Formal Methods and Tool-suites for CPS Security, Safety and Verification

Lectures 1 and 2: MBSE for CPS

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Marktoberdorf International Summer School on Engineering Secure and Dependable Software Systems

THE NEXT FRONTIER IN ENGINEERING RESEARCH AND EDUCATION

- First 50 years of the 21st century will be **dominated** by advances in methods and tools for the **synthesis, implementation and operation of complex engineered systems to meet specifications in an adaptive, safe, (semi-) autonomous way**

- Evident from the areas emphasized by governments, industry and funding agencies world-wide:
  - **energy and smart grids**
  - **biotechnology**
  - **systems biology**
  - **nanotechnology**
  - **the new Internet and IoT**
  - **collaborative robotics**
  - **software critical systems**
  - **homeland security**
  - **custom materials design**
  - **systems healthcare**
  - **network science**
  - **smart enterprises**
  - **environment and sustainability**
  - **intelligent buildings and cars**
  - **precision health care**
  - **pharmaceutical manufacturing**
  - **broadband wireless networks – 5G**
  - **sensor networks**
  - **smart transportation systems**
  - **security-trust-privacy-authentication**
  - **cyber-physical systems**
  - **web-based social and economic networks**
  - **human - machine collaboration**
  - **neuromorphic AI**

AKA

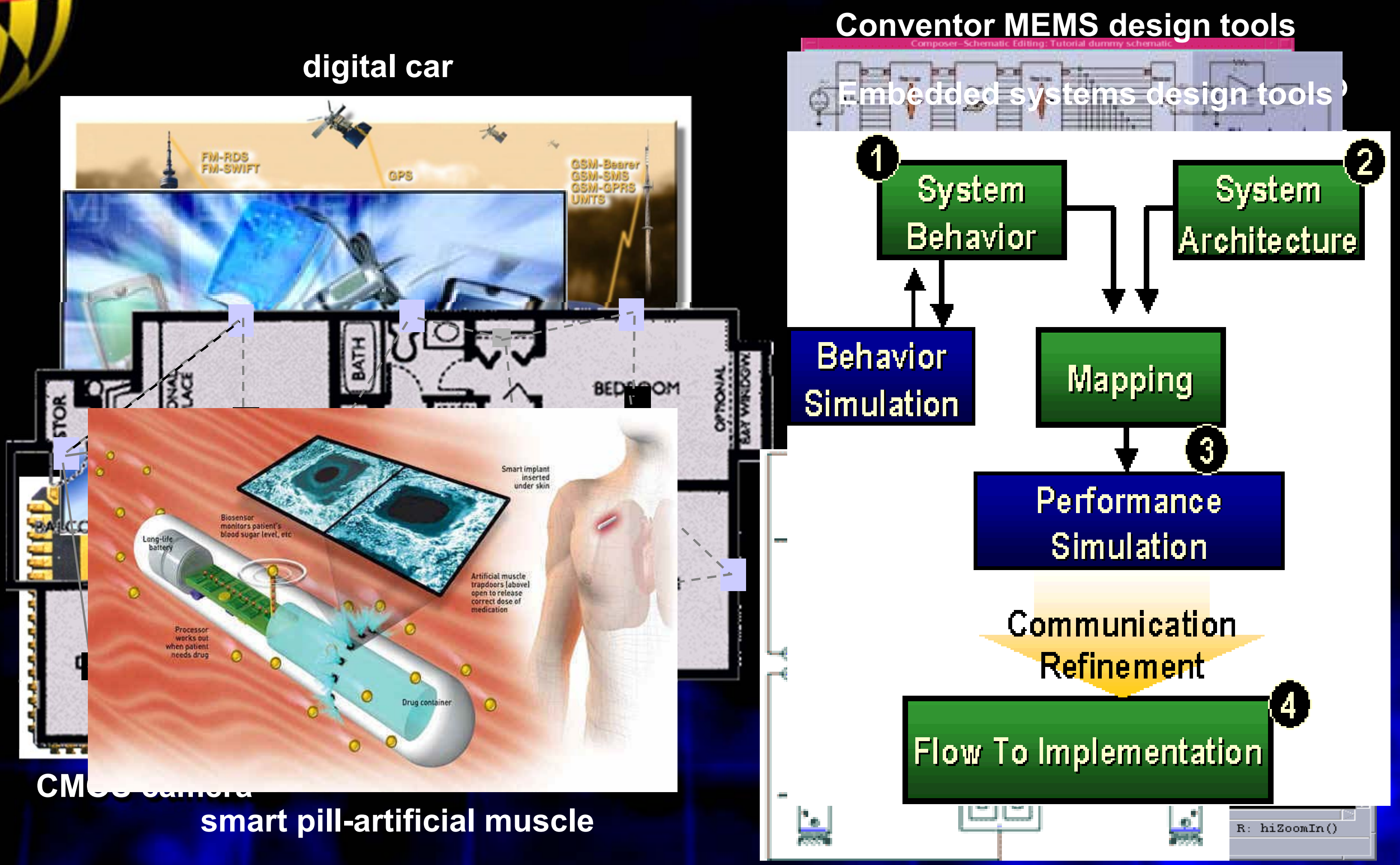
The Next Wonder – MBSE and MBE: from ideas to "making things and services"

Outline

- The Vision and its development
- What happened since then?
- Key challenges -- Model-based Systems Engineering
- Example applications: Microgrids, modern-aircraft, sensor networks, energy efficient buildings, robotics and micro-robotics, collaborative robotics, wireless security, social networks over the Web, Health Care (ICU), democratizing manufacturing, personalized medicine
- Reform Engineering Education
- Concluding remarks – future directions – open problems

The Two Faces of Information Technology in Engineering

(*Baras -- 2003 White Symposium*)



Ubiquitous presence of IT components as "building blocks"

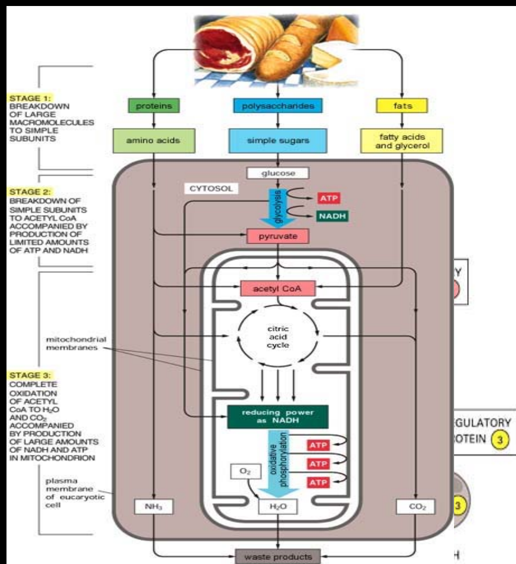
Increasing use of "system level" design and manufacturing CAD tools

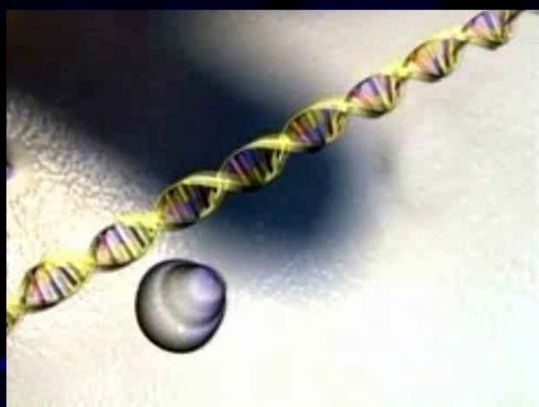
From IT abstractions to “hardware”

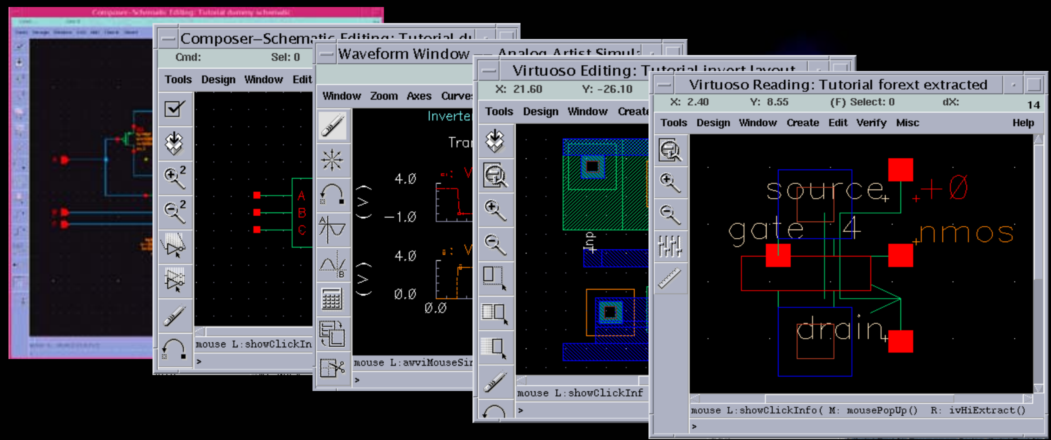
(*Baras -- 2003 White Symposium*)

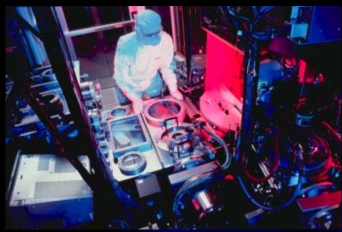
From DNA ‘programs’ to living organisms

From CAD schematics to chips



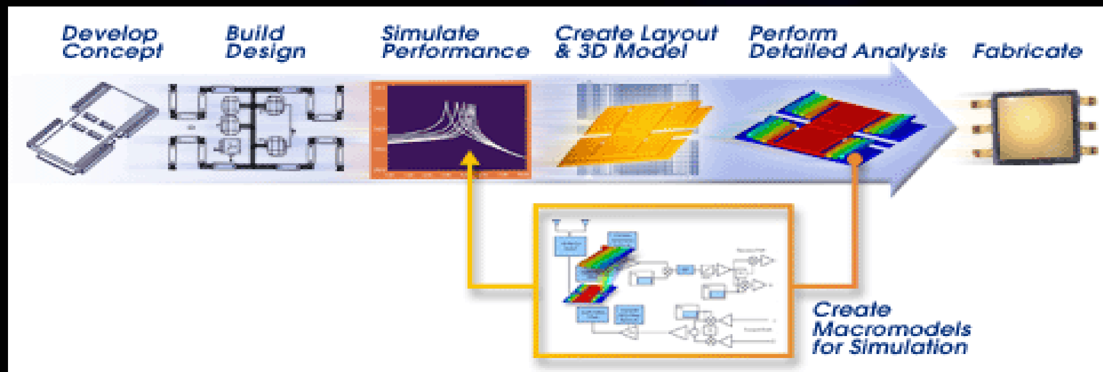


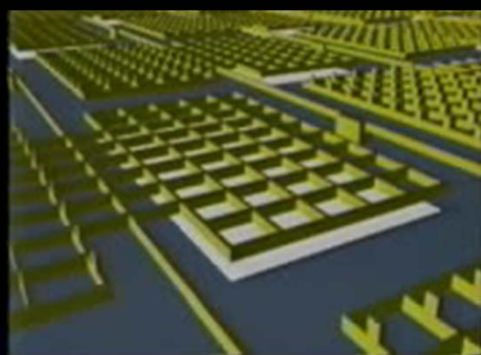


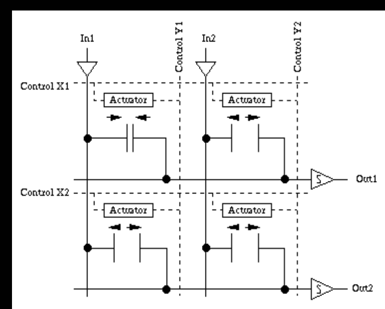


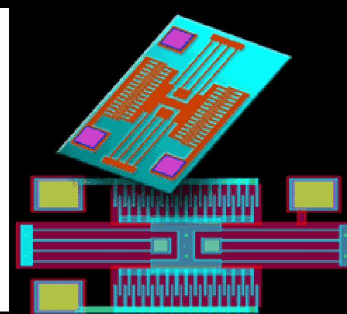
From IT abstractions to “hardware”

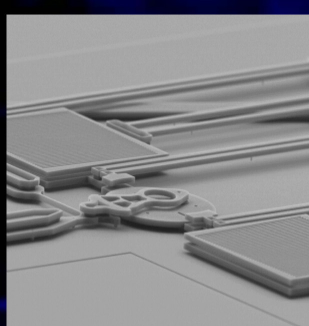
(*Baras -- 2003 White Symposium*)

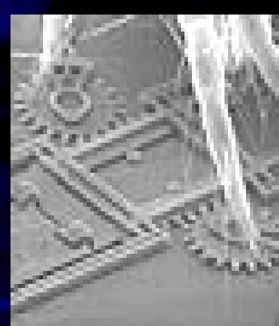


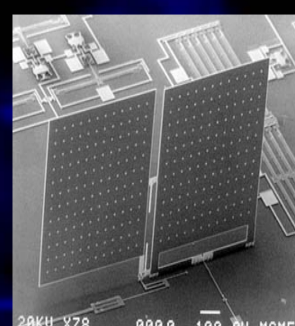


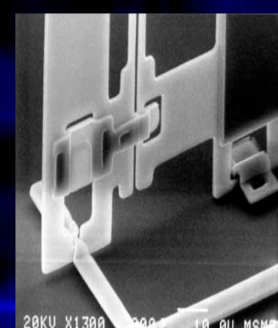


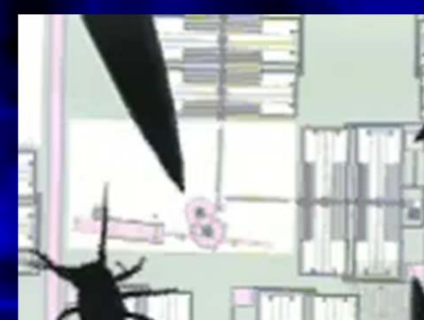








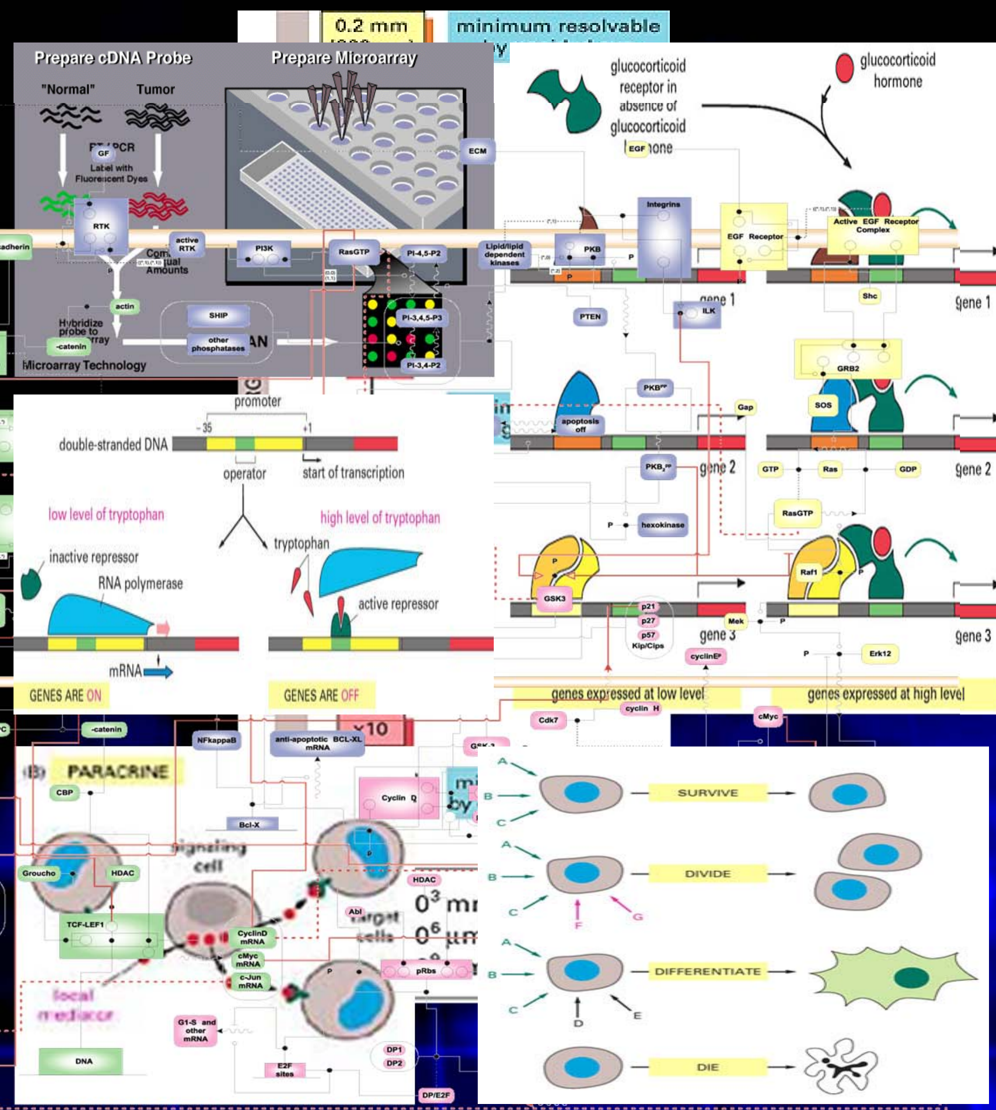




Why IT? Why the Two Faces?

(*Baras -- 2003 White Symposium*)

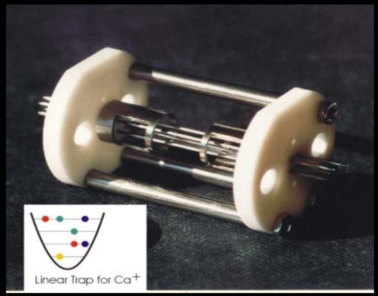
- A means for interfacing heterogeneous components and controlling complexity
  Embedded software and systems
- Micro-sensors, micromotors, MEMS
- Manufacturing 'ahead' of design; design verification
  Development and use of formal models and methods
- Microarrays, metabolic pathways, systems biology
- Signaling and communication
- Languages for hardware, cells, ….
  (XML, UML, DCL, SBML)
- Learning from biology (integration)

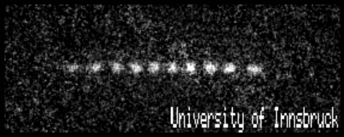


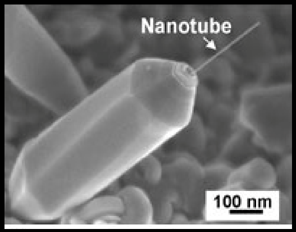
Challenges: A Glimpse into the Future (*Baras -- 2003 White Symposium*)

- Computing over new physical domains (quantum, organic, biological)

- from abacus to qubits
- entanglement
- nuclear spin, electron spin
- photon polarization, ion trap

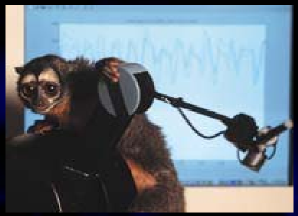


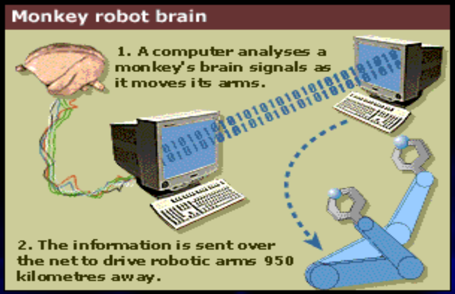




- Send a program over a network and at the other end receive hardware

- Communicating minds





- Swarm intelligence

RESEARCH

- At the interface of bio - nano - info
- Self - assembled systems

EDUCATION

- Teach holistic engineering

What has happened since then?

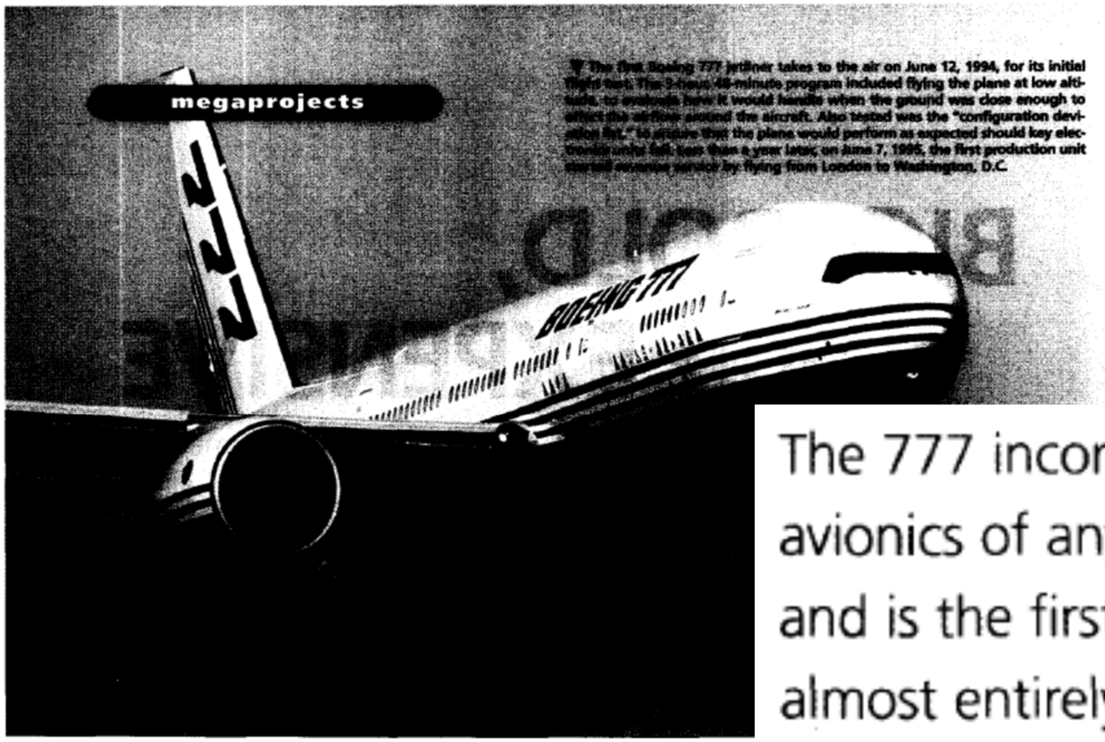
- **Design and manufacturing from Boeing 777 aircraft to Boeing 787 aircraft …**
- **Humans become integral part of systems -- *iPhone*, …**
- **Cyber-Physical Systems (CPS) …**
- **Social networks over the Web mushroomed …**
- **Economic networks over the Web mushroomed …**
- **Renewable energy, smart grid …**
- **Individual human genome generation becomes fast, inexpensive …**

What has happened more recently?

- **Multisensory environmental monitoring spreads…**
- **Autonomous and connected cars designed and tested …**
- **Cloud Computing, "Big Data", …**
- **Health information technology spreads …**
- **Internet of Things, Industrie 4.0, Industrial Internet**
- **First "printed" car …**
- **"Crowd sourcing" and manufacturing …**

Boeing’s Seventh Wonder

(*IEEE Spectrum, 1995 October*)



▼ The first Boeing 777 jetliner takes to the air on June 12, 1994, for its initial flight test. The 3-hour, 48-minute program included flying the plane at low altitude, to evaluate how it would handle when the ground was close enough to affect the airflow around the aircraft. Also tested was the "configuration deviation list," to ensure that the plane would perform as expected should key electronic units fail. Less than a year later, on June 7, 1995, the first production unit started revenue service by flying from London to Washington, D.C.

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:

*Relative to the 767

20%* reduction in fuel and CO_2

28% below 2008 industry limits for NOx

60%* smaller noise foot print

Advanced Wing Design

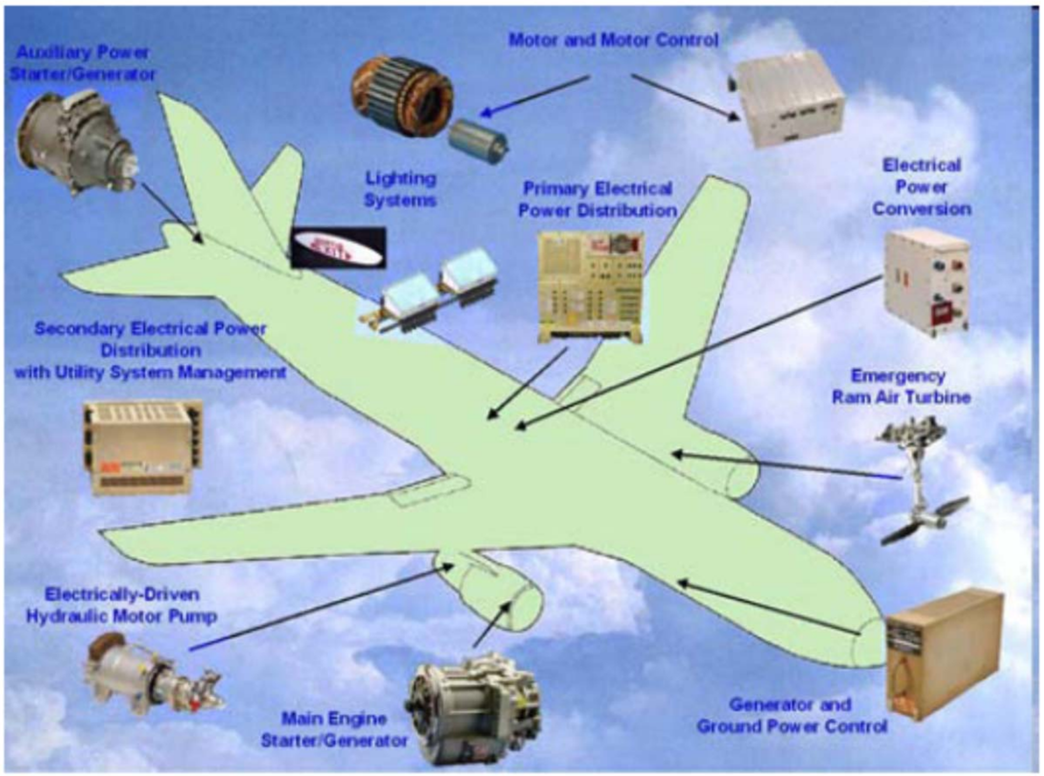
Innovative Systems Technologies

Enhanced Flight Deck

Composite Primary Structure

Advanced Engines and Nacelles

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



[Image: hamiltonsunstrand.com]

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

Joint with UTRC

The Institute for Systems Research

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

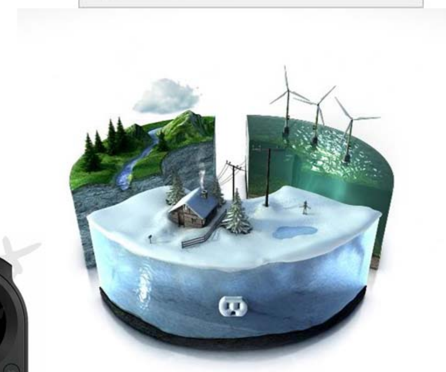
It is billed as the future of commerce: swiping a smartphone at the checkout counter instead of a credit card.

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

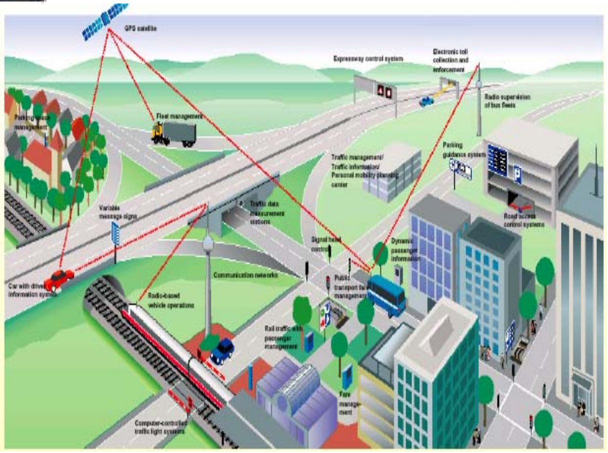
- UI for “Everything”
  - Devices with Computing Capabilities & Interfaces
- Network Communication
  - Devices Connected to Home Network

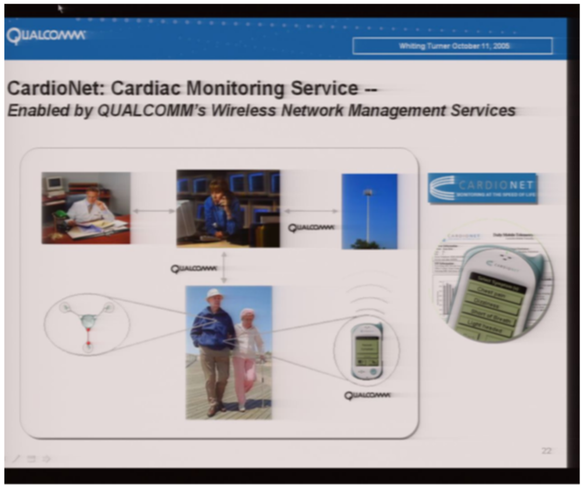
- Media: Physical to Digital
  - MP3, Netflix, Kindle eBooks, Flickr Photos
- Smart Phones
  - Universal Controller in a Smart Home

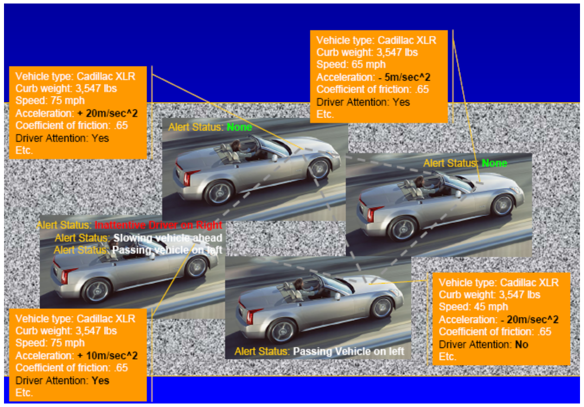


- Smart Meters & Grids
  - Demand/Response System for “Power Grid”
- Wireless Medical Devices
  - Portable & Wireless for Real-Time Monitoring

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

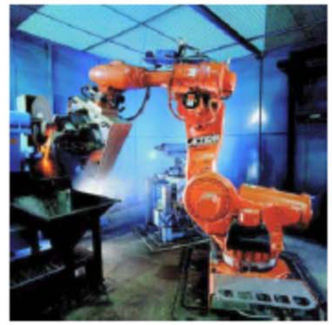
- From very small: Ubiquitous, Pervasive, Disappearing, Perceptive, Ambient
- To very large: Always Connectable, Reliable, Scalable, Adaptive, Flexible

Emerging Service Models

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

Cyber-Physical Systems

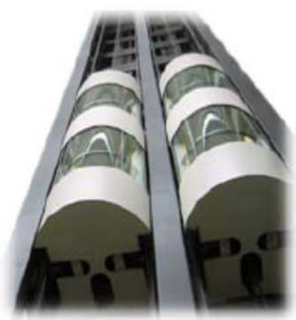
Automotive



Industrial automation

Robotics

Aeronautics



Elevators

Building automation

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 CPS;
- 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**.

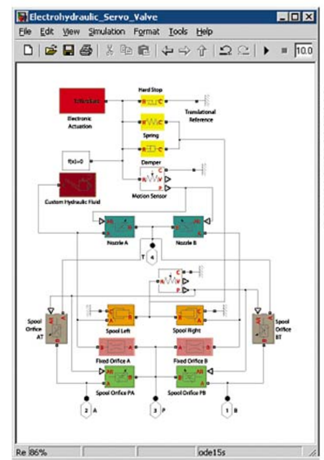
Virtual Engineering Everywhere Multi-Physics models

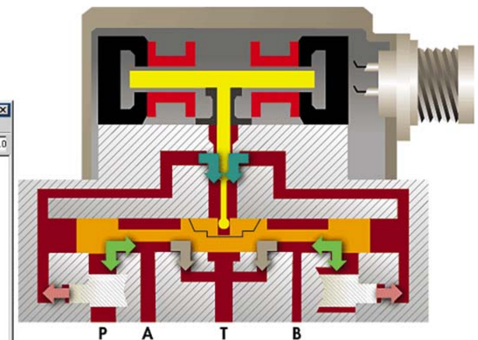
Helping over 30 different teams and skills in the company work together

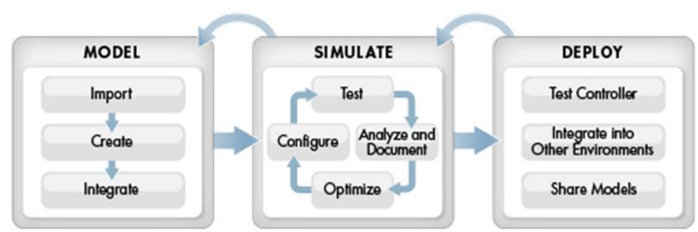
Linking over 40 different EE design representations throughout the entire development process

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

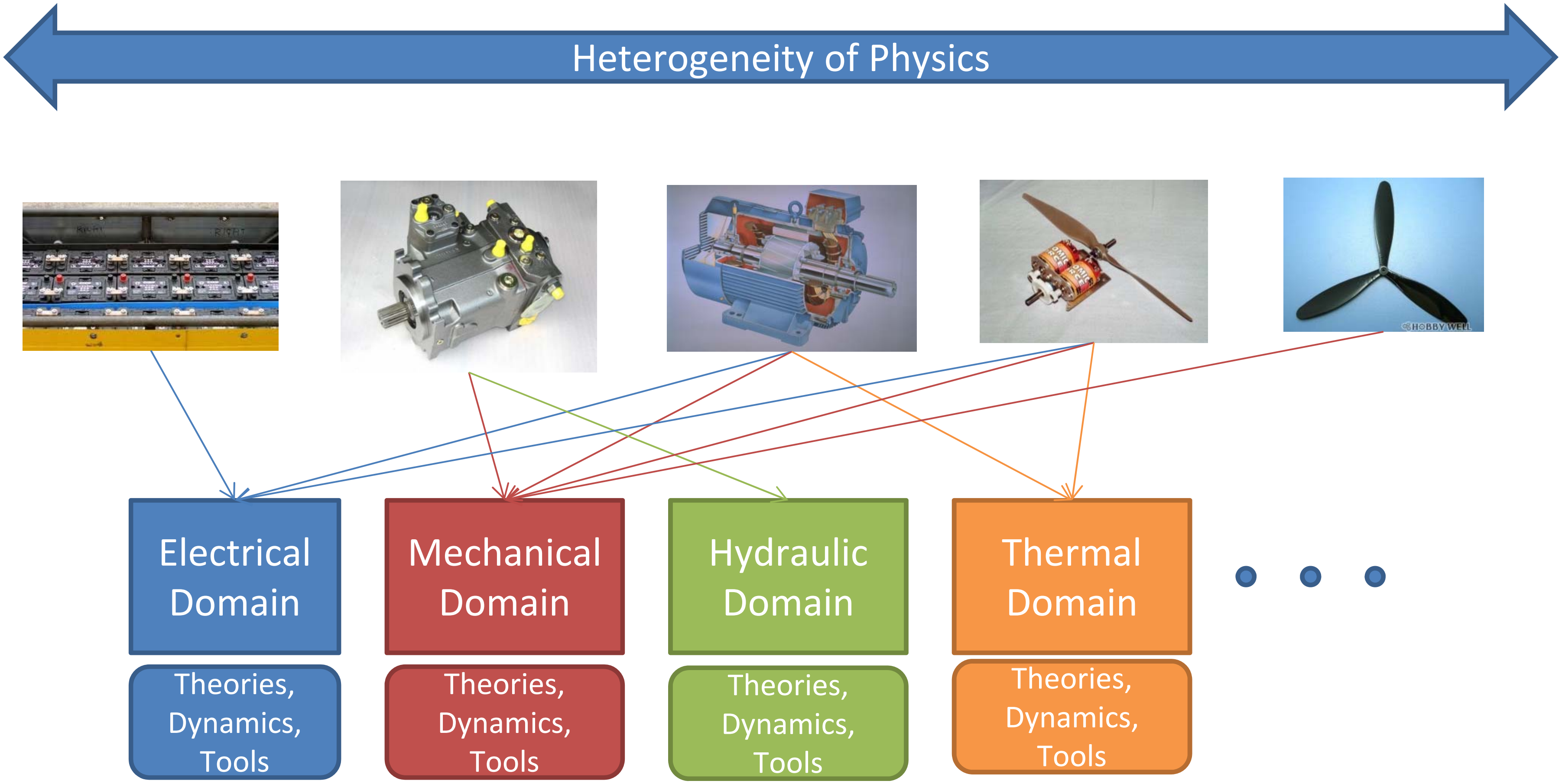
Model based design and executable specification in the OEM/supplier chain





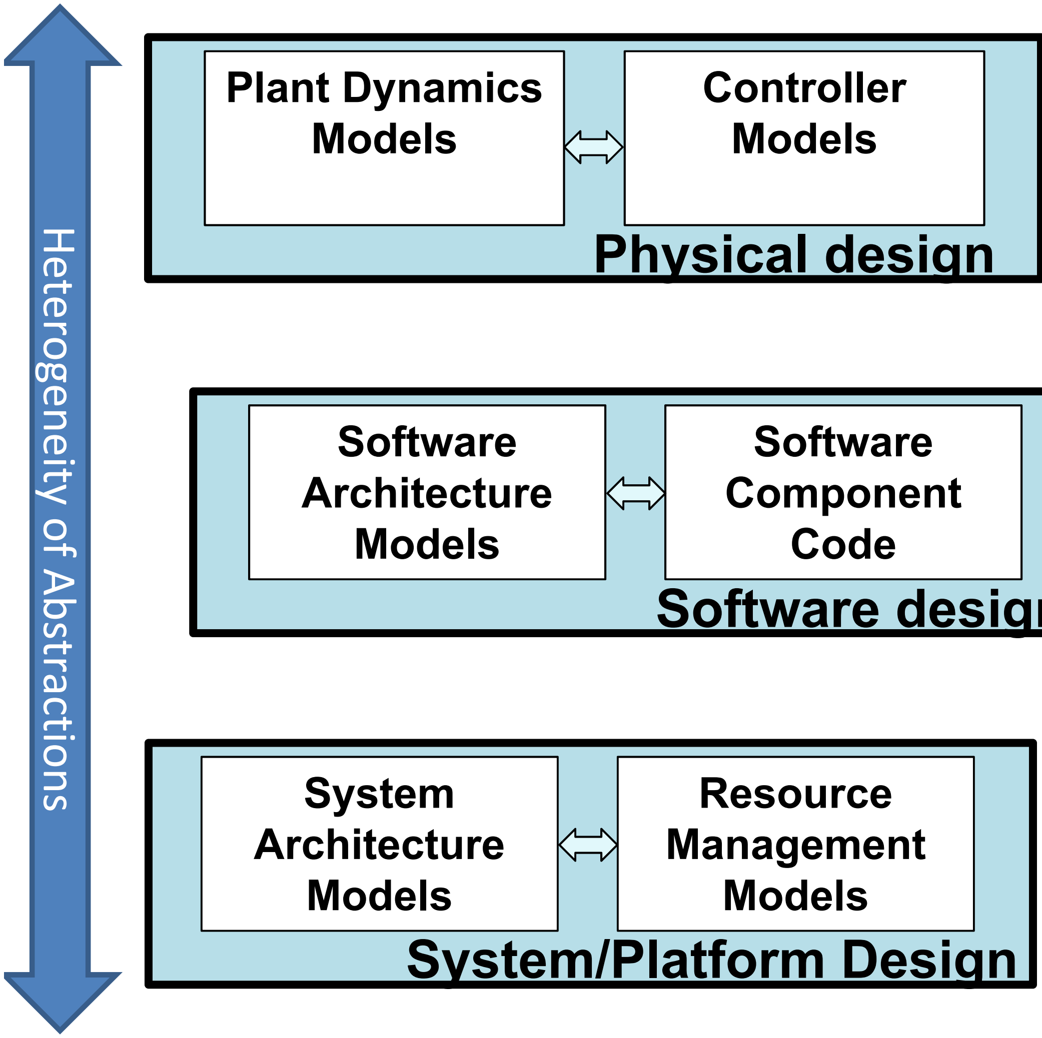


Model Integration Challenge: Physics



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 (MBSE)

