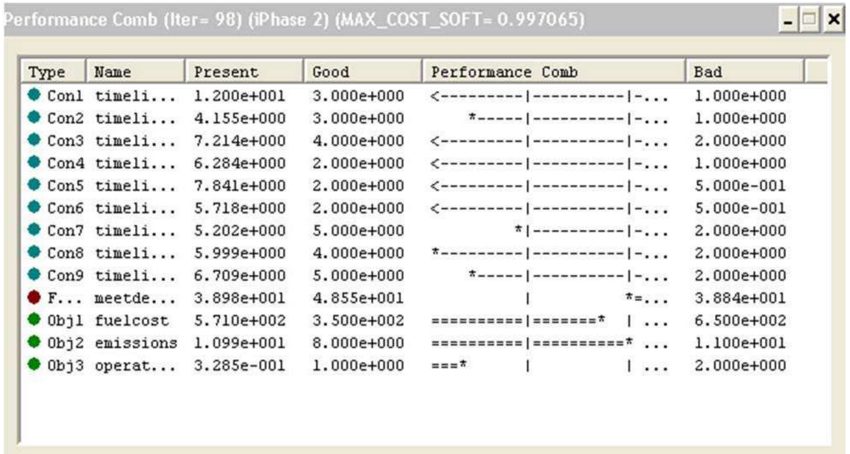
## Advantages

- ✓ Graph transformation theory provides strong semantics and can lead to satisfaction of formal properties, i.e correctness, completeness, etc
- ✓ Graphical representation of meta-models and transformation rules
- ✓ Generated Java code could be easily integrated with modern tools
- ✓ Strong support/developing team
- ✓ Eclipse - open source environment

# IMH and Consol-Optcad Integration

## Consol-Optcad

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



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

<table>
<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
<tr><td>Con1</td><td>timeli...</td><td>1.200e+001</td><td>3.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con2</td><td>timeli...</td><td>4.155e+000</td><td>3.000e+000</td><td>*-----|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con3</td><td>timeli...</td><td>7.214e+000</td><td>4.000e+000</td><td><---------|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>Con4</td><td>timeli...</td><td>6.284e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con5</td><td>timeli...</td><td>7.841e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con6</td><td>timeli...</td><td>5.718e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con7</td><td>timeli...</td><td>5.202e+000</td><td>5.000e+000</td><td>*|----------|-...</td><td>2.000e+000</td></tr>
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<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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***Fig. 1***: Pcomb