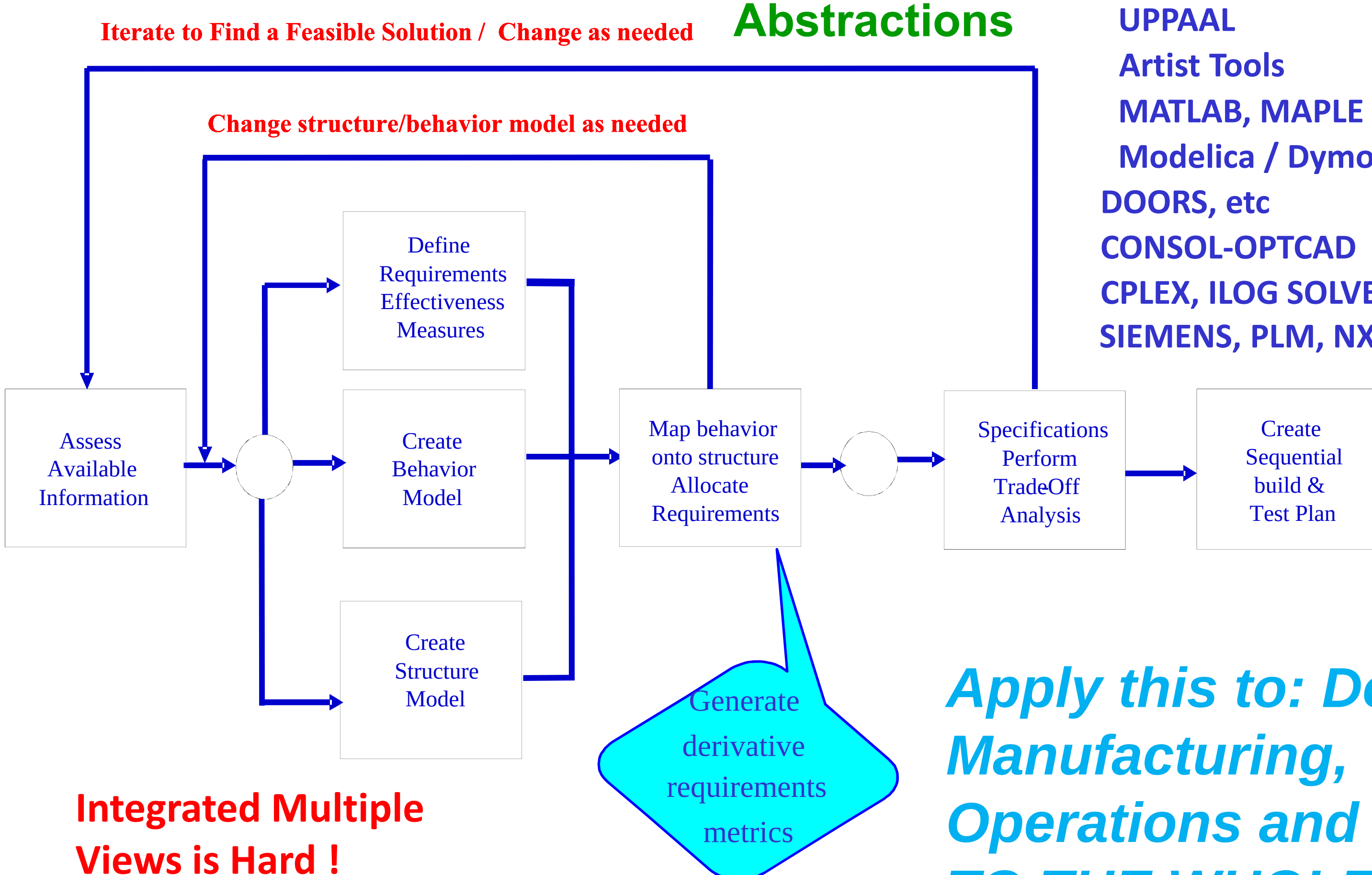
The Institute for Systems Research

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

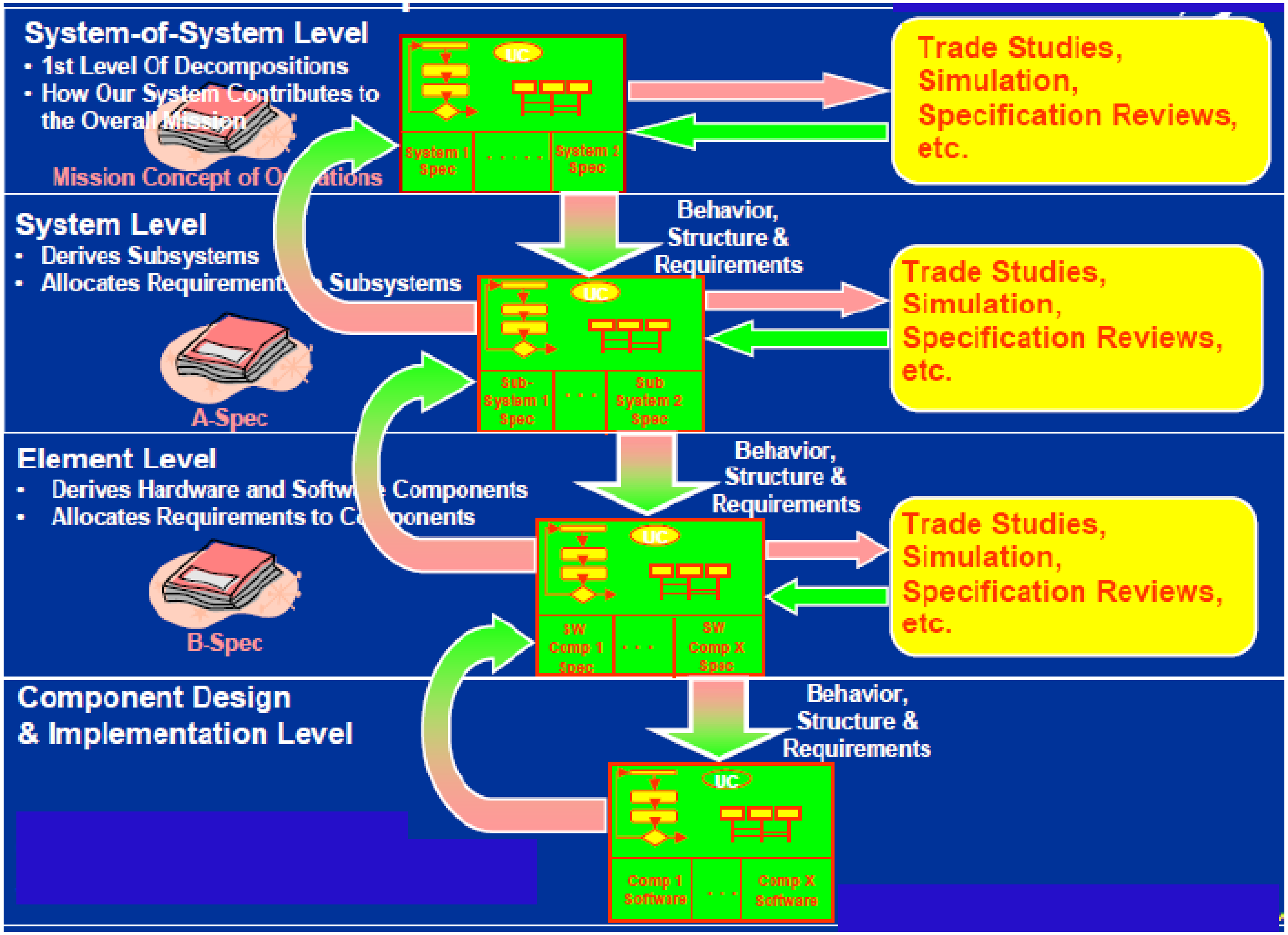
DOORS, etc
CONSOL-OPTCAD
CPLEX, ILOG SOLVER,
SIEMENS, PLM, NX, TEAM CENTER



Integrated Multiple Views is Hard !

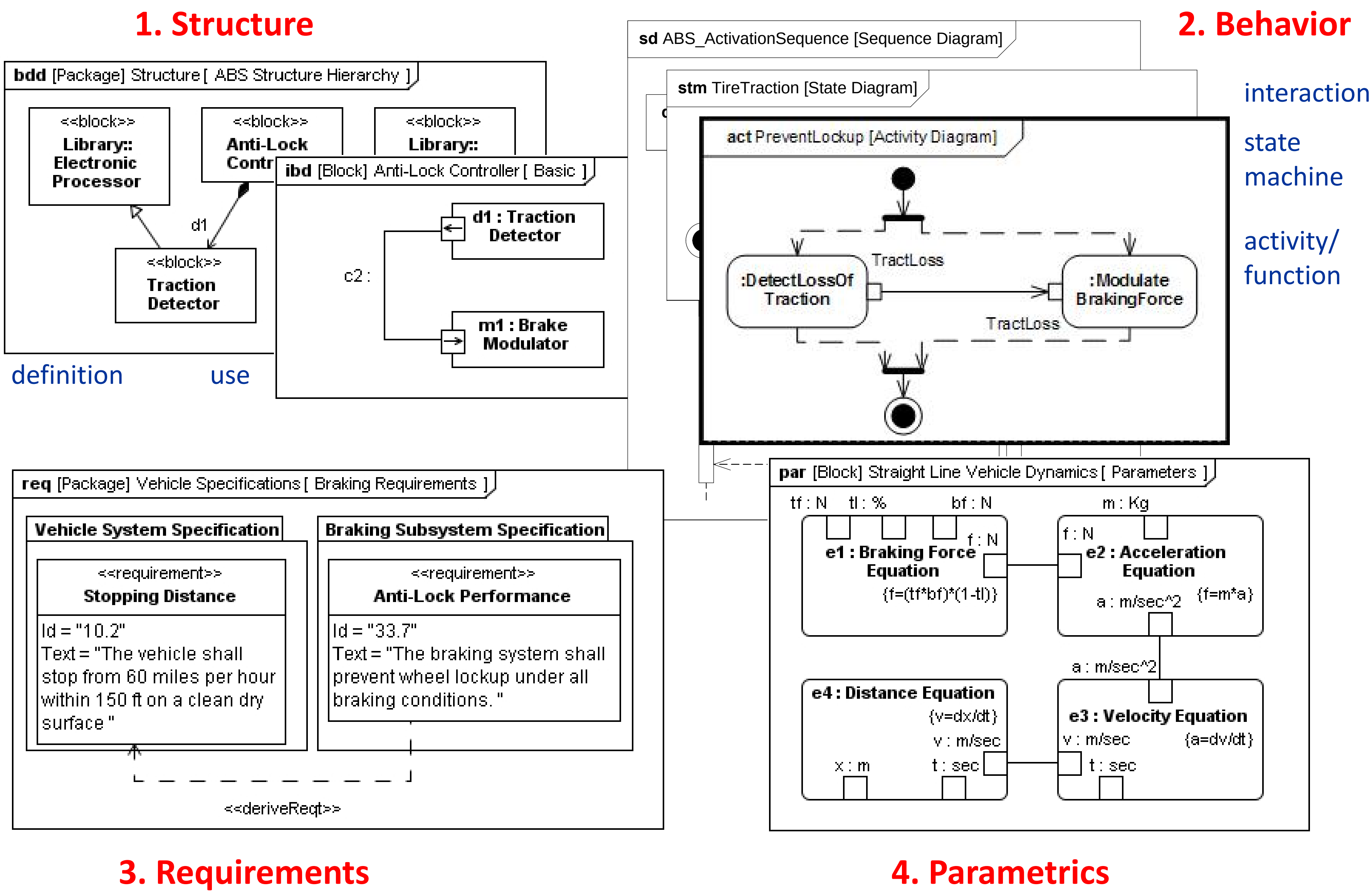
Apply this to: Design, Manufacturing, Operations and Management
TO THE WHOLE LIFE-CYCLE
⇛ MBE

Layered MBSE -- Hierarchies

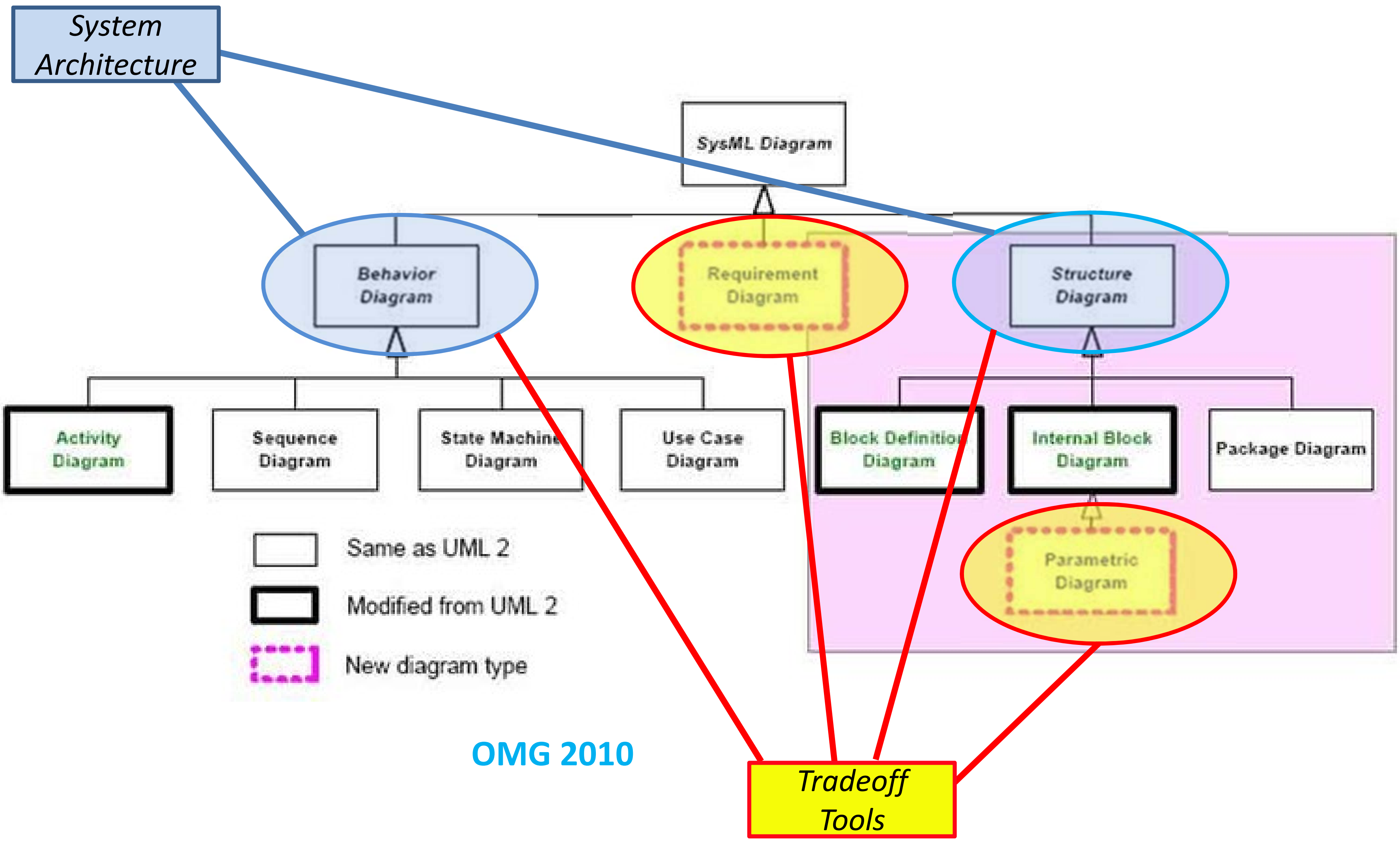


(Watson 2008, Lockheed Martin)

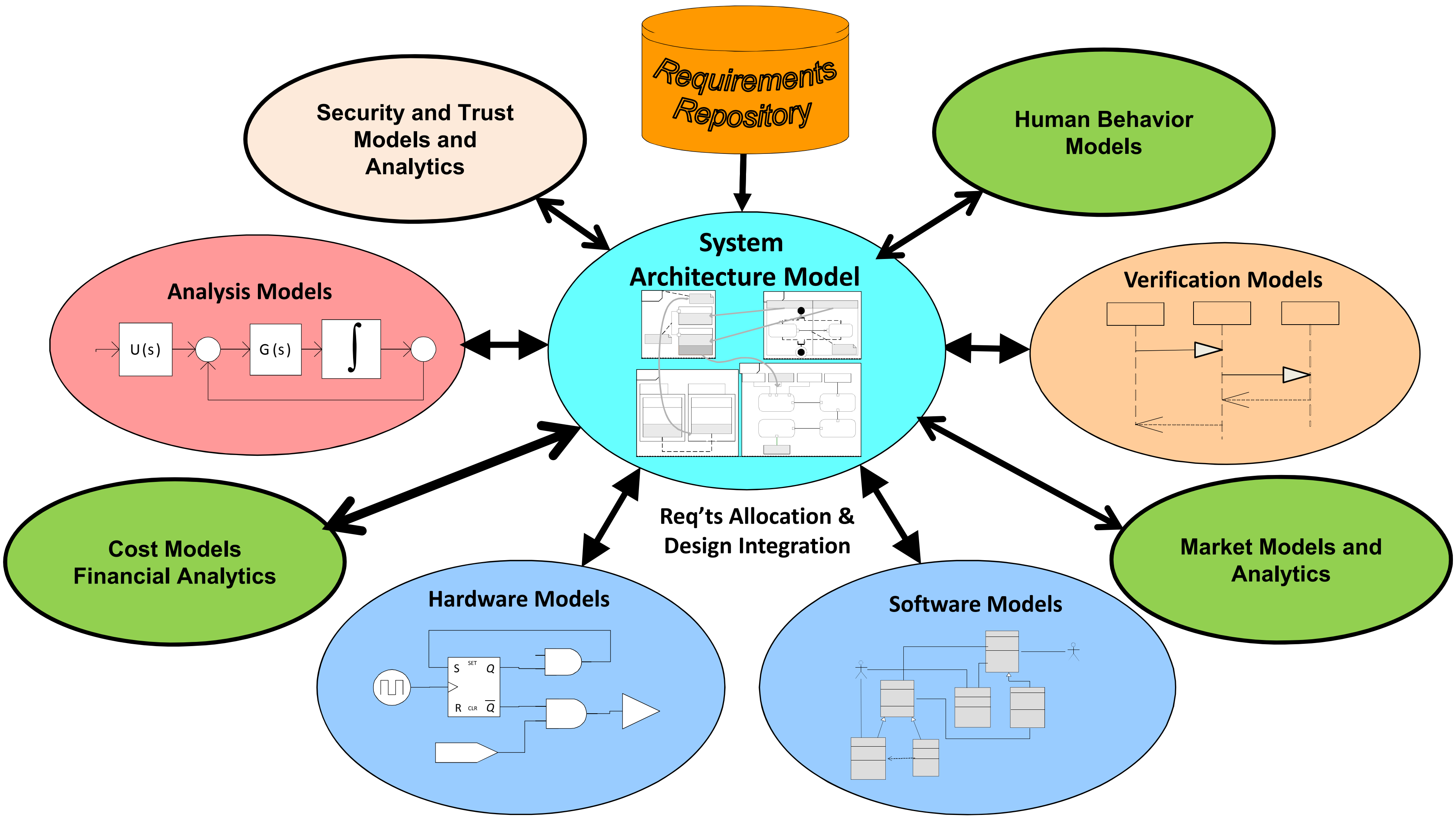
FOUR PILLARS OF SYSML



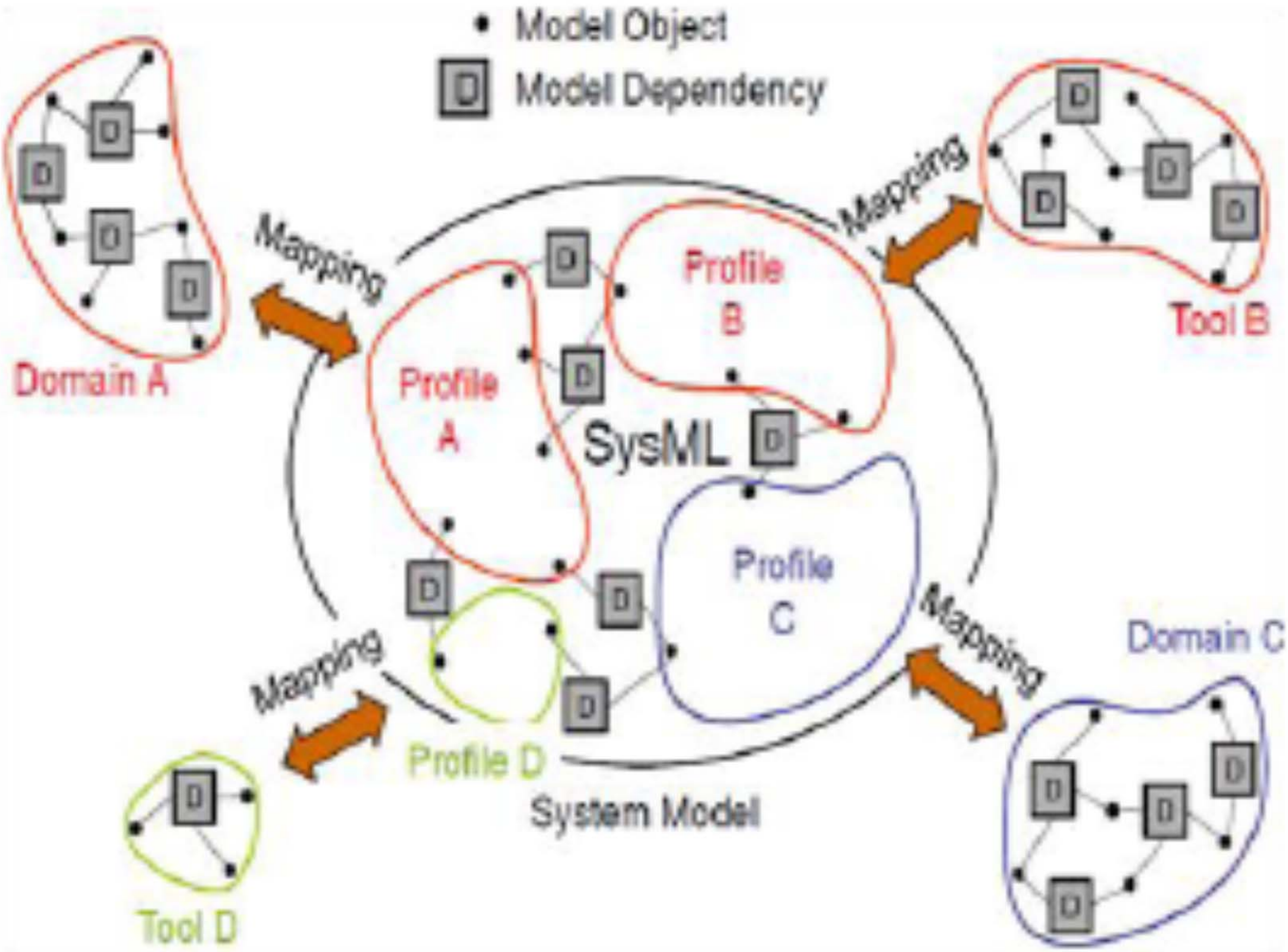
SysML Taxonomy



Using *System Architecture Model* as an Integration Framework



System Modeling Transformations--Metamodeling (Models of Models)



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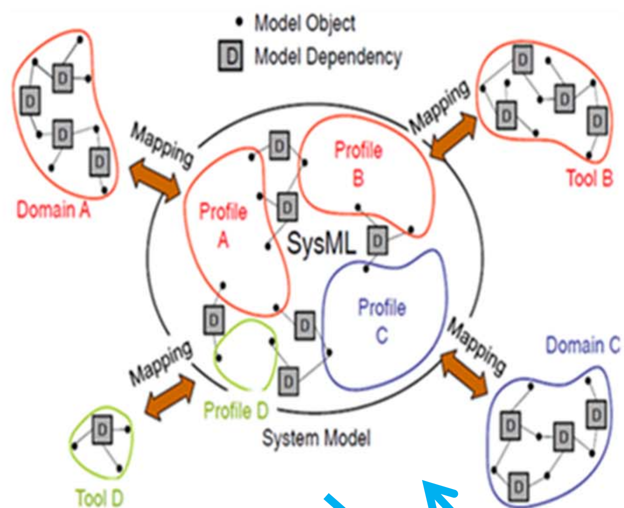
A Rigorous Framework for Model-based Systems Engineering

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**

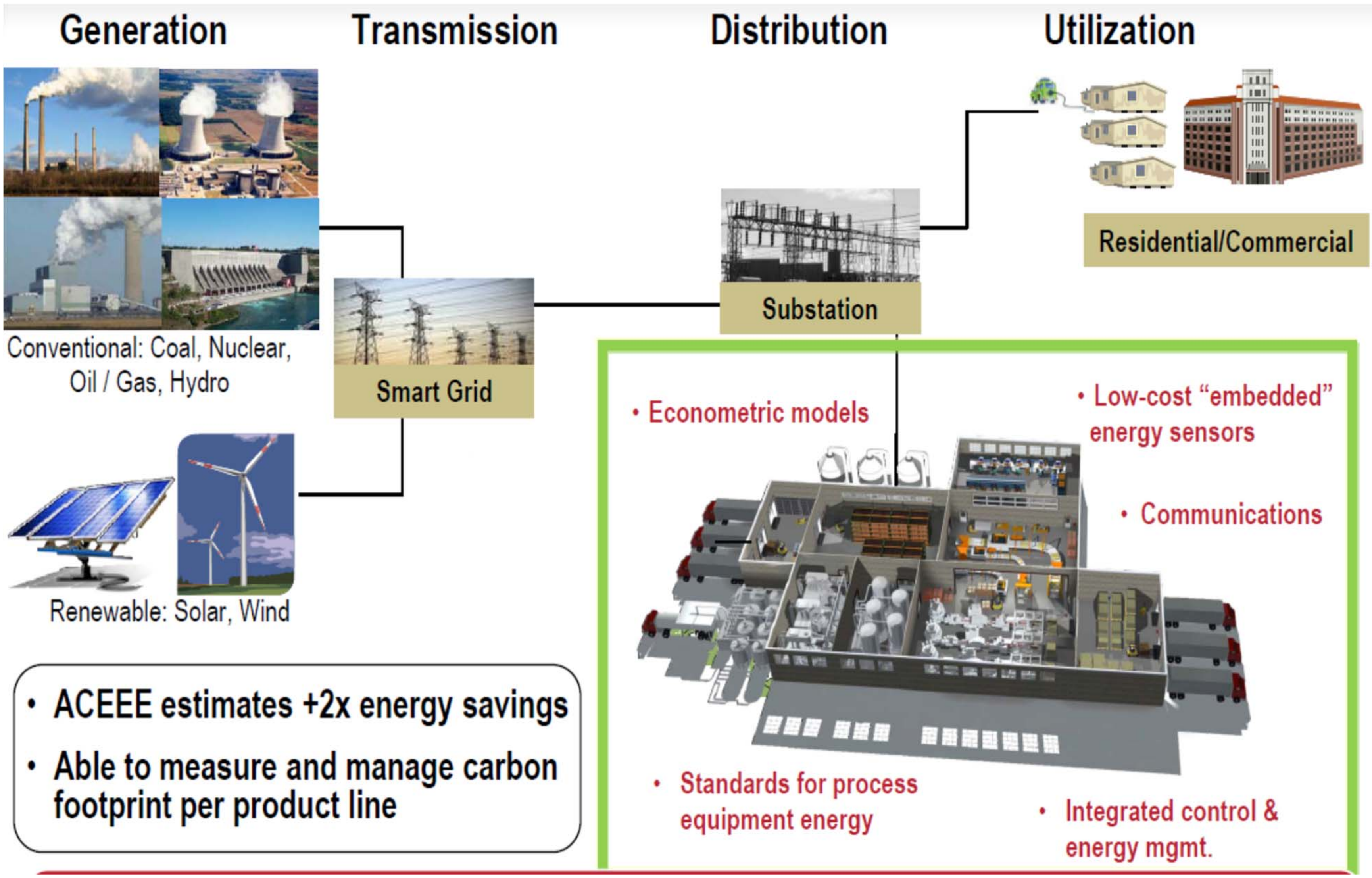
APPLICATIONS

- **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
- **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?**

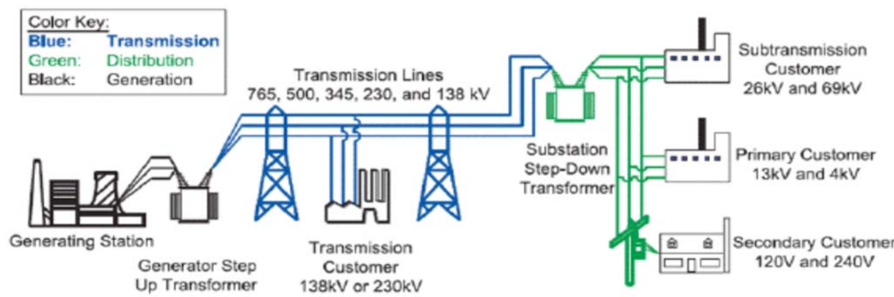
Smart Grids in a Network Immersed World

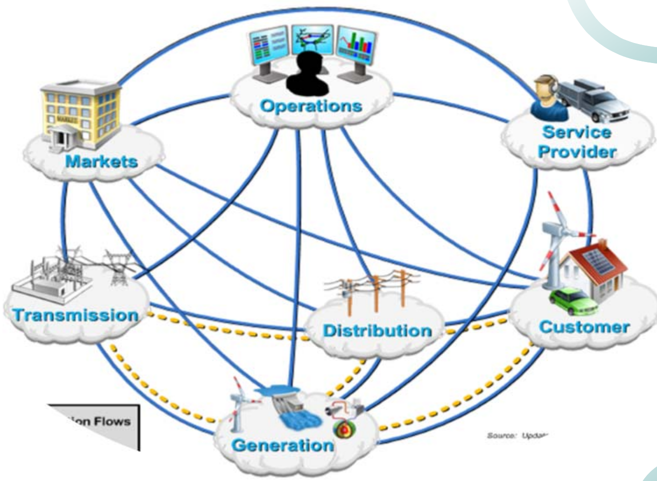


Courtesy: Rockwell

Smart Grid – Microgrids Architecture

Grid 1.0
Legacy Grid





Grid 2.0
Smart Grid

Grid 3.0
Future Grid

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

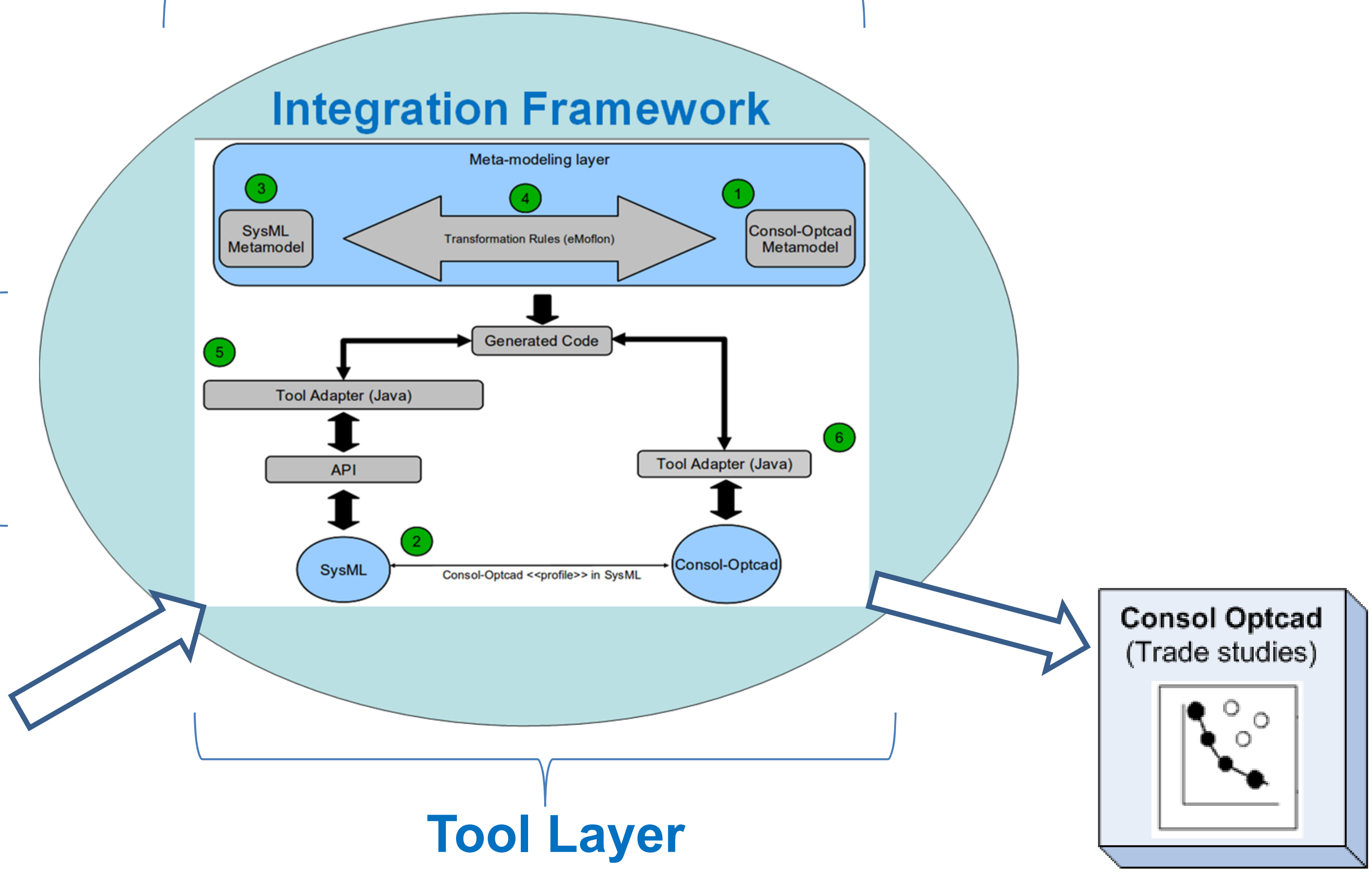
Overview

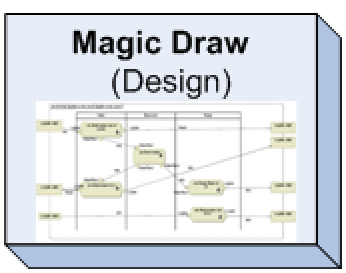
Meta-modeling Layer

(Enterprise Architect + eMoflon, Eclipse development environment)

Tool Adapter Layer

(Middleware)





Tool Layer

(Magic Draw, Consol Optcad)

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

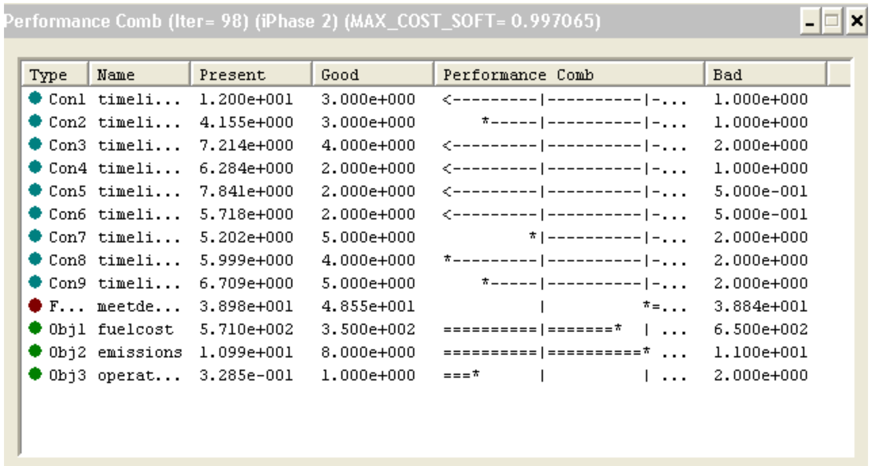
Advantages

- ✓ 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)

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

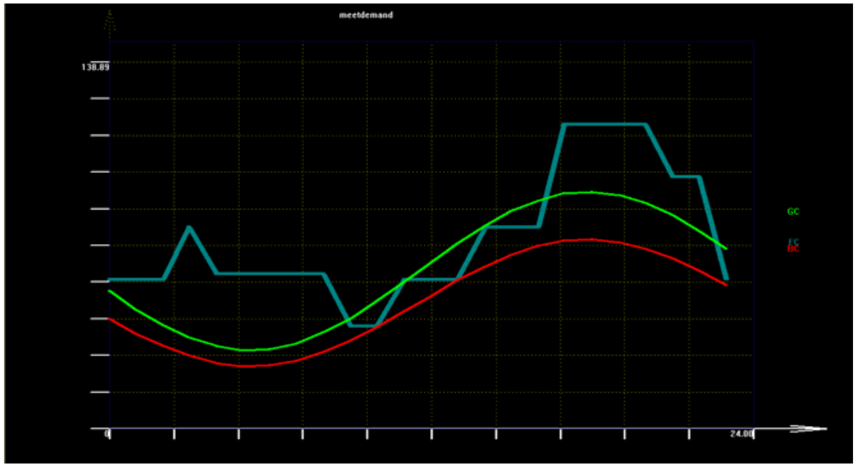


Fig. 2: Example of a functional constraint

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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

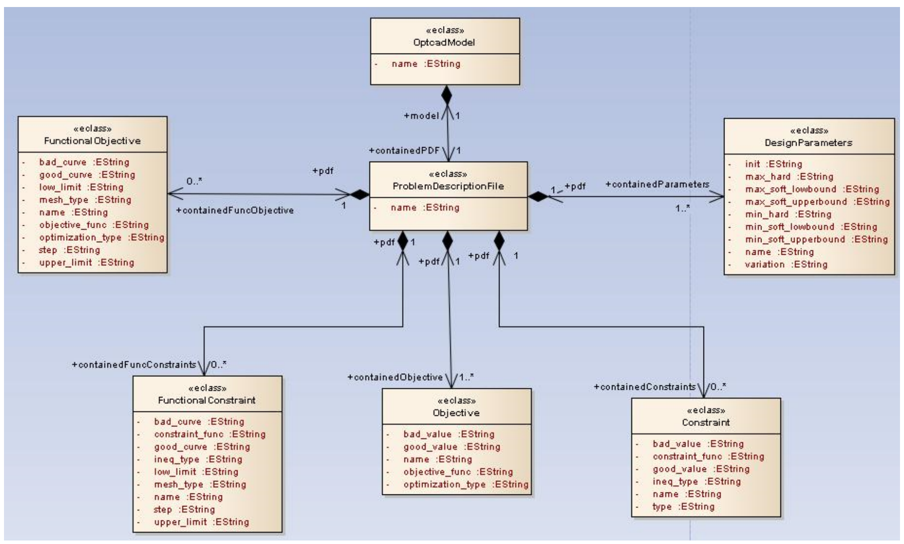

Fig. 4: Consol-Optcad metamodel

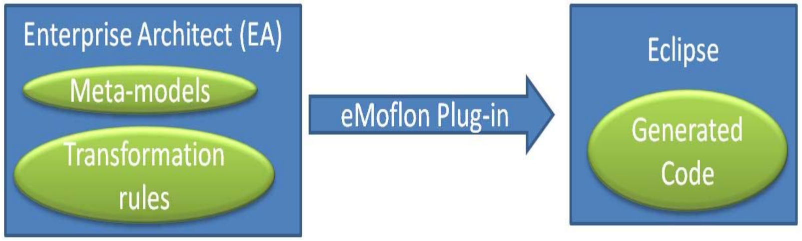

Fig. 3: eMoflon high-level architecture

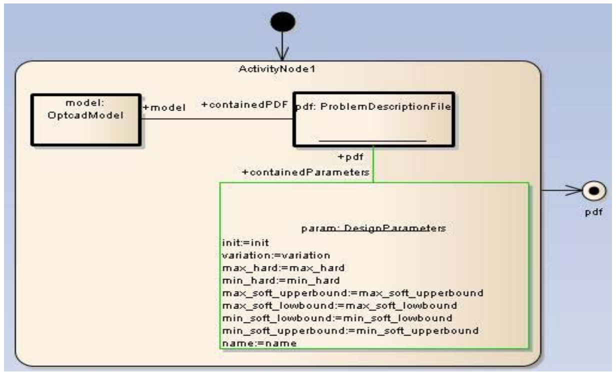

Fig. 5: Story diagram

IMH and Consol-Optcad Integration

Working Example

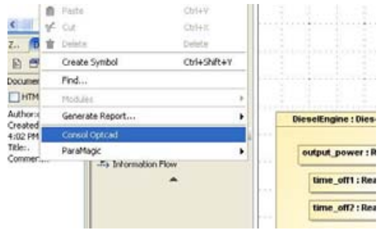

Fig. 11: Initiate transformation

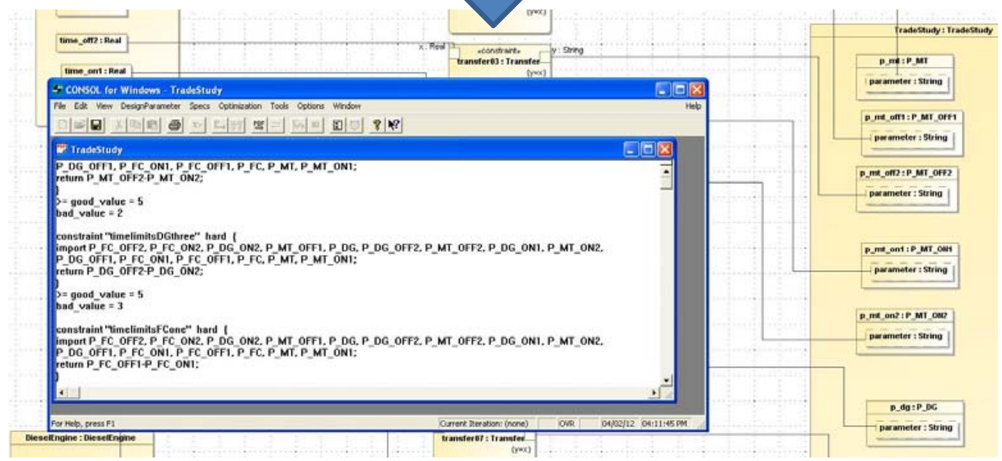

Fig. 12: Consol-Optcad environment

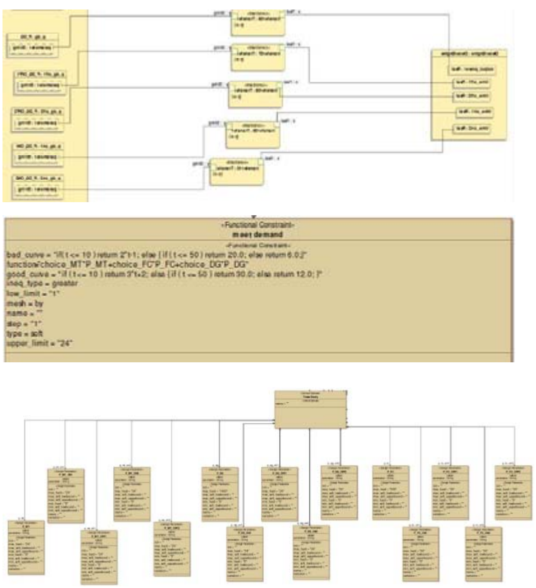

Fig. 10: Models in SysML

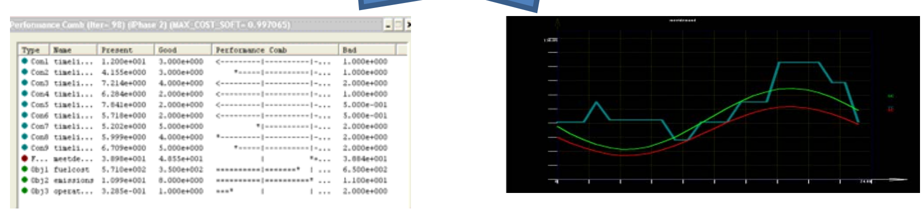

Fig.13: Perform trade-off analysis in Consol-Optcad

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Microgrid Problem Formulation