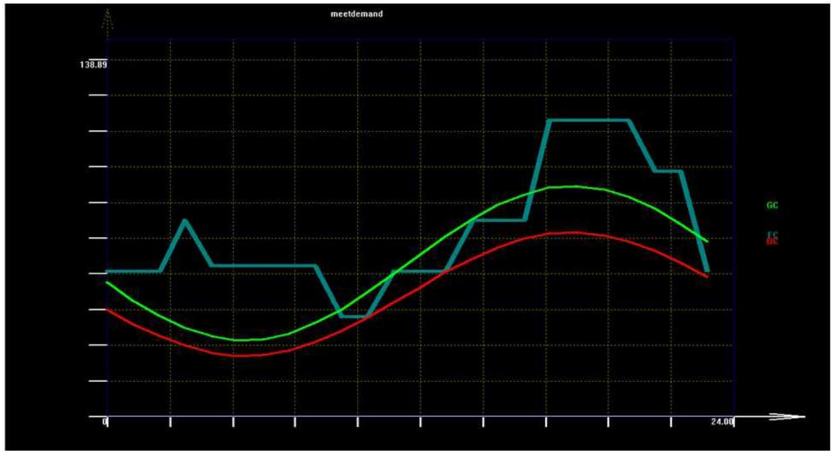



***Fig. 2***: Example of a functional constraint

# 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

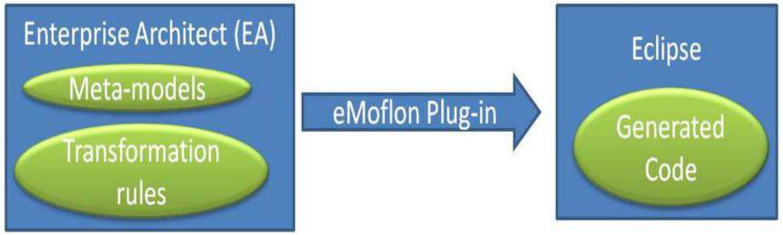



***Fig. 3***: eMoflon high-level architecture

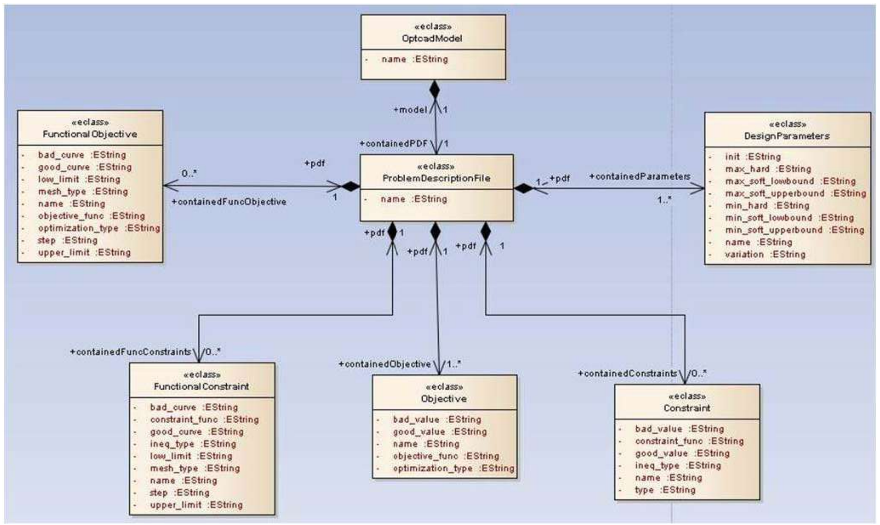



***Fig. 4***: Consol-Optcad metamodel

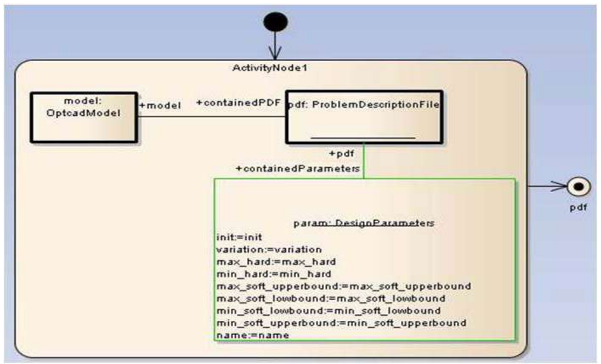



***Fig. 5***: Story diagram

# IMH and Consol-Optcad Integration

## Working Example

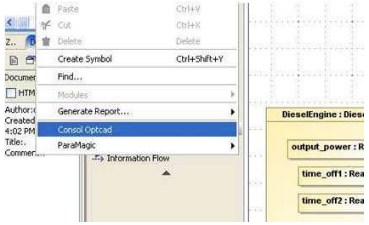


*Fig. 11*: Initiate transformation

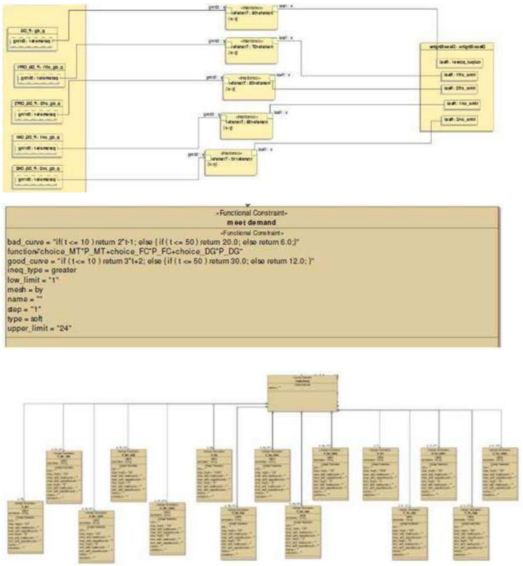


*Fig. 10*: Models in SysML

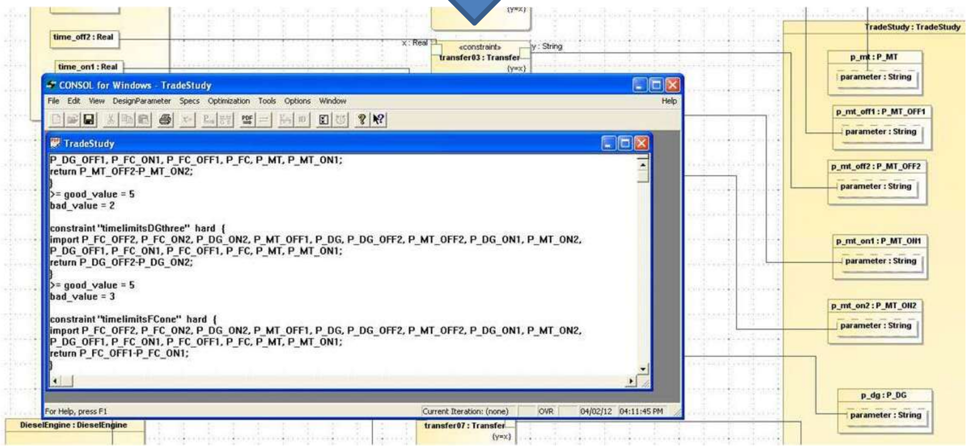
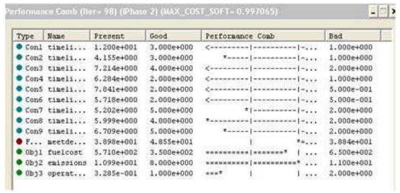


*Fig. 12*: Consol-Optcad environment



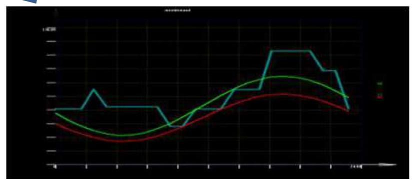


***Fig.13*: Perform trade-off analysis in Consol-Optcad**

# Microgrid Problem Formulation

## Objectives

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

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

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

$P_i$ : power output of each generating unit

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

$n_i$ : efficiency of the generating unit i

$N$ : number of generating units

$M$ : number of elements considered in emissions objective

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

# Microgrid Problem Formulation

## *Constraints*

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

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

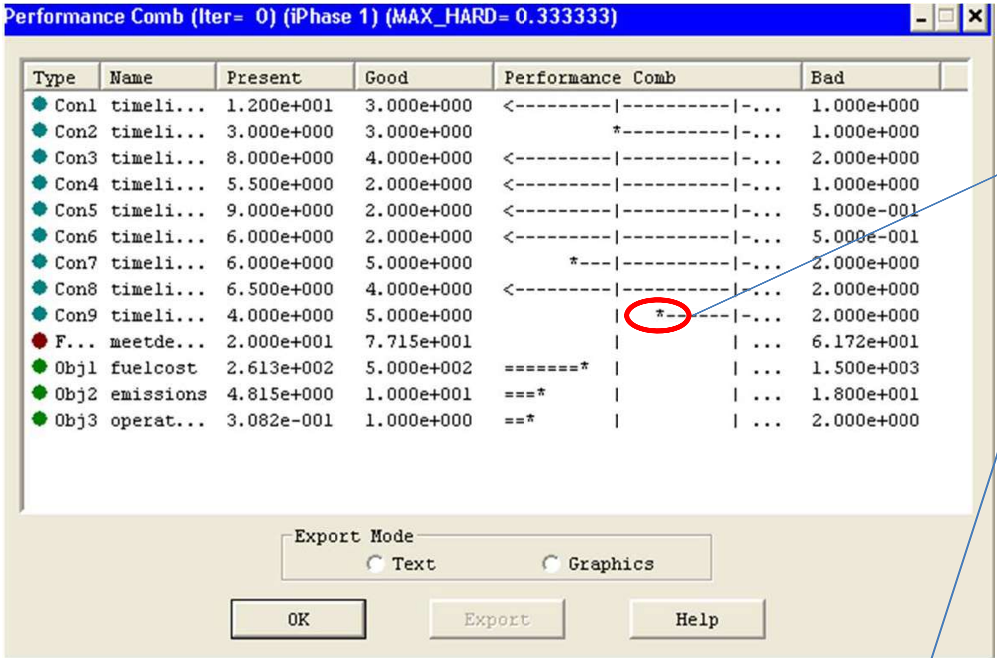
## *Constraints for correct operation of the generation unit*

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

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

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

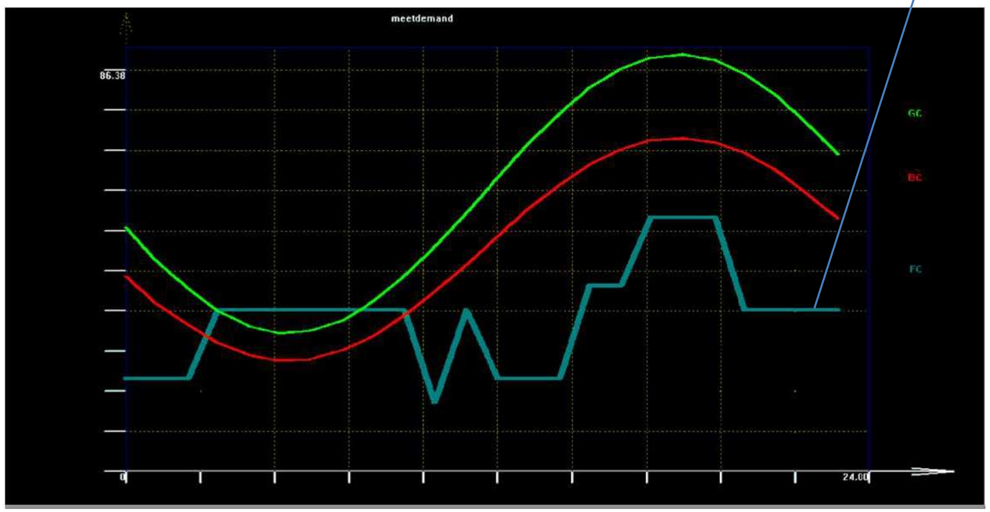
# Tradeoff Study in Consol-Optcad



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

| 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 |

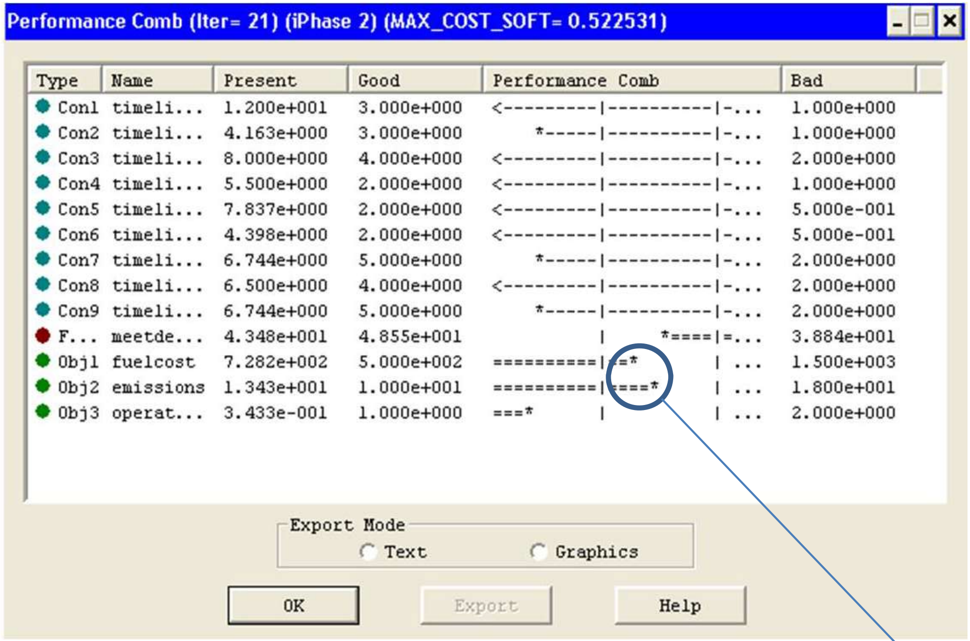





## *Iteration 1 (Initial Stage)*

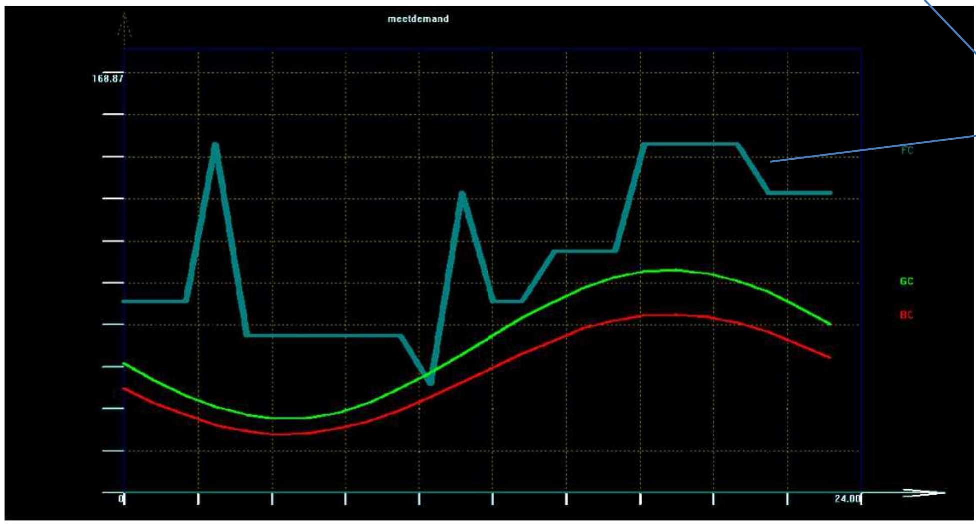
- ✓ Hard constraint not satisfied
- ✓ Functional Constraint below the bad curve
- ✓ All other hard constraints and objectives meet their good values
- ✓ Usually the user does not interact with the optimization process **until all hard constraints are satisfied**

# Microgrid: Trade-off Study




<table>
<tr><th>Type</th><th>Name</th><th>Present</th><th>Good</th><th>Performance Comb</th><th>Bad</th></tr>
<tr><td>Con1</td><td>timeli...</td><td>1.200e+001</td><td>3.000e+000</td><td><---------|----------|-...</td><td>1.000e+000</td></tr>
<tr><td>Con2</td><td>timeli...</td><td>4.163e+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>7.837e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con6</td><td>timeli...</td><td>4.398e+000</td><td>2.000e+000</td><td><---------|----------|-...</td><td>5.000e-001</td></tr>
<tr><td>Con7</td><td>timeli...</td><td>6.744e+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>6.744e+000</td><td>5.000e+000</td><td>*-----|----------|-...</td><td>2.000e+000</td></tr>
<tr><td>F...</td><td>meetde...</td><td>4.348e+001</td><td>4.855e+001</td><td>| *====|=...</td><td>3.884e+001</td></tr>
<tr><td>Obj1</td><td>fuelcost</td><td>7.282e+002</td><td>5.000e+002</td><td>==========|=* | ...</td><td>1.500e+003</td></tr>
<tr><td>Obj2</td><td>emissions</td><td>1.343e+001</td><td>1.000e+001</td><td>==========|====* | ...</td><td>1.800e+001</td></tr>
<tr><td>Obj3</td><td>operat...</td><td>3.433e-001</td><td>1.000e+000</td><td>===* | | ...</td><td>2.000e+000</td></tr>
</table>





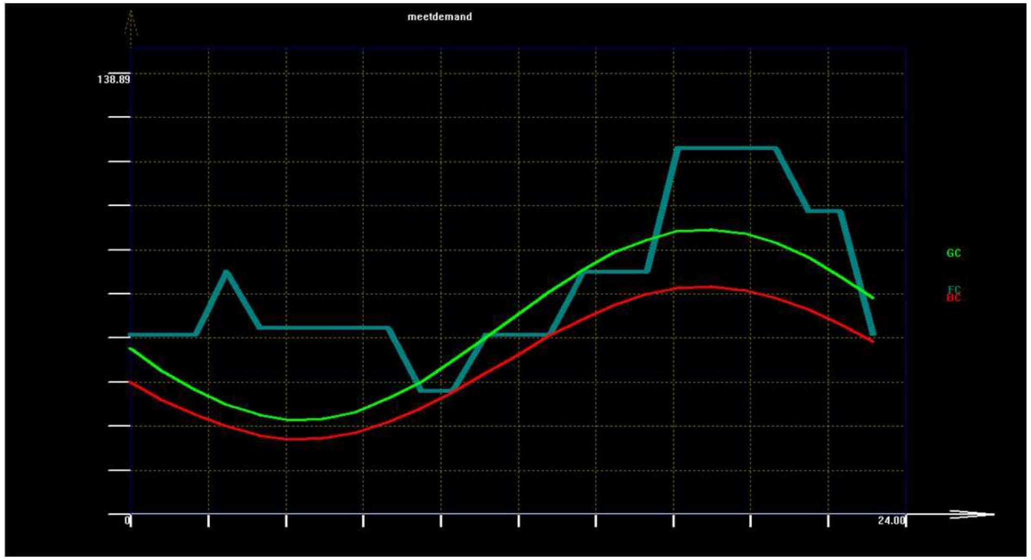

*Iteration 28 (User Interaction)*

- ✓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)