Objectives

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

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

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

P_i : power output of each generating unit

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

n_i : efficiency of the generating unit i

N : number of generating units

M : number of elements considered in emissions objective

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

Microgrid Problem Formulation

Constraints

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

  Functional constraint and shall be met for all values of the free parameter *t*

- Each power source should turn on and off only 2 times during the day

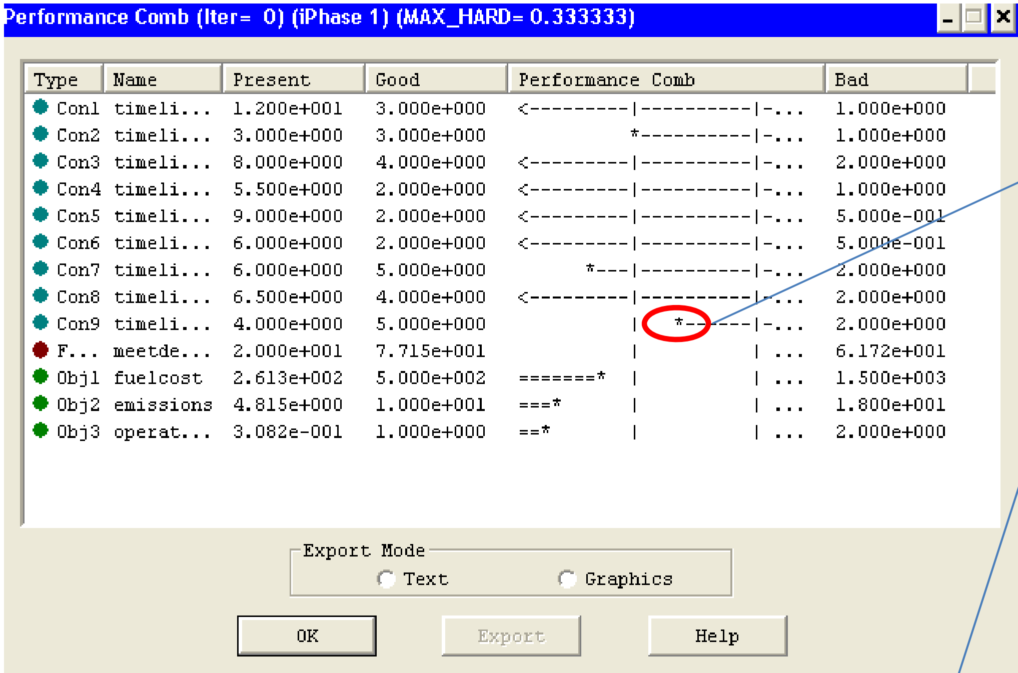
Constraints for correct operation of the generation unit

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

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

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

Tradeoff Study in Consol-Optcad



<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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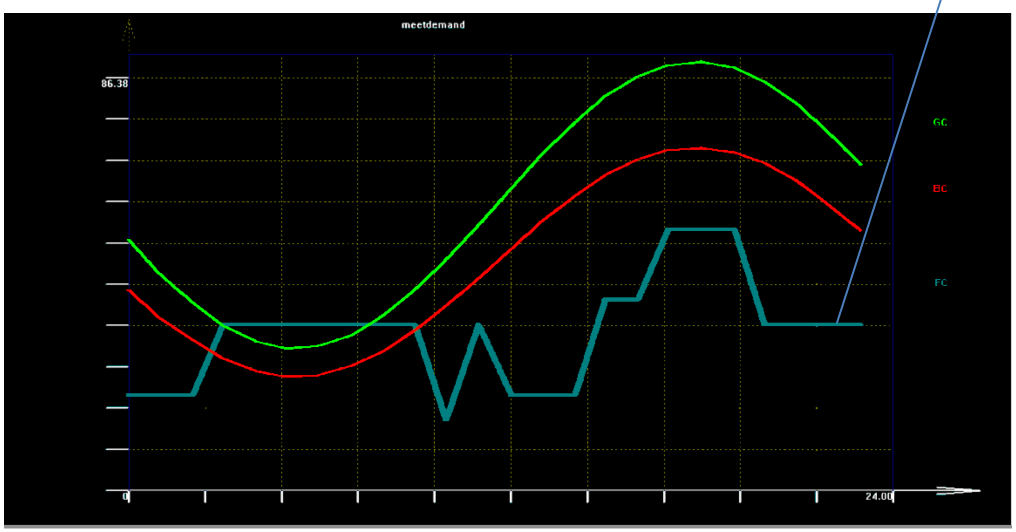

Iteration 1 (Initial Stage)

- ✓ 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**

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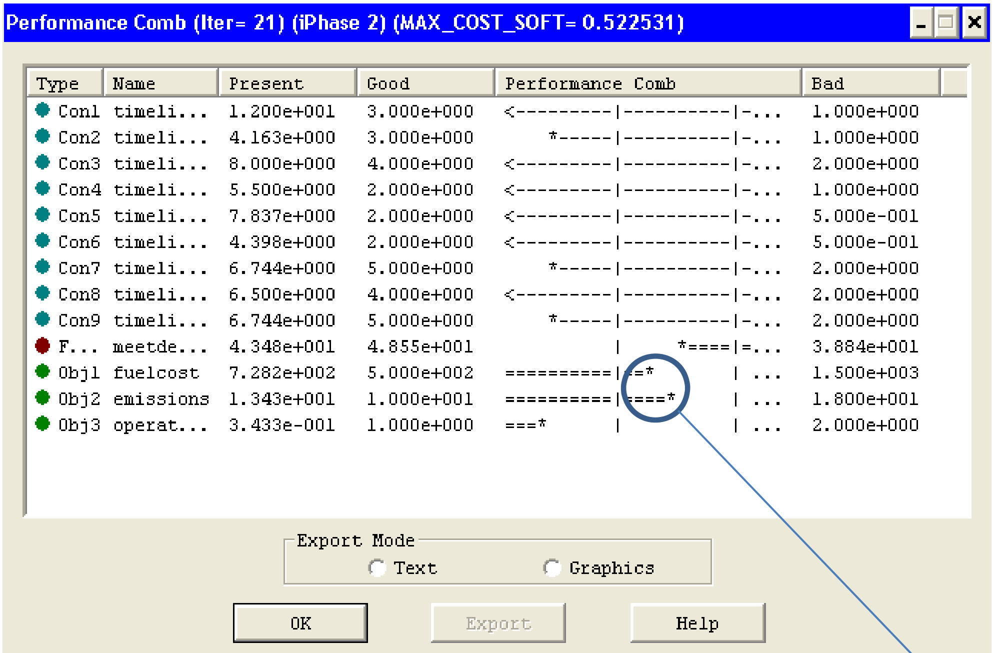
Microgrid: Trade-off Study



Type	Name	Present	Good	Performance Comb	Bad
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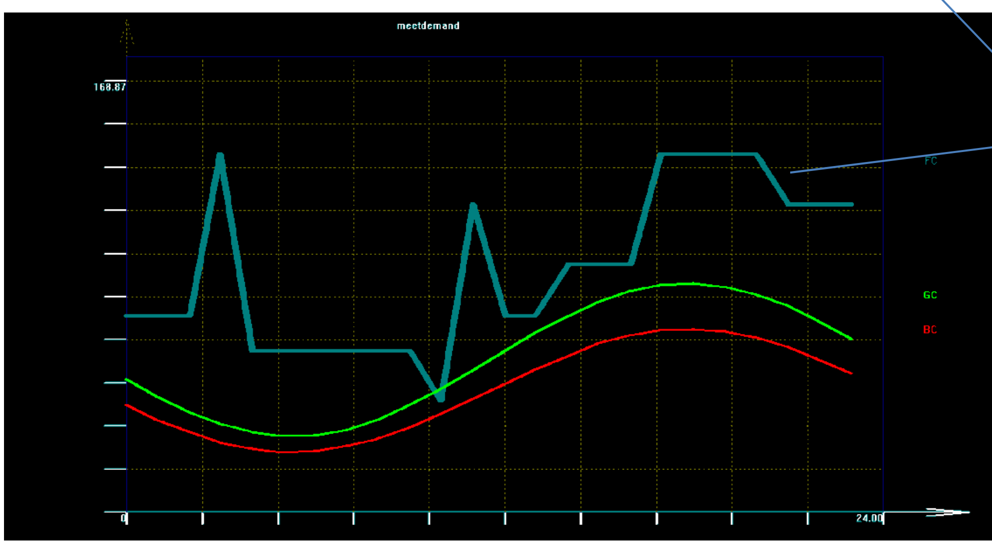
Con3	timeli...	8.000e+000	4.000e+000	<---------|----------|-...	2.000e+000
Con4	timeli...	5.500e+000	2.000e+000	<---------|----------|-...	1.000e+000
Con5	timeli...	7.837e+000	2.000e+000	<---------|----------|-...	5.000e-001
Con6	timeli...	4.398e+000	2.000e+000	<---------|----------|-...	5.000e-001
Con7	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)

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Trade-off Study in Consol-Optcad

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

<table>
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<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>
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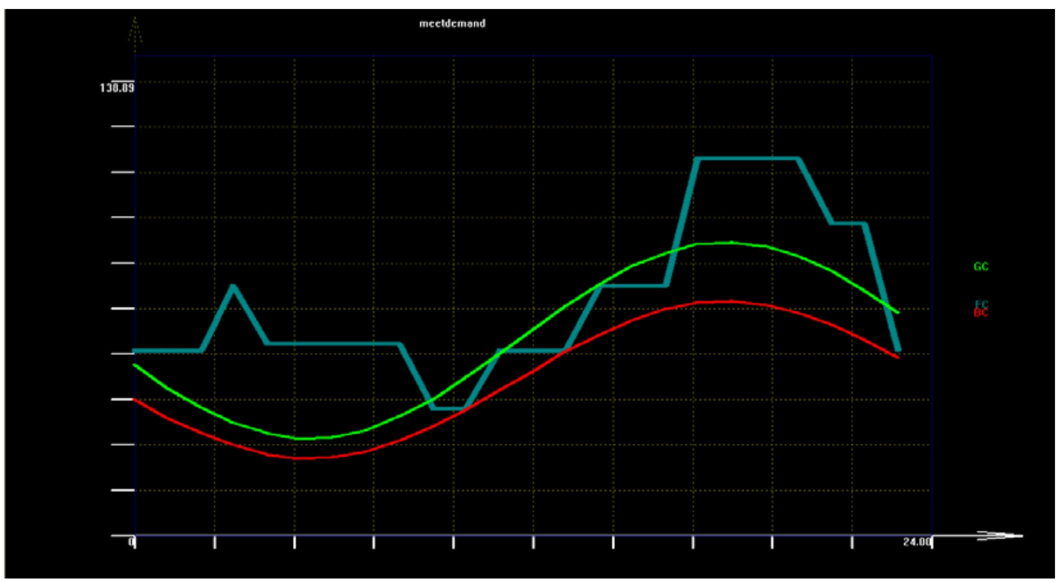


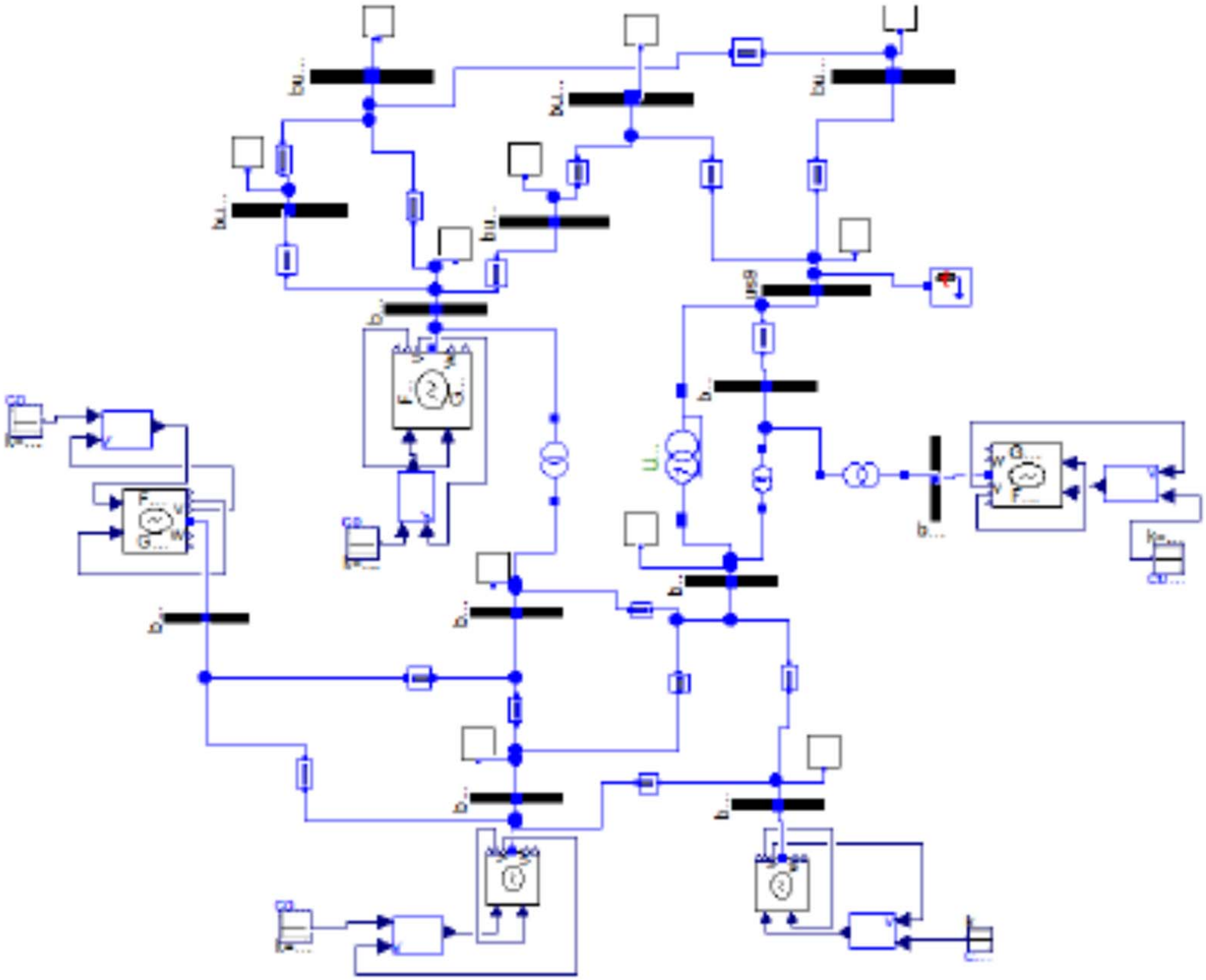
Iteration 95 (Final Solution)

- ✓ 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

New Integrated Modeling Hub

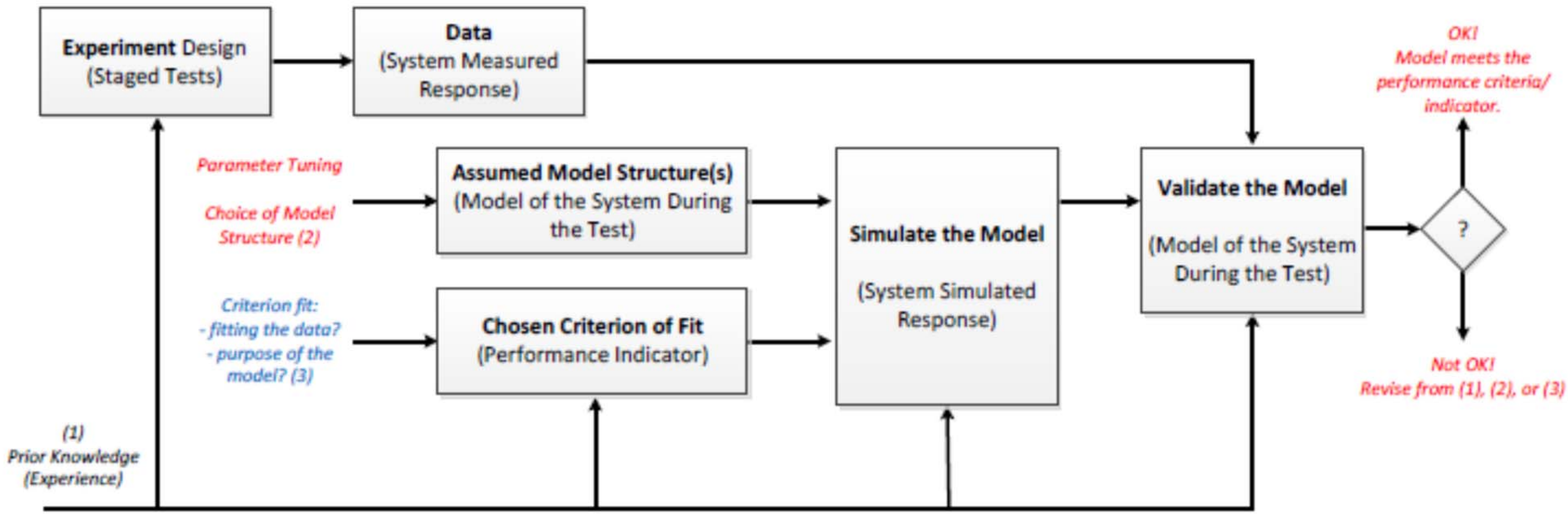
- Open source
- Open Modelica
- UML/SysML Papyrous
- SciLab
- Building results and models of the iTesla project (EU) http://www.itesla-project.eu/
- Libraries of components
- Examples from Norwegian Grid
- Validate components
- Hybrid systems models result

iTesla Models - Modelica



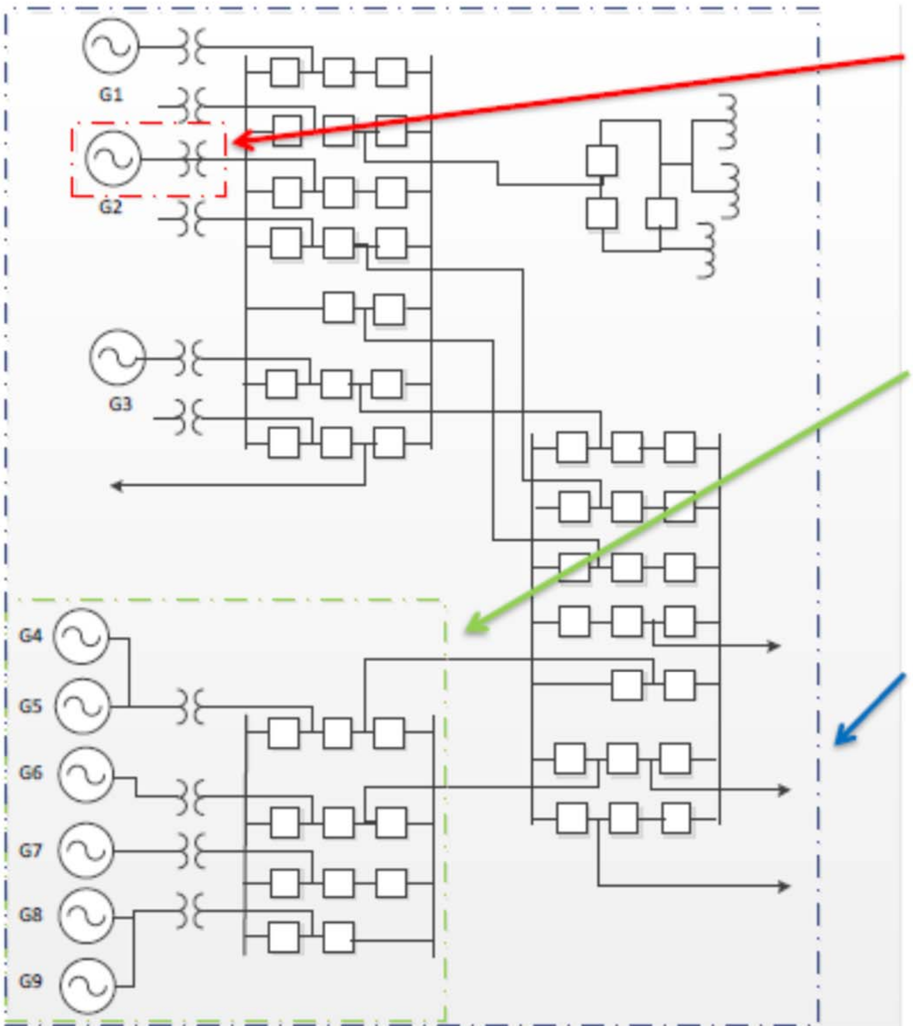
IEEE 14 bus system model

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

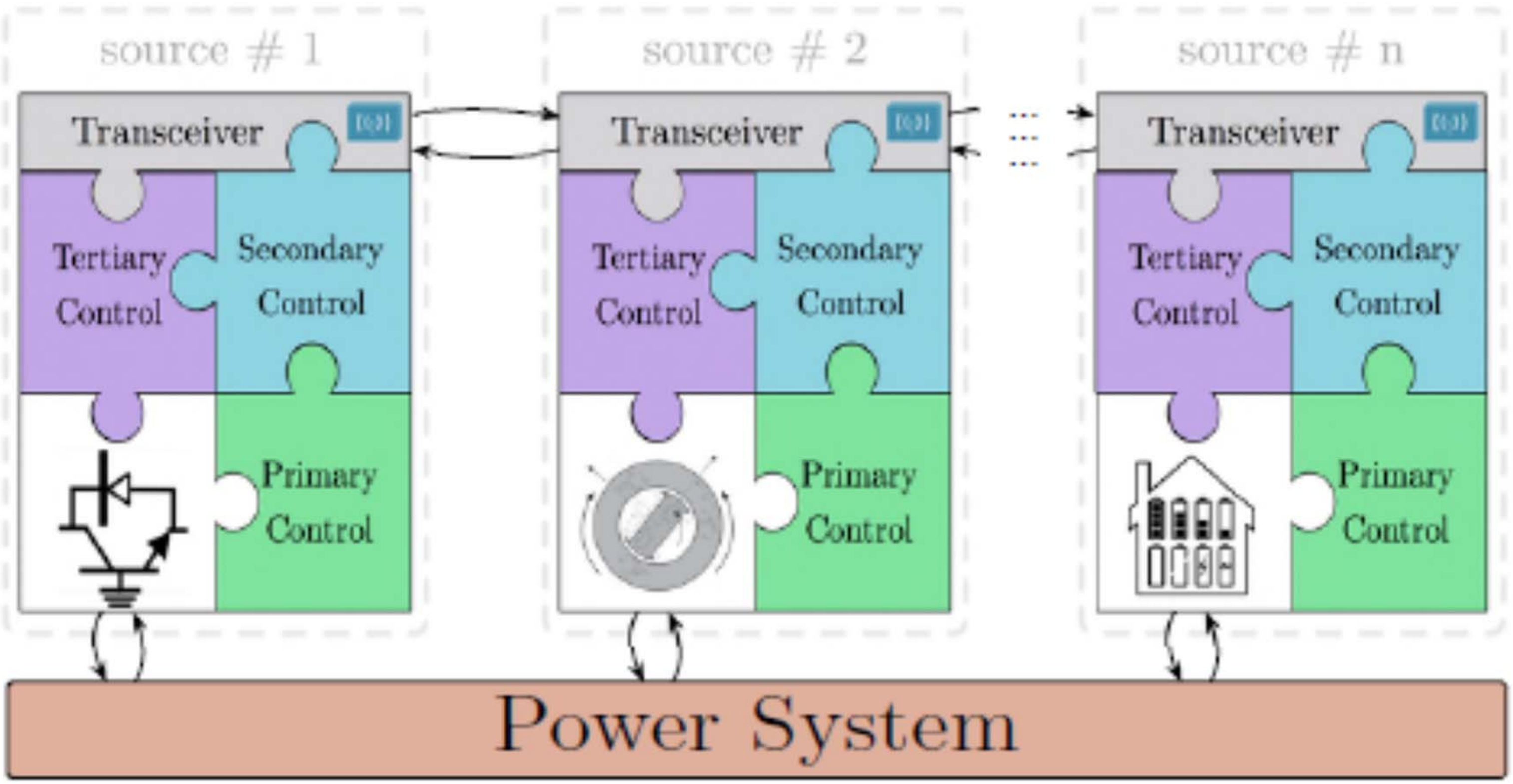
- Other port-Hamiltonian subsystems can be added like capacitor banks, transformers etc.
- Another model of the transmission line, e.g., partial differential equation models.
- Other load models.
- A different (simpler) port-Hamiltonian model of the generator.
- Techniques like Kron reduction can be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

Adapt Grid Hierarchy for the Future: How?

Plug'n'play architecture

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



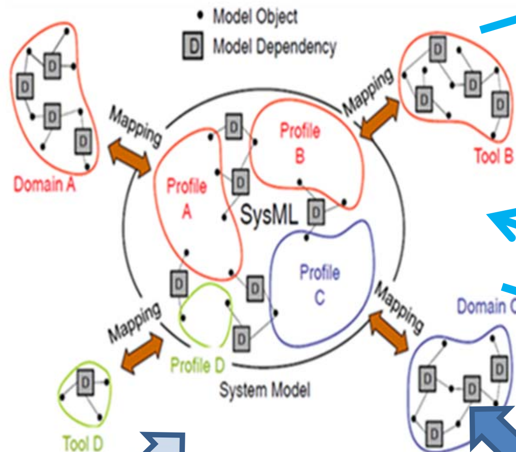
Latest Vision and Collaborations

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

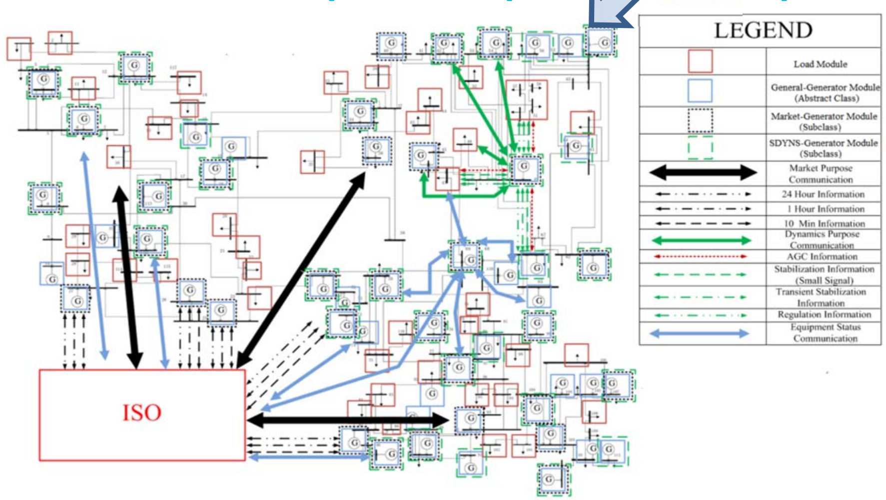


ILOG SOLVER, CPLEX, CONSOL-OPTCAD

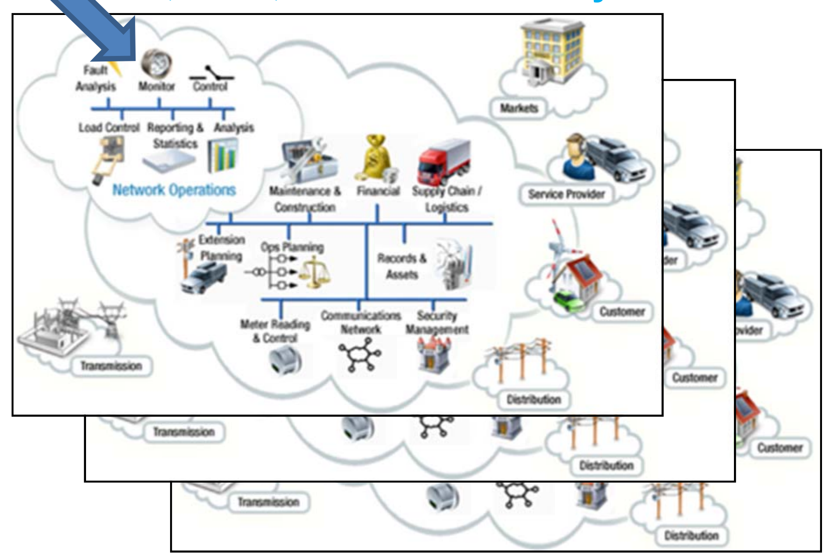
Databases
Libraries of system components and models

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

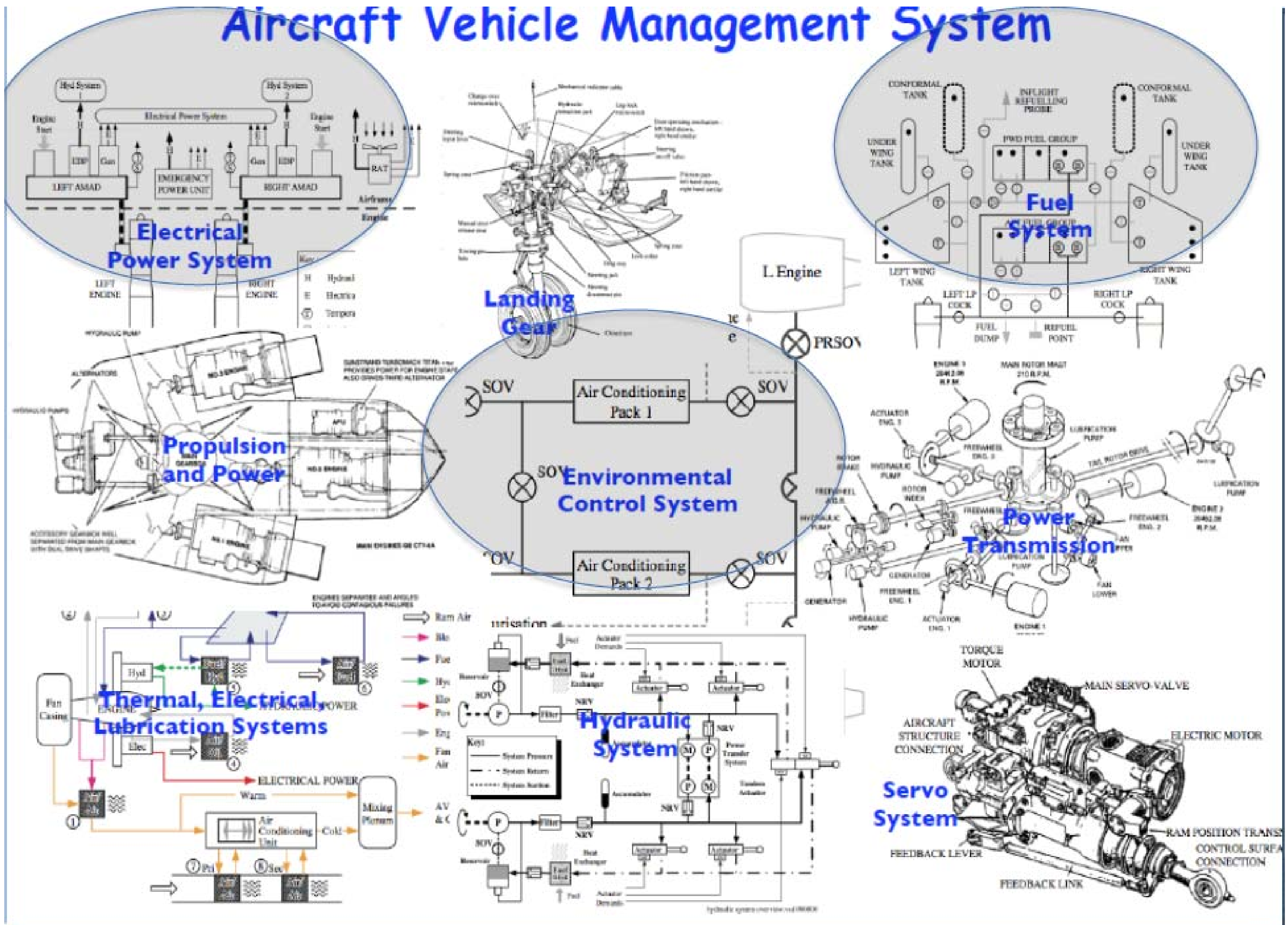
CMU: DyMonDS based Smart Grid in a Room Simulator
End-to-End Stable Optimal Dispatch Concepts



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

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

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

Iteration 1 (Initial Stage)

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

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

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

Iteration 16 (User Interaction)

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

Trade-off Study in Consol-Optcad

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

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

Iteration 29 (Final Solution)

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

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

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

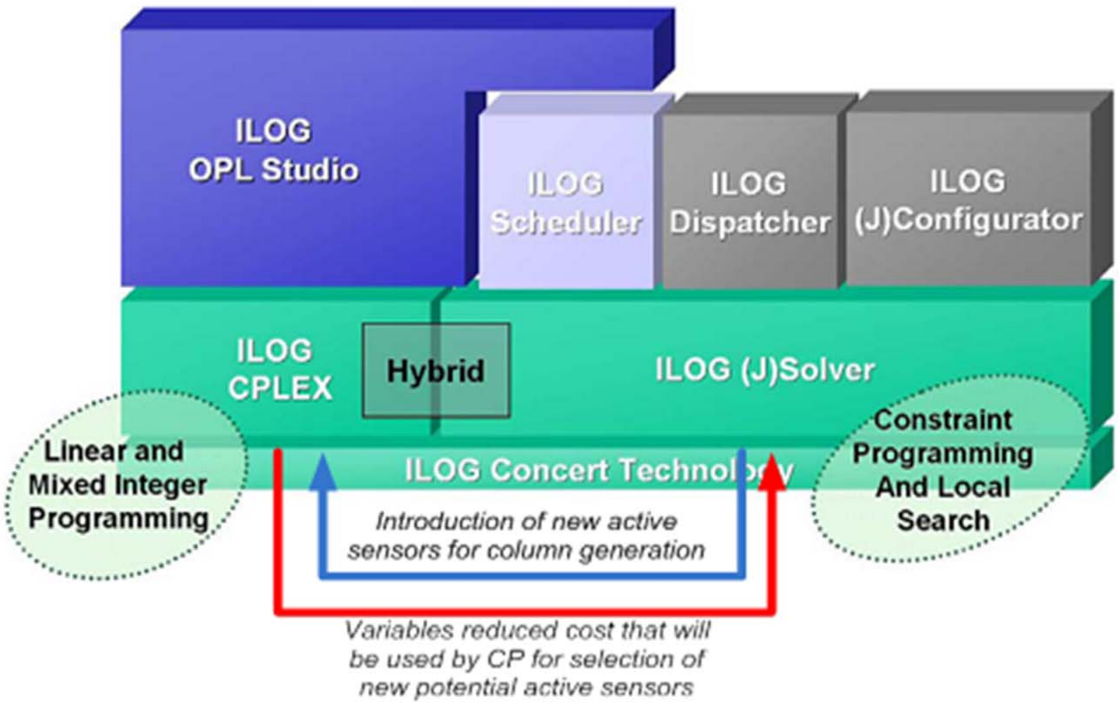
Name	Value	Variation	Wrt 0	Wrt Prev	Freeze
P_ENG1_L	3.382e+004	1.000e+000	-19%	0%	UnFrozen
P_ENG1_R	1.138e+005	1.000e+000	-6%	0%	UnFrozen
P_ENG2_L	3.382e+004	1.000e+000	-19%	0%	UnFrozen
P_ENG2_R	1.138e+005	1.000e+000	-6%	0%	UnFrozen
n_lf	5.376e-001	1.000e+000	-10%	0%	UnFrozen
n_hf	5.376e-001	1.000e+000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

Results

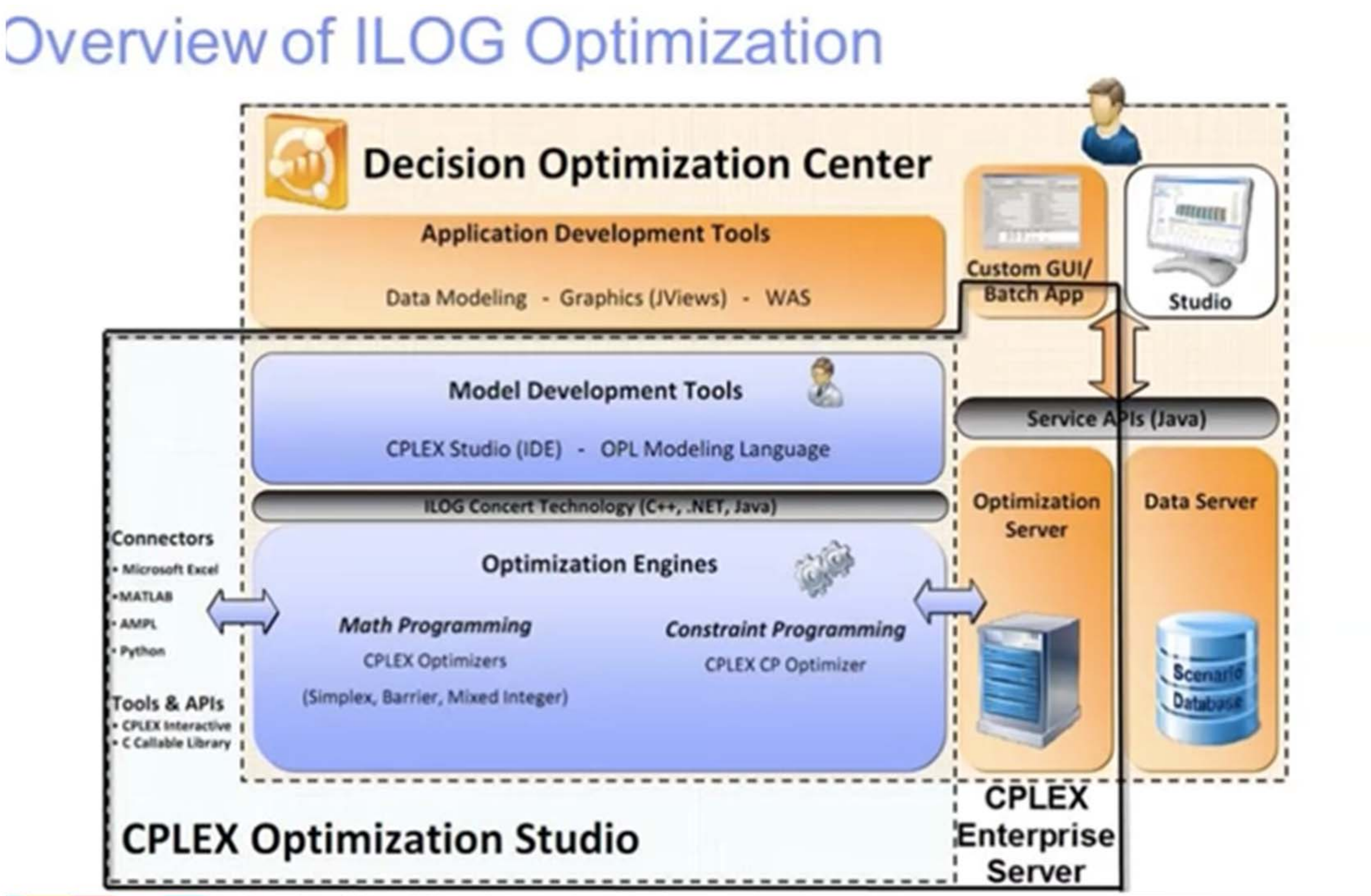
- ✓ Values of the design variables
- ✓ Percentage of change from the initial value