| 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 |



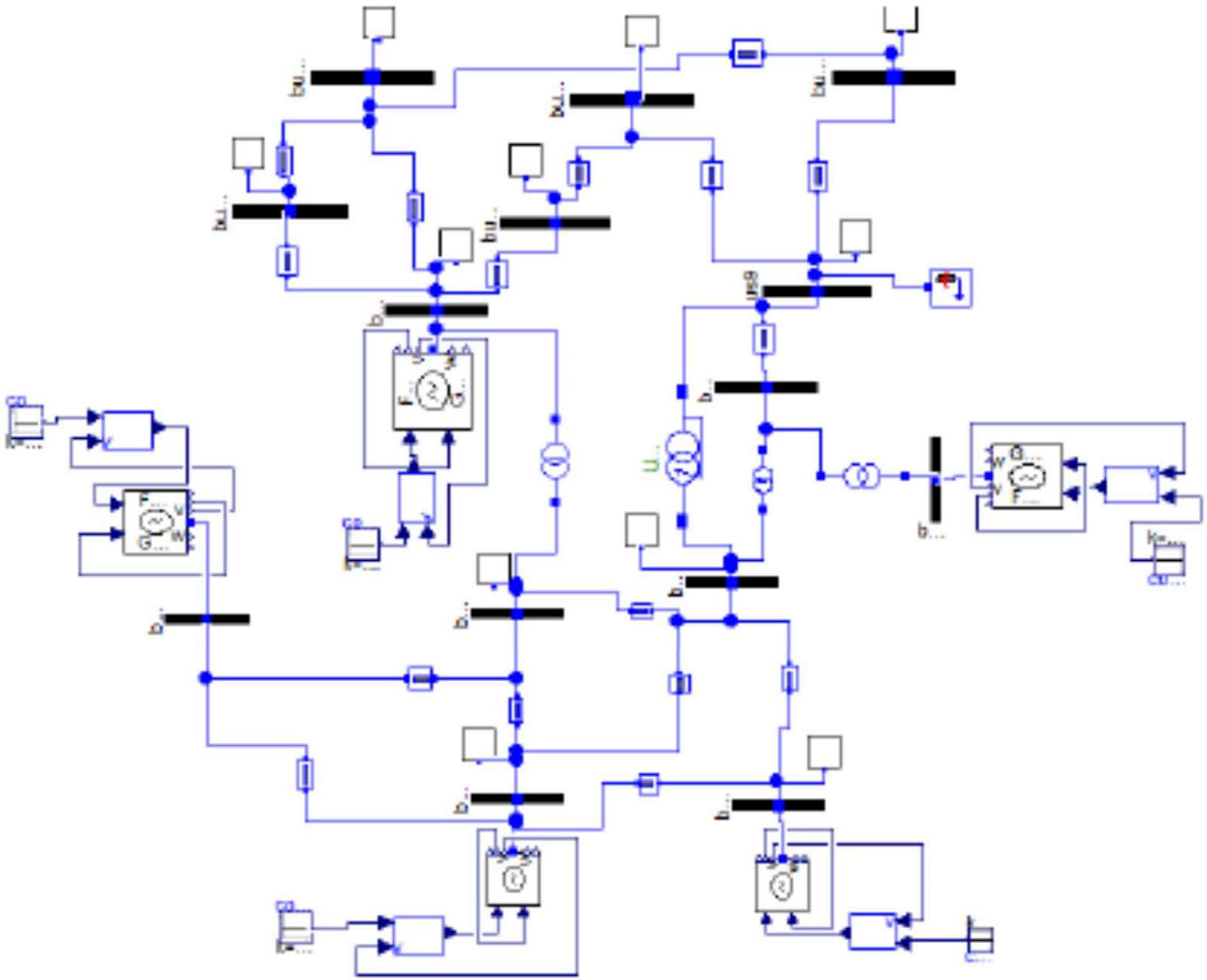

## *Iteration 95 (Final Solution)*

- ✓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

# New Integrated Modeling Hub

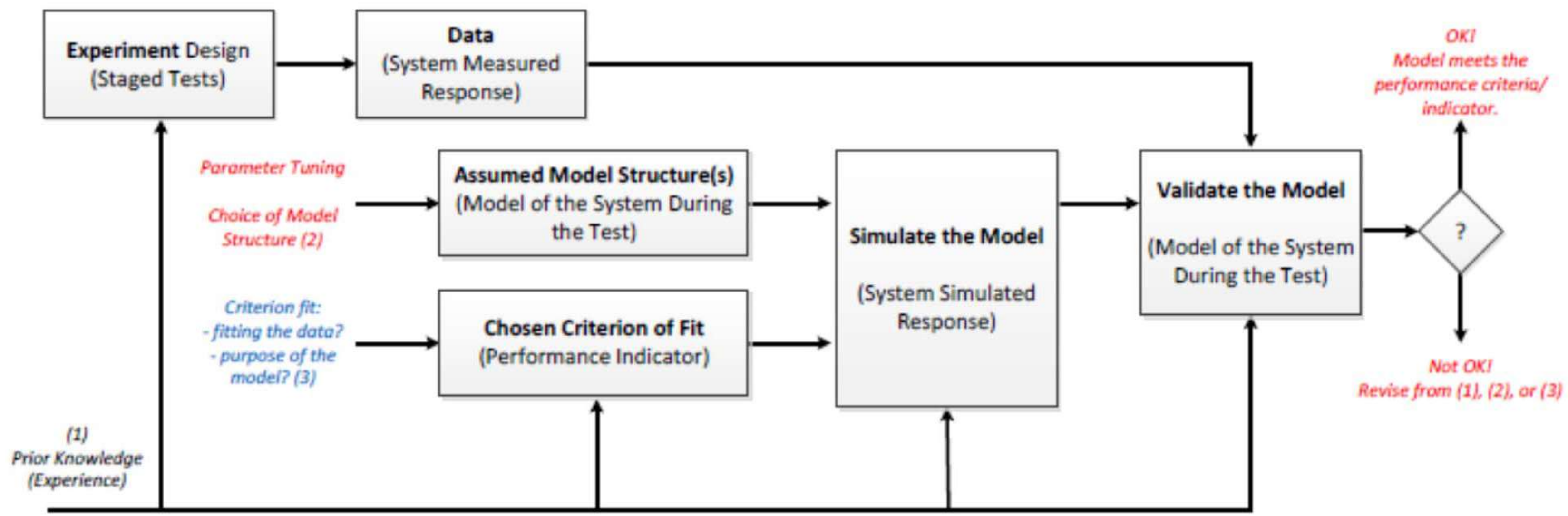
- Open source
- Open Modelica
- UML/SysML Papyrous
- SciLab
- Building results and models of the iTesla project (EU) http://www.itesla-project.eu/
- Libraries of components
- Examples from Norwegian Grid
- Validate components
- Hybrid systems models result