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



IBM Decision Optimization Center



MBSE Approach to Energy Efficient Buildings

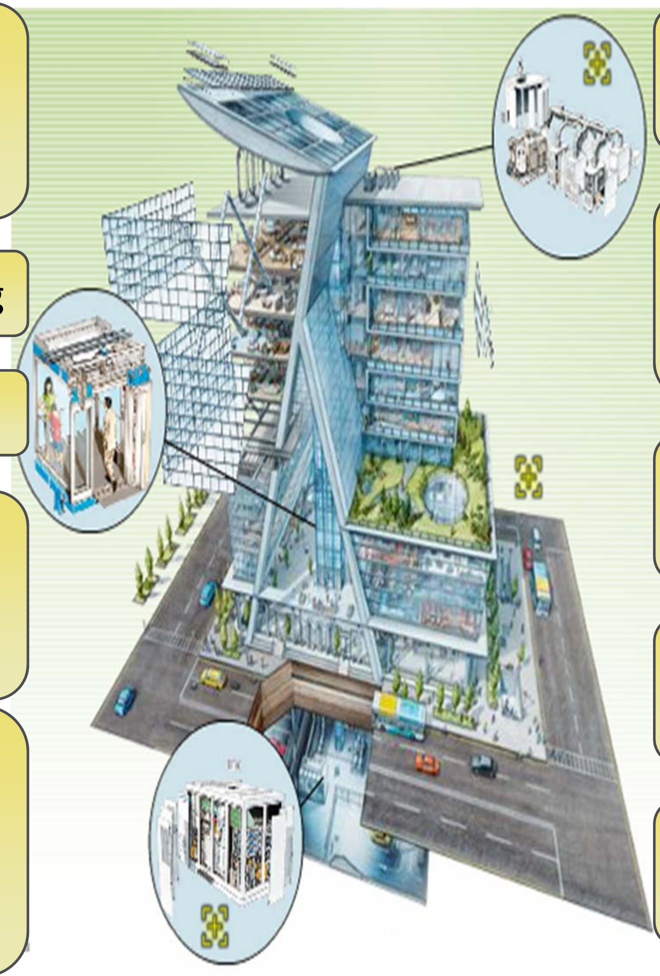
Buildings Design Energy and Economic Analysis

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

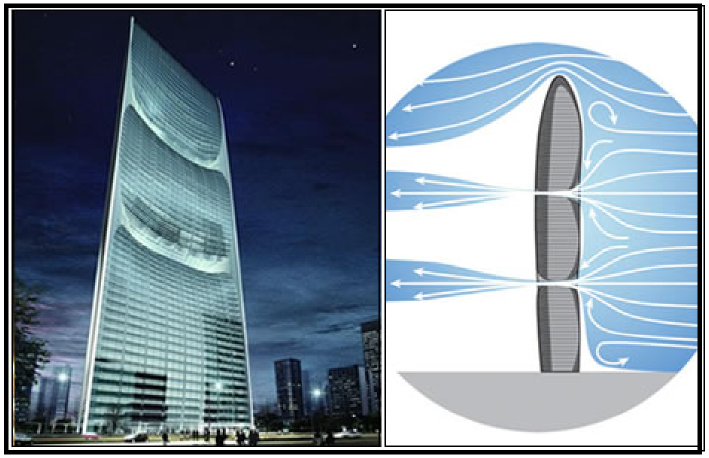
Power Delivery and Demand Response

Building Materials, Misc. Equipment

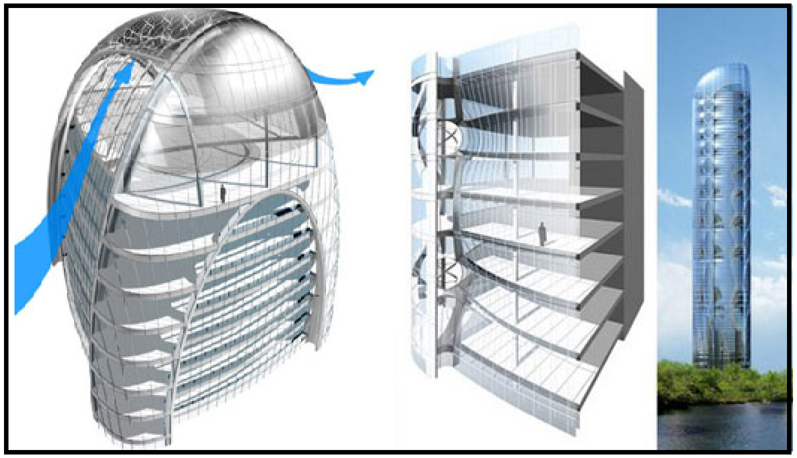
Buildings as Cyber-Physical Systems

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

Pearl River Tower Complex



Green Technology Tower –– Architectural Proposal for Chicago



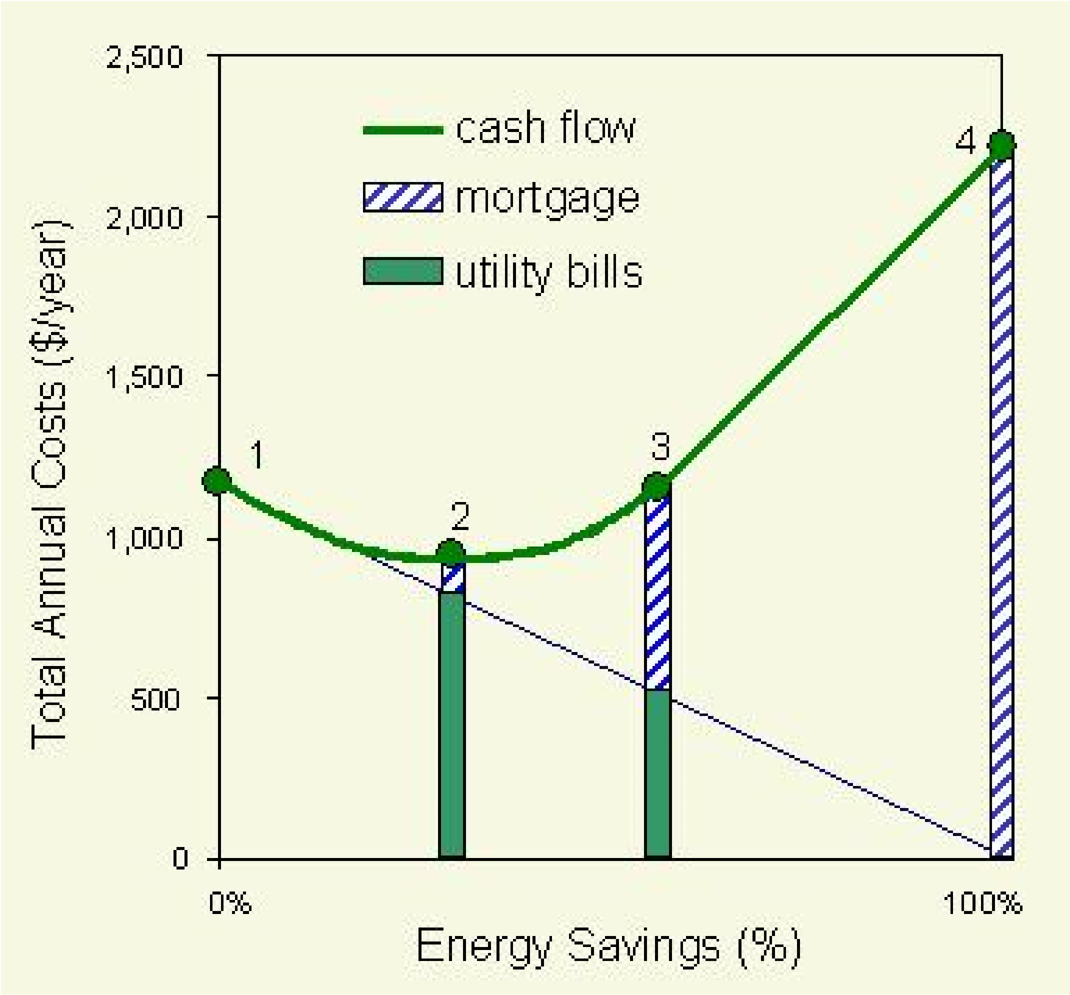
NET-zero Energy Building

NIST Net Zero Energy Residential Test Facility

Courtesy J. Kneifel (2012)

NET-zero Energy

Path to NZE

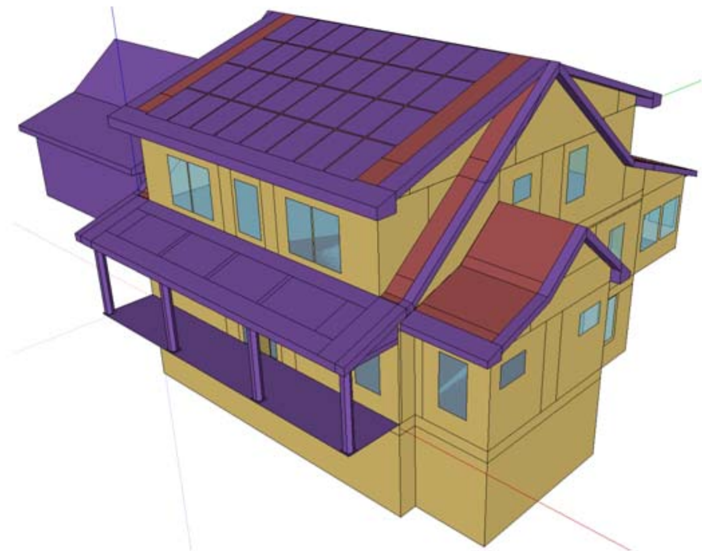


Courtesy BEopt

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

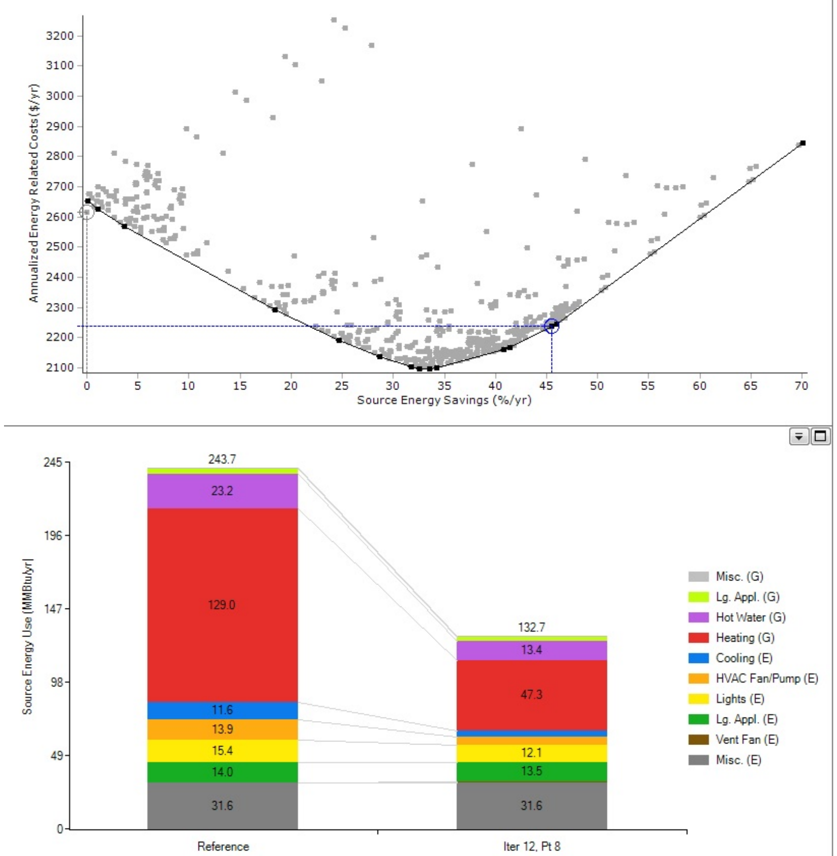
- Developed by NREL
- Software that couples with EnergyPlus (and DOE2) that acts as an optimized simulation controller and provides easy analytic capabilities
- Extends functionality of EnergyPlus

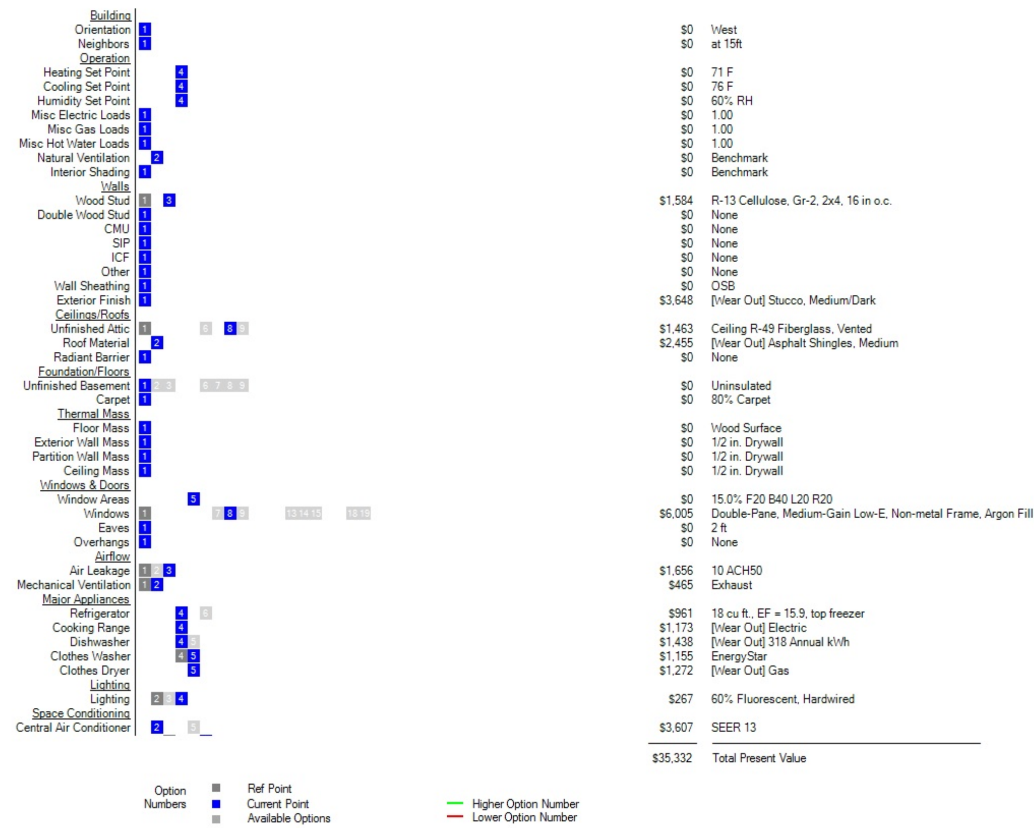
BEopt – Pros

- 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





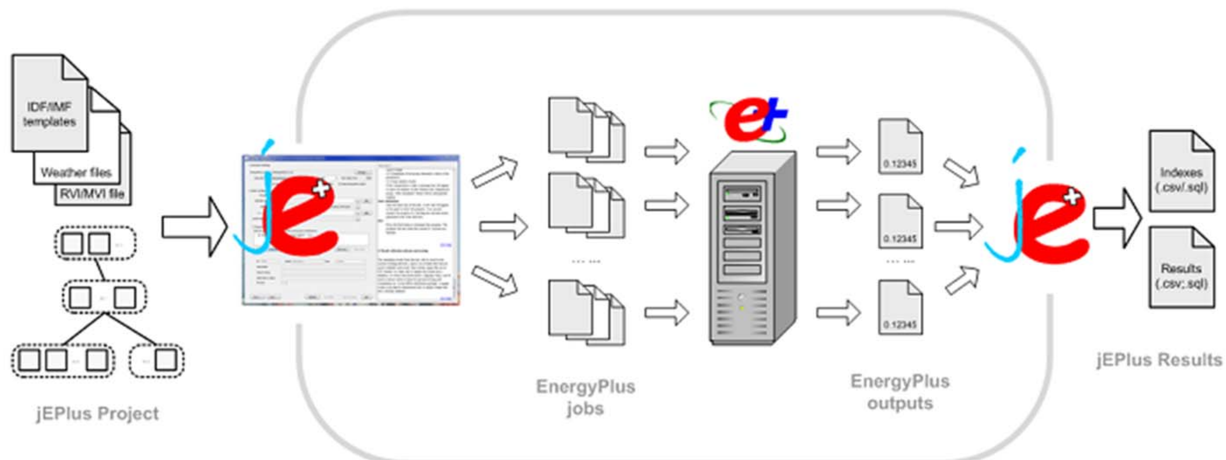
CURRENT CAPABILITIES AND SOFTWARE

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

MULTI-OBJECTIVE OPTIMIZATION

Problem Formulation

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

Initial Cost Objective Function

Minimize

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

where

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

MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

Minimize

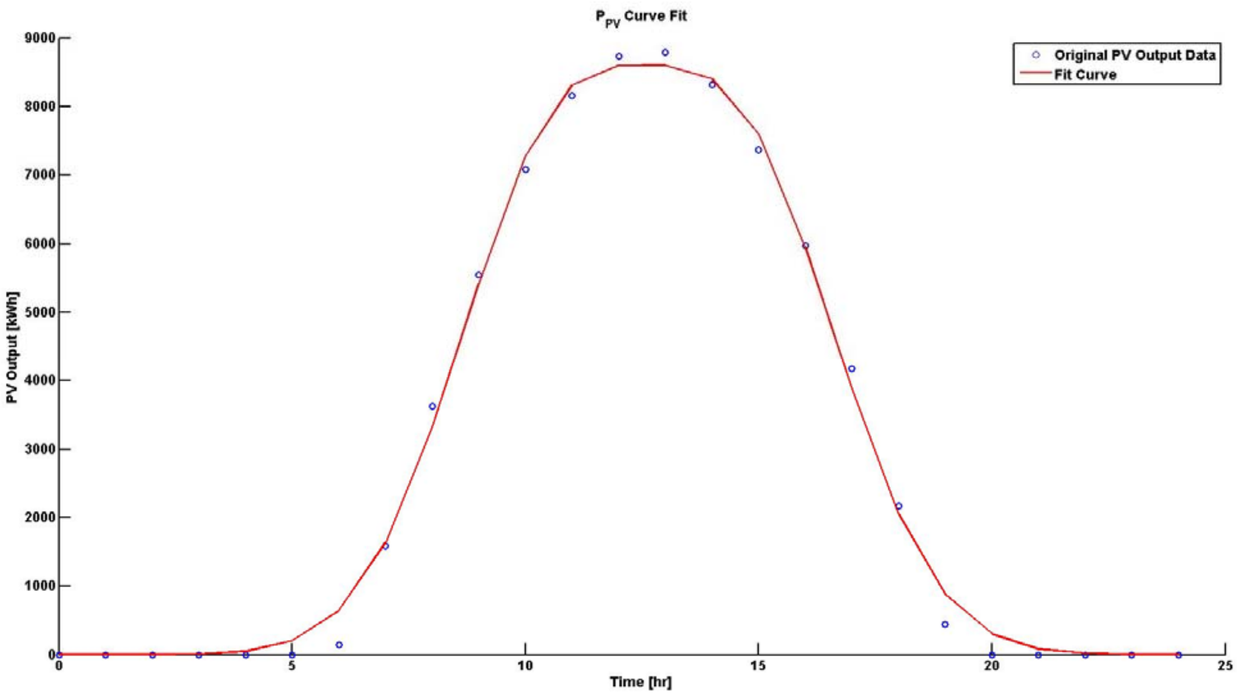
$$EU = \sum_{t=0}^{24} \frac{(P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op})}{60000}$$

β_t is the On/Off factor for the HVAC unit at timestep t
$P_{HVAC}^{op} = 1000$

MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

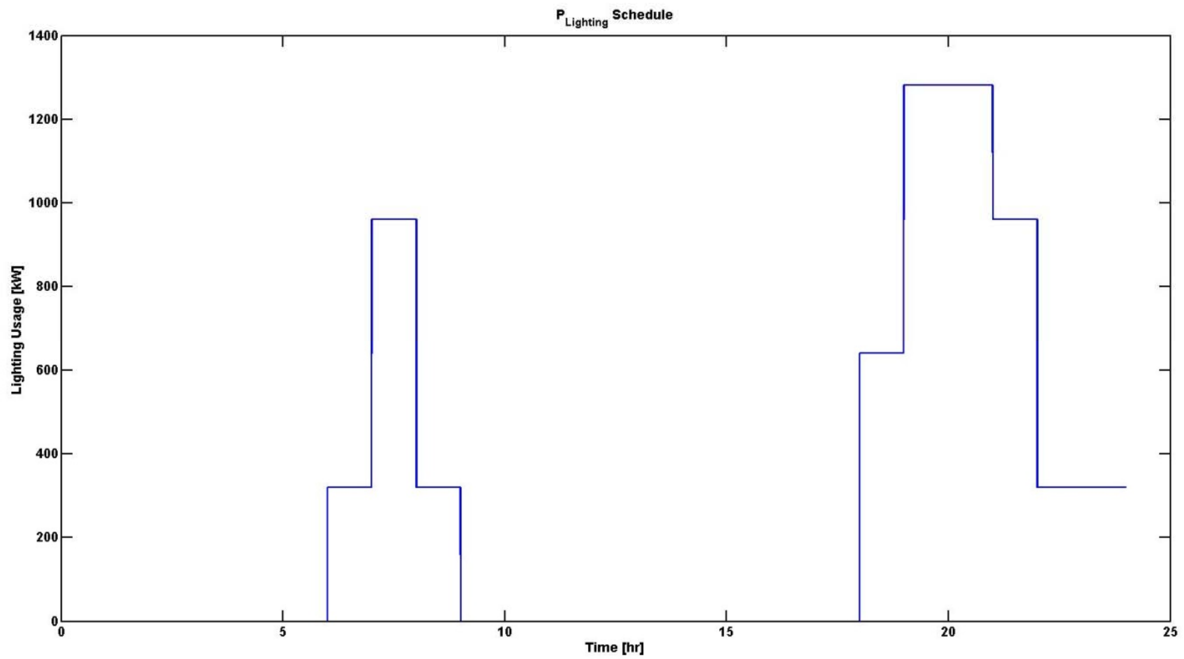
$$P_{PV}(t) = \frac{-x_8}{10240}\left(6970\mathrm{e}^{-\left(\frac{t-14.66}{3.014}\right)^2} + 6870\mathrm{e}^{-\left(\frac{t-10.55}{2.954}\right)^2}\right)$$



MULTI-OBJECTIVE OPTIMIZATION

Energy Use Objective Function

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



MULTI-OBJECTIVE OPTIMIZATION

Operational Cost Objective Function

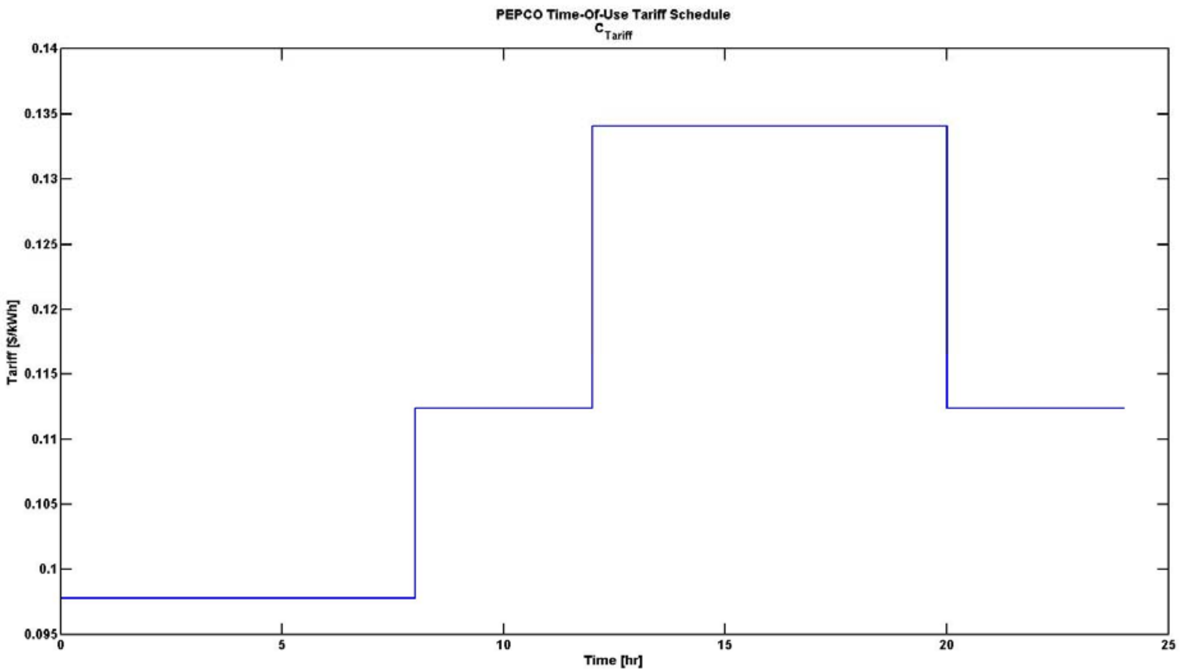
Minimize

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

MULTI-OBJECTIVE OPTIMIZATION

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

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

MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

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

$$C_p = 0.24 \ \frac{\mathrm{Btu}}{{}^\circ\mathrm{F} \cdot \mathrm{lb_m}}$$

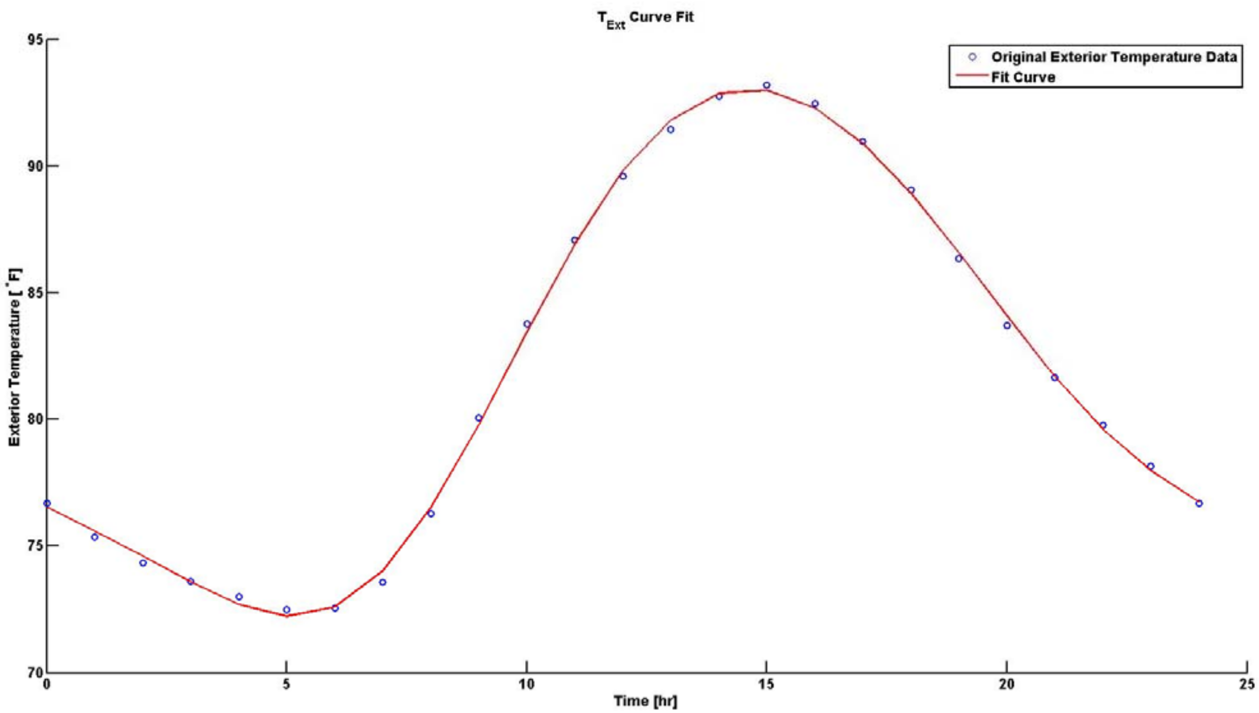
$$\rho = 0.075 \ \frac{\mathrm{lb_m}}{\mathrm{ft}^2}$$

$$V_{room} = 12800 \ \mathrm{ft}^3$$

MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

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



MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

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

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

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

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

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

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

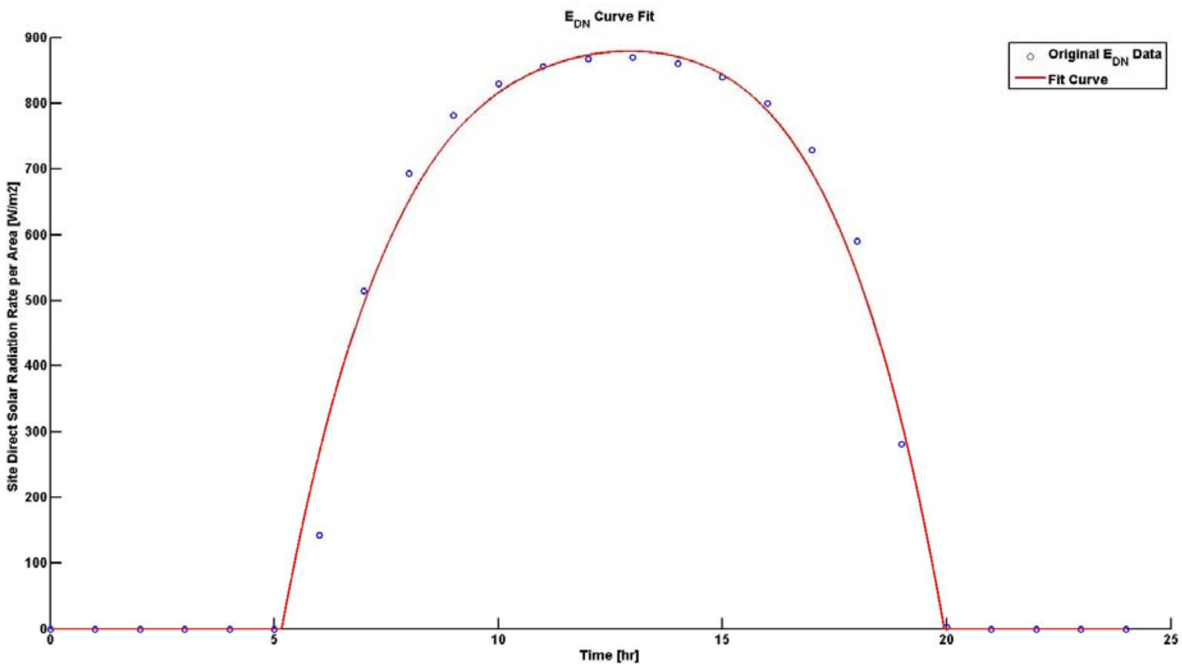
where $A_{win} = 137.5\text{ft}^2$

MULTI-OBJECTIVE OPTIMIZATION

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

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

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

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

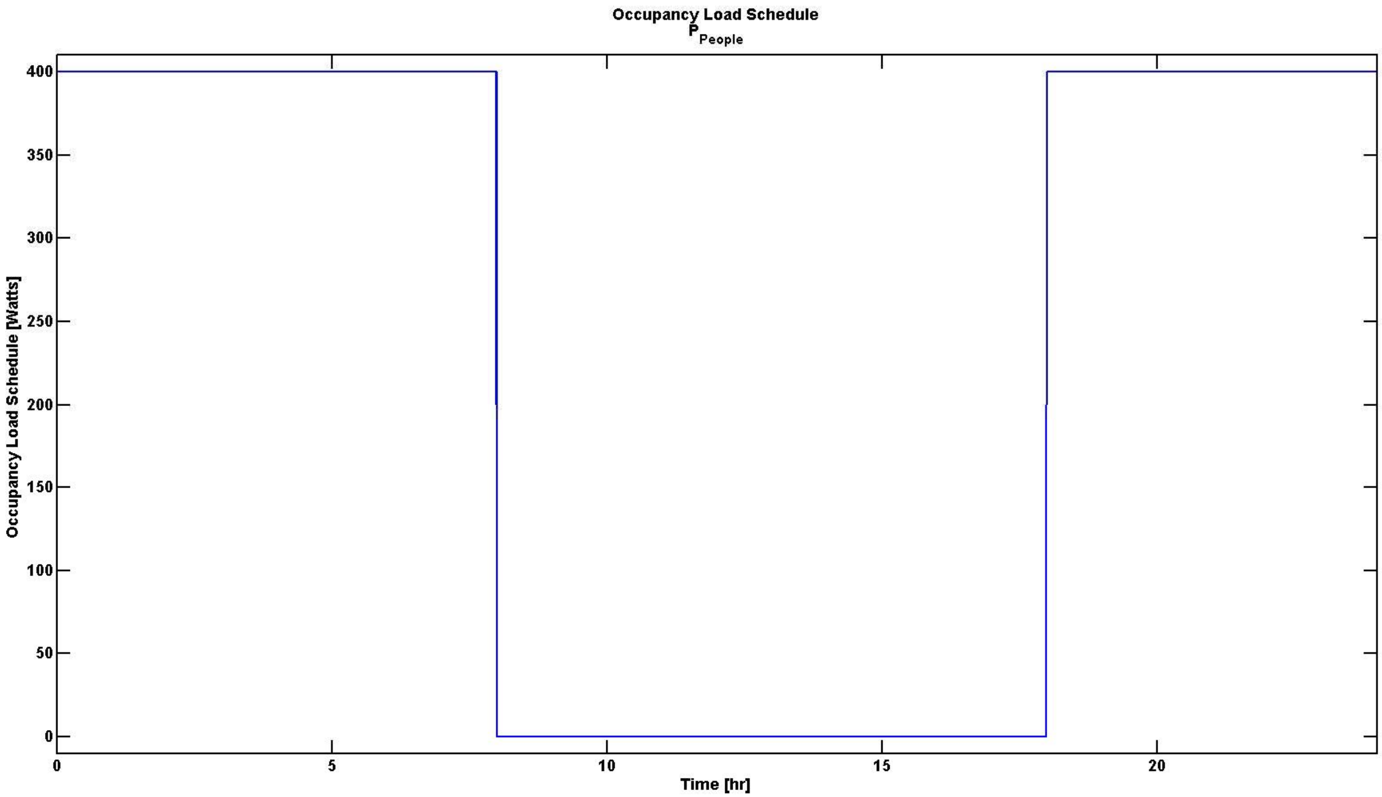
$$Q_{HVAC} = \frac{3500\, beta_t}{3.412}$$

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

MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

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



MULTI-OBJECTIVE OPTIMIZATION

Simulation

Initial Values

Design Parameters:

x1 - Exterior Wall Insulation [R] = 19.00

x2 - Roof Insulation [R] = 50.00

x3 - Window U-Value [U] = 0.35

x4 - Window SHGC [SHGC] = 0.35

x5 - Infiltration [ACH] = 3.00

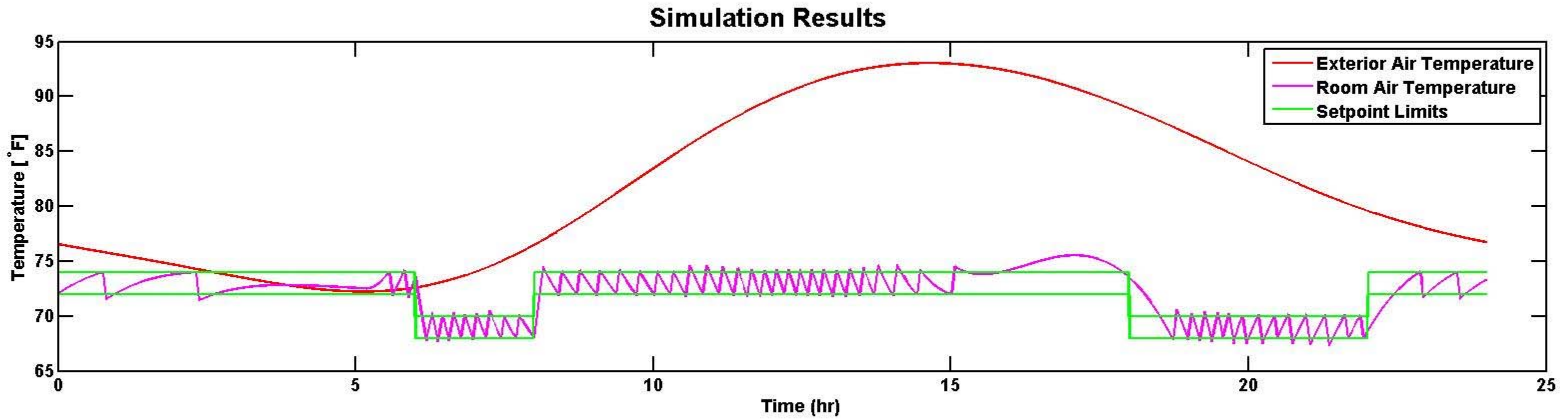
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

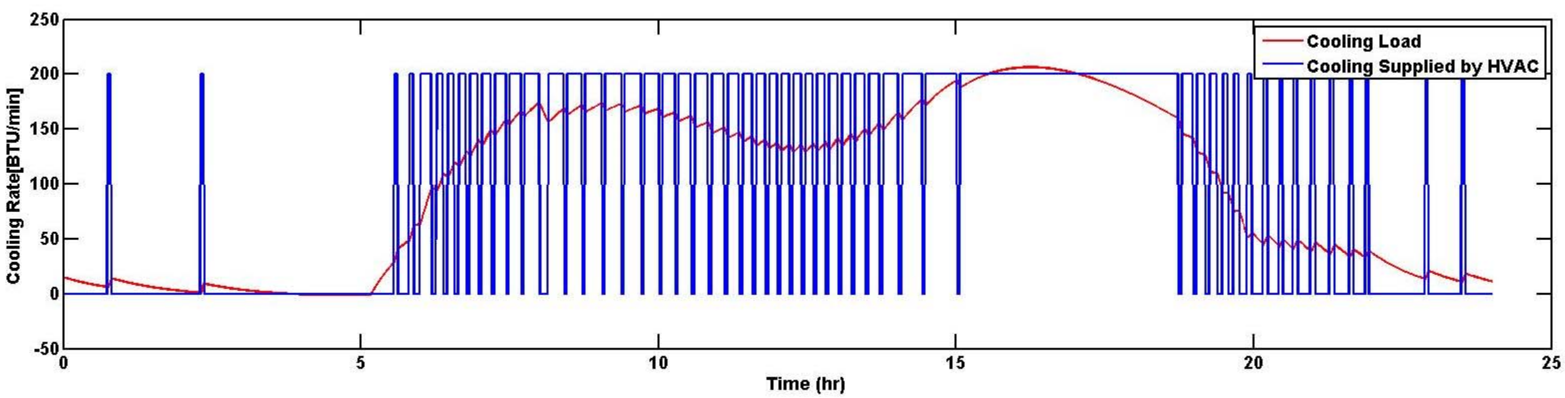
x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

MULTI-OBJECTIVE OPTIMIZATION

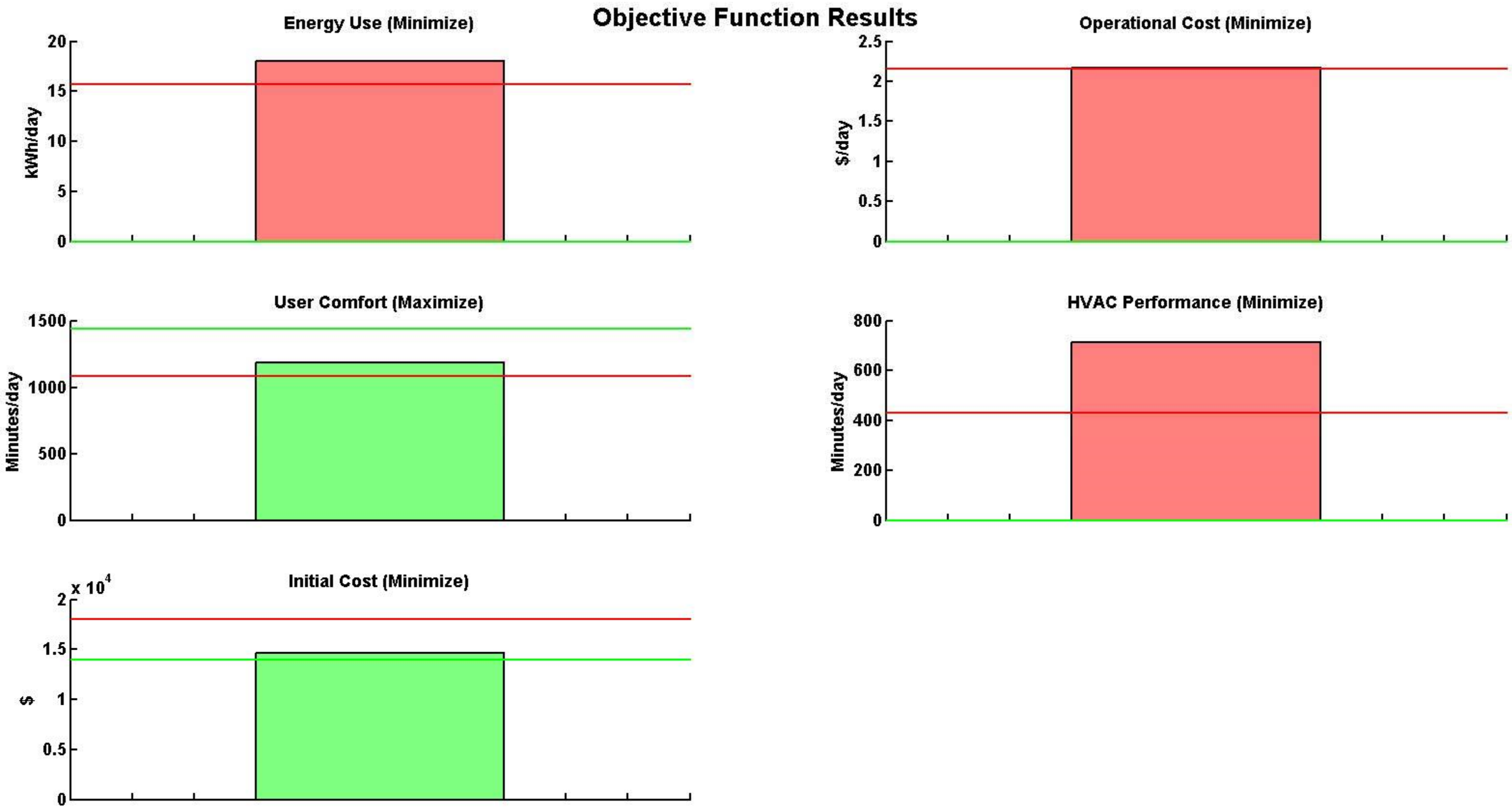
Simulation





MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation

Next Iteration

Design Parameters:

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

x2 - Roof Insulation [R] = 50.00

x3 - Window U-Value [U] = 0.35

x4 - Window SHGC [SHGC] = 0.35

x5 - Infiltration [ACH] = 3.00

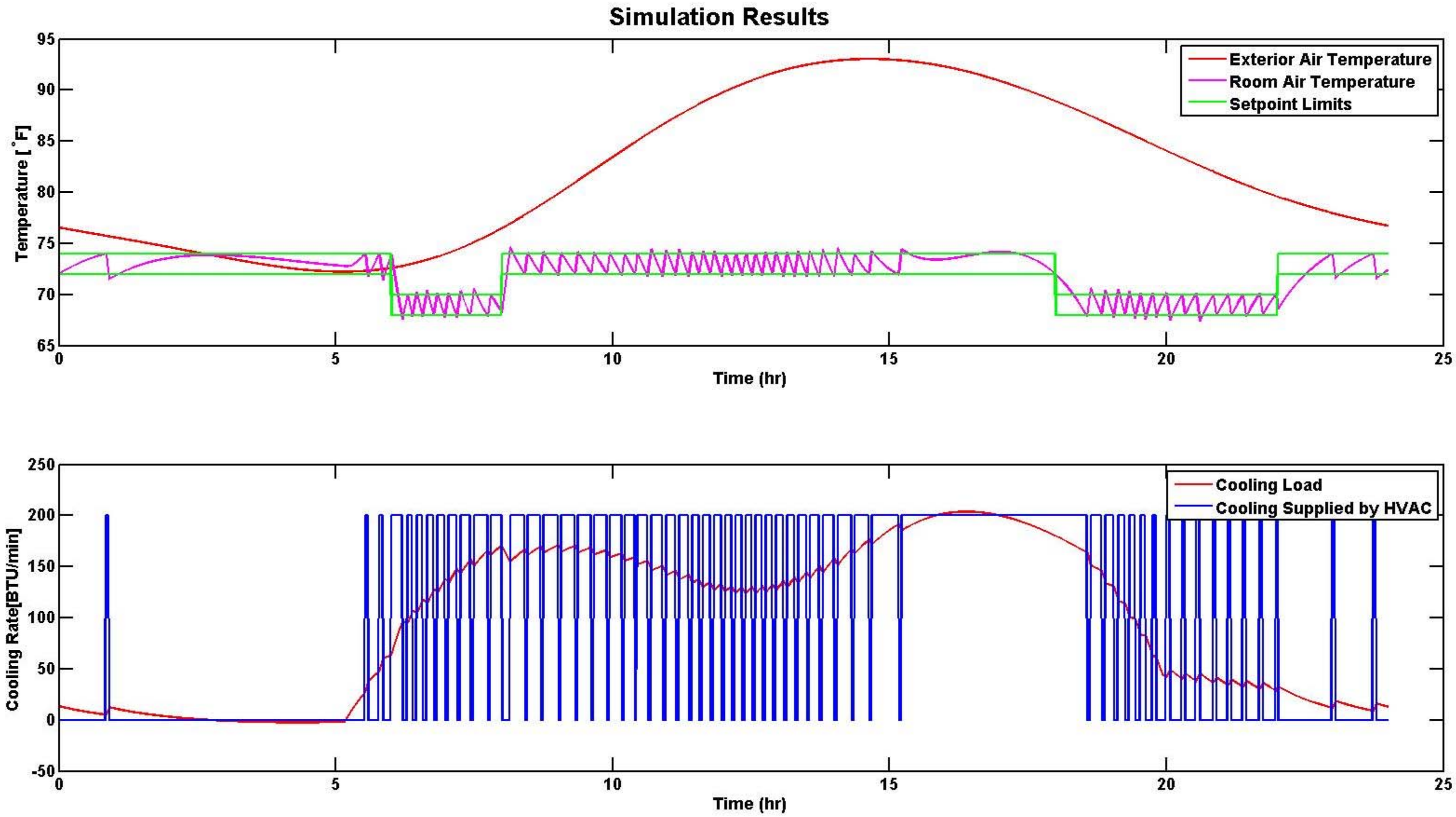
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

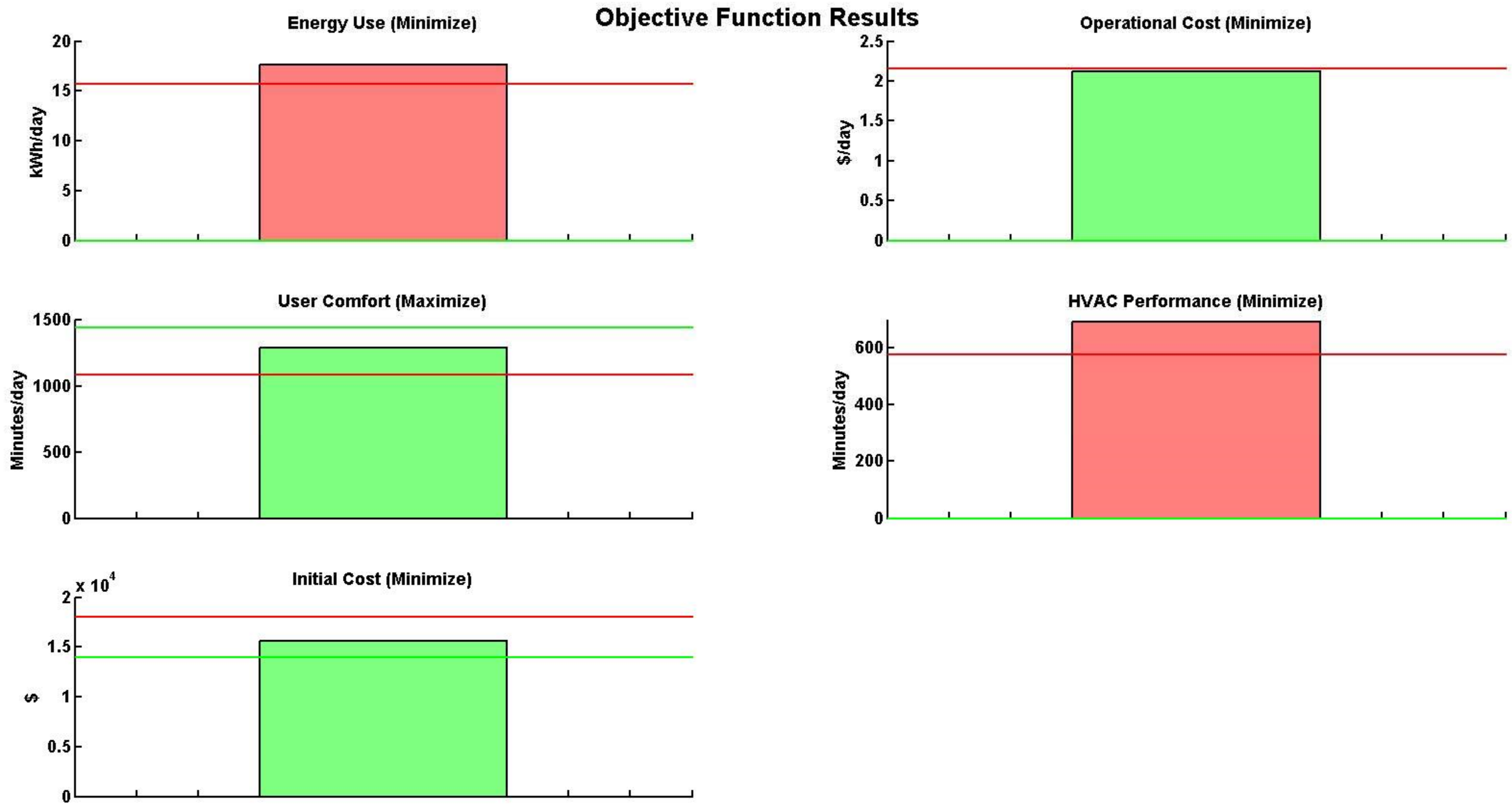
MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation



MULTI-OBJECTIVE OPTIMIZATION

Simulation

Next Iteration

Design Parameters:

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

x2 - Roof Insulation [R] = 50.00

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

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

x5 - Infiltration [ACH] = 3.00

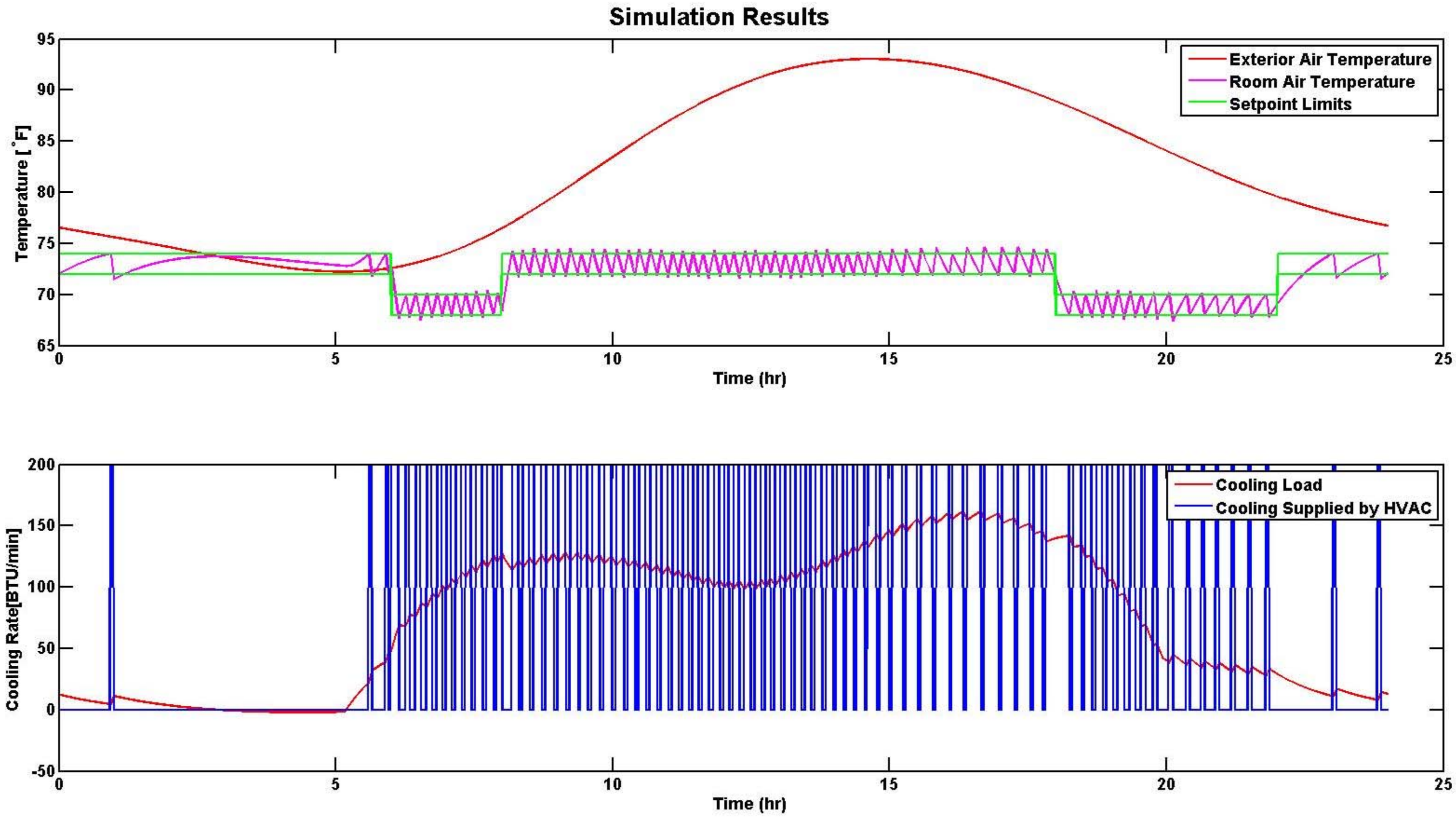
x6 - HRV/Ventilation [% Energy Recovered] = 0.00

x7 - Lighting [% Efficient Lighting] = 0.75

x8 - PV [Watt] = 0

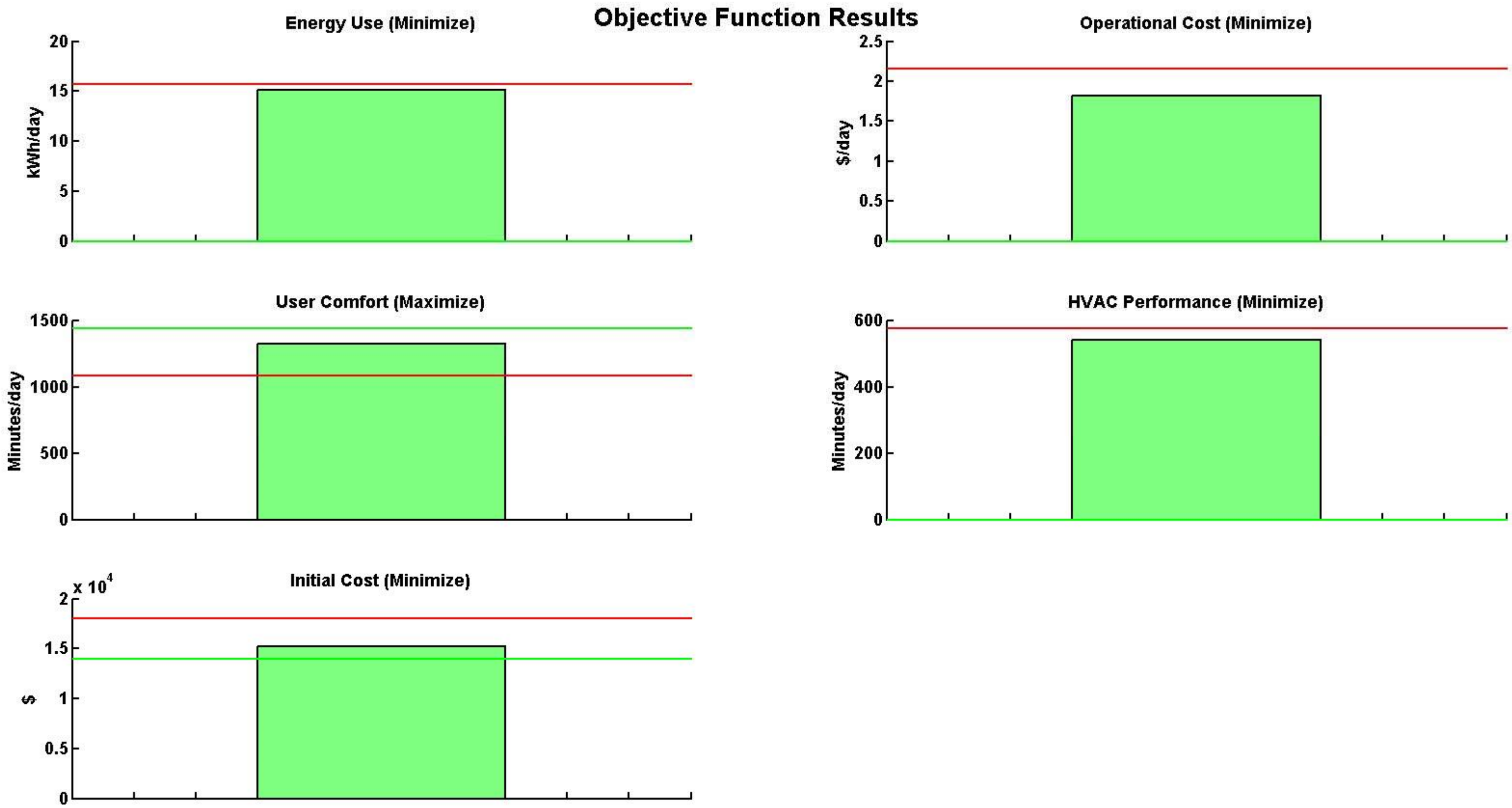
MULTI-OBJECTIVE OPTIMIZATION

Simulation



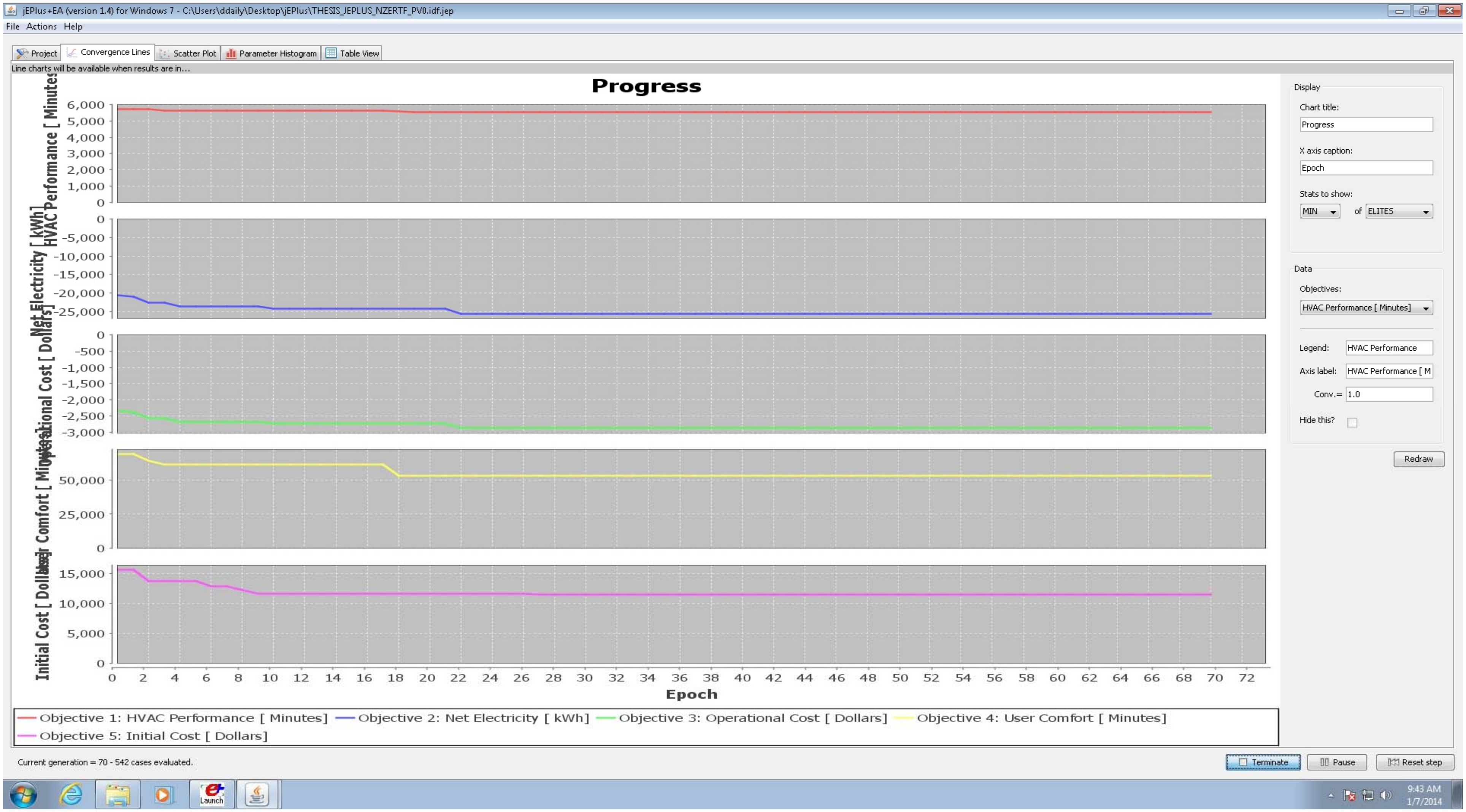
MULTI-OBJECTIVE OPTIMIZATION

Simulation



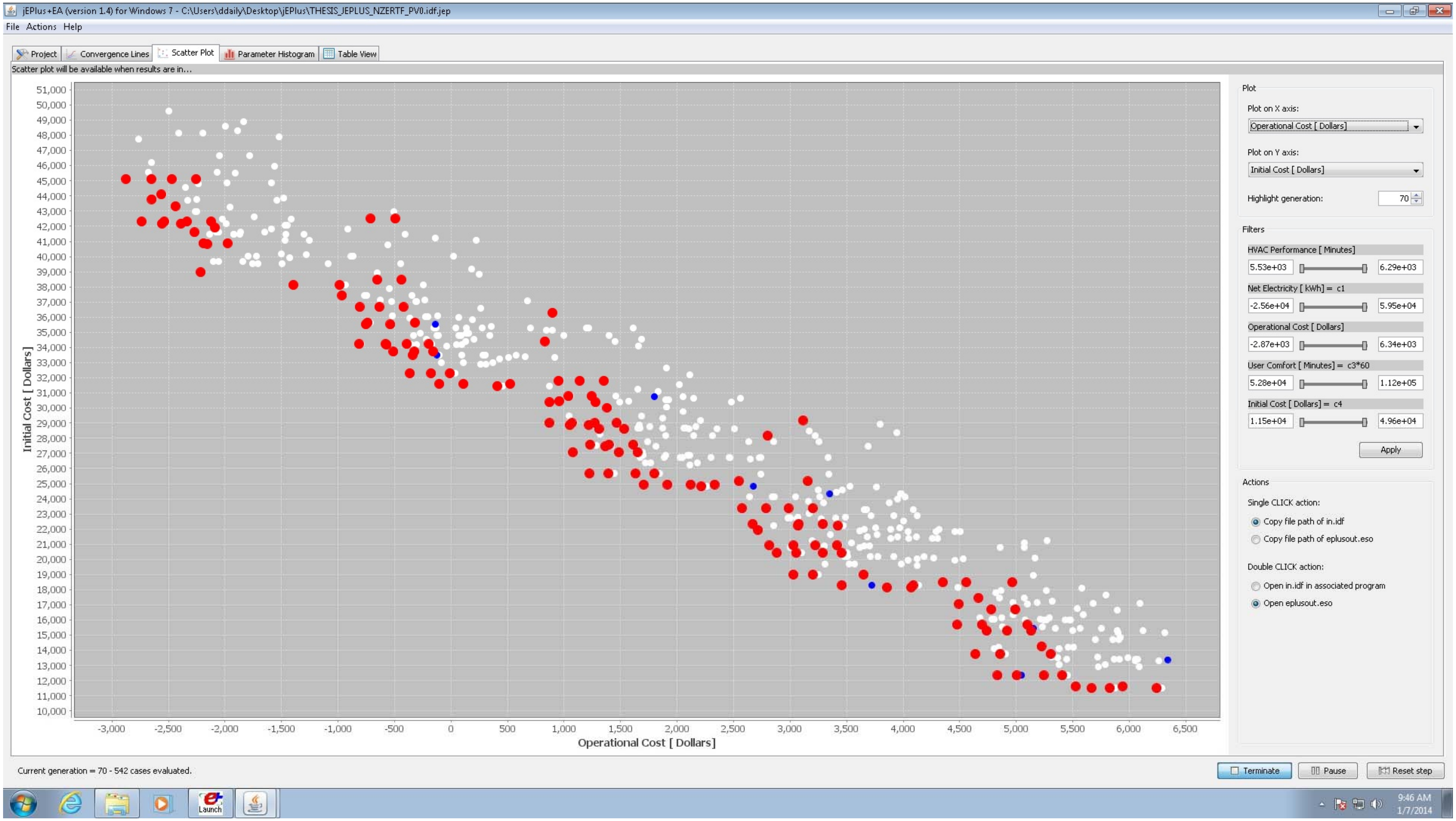
JEPLUS+EA OPTIMIZATION

Simulation



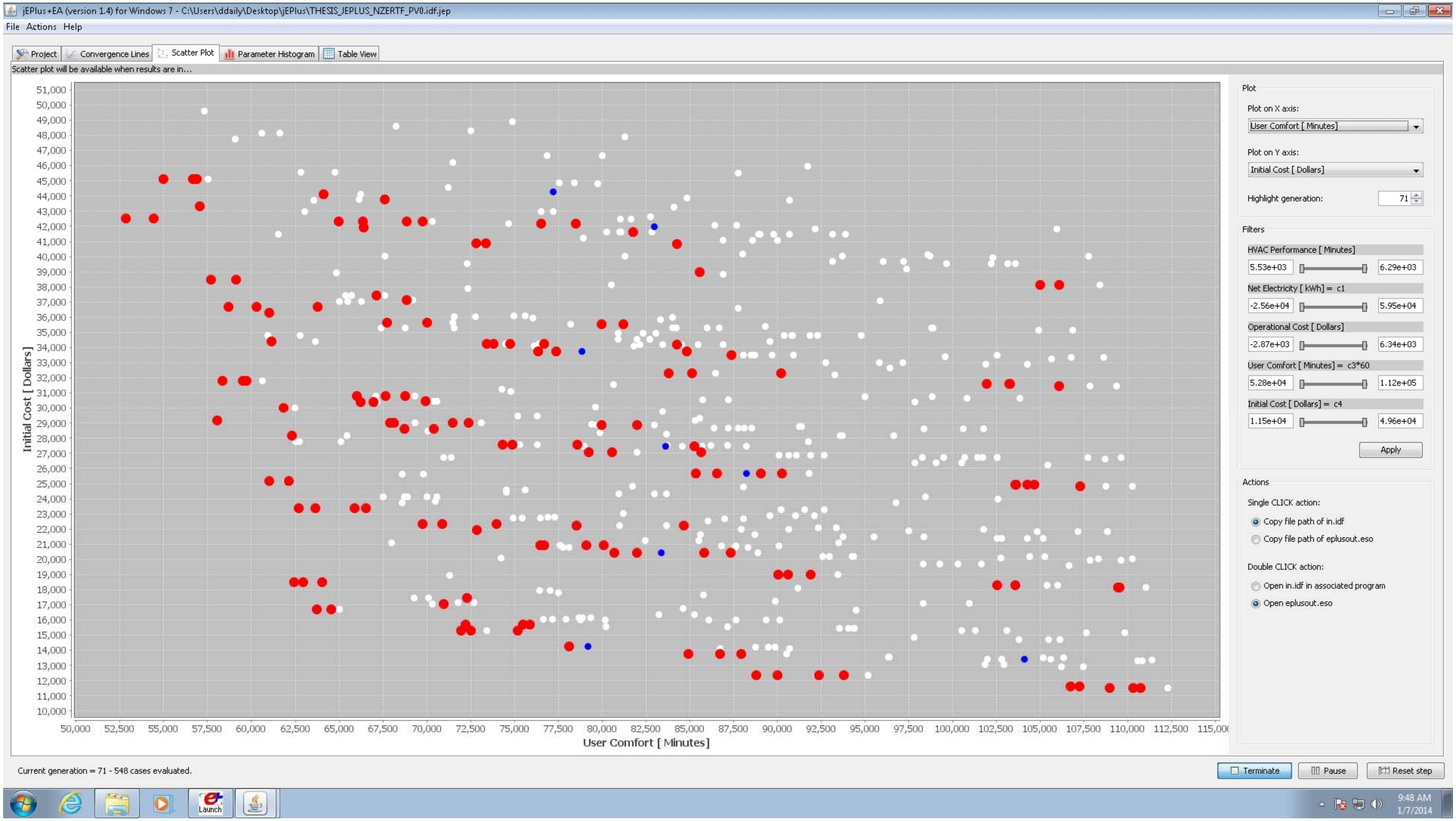
JEPLUS+EA OPTIMIZATION

Simulation



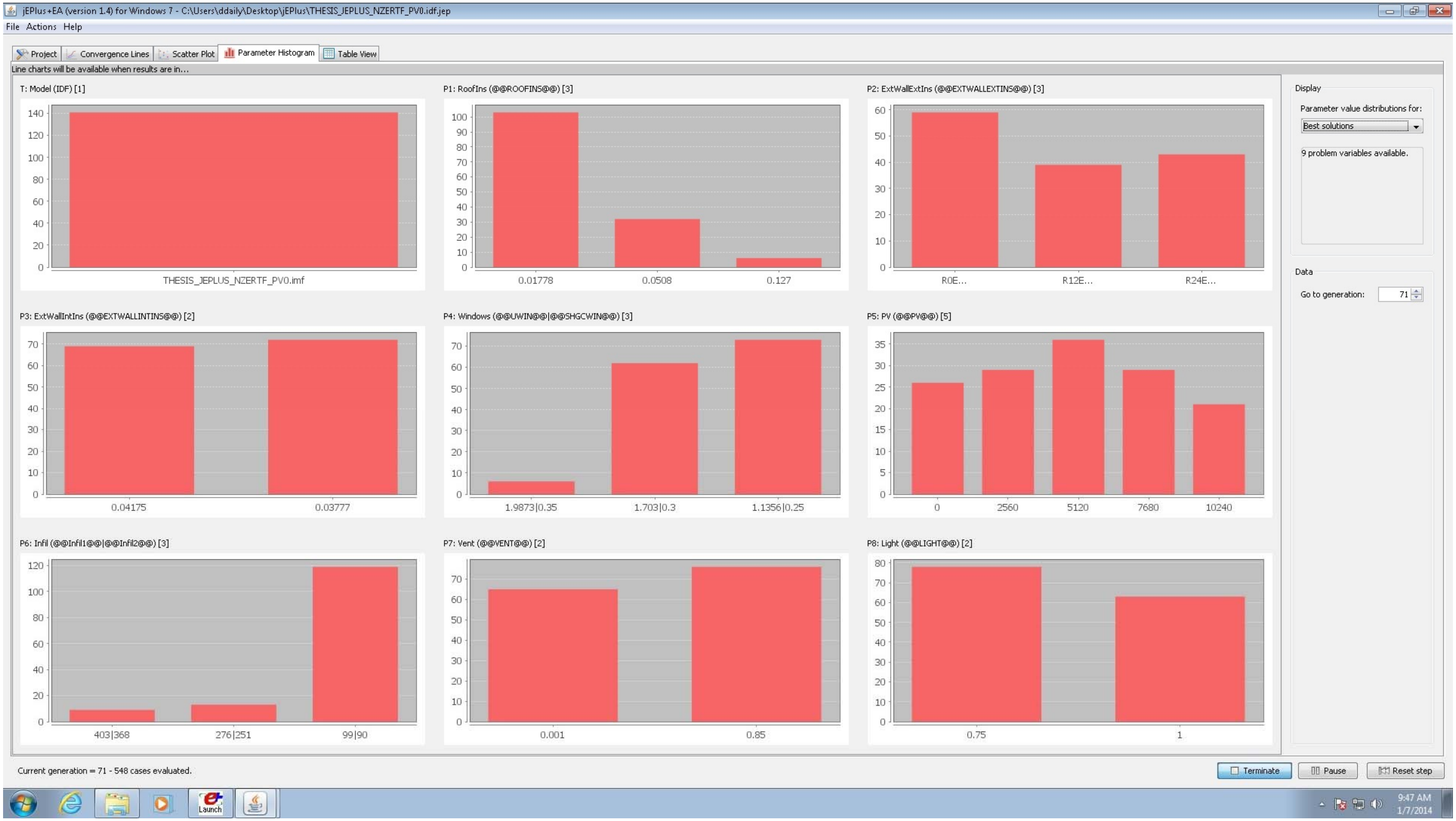
JEPLUS+EA OPTIMIZATION

Simulation



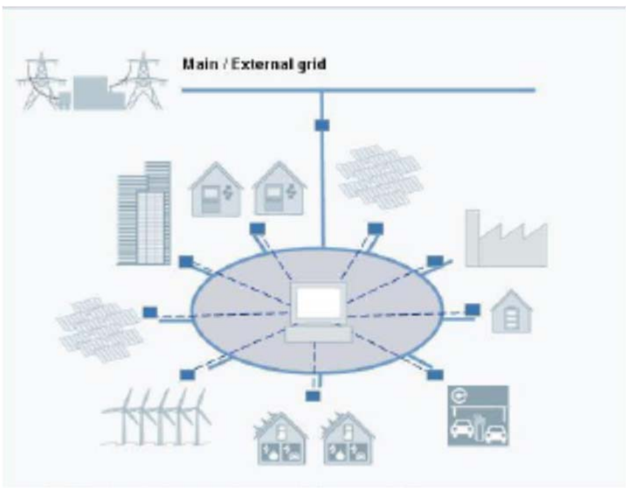
JEPLUS+EA OPTIMIZATION

Simulation



Integrating Siemens PLM Tools for MBSE in Energy Efficiency

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



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

Smart Manufacturing

Smart Manufacturing refers to **manufacturing production systems at the equipment, factory, and enterprise levels** that integrate cyber and physical systems by combining:

- **smart operating systems** to **monitor, control, and optimize performance**
- **systems engineering-based architectures and standards**, and
- **embedded and/or distributed sensing, computing, communications, actuation, and control technologies**

to enable **innovative production, products**, and/or **systems of products** that enhance ***economic and sustainability performance***

Virtual Engineering Everywhere

(Automotive manufacturing, AUTOSAR,…)

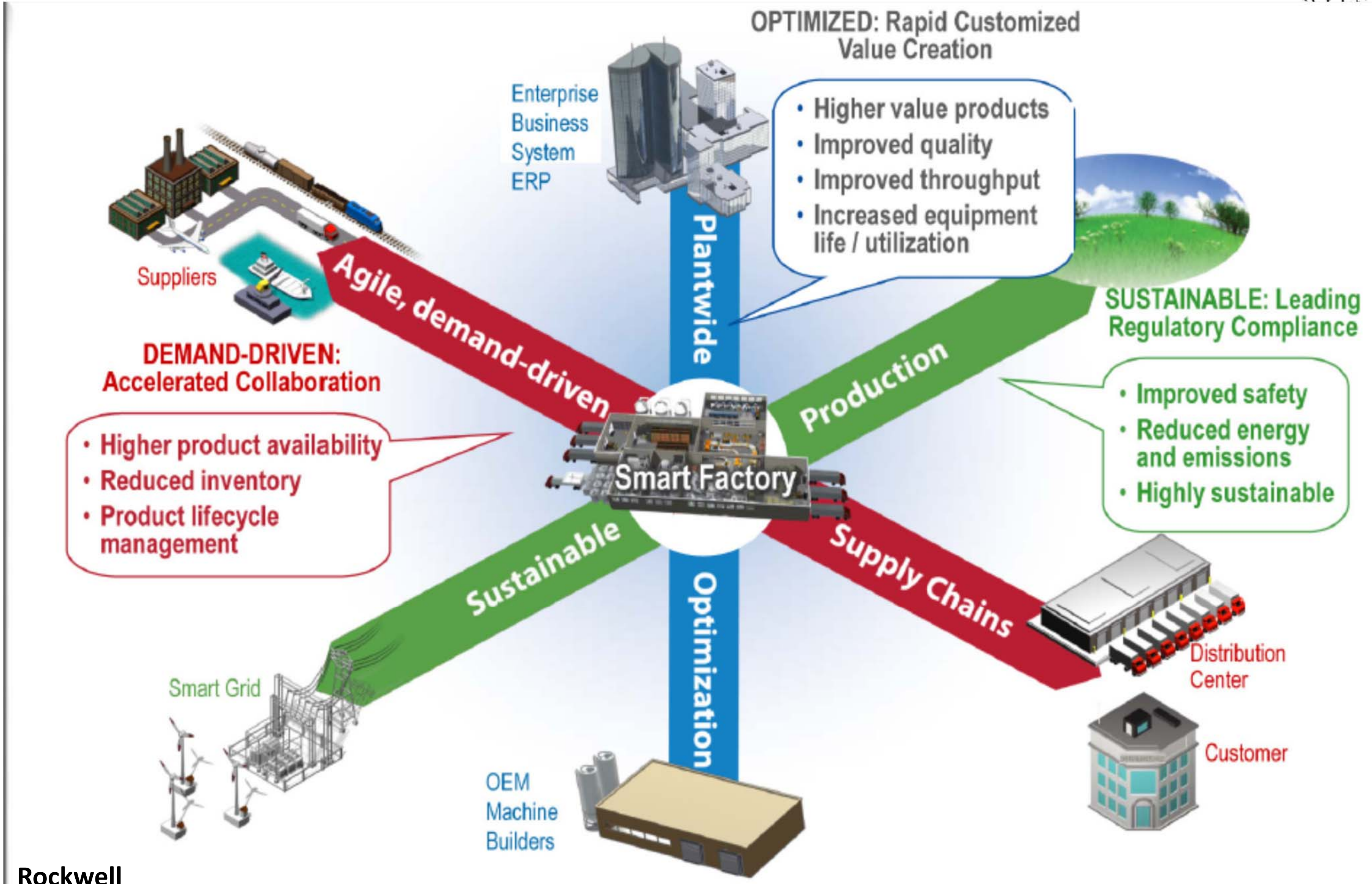
Helping over 30 different teams and skills in the company work together

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

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

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

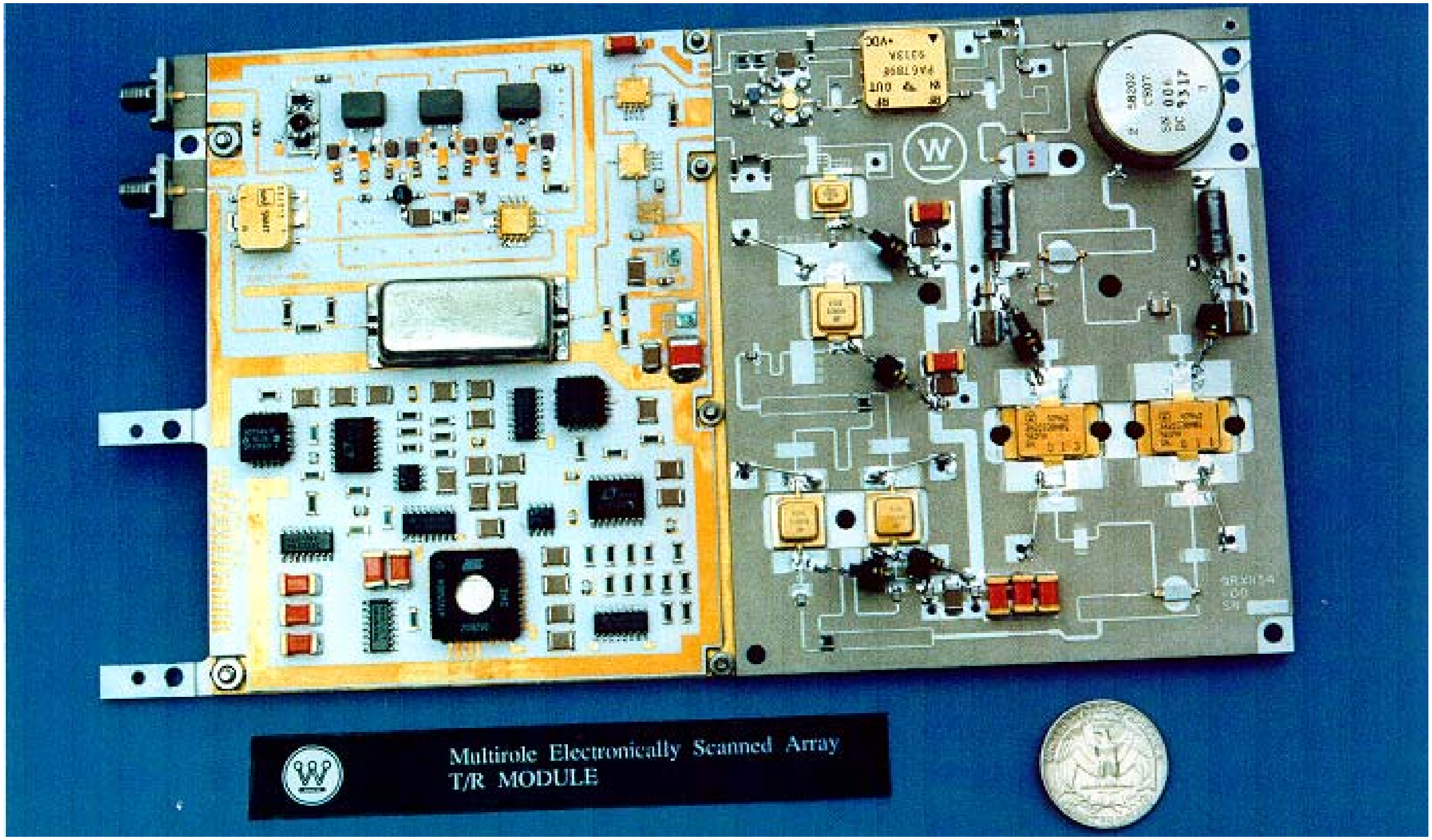
Smart Manufacturing



Rockwell

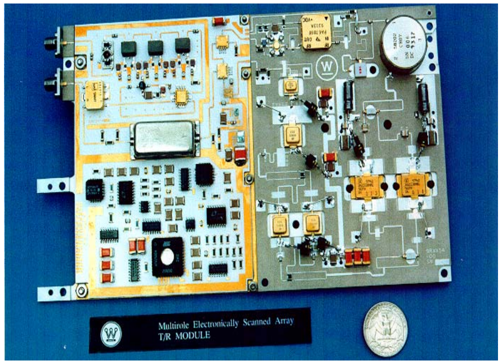
Microwave Transmit/Receive Modules

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

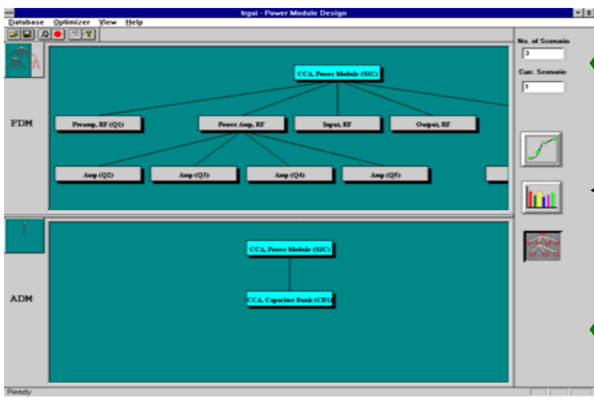


The Institute for Systems Research

Integrated Product and Process Design of T/R Modules



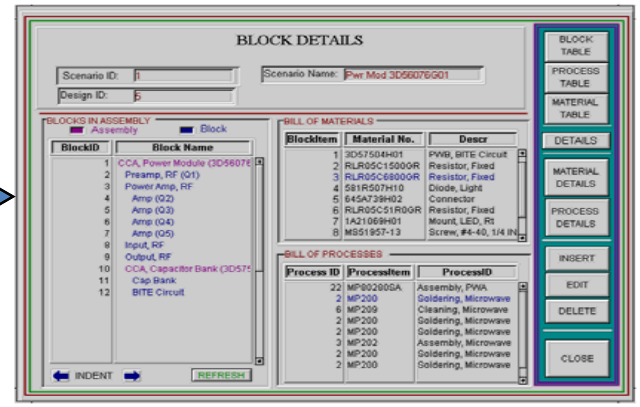
PROBLEM **Integrate Electronic and Mechanical Design**
information interchange among tools used by designers
Identify alternative components
integration with part catalogs, corporate databases
Help generate and evaluate alternative designs
estimate cost, manufacturing time, reliability, etc.evaluate tradeoffs
Help generate process plans
process parameters, time estimates, etc.