# iTesla Models - Modelica



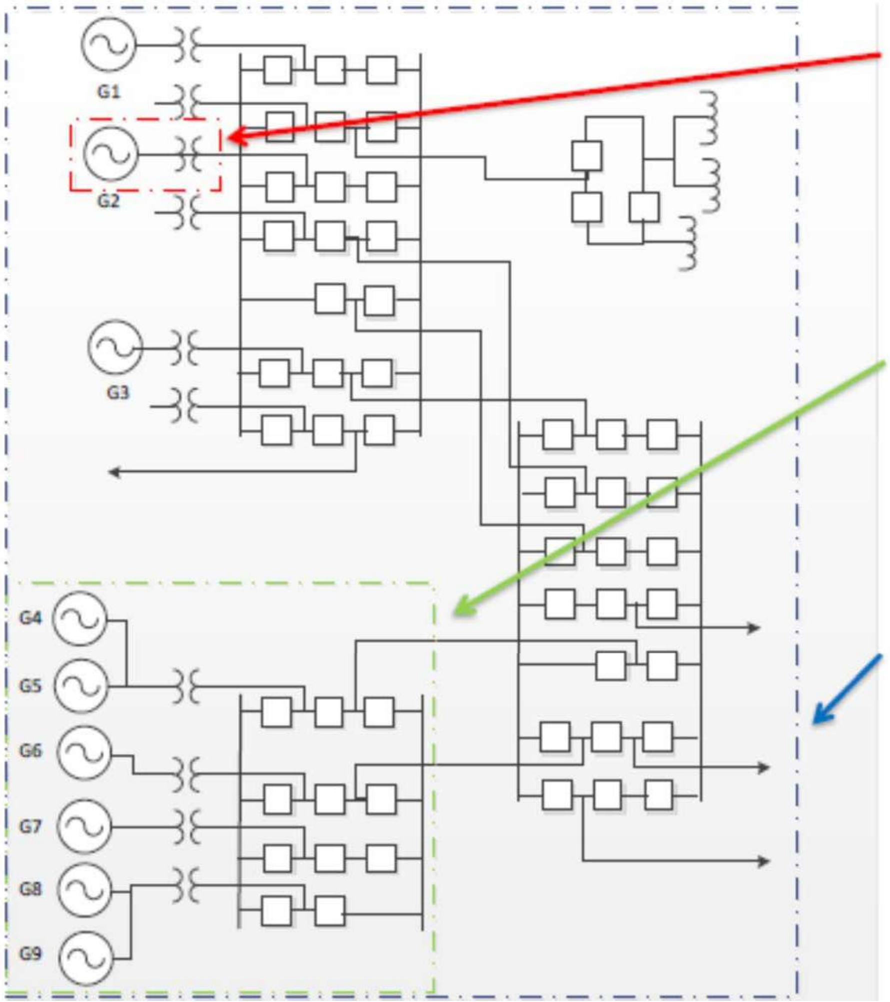
IEEE 14 bus system model

# Model Validation -- Composability




- A model should never be accepted as a final true description
- of the actual power system
- Just a suitable "good enough" description of the system for
- Specific aspects
- Model validation: confidence, uncertainties, tolerances
- Major challenge: Composition and uncertainty quantification

# Different Validation Levels




- Component level
  - e.g. generator such as wind turbine or PV panel
- Cluster level
  - e.g. gen. cluster such as wind or PV farm
- System level
  - e.g. power system small-signal dynamics (oscillations)

<u>Major challenge</u>: Quantify accuracy and uncertainty as we move up and down the levels, for both logical and numerical variables

# Port-Hamiltonian Models to the Rescue

**Key ideas:**

- Plant and controller – energy processing dynamical systems
- Exploit the interconnection – control as interconnection
- Shape energy
- Modify dissipation
- Work across multiple physics
- Work for many performance metrics not just stability
- Automatic composability -- scalable
- Underlying math models for Modelica!

# Port-Hamiltonian Models: Power Grids

- Power grid structure components: generators, loads, buses, transmission lines, switch-gear, …
- Handle transient stability problem naturally
- Power network as graph
- Edges: generators, loads, transmission lines
- Nodes: Buses
- Reduced graph – transmission lines

# Edge Dynamics

Each edge element is represented as a

**port-Hamiltonian system**

$$\dot{x} = [\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u,$$

$$y = g^T(x)\nabla H(x)$$

where $x$ is the state, $\mathcal{J}^t(x) = -\mathcal{J}(x), \mathcal{R}^t(x) = \mathcal{R}(x) \geq 0$, and $H(x)$ are the interconnection, damping and energy functions, respectively.

The interconnection of all these port-Hamiltonian systems using Kirchhoff's laws will result in a total port-Hamiltonian system.

# Complete Model

In shorthand notation we have the port-Hamiltonian model

$$\dot{x} = [\mathcal{J} - \mathcal{R}]\nabla H(x) + gu$$
$$y = g^t \nabla H(x)$$

where

$$\mathcal{J} = \begin{bmatrix} 0 & 0 & \mathbb{I} & 0 & 0 & 0 & 0 \\ 0 & 0 & M_1^t & M_2^t & 0 & 0 & 0 \\ -\mathbb{I} & -M_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -M_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\mathbb{I} \\ 0 & 0 & 0 & 0 & 0 & \mathbb{I} & 0 \end{bmatrix}$$

# Port-Hamiltonian Models

- Other port-Hamiltonian subsystems can be added like capacitor banks, transformers etc.
- Another model of the transmission line, e.g., partial differential equation models.
- Other load models.
- A different (simpler) port-Hamiltonian model of the generator.
- Techniques like Kron reduction can be used to simplify the graph.

- We have extended the concept to hybrid systems
- Port-Hamiltonian on hypergraphs
- Connections with Noether's Theorem and Invariants – very useful in optimization
- Very useful in Uncertainty quantification

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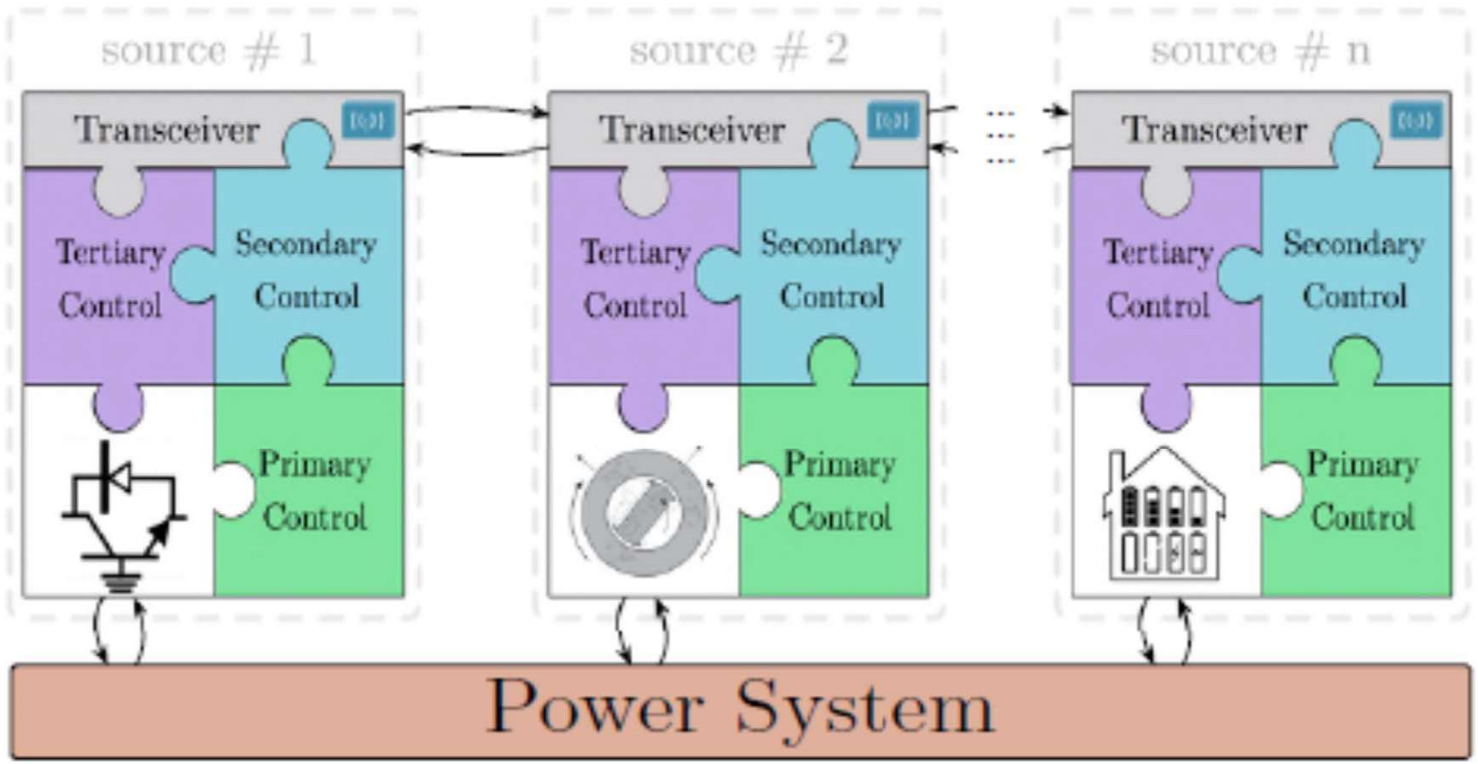
# Adapt Grid Hierarchy for the Future: How?