Assembly Data Model
Process Designer View

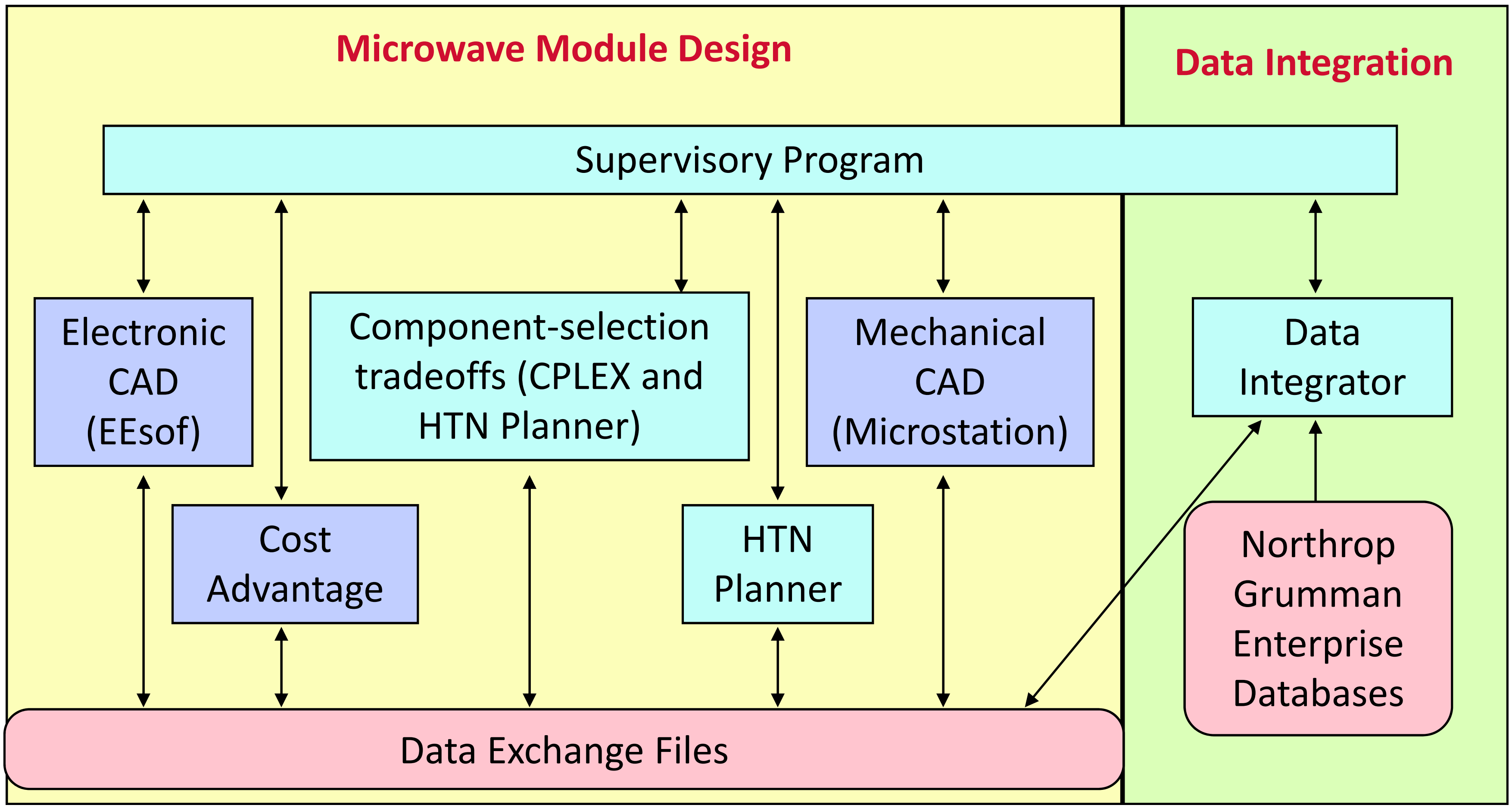
Entity-Relation Diagrams

Functional Data Model
Product Designer View



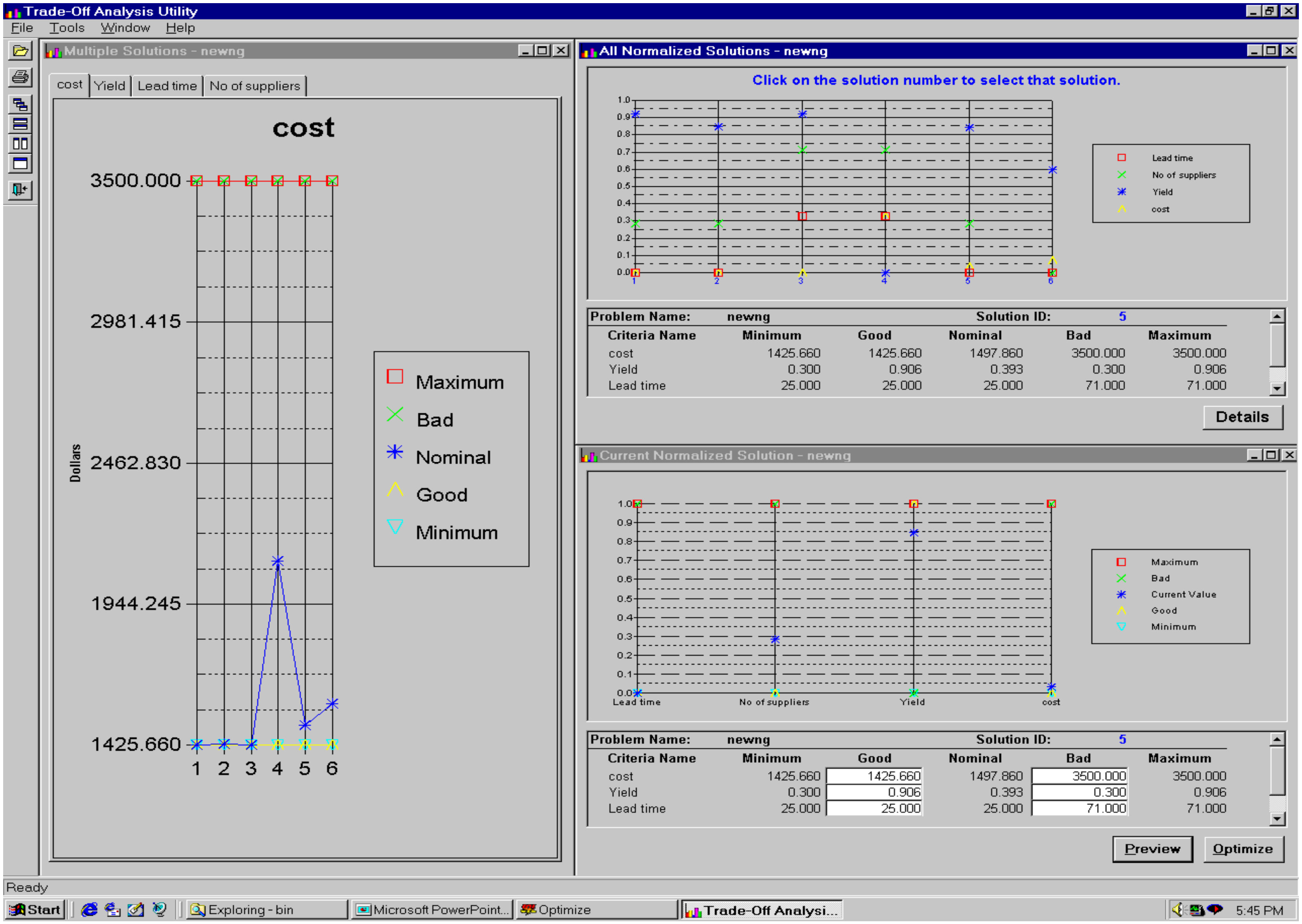
SOLUTION **Object-Relational Databases and Middleware to integrate heterogeneous distributed data sources:**
multi-vendor DB, text, data, CAD drawings, flat, relational, object DBs
Entity-Relation Diagrams to provide multiple expert views of the data and integrate product and process design phases into a single system environment
Hierarchical Task Network planning to explore alternate options at each level of the product: parts and material, processes, functions assemblies
Multicriteria Optimization for trade-offs: cost, quality, manufacturability, ...

IPPD System Architecture

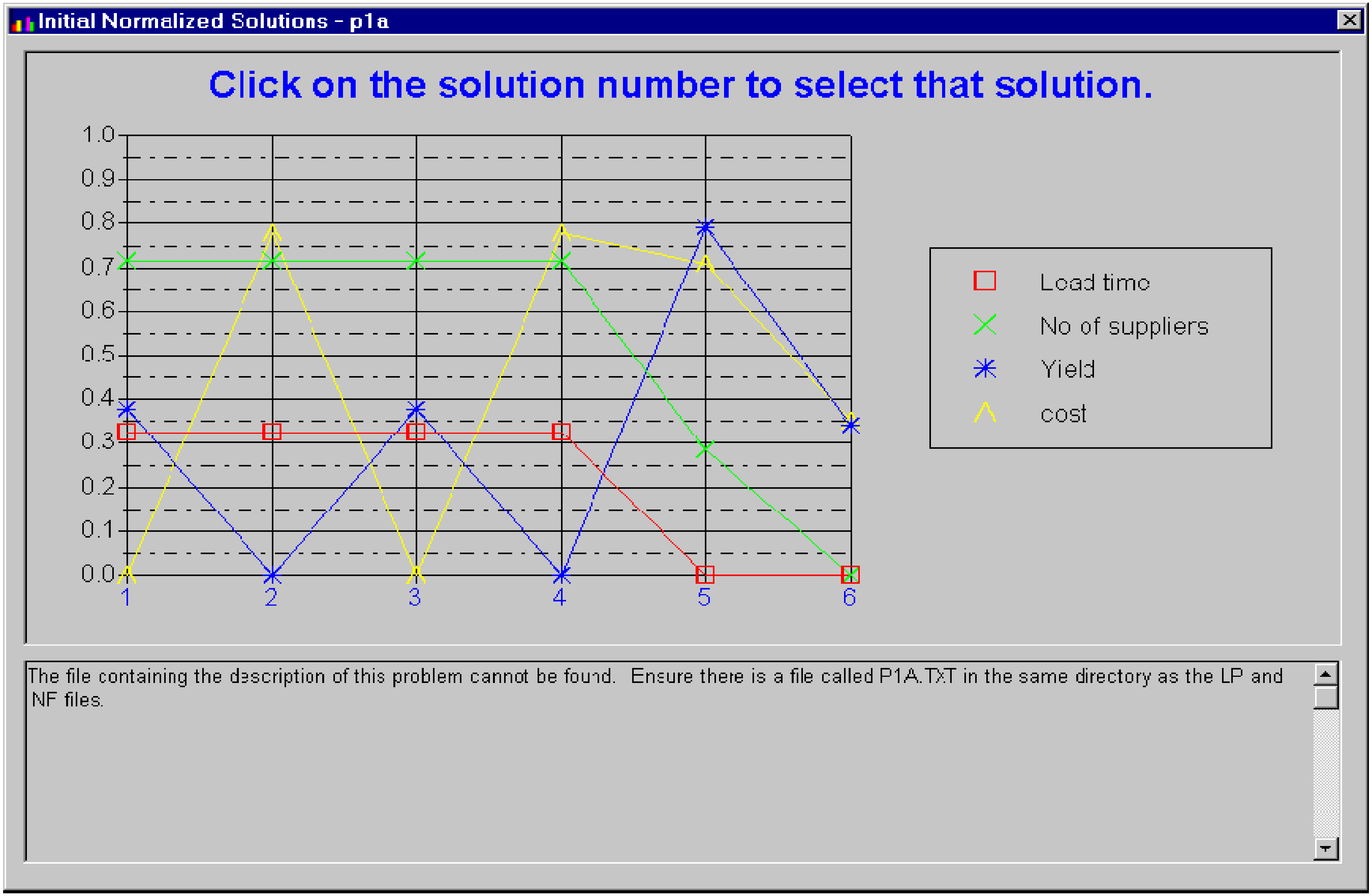


The Institute for Systems Research

Tradeoff Analysis via Multicriteria Optimization



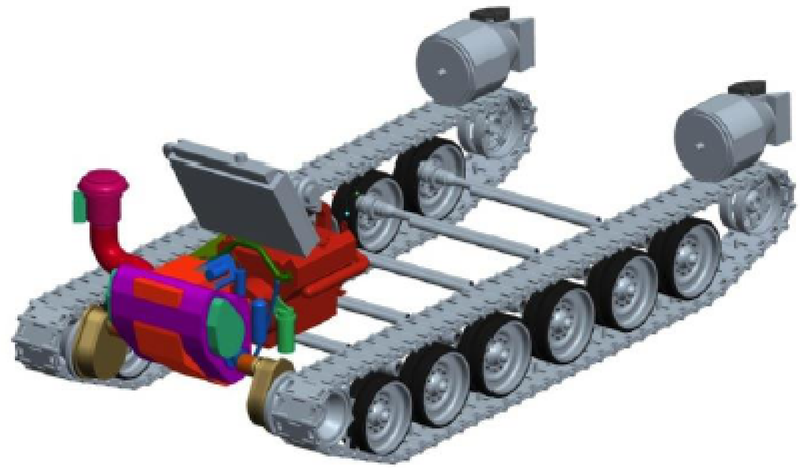
Tradeoff Analysis via Multicriteria Optimization (cont.)

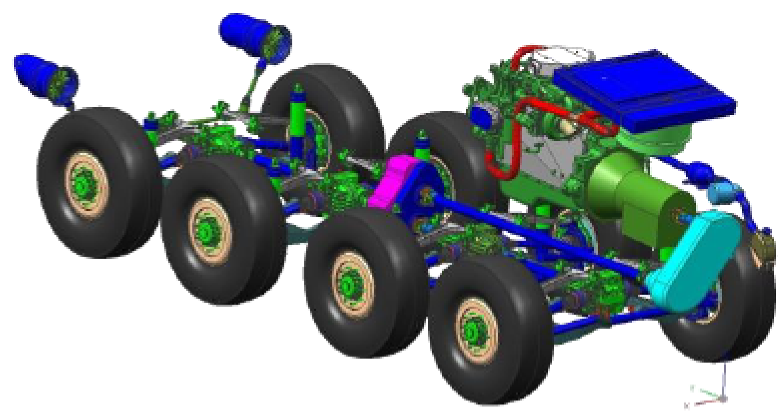


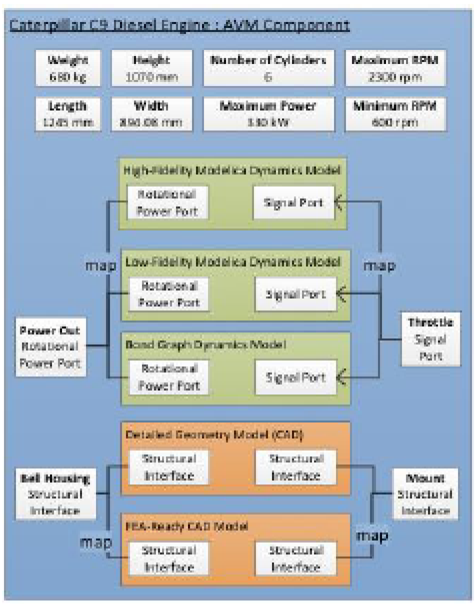
META – iFAB – AVM: Component Models

As of today:

- 131 component classes
- 469 component instances
- 43 parametric components
- 112 ITAR protected models
- 357 non-ITAR protected models





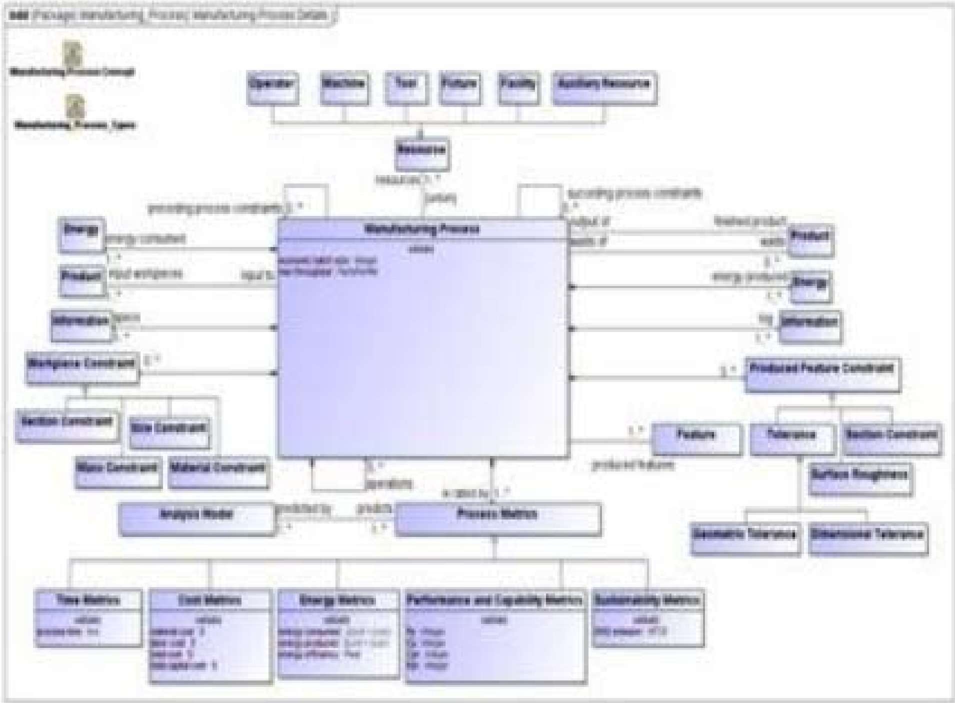


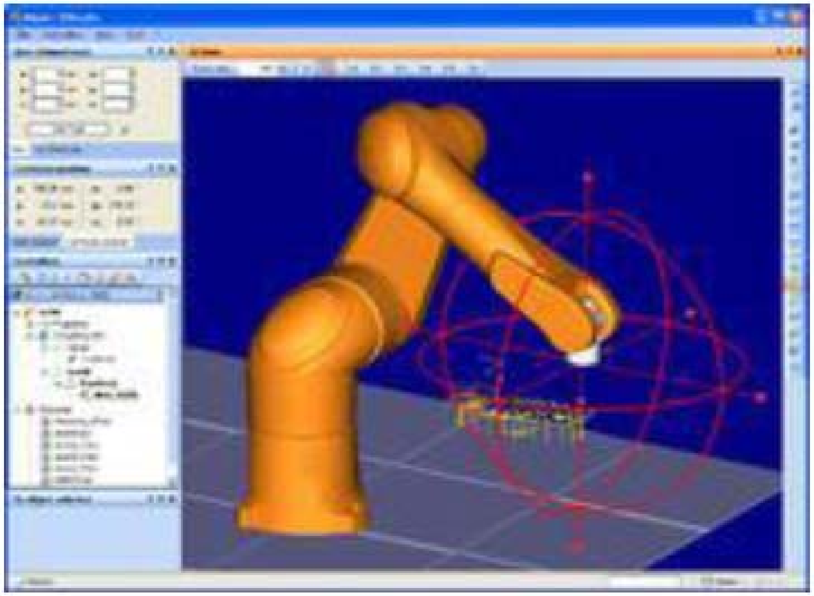
Source: Ricardo PLC

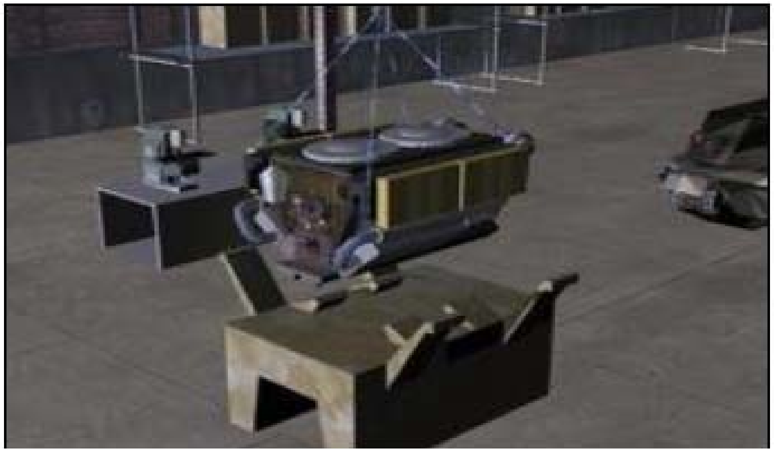
META – iFAB – AVM: Manufacturing Process Models Semantics Across Domains

As of today:

- 7 material shaping processes
- 19 general processes
- 231 machine instantiations
- 64 manual labor units
- 3,212 tools



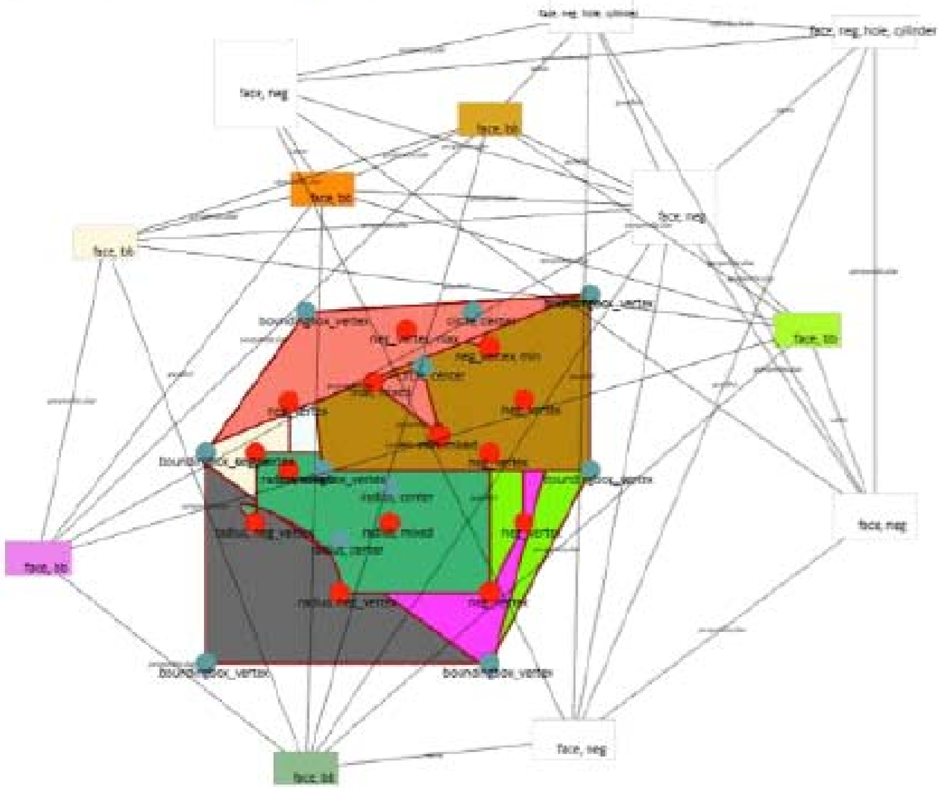




Sources: Penn State ARL; GM Research

META – iFAB – AVM: Design Decomposition

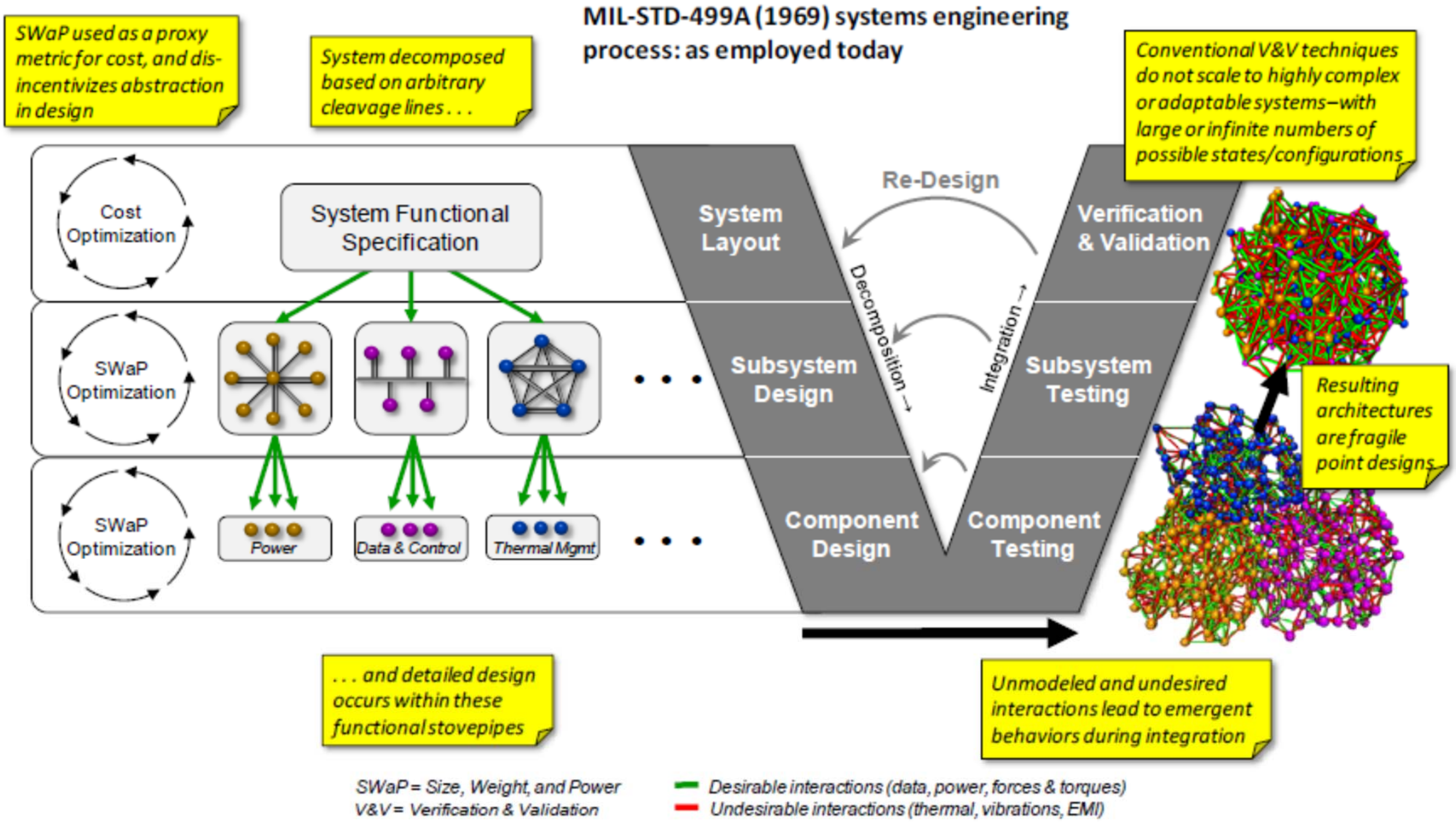
Topological Decomposition



"Reverse Composition"

Source: Xerox PARC

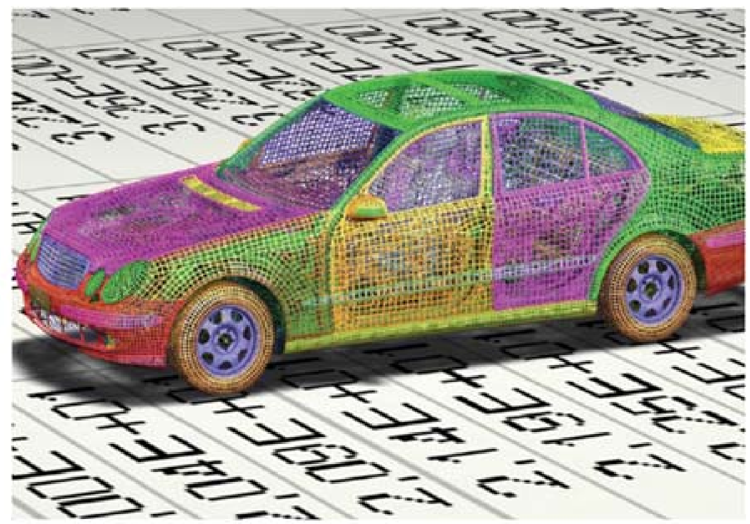
Need to Improve Systems Engineering Methods and Tools Dramatically

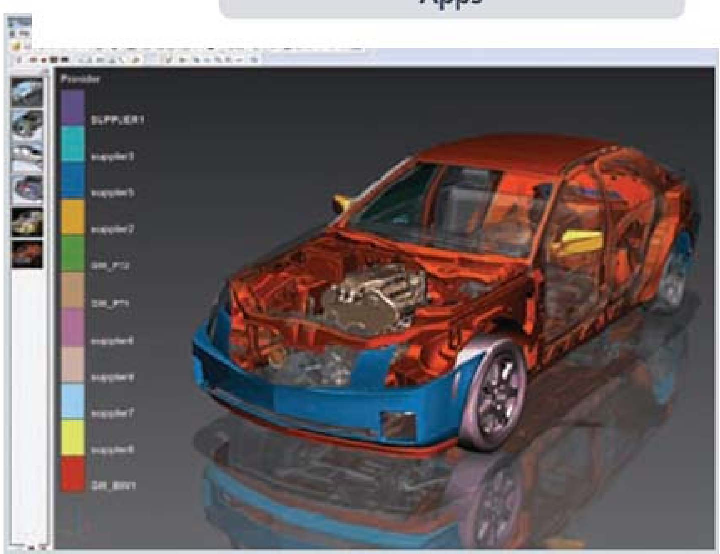


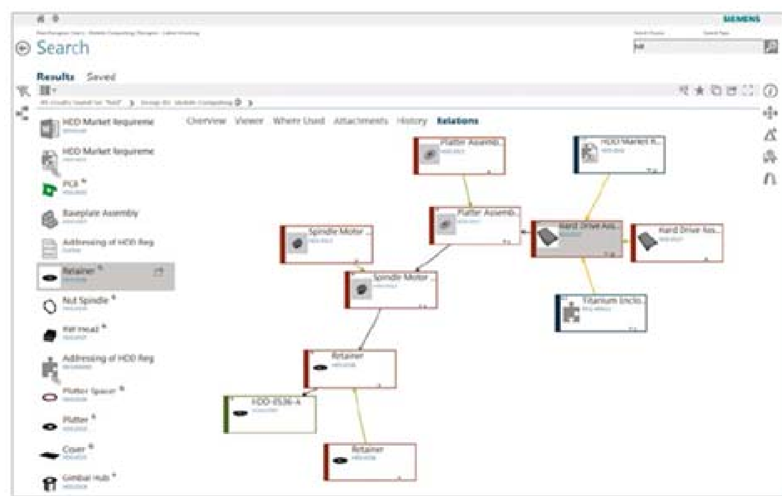
Source: Paul Eremenko, DARPA/TTO

The Institute for Systems Research

Integrating in Hubs
Siemens PLM Tools: Automotive





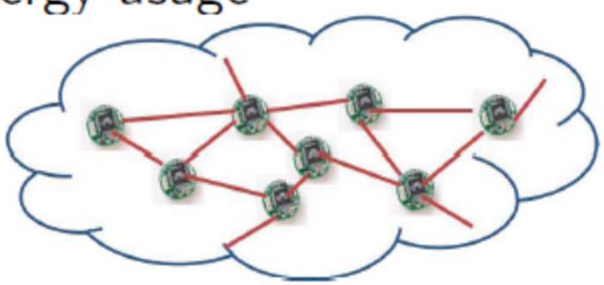


SIEMENS

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)

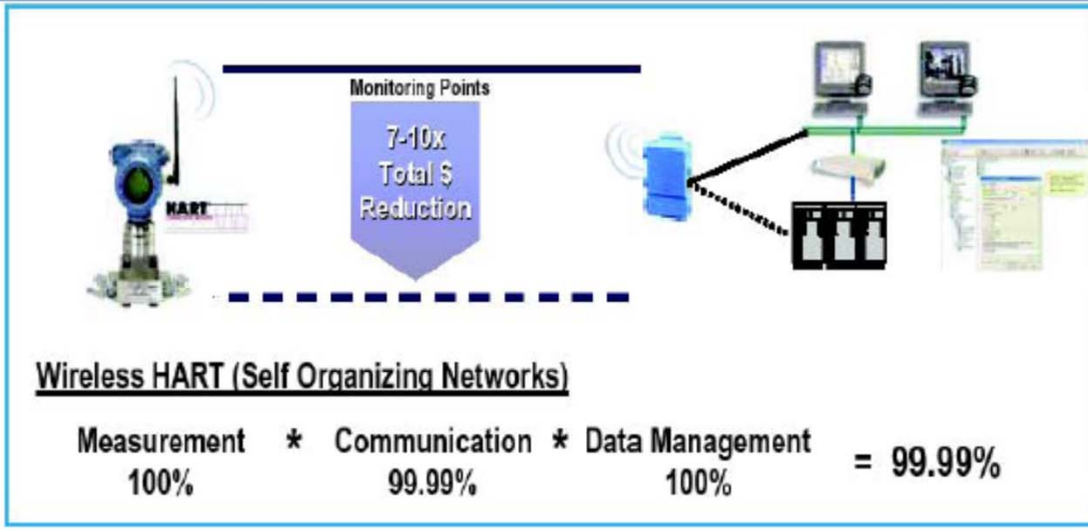
- Robust estimation
  - Noisy measurements
  - Lossy communication
- Real-time control
  - Safety
  - Performance

COTS IT for SCADA

- Cost ↓, Reliability ↑
- Digital and IP based: New vulnerabilities!
- Reliability $\nRightarrow$ Security

Wired networks are costly to maintain

Typical industrial infrastructure ~ $10B



Courtesy: Emerson

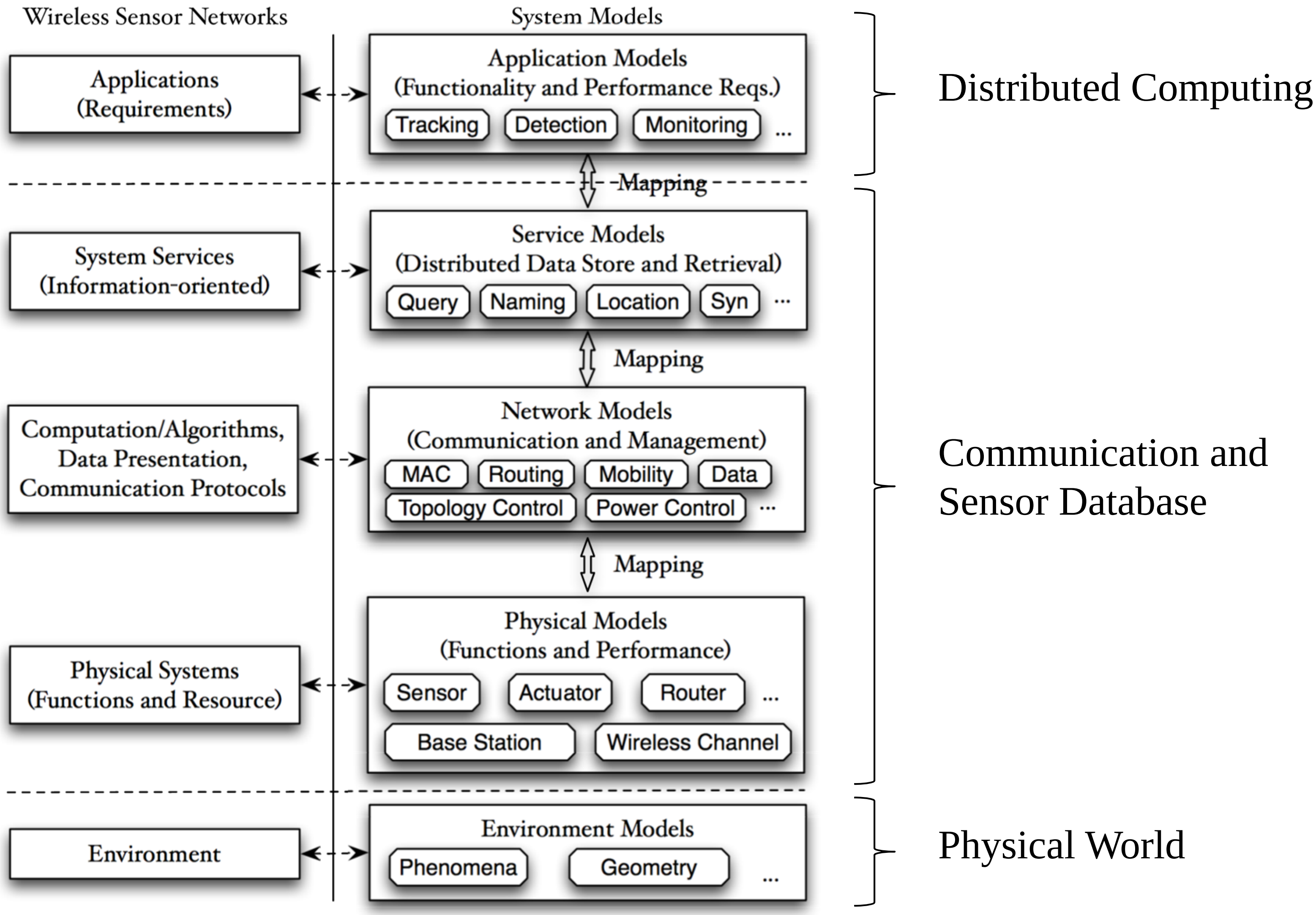
MBSE for Wireless Sensor Networks: Contributions

- 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

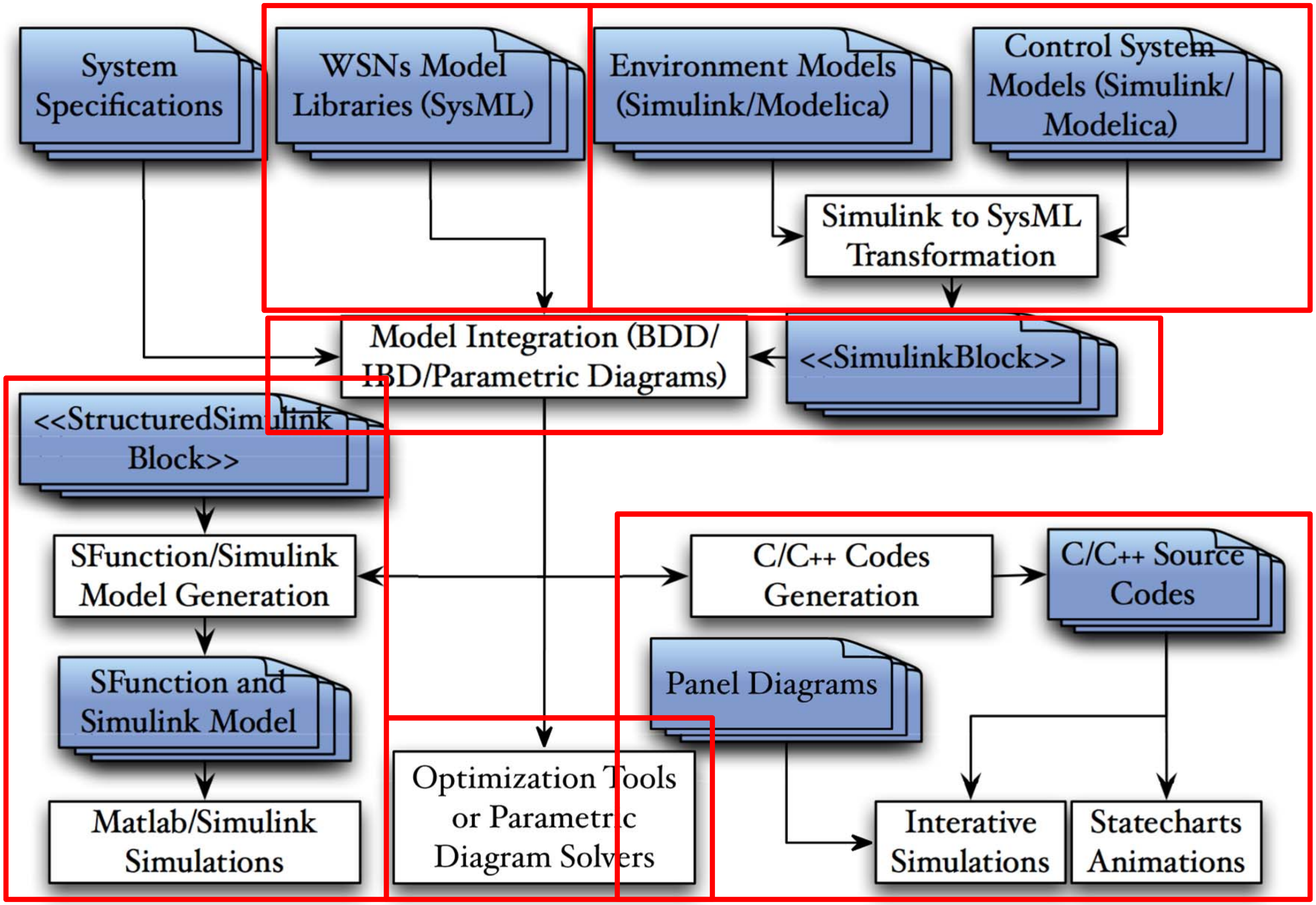
MBSE for Wireless Sensor Networks

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

System Framework

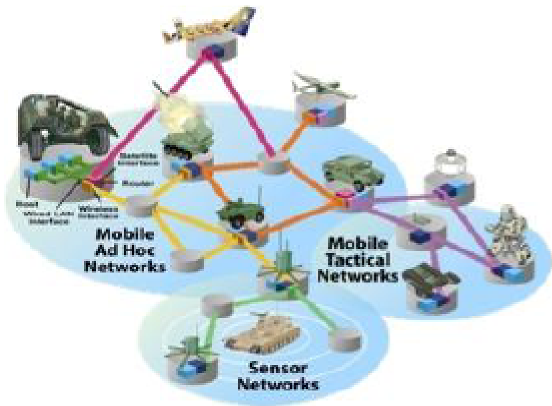


MBSE for Sensor Networks



Component Based Networking: Network MBSE for MANET

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



Dynamic Interconnection and Interoperability

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

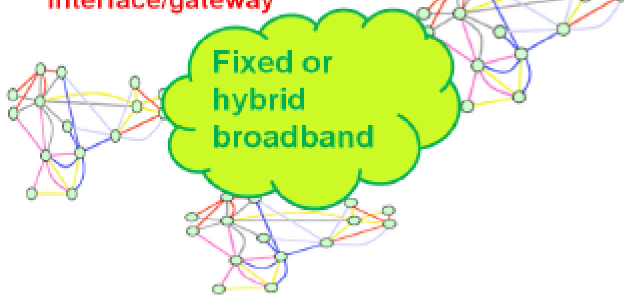
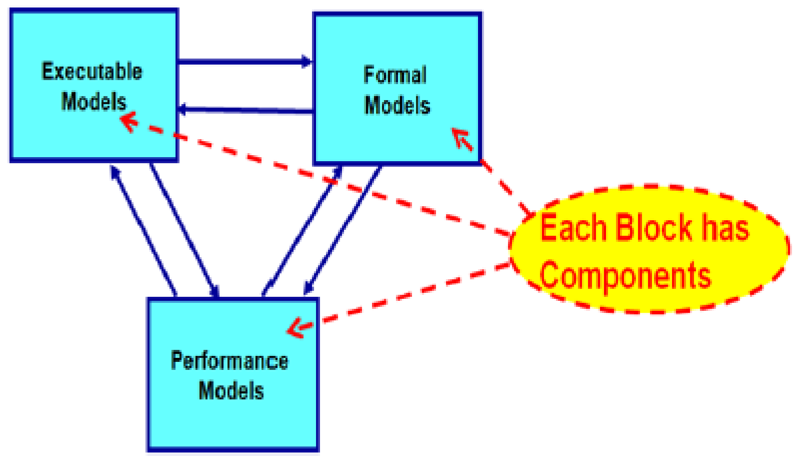


Fig.1: Intelligent Wireless Multi-Nets

Fig.2: Component Based Networking

Component-Based Network Synthesis



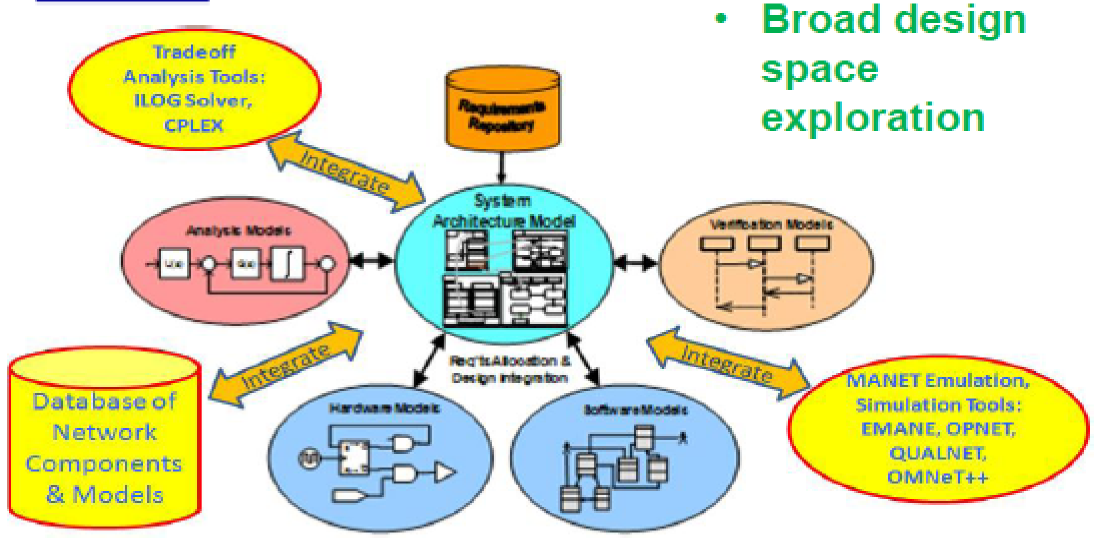


Fig. 3: Network MBSE Toolset : integrating **SysML** Architecture Model with DB of network models, emulation-simulation models, tradeoff tools

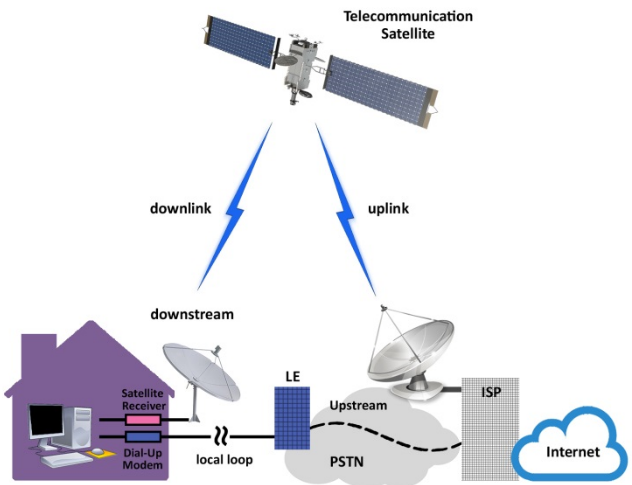
BENEFITS

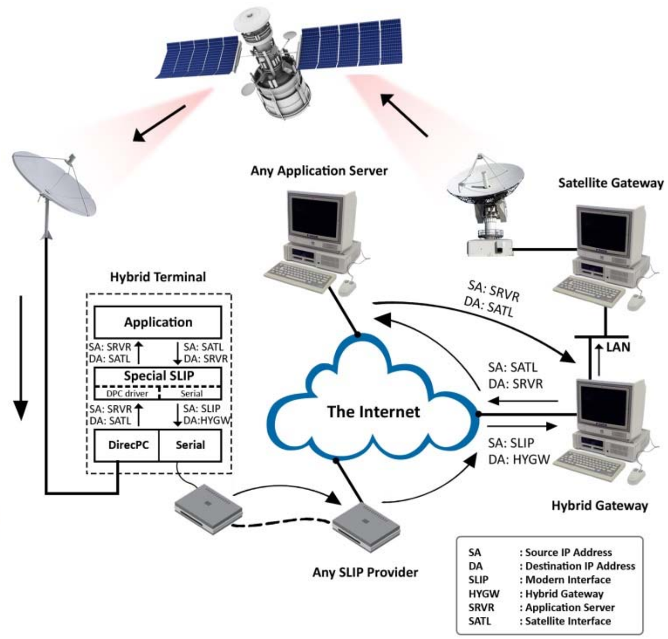
- Reduced MANET cost and fielding time
- Modularity and re-use
- Increased agility in designing, modifying and fielding new MANET
- Broad design space exploration

Internet over Satellite

- Internet explosion over all types of networks
- Satellites viable Internet “nodes”

1995--DirecPC Turbo Internet^{TM}





- *5 times faster*
- *Asymmetry – usability issues*

- 1994 -- Initial Internet over satellite protocol, involved: splitting the connection, address spoofing, selective acknowledgment.
- They informed TCP that delay in ACKs was due to physical path delay and not to congestion (as TCP is designed to assume).

Collaboration with HNS

Continuous cost/performance improvement

1995 DirecPC

1999 DirecDuo

2001 DiRECWAY

DW4000

- PC-hosted, consumer terminal

DW4020

- Satellite IP router
- DHCP
- NAT
- Self-hosted
- Enterprise focus

DW6000

- Single module unit
- Integrated dial backup

DW7000

- 3 x throughput increase
- High-speed inroutes to 1.6 Mbps
- Dual LAN subnets
- Integrated serial-to-IP conversion
- Multiband Support
- RIPv2

HN7000S

- DVB-S2 with ACM
- AIS Adaptive Inroute
- Closed-loop timing
- VRRP / PBR
- Integrated VoIP (HN7740S)

INTRODUCED **Multimedia Appliance**

INTRODUCED **Voice Appliance**

INTRODUCED **Serial Appliance**

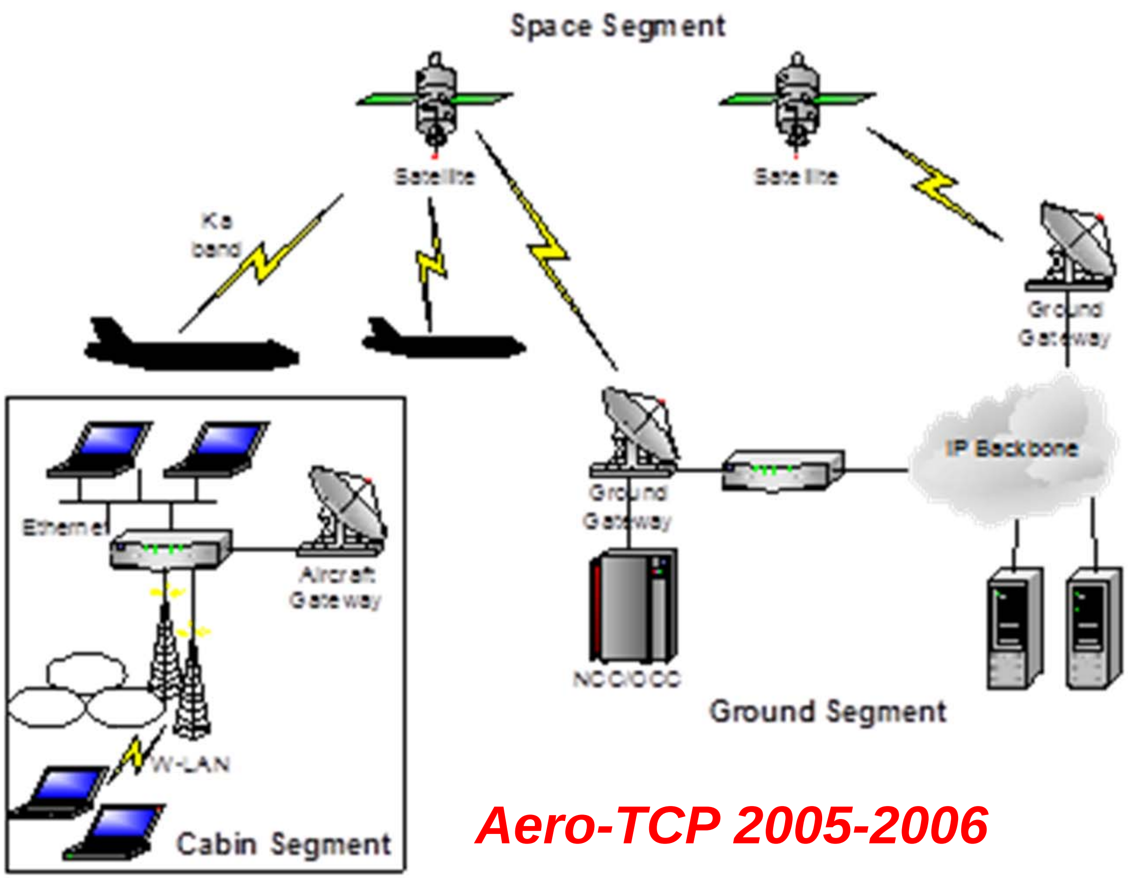
IPoS™

TIA, ETSI, ITU Open Standard Platform

2001	2002	2003	2004	2005	2006	2007

Aero-TCP

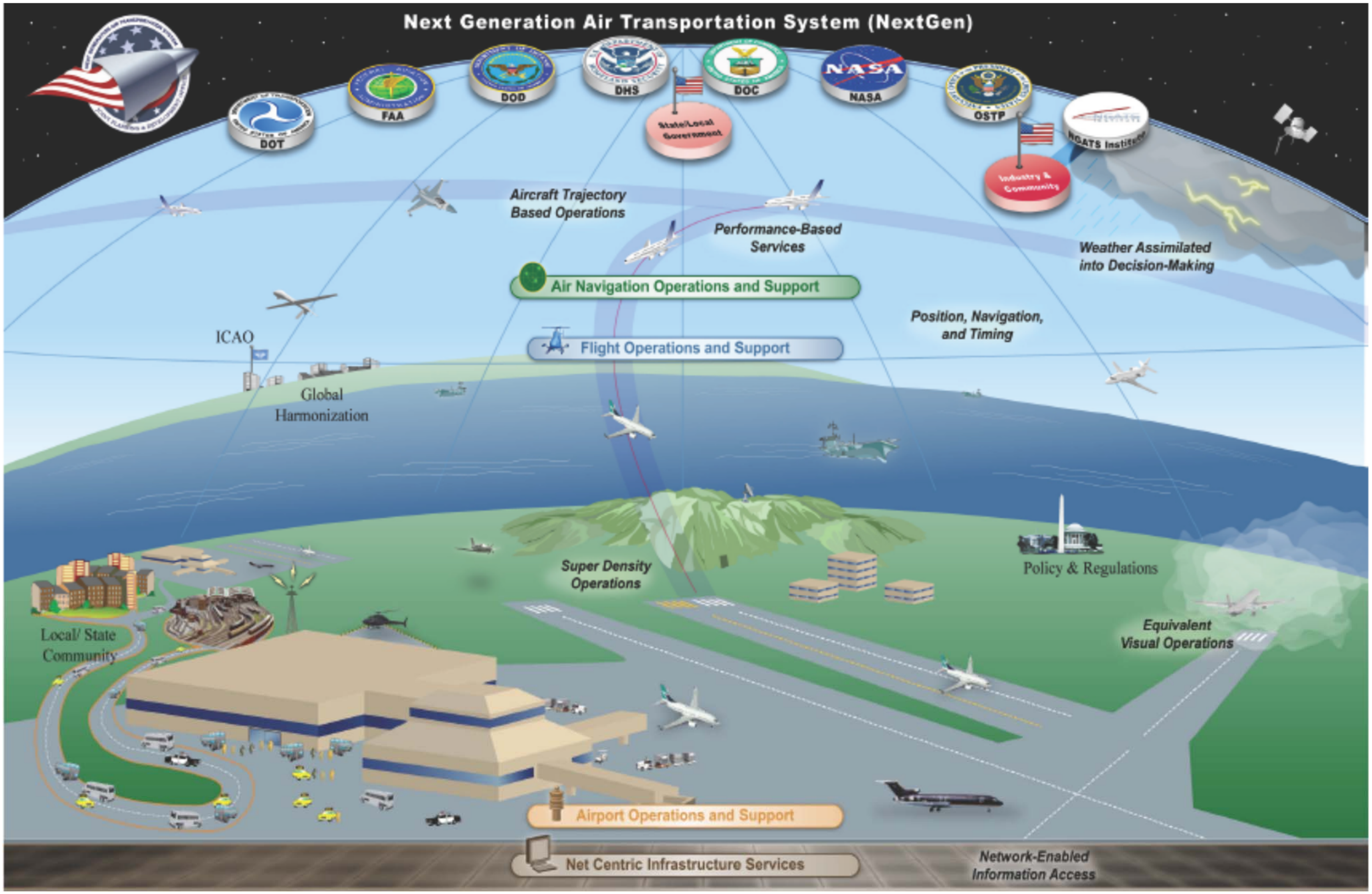
Boeing Connexion 2001-2006



Aero-TCP 2005-2006

Since 2011 satellite-based ***broadband Internet to planes*** has received much attention from airlines and the FCC, with deployment of in-flight satellite-based Internet service

FAA NEXTGEN

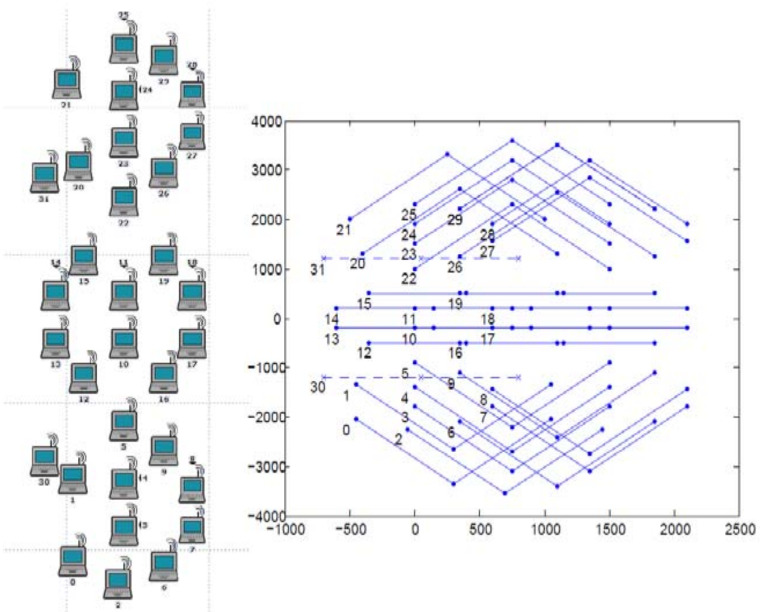


Next Generation Air Transportation System (NextGen)
DOT
FAA
DOD
DHS
DOC
NASA
OSTP
NGATS Institute
State/Local Government
Industry & Community
Aircraft Trajectory Based Operations
Performance-Based Services
Weather Assimilated into Decision-Making
Air Navigation Operations and Support
Flight Operations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

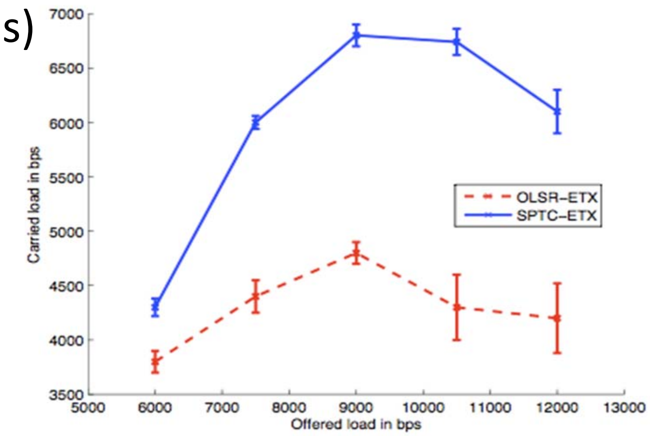
Components for Routing Protocols

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

3 Platoon Mobility Scenario



Long connection from 20 to 0 (platoon heads)



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

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

Satellite Constellations

- More than 50% of the world's population without Internet access; 3 ... occupies less than ...

- Mobile w ... story
- Can brin ... places
- More dev ... ters, sensors, ...
- Need co...
- OneWeb (Qualcom ... son), Airbus, Arianespace): one ... es at 1,200km), great coverage, Internet ... nderserved areas

- Integrates with terr ... d 3G, 4G LTE and Wi-Fi services
- Creates huge opportunities for economic growth world-wide

5G Vision

End-to-end ecosystem to enable a fully mobile and connected society

Value creation towards customers and partners, with existing and emerging use cases

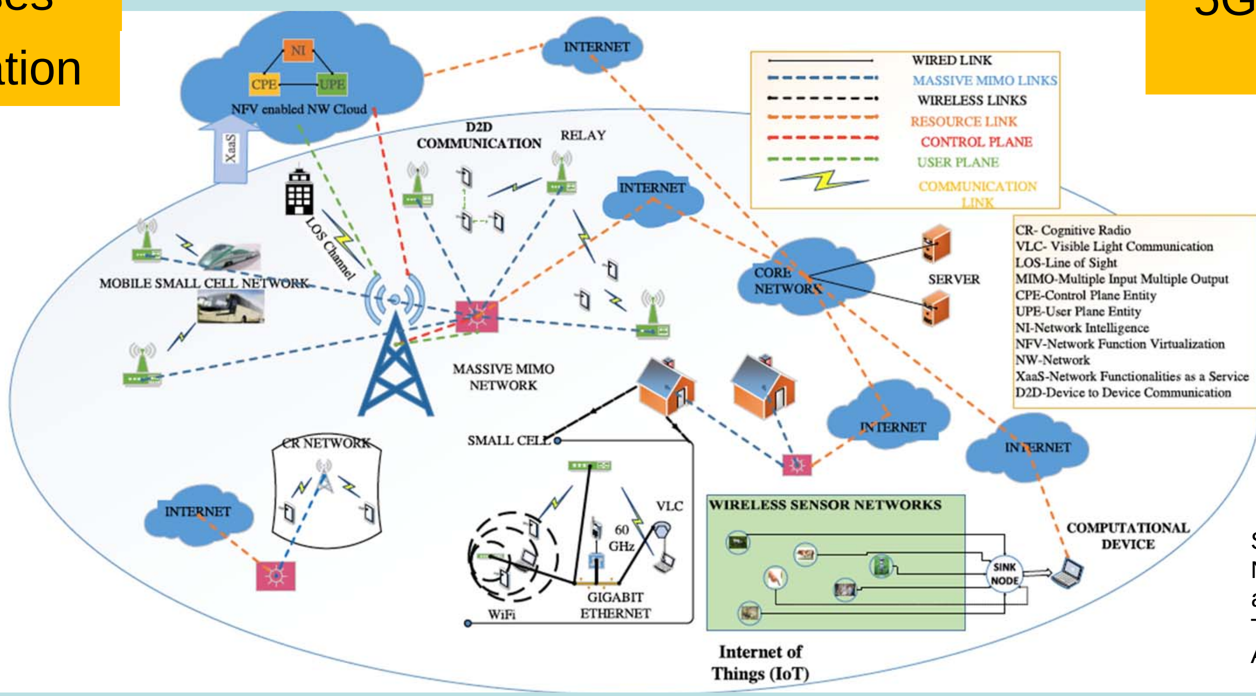
Delivered with consistent experience

Enabled by sustainable business models

5G Use Cases

5G Value Creation

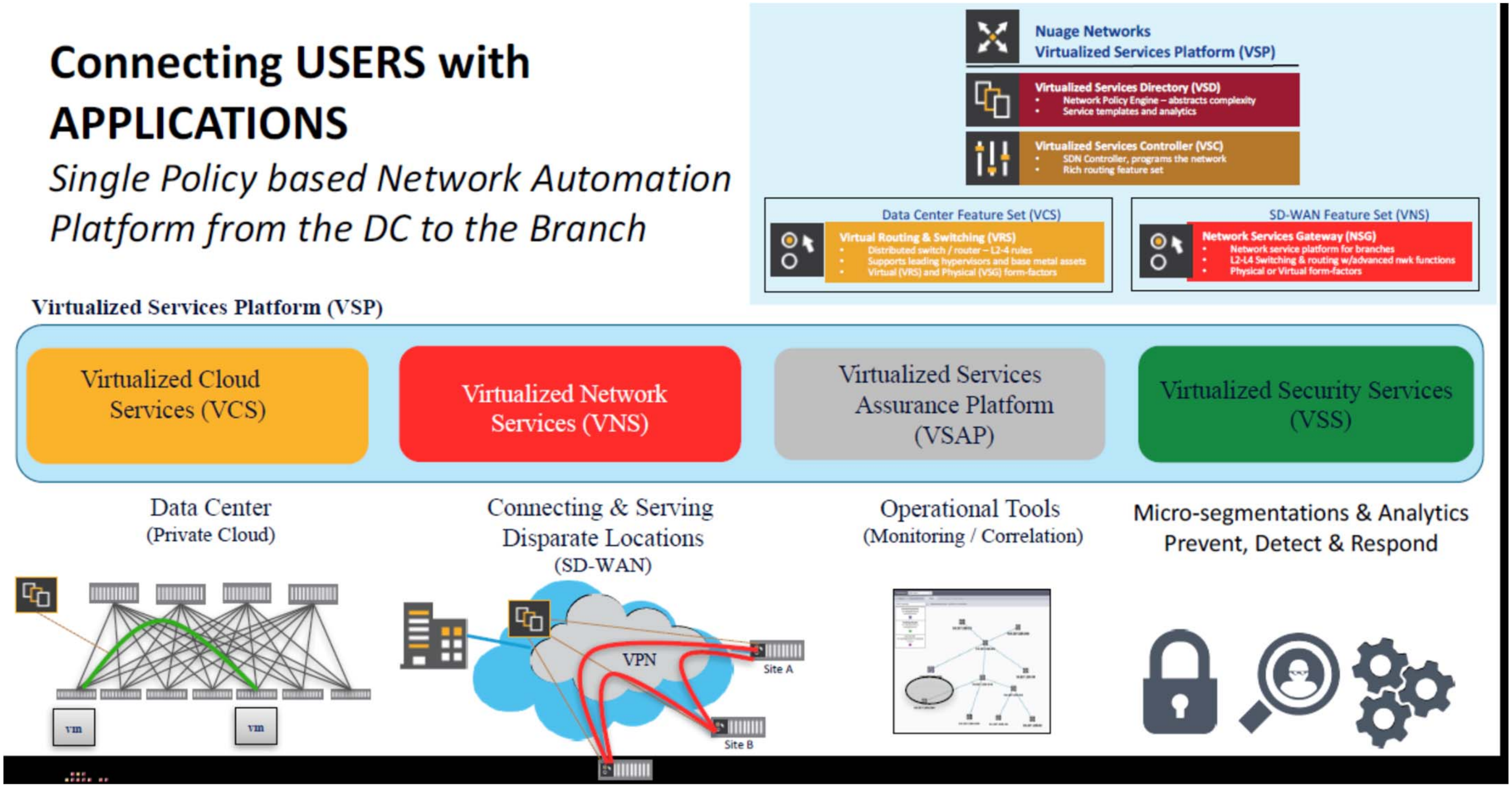
5G Business Models



SRC: A Survey of 5G Network: Architecture and Emerging Technologies, IEEE Access, 2015

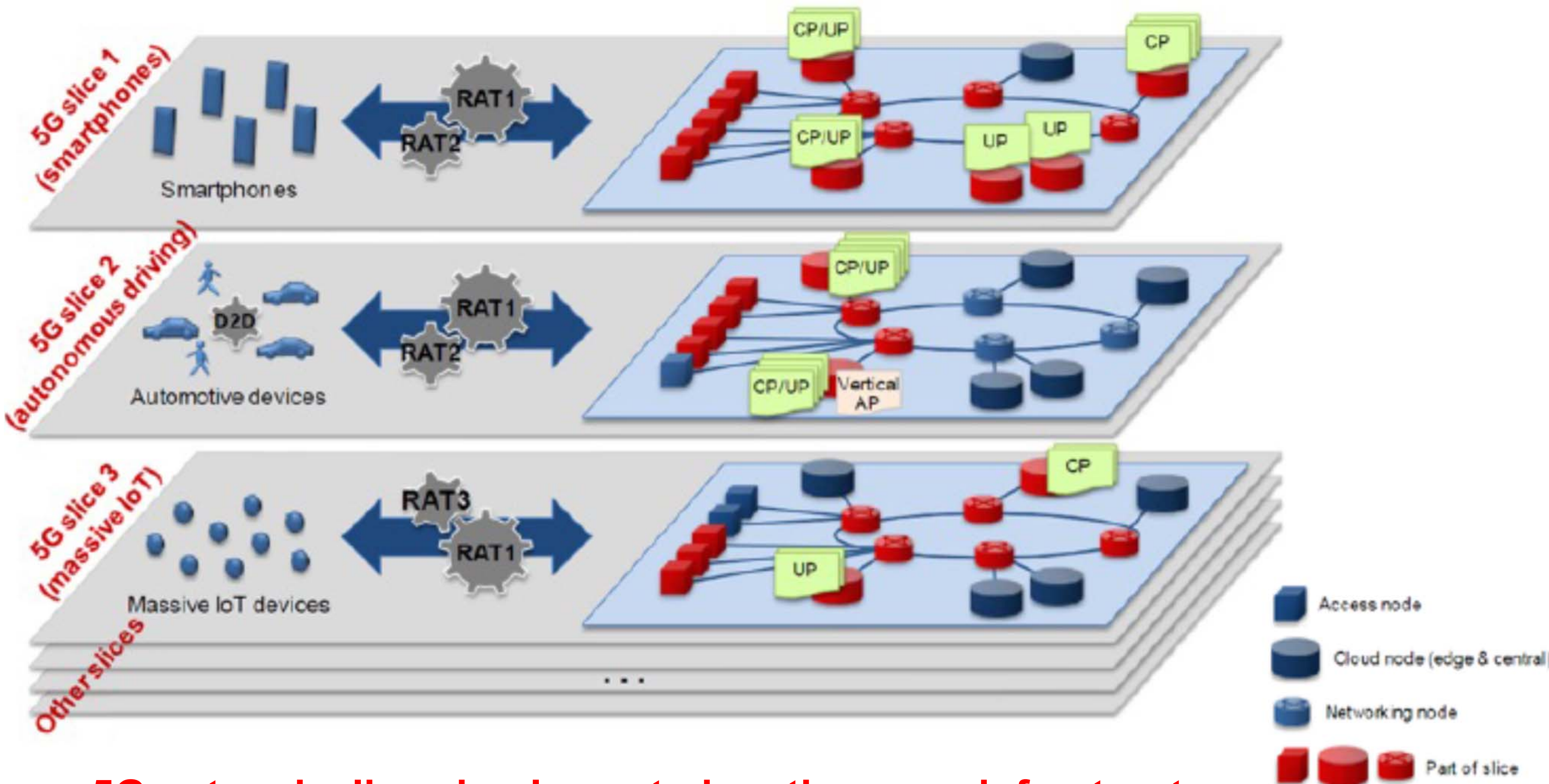
Network of networks," i.e., a heterogeneous system comprising a variety of air interfaces, protocols, frequency bands, access node classes, and network types

Virtualizing the Network – Network as a Service (NaaS)?



Ericsson

Network Slicing



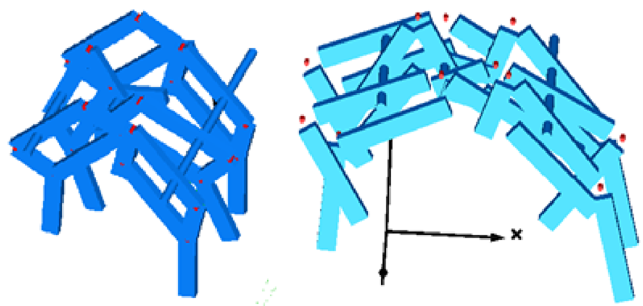
5G network slices implemented on the same infrastructure

SRC: NGMN

MBSE for Robotic Arms and Grippers

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

Application to Microrobotics

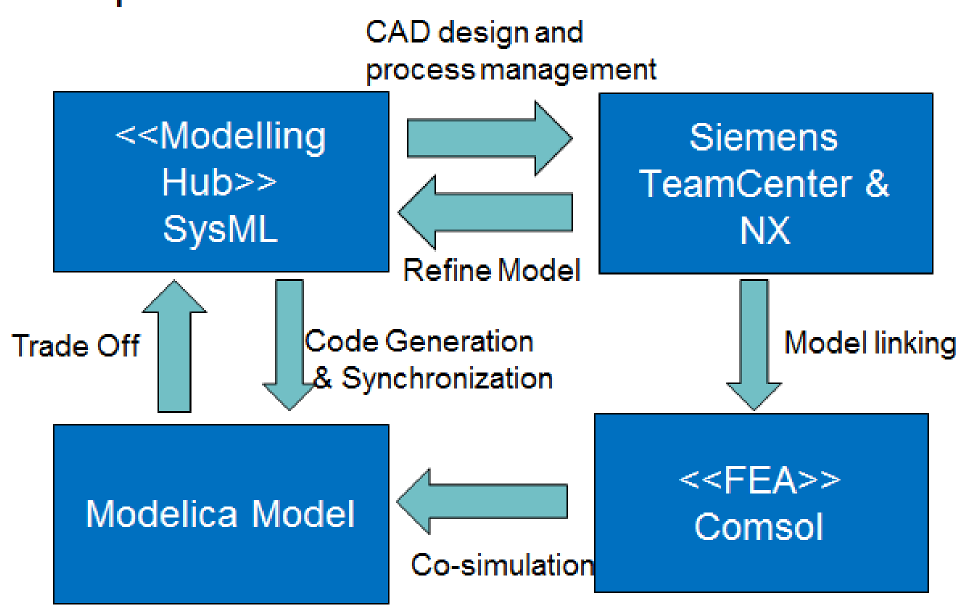


(a) (b)

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

Siemens Tools Utilization

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



Microrobot

Kinematics

- Coordinate transformations

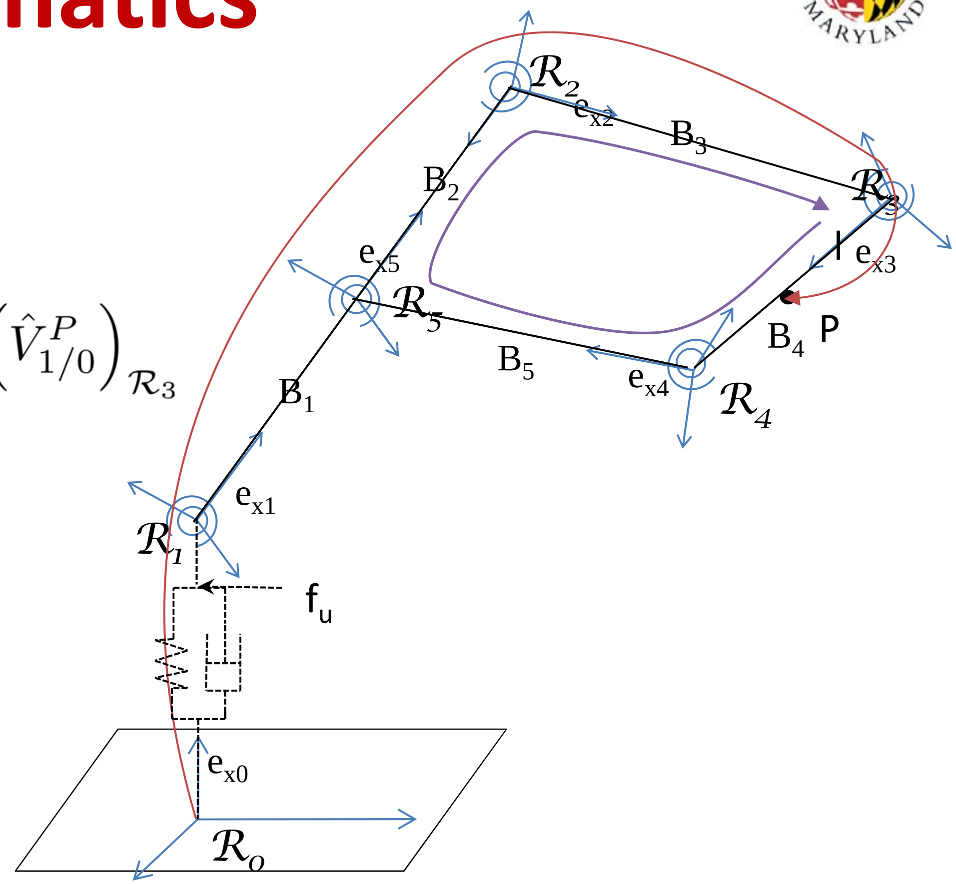
$$\left(\hat{V}^P_{3/0}\right)_{\mathcal{R}_3} = \left(\hat{V}^P_{3/2}\right)_{\mathcal{R}_3} + \left(\hat{V}^P_{2/1}\right)_{\mathcal{R}_3} + \left(\hat{V}^P_{1/0}\right)_{\mathcal{R}_3}$$

- Direct Kinematics

$$\left(\hat{V}^P_{3/2}\right)_{\mathcal{R}_3} = \begin{pmatrix} \dot{\theta}_3 e^3_z \\ l e^3_x \times \dot{\theta}_3 e^3_z \end{pmatrix}$$

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

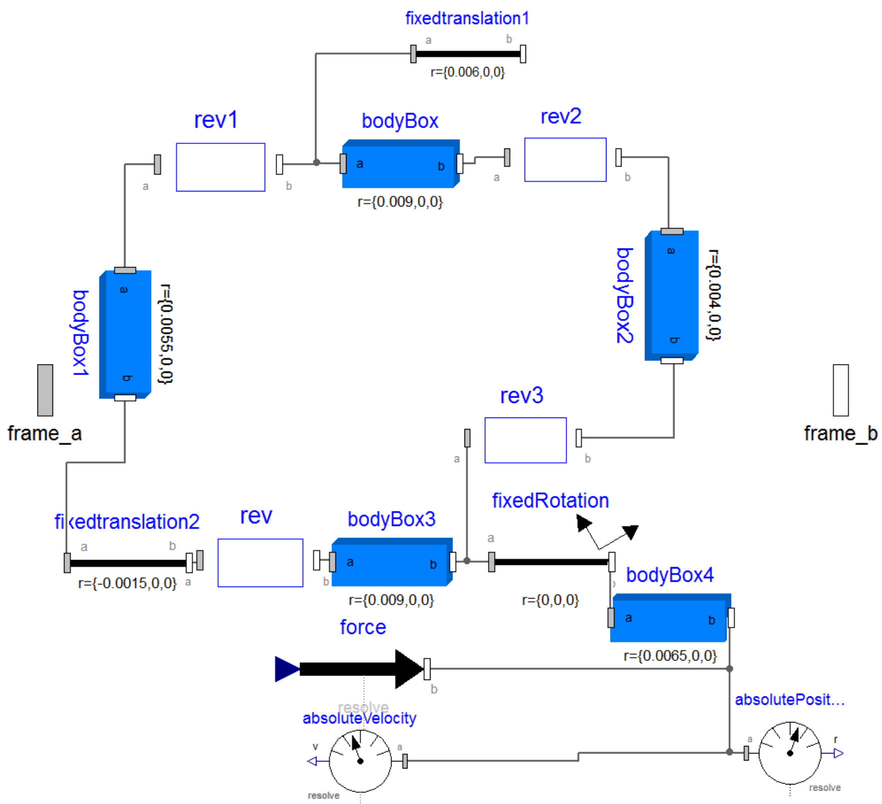
$$\left(\hat{V}^P_{1/0}\right)_{\mathcal{R}_3} = \begin{pmatrix} \dot{\theta}_1 e^1_z \\ (l_1 e^1_x + l_2 e^2_x + l e^3_x) \times \dot{\theta}_1 e^1_z \end{pmatrix}$$



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

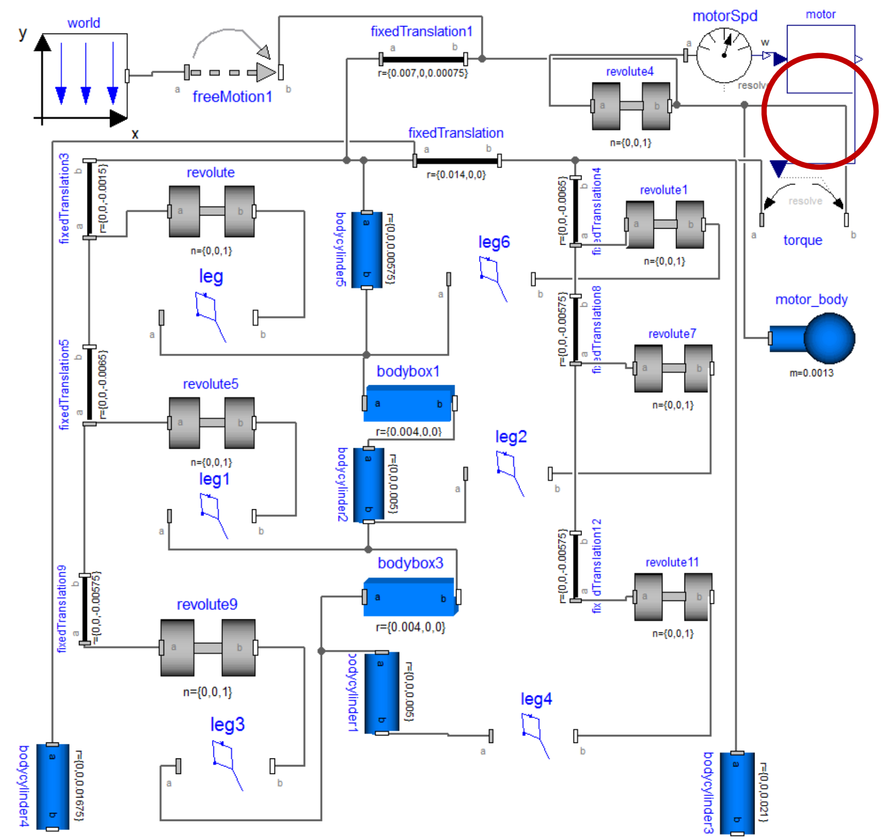
Modelica Model

- Leg Model



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

- Overall Model



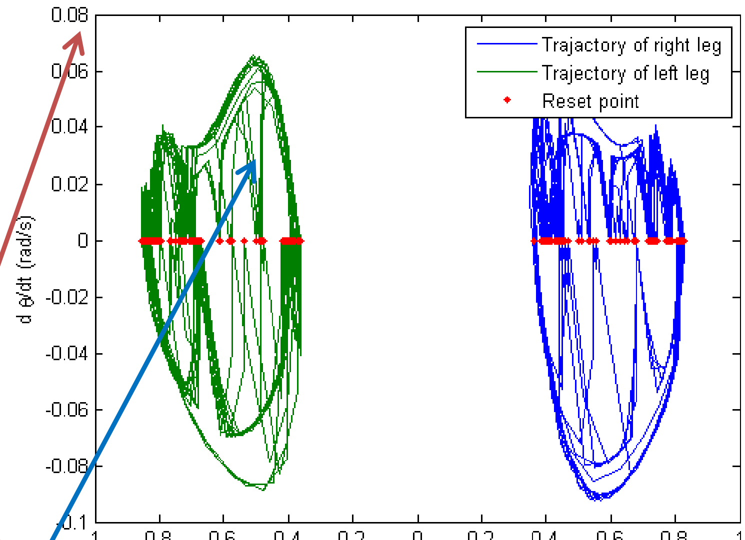
Simplified structure of the robot using the leg submodel. Highlighted submodel is an electrical motor model, includes a Pulse Width Modulation controller, which is the Cyber part of the robot.