## Plug'n'play architecture

flat hierarchy, distributed, no time-scale separations, & model-free

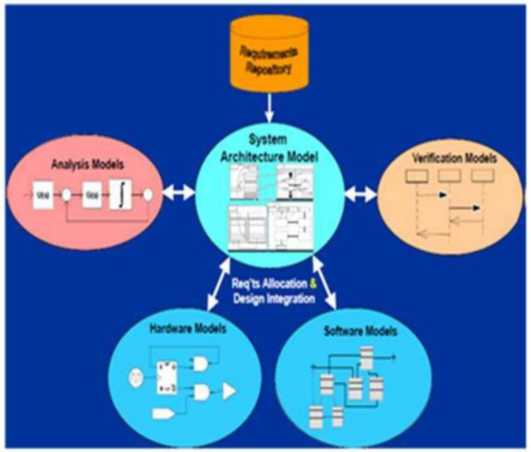


# *Latest Vision and Collaborations*

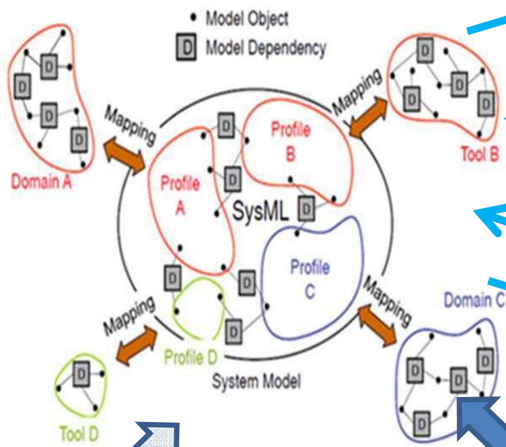
**MBSE Challenge & Need:**
**Develop scalable holistic methods, models and tools for future grids**
**Real-time distributed dispatch**
**Distributed sensing and control**
**Architecture design and evaluation**

## UMD: Integrated Modeling Hub
## Power grids, Smart grids

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




System Modeling Transformations

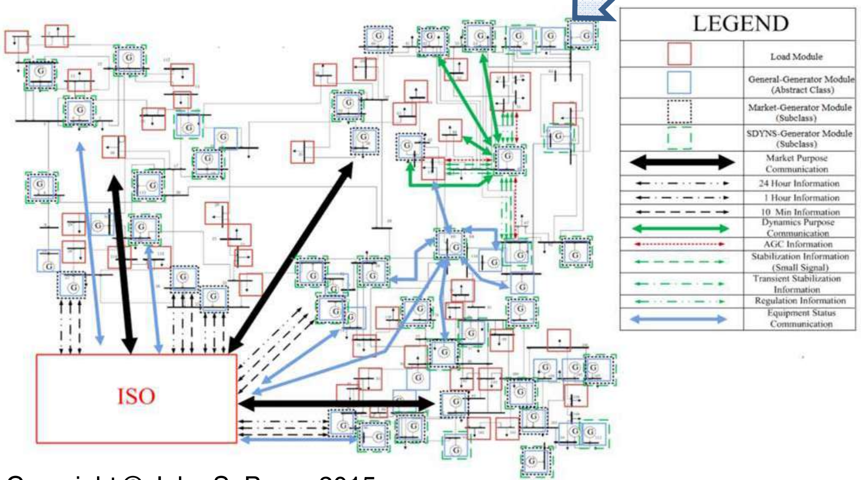



ILOG SOLVER, CPLEX, CONSOL-OPTCAD

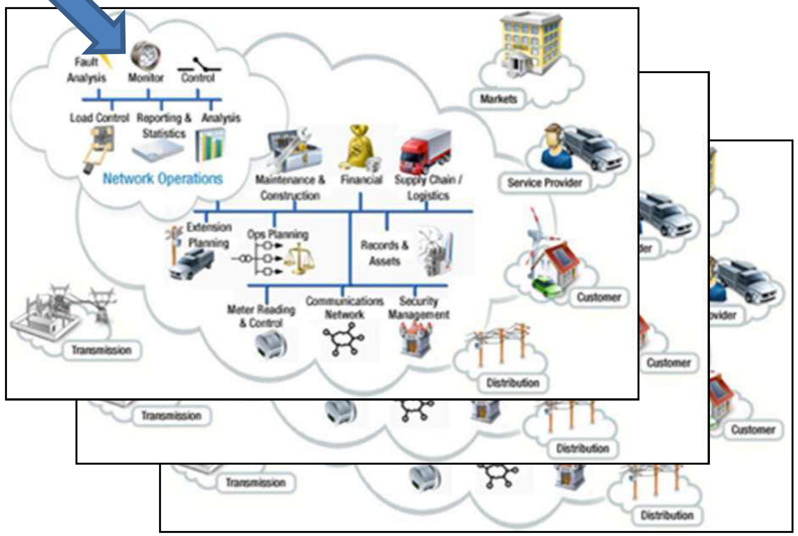
Databases
Libraries of system components and models

**Multi-metric tradeoffs**
**Design/Operation space Exploration**
**System model updates**
**Architecture exploration**
**Real-time user interaction**

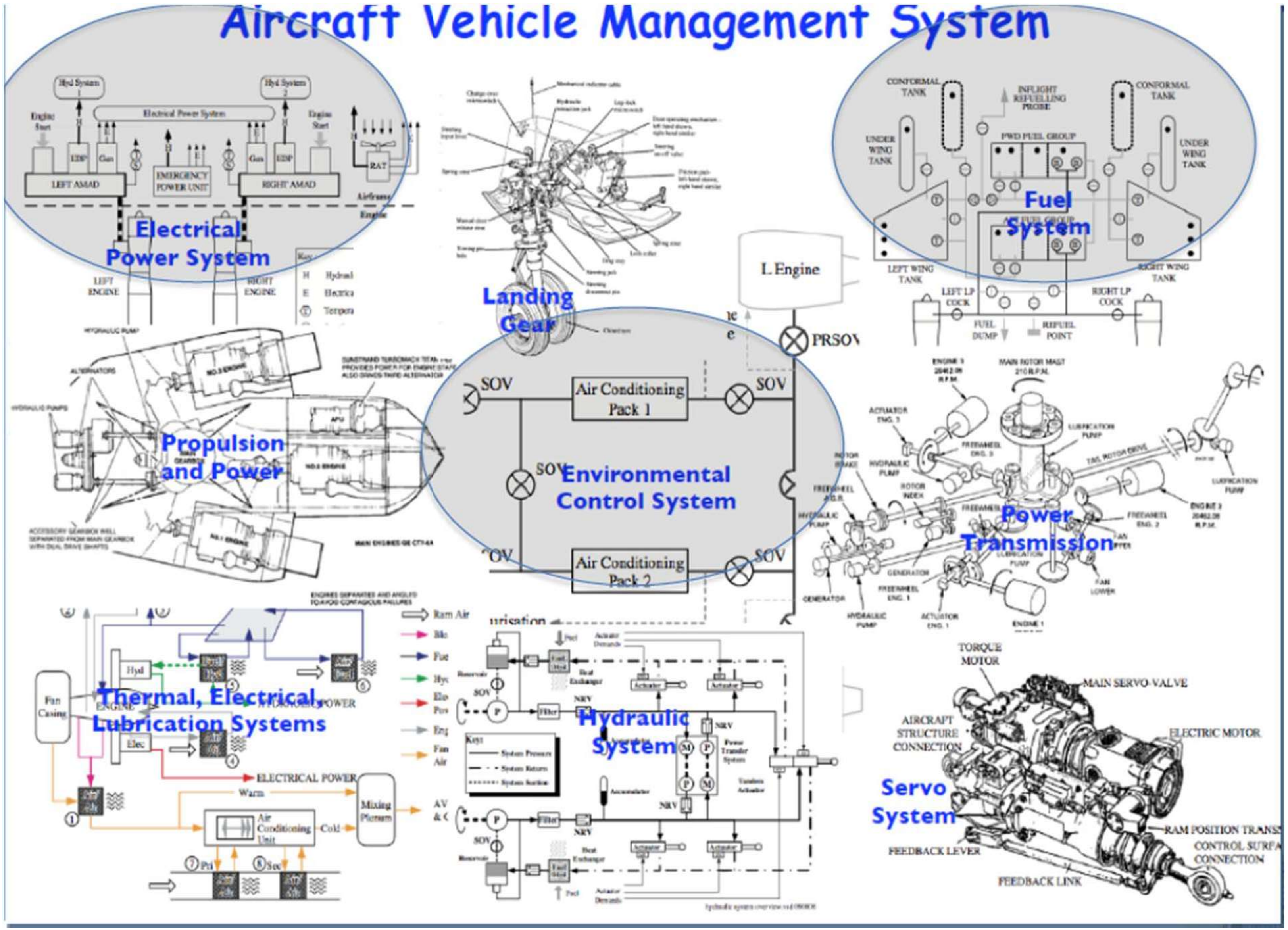
## CMU: DyMonDS based Smart Grid in a Room Simulator
## End-to-End Stable Optimal Dispatch Concepts




## HU, UMD, NIST and Industry Testbeds



# Aircraft Vehicle Management System



# VMS Problem Formulation

## Objectives

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

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

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

## Constraints

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

$P_i$ : power output of each engine (design variable)

*N* : number of buses allocated to each engine

*M*: number of engines in the current configuration

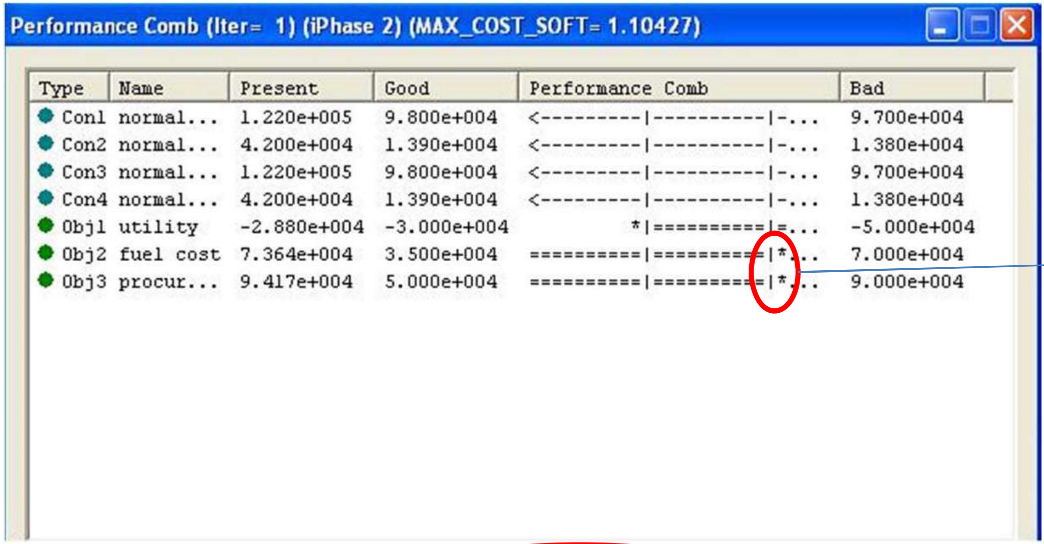
$n_i$ : efficiency of engine *i*

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

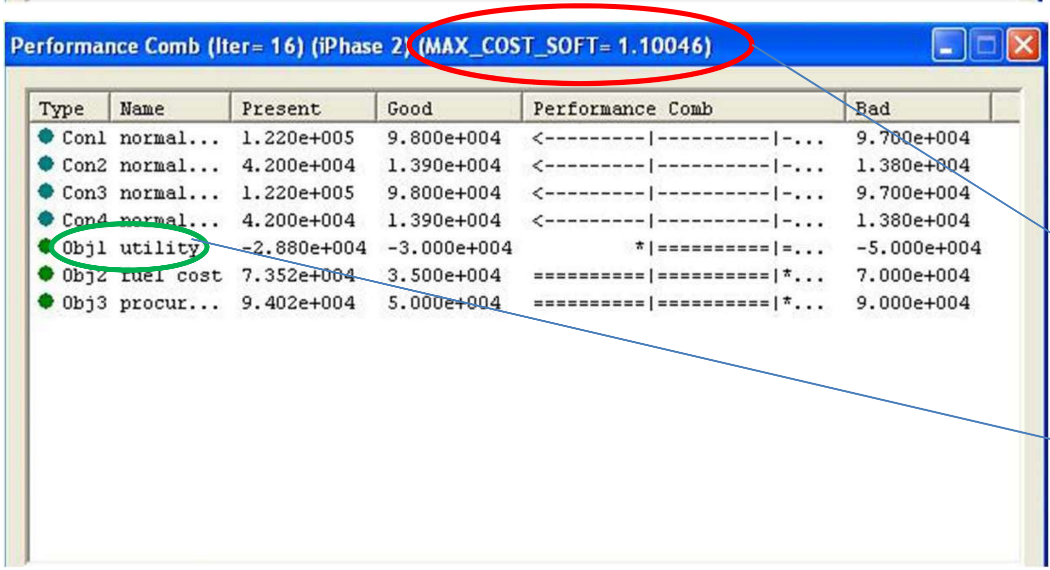
$Load_{i\_shedable}$ : constant - shedable load of bus *i*

$C_i$ : constant - rate of consumption cost for each engine

# VMS Tradeoff Study




<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>




<table>
<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>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 1 (Initial Stage)*