Limit Cycle Analysis and Adding PWM

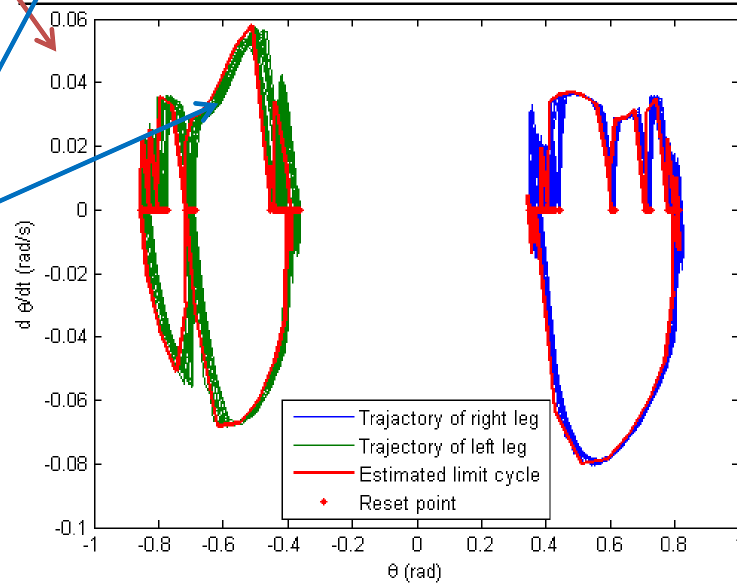
- New geometry alters the problem dramatically.
  - Although the new joint dimension should improve stability, it is hard to verify.
  - Howev… used, t… able to… high te… joints, unless motor output is increased dramatically. So no comparison is given here.
  - By che… we find th… helpfu… jumpi…

Note decreases in limit cycle size in derivative direction

Note changes in reset points of limit cycles



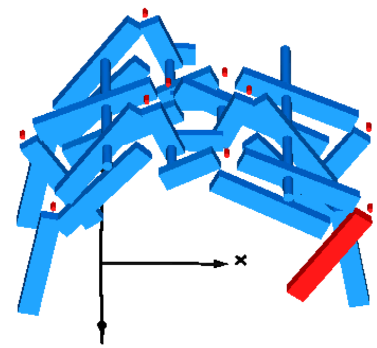
Before adding PWM



After adding PWM

Animation of First Model

Second Model



CPS Architectures

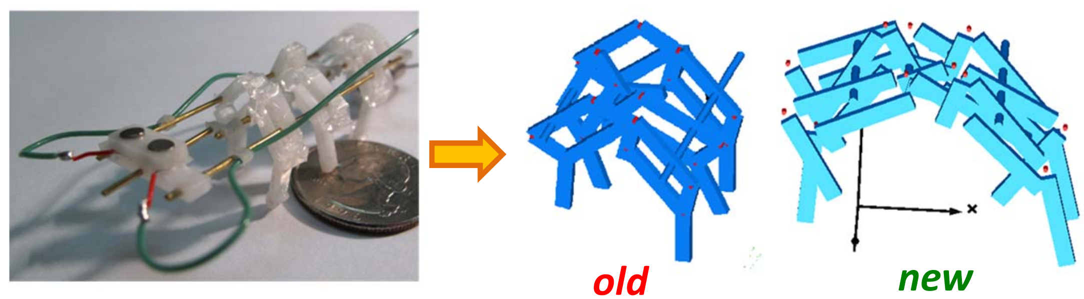
- **Architecture** : description of structure and behavior components of a system together with their configuration and interfaces and interconnections.
- **Architecture for CPS** is challenging : account for both the physical and cyber constraints – e.g. physical and material laws as well as geometric laws will guide the physical part
- Various concepts of time and their constraints. Extensions of current distributed architectures for computers at all scales, including both digital and analog components need to be considered
- Interplay between the principles and rules of architectures from the physical and cyber sides need to be considered and brought to harmony

Materials-Geometry-Controls

Composite wing – new control algorithms
All-electric platform – new aircraft VMS

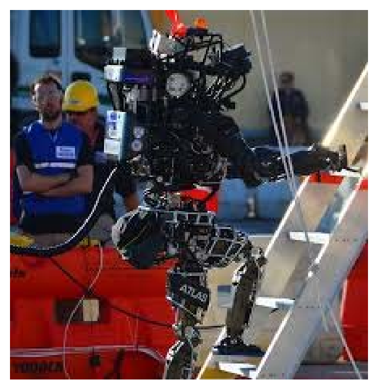
Smart suit – improve physical endurance & energy harvesting

Robotic lizards – new motion-material-geometry



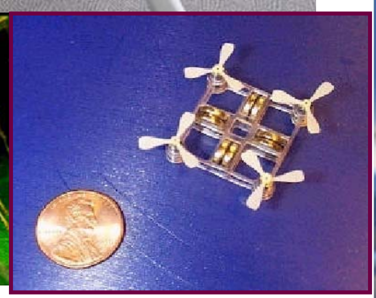
Fast micro-robots – new joint design of geometry-material-controls – More stable and faster running

Social and Cognitive Robotics: Collaborative Autonomy



AUTONOMOUS SWARMS – NETWORKED CONTROL

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

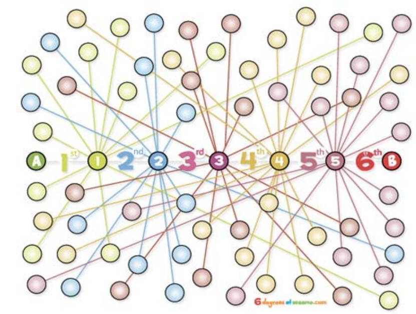


Social Networks over the Web

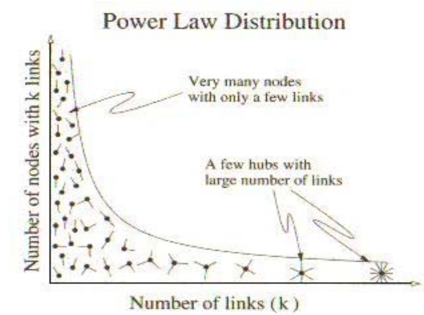
- We are much more “social” than ever before
  - Online social networks (SNS) permeate our lives
  - Such new Life style gives birth to new markets
- Monetize the value of social network
  - Advertising - major source of income for SNS
  - Joining fee, donation etc.
  - …
- Need to know the common features of social networks

Social Networks -- Challenges

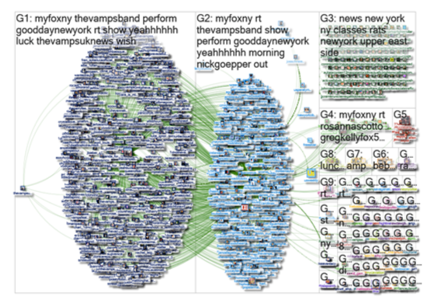
- We are much more “social” than ever before
  - Online social networks (SNS) permeate our lives
  - Such new Life style gives birth to new markets
- Monetize the value of social network
- Major characteristics of social networks
  - The small-world effect (6 degree of separation)
  - Scale-free degree distribution (power-law)
  - Community structure (clustering)
- Statistical models
  - Random Graph (Poisson, exponential)
  - Small-World
  - Preferential Attachment
- SNS applications (e.g. advertising) should consider these properties



Small-world effect



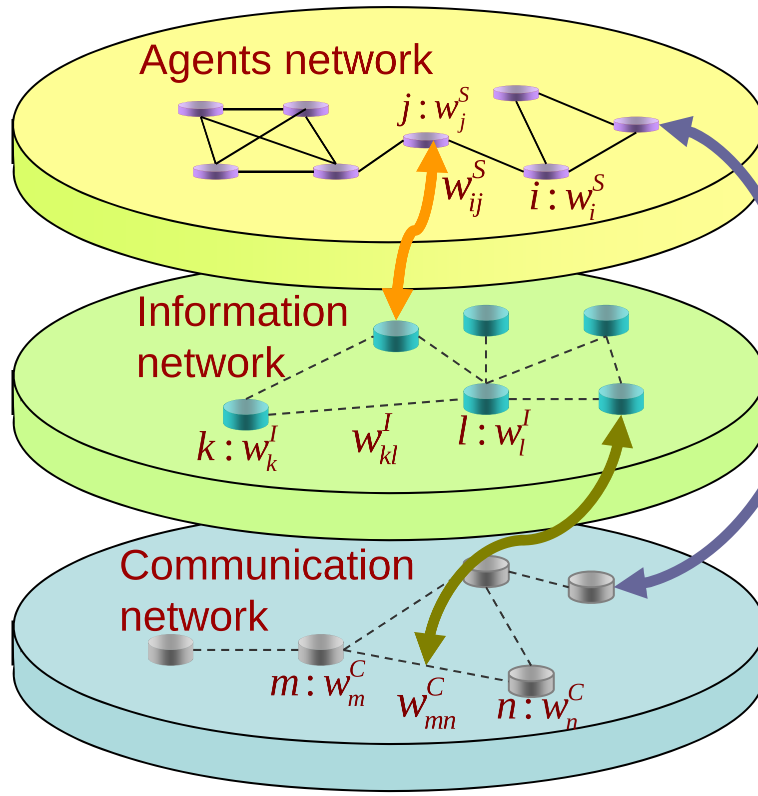
Scale-free distribution



Community structure

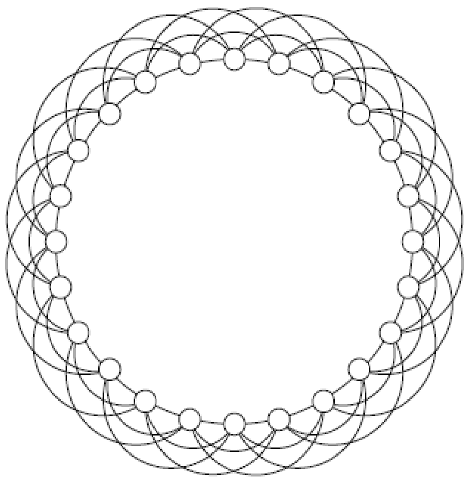
Multiple Coevolving Multigraphs

- Multiple Interacting Graphs
  - *Nodes*: agents, individuals, groups, organizations
  - Directed graphs
  - *Links*: ties, relationships
  - Weights on links : value (strength, significance) of tie
  - Weights on nodes : importance of node (agent)
- **Value directed graphs with weighted nodes**
- **Real-life problems: Dynamic, time varying graphs, relations, weights, policies**

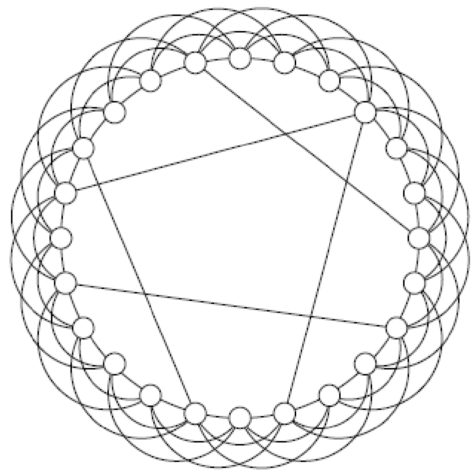


Networked System architecture & operation

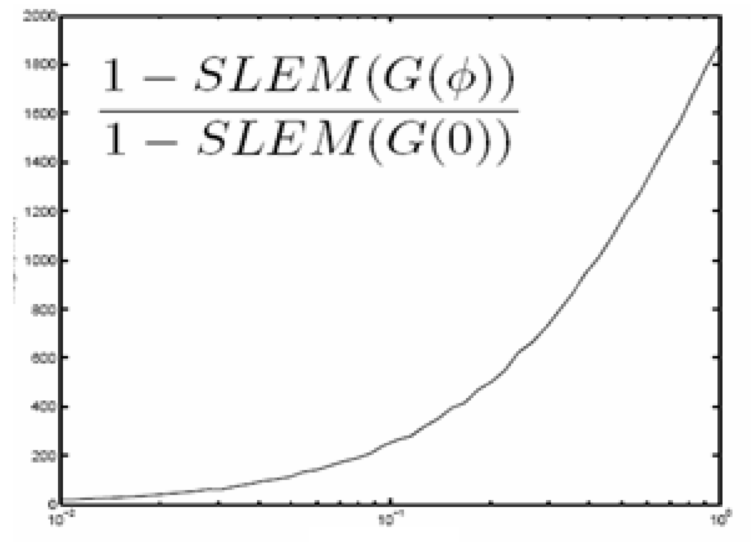
Small World Graphs



Simple Lattice
C(n,k)



Small world: Slight variation adding $nk\Phi$



\phi
C(1000,5)

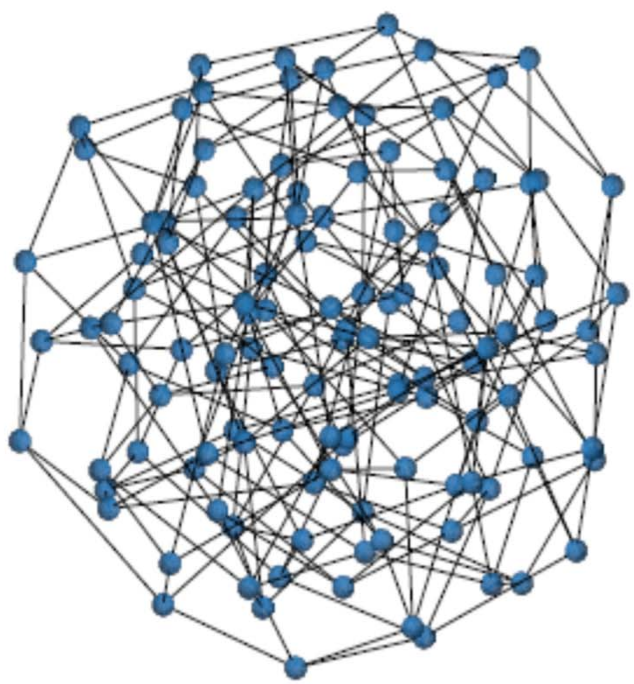
Adding a **small portion** of well-chosen links →
significant increase in convergence rate

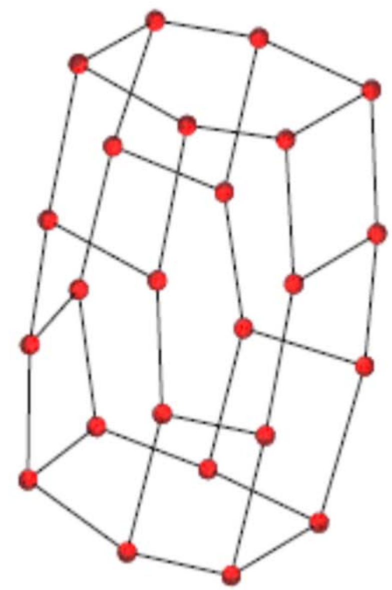
Expander Graphs

- First defined by Bassalygo and Pinsker -- 1973
- Fast synchronization of a network of oscillators
- Network where any node is "nearby" any other
- Fast 'diffusion' of information in a network
- Fast convergence of consensus
- Decide connectivity with smallest memory
- Random walks converge rapidly
- Easy to construct, even in a distributed way (ZigZag graph product)
- Graph G, ***Cheeger constant h(G)***
  - All partitions of G to S and S^c ,

    $h(G)$=min (#edges connecting S and S^c) / (#nodes in smallest of S and S^c)
- (k, N, ε) **expander** : $h(G) > \varepsilon$; **sparse but locally well connected** **(1-*SLEM*(*G*) increases as $h(G)^2$)**

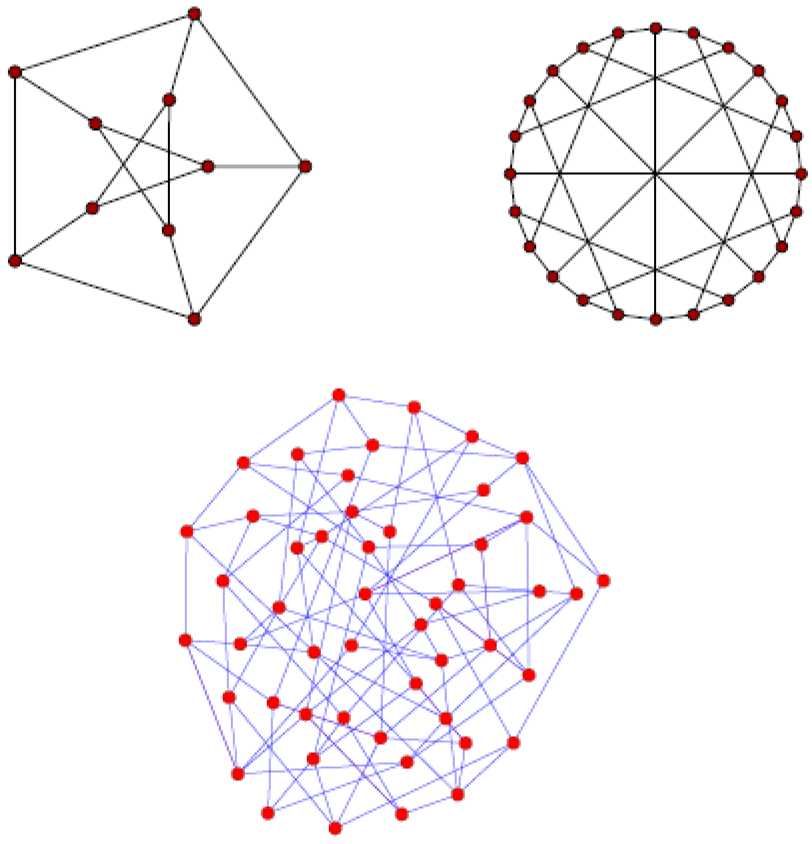
Expander Graphs – Ramanujan Graphs





Construction of Networks by Computational Optimization

Examples of resulting topologies

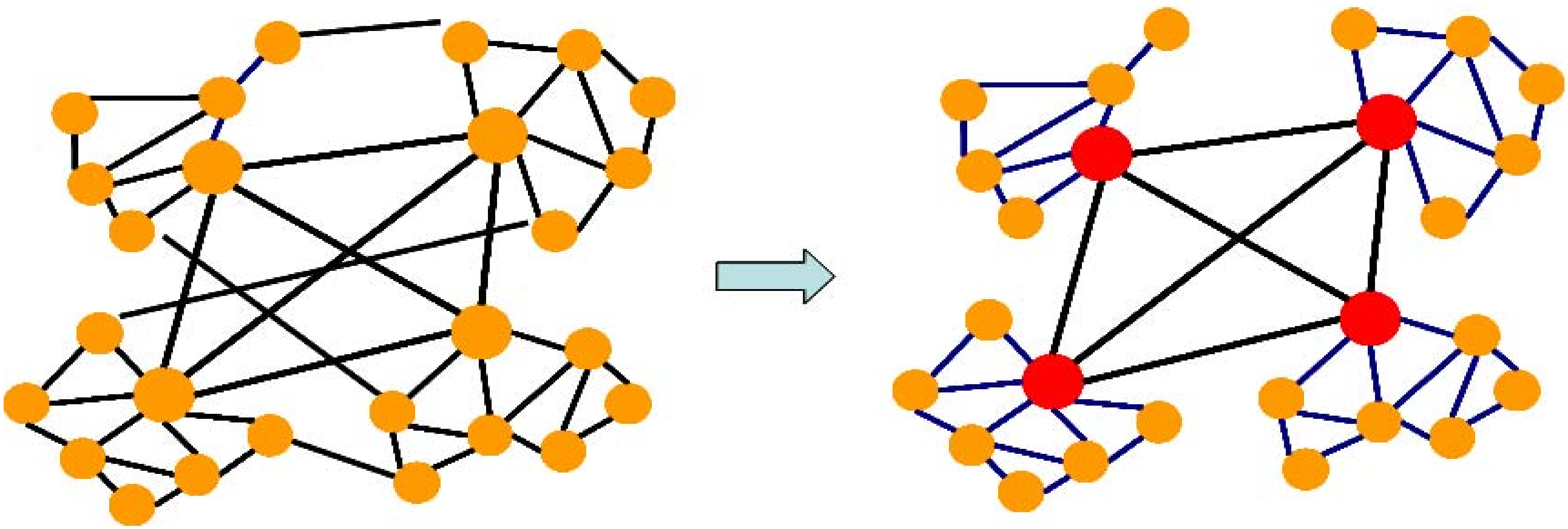


Distributed self - organization

Determine leaders → Find influence → Remove unnecessary links

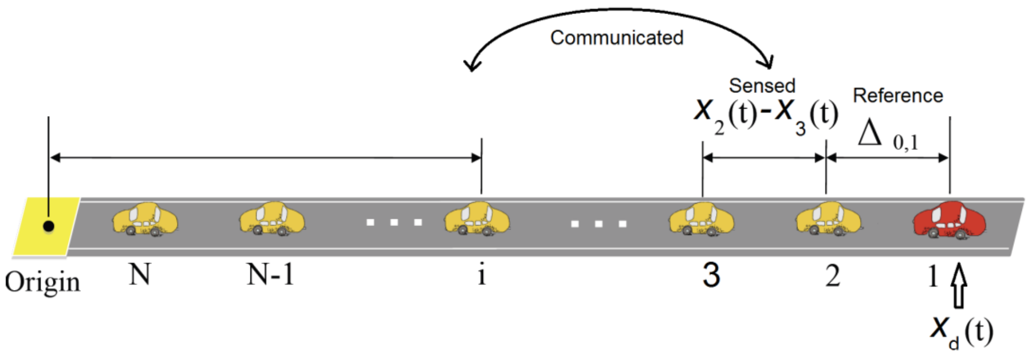
Semi-decentralized

Decentralized: Dirichlet problem on the graph



Goal: design a scheme that gives each node a vector of compact global information

Vehicle Platooning Problem



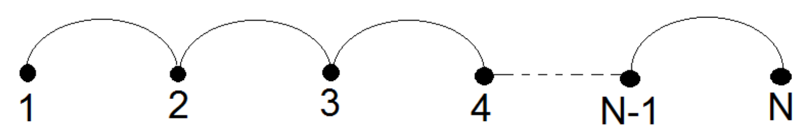
Vehicles have identical linear dynamics $\ddot{x}_i = u_i$.

Controller *i* applies linear feedback law based on information available to it:

$$u_i = \frac{1}{\deg(i)} \sum_{j \in N(i)} \left[-k\left(x_i - x_j - \Delta_{i,j}\right) - b\left(\dot{x}_i - \dot{x}_j\right)\right] + \delta(1,i)\left[-k\left(x_1 - x_{1,d}\right) - b\left(\dot{x}_1 - \dot{x}_{1,d}\right)\right].$$

Control objective: maintain reference inter-vehicle spacing under the constraint that individual control depends only on information available to that individual. The lead vehicle alone is provided the desired trajectory information $x_d(t)$

'Local' information patterns i.e. based only on sensed information from predecessor and follower



Vehicle Platooning Problem (cont.)

This problem has been studied extensively with this information pattern and the following limitations are known to occur for any 'local' information pattern.

- The least damped eigenvalue of the closed loop matrix scales as $O(1/N^2)$.
- String instability is inevitable- disturbances acting on an individual grow without bounds in the size of the platoon.
- It is not possible to achieve coherence or resemblance to a rigid lattice as the formation moves.

With technological advances, inter-vehicle communications are possible: More general information patterns feasible.

Bottom line:
Nearest neighbor type information patterns lead to inadequate control performance.

Choosing the Right Information Pattern

Information pattern	Communication load ~ |Edges|	Stability margin
Nearest neighbor type	O(N)	$O(1/N^2)$
Complete graph	$O(N^2)$	At most O(1/N)

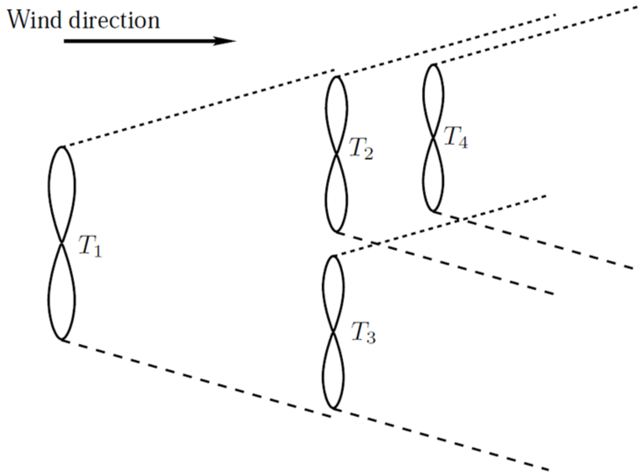
- Is there something in between? Does there exist a “family” of graphs such that one can get improved control performance while limiting the communication load?

- Our result (Menon-Baras 2012):

Expander families	O(N)	At most O(1/N)

Maximizing Power Production of a Wind Farm[1]

Horns Rev 1. Photographer Christian Steiness



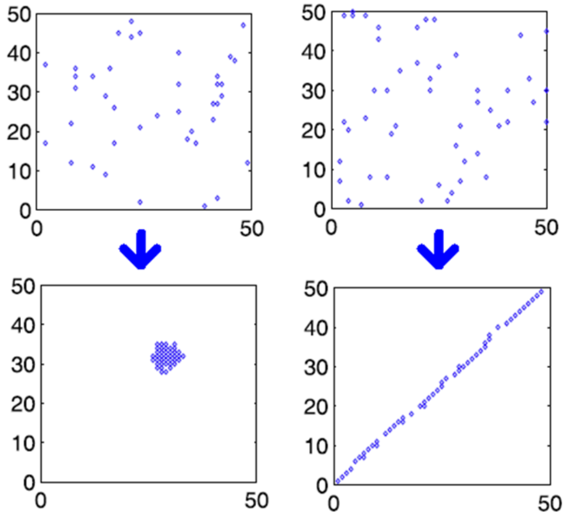
Schematic representation of a wind farm depicting individual turbine wake regions.

- No good models for aerodynamic interaction between different turbines.
- Need on-line decentralized optimization algorithms to maximize total power production.

Assign individual utility
$u_i(t) =$ power produced by turbine *i* at time *t*
such that maximizing $\sum_i u_i(t)$ leads to desirable behavior.

[1]. Marden et. al., "A model free approach to wind farm control using game theoretic methods", 2012, under review.

Formation Control of Robotic Swarms



Simulation results demonstrating rendezvous and gathering along a line[2]

- Deploy a robotic swarm in unknown environment: obstacles, targets etc. have to be discovered.[3]
- The swarm must form a prescribed geometric formation.
- Robots have limited sensing and communication capabilities.

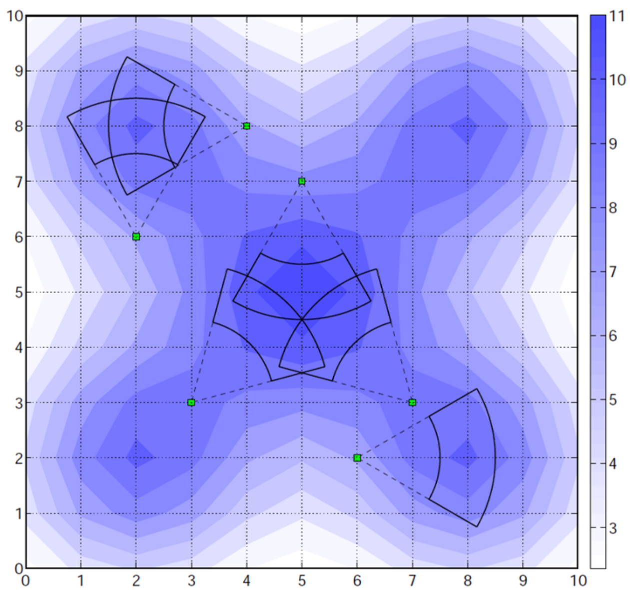
For rendezvous, design individual utility

$$u_i(s_i) = \frac{1}{|\{s_j \in S: \|s_i - s_j\| < r\}|} - \alpha\, dist_r(s_i, obstacle),$$

such that minimizing $\sum_i u_i(t)$ leads to desirable behavior.

[2] Xi, Tan and Baras, "Decentralized coordination of autonomous swarms using parallel Gibbs sampling", Automatica, 2010.
[3]. Baras et. al., "Decentralized Control of Autonomous Vehicles", Proc. of 42nd IEEE CDC, 2003.

Mobile Visual Sensor Network Deployment



Darker the shade of blue, more the interest in the site. Sectors represent sensor position and camera viewing angle.[4]

- We wish to monitor events in different sites of varying interest levels.
- All robots monitoring a small set of high interest sites is undesirable w.r.t. coverage.
- Cost associated with information processing.
- How to deploy so “effective coverage" is ensured at “reasonable cost".

Design individual utility

$$u_i(s,c) = \sum_{s' \in NB(s,c)} \frac{q(s')}{n(s')} - f_i(c),$$

such that maximizing $\sum_i u_i(t)$ leads to desirable behavior.

(here q(s)= interest in observing s, n(s) = number of agents observing s, NB(s,c) = subset of S observable from s when camera viewing angle= c, and $f_i(c)$ = processing cost when the camera viewing angle is c.)

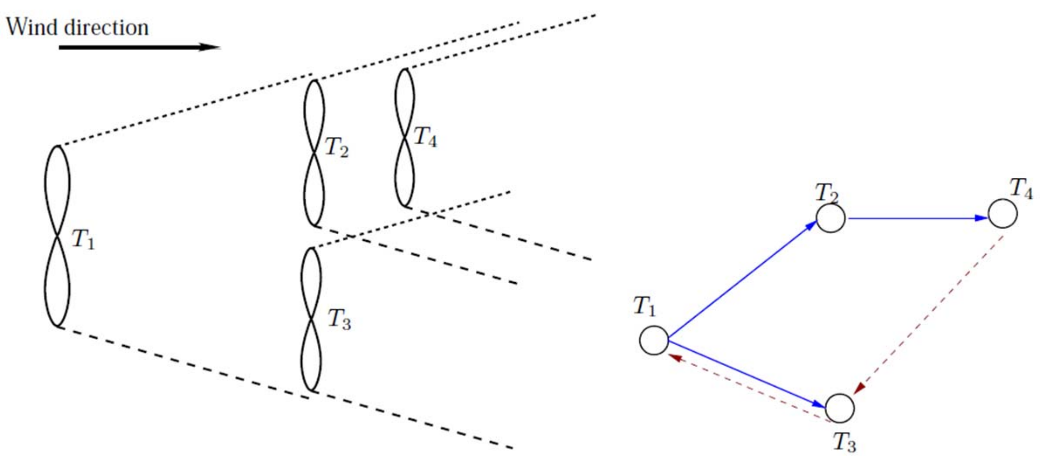
[4]. Zhu and Martinez, “Distributed coverage games for mobile visual sensor networks", to appear in SIAM J. Control and Optimization.

System Designer's Perspective

Like agents, system designer does not know exact functional form of the payoffs.
→ The system designer may have “coarse information" about which agents' action can affect which others.

Interaction graph models such coarse information: It's a directed graph where a link from i to j implies actions of agent i affect the payoff of agent j.

Communication graph models explicit inter agent communications: It's a directed graph where a link from i to j implies agent i can send information to agent j.

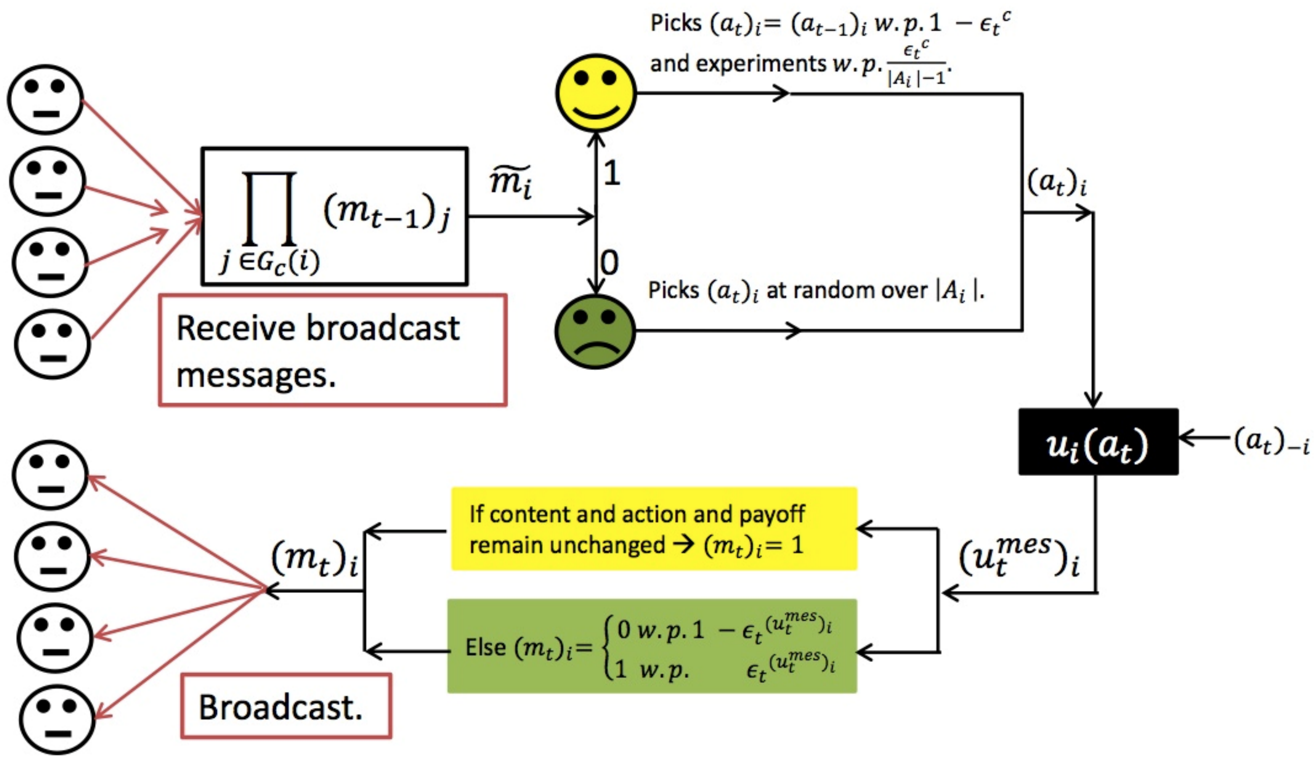


The wind farm example is considered in the figure:

- blue lines are edges in the interaction graph and,
- the red lines in the communication graph.

Distributed Simple Algorithm

Based on Marden et al[5], endow each agent with a state $x_i = (a_i, m_i); m_i \in \{0,1\}$ is the mood of agent i, with 1 corresponding to a "content" agent and 0 to a "discontent" one.



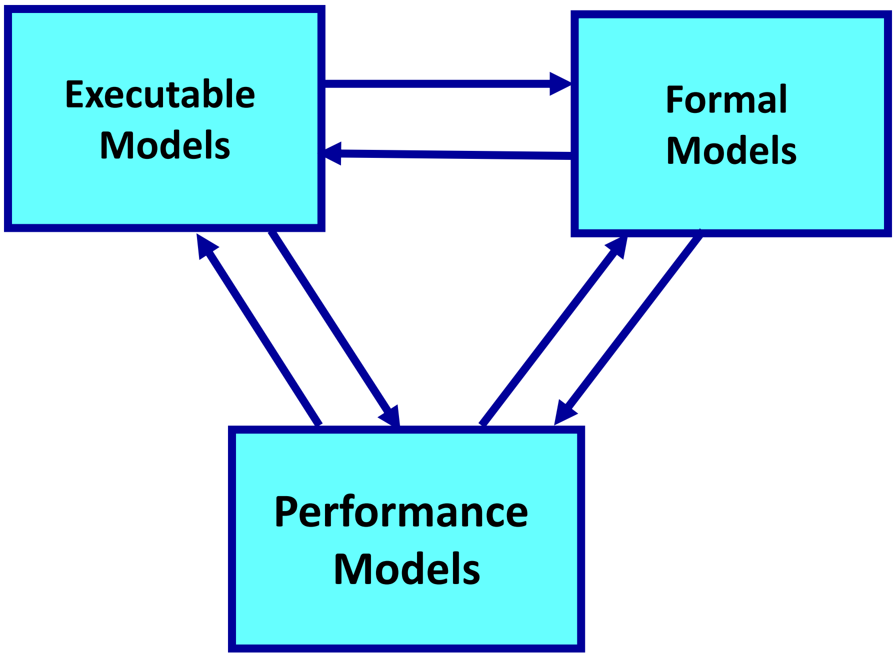
Differences from the algorithm in [5] :

- No explicit inter-agent communication is used in [5].
- Some assumptions on utilities are made in [5] to prove feasibility.
- is held constant for some in [5].

Exploration vs. exploitation?

[5]. Marden, Young and Pao, "Achieving Pareto optimality through distributed learning", 2011, Under review.

Component-based Networks and Composable Security



Studying compositionality is necessary!

Universally Composable Security of Network Protocols:

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

Key question addressed :

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

Universally Composable Security (UCS)

Results todate (Canetti, Lindell, …) :

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

Cars are Heavily Computerized: Electronics in Cars and Vulnerabilities

UW/UCSD Work:

Kosher et al., IEEE Symposium on Security and Privacy, '10

- Reach CAN bus through diagnostic port

Checkoway et. al., USENIX Security, '11

- Remote attacks
- Insert virus into computer system in mechanic shop
- Bluetooth
- Telematics unit
- CD player

Hardware-Software integrated Security