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

## *Iteration 16 (User Interaction)*

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

# Trade-off Study in Consol-Optcad

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

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

```
=======================================
 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)*

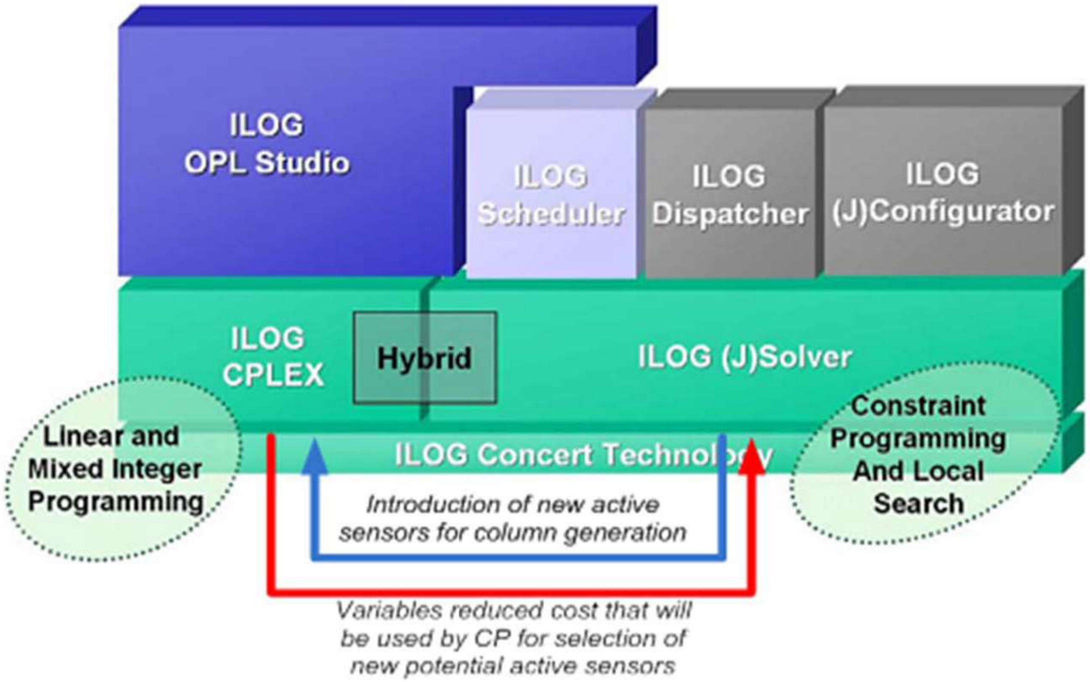
- ✓ Hard constraints are satisfied
- ✓ All objectives within specified limits

## *Results*

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

# INTEGRATION OF CONSTRAINT-BASED REASONING AND OPTIMIZATION FOR TRADEOFF ANALYSIS AND SYNTHESIS

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



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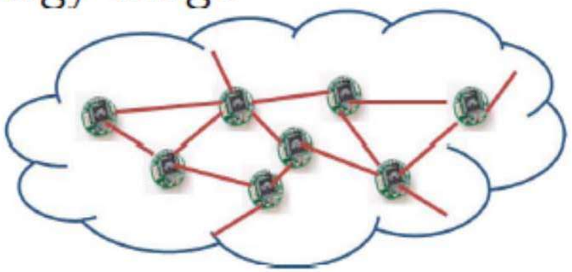
# Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

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



# SCADA Systems

Supervisory Control & Data Acquisition (SCADA)

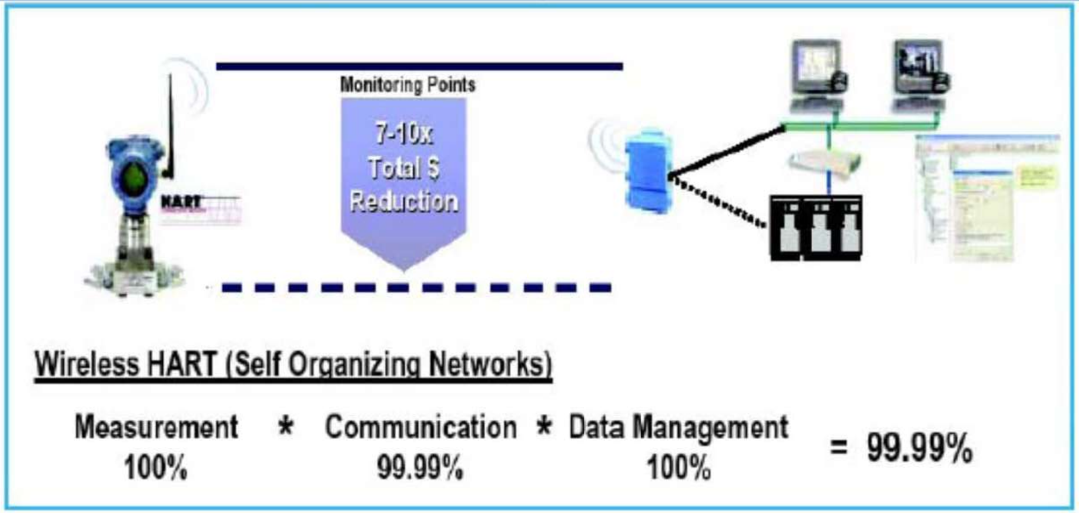
- Robust estimation
  - Noisy measurements
  - Lossy communication
- Real-time control
  - Safety
  - Performance

COTS IT for SCADA

- Cost ↓, Reliability ↑
- Digital and IP based: New vulnerabilities!
- Reliability ⇏ Security

Wired networks are costly to maintain

Typical industrial infrastructure ~ $10B




Courtesy: Emerson

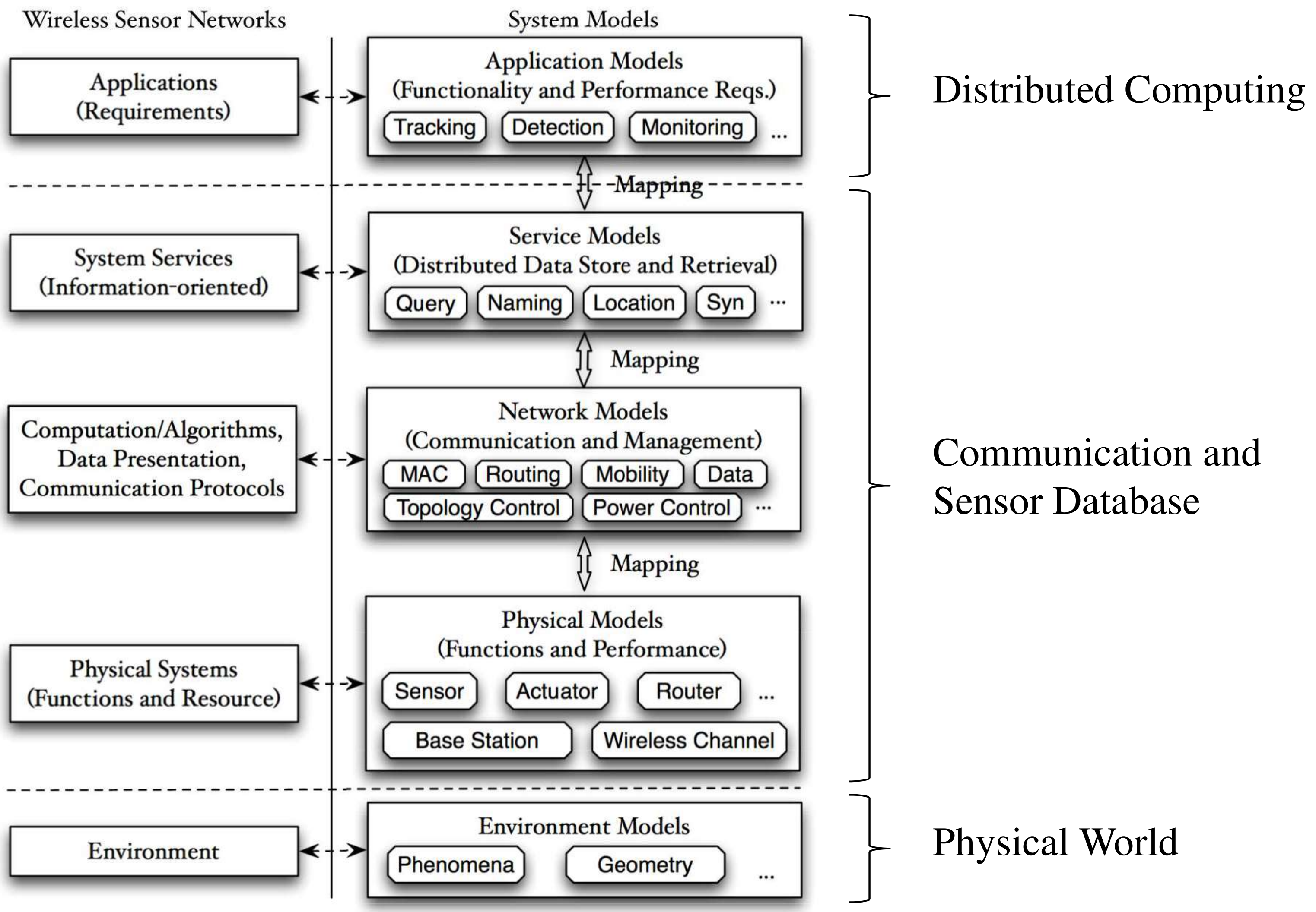
# MBSE for Wireless Sensor Networks: Contributions

- 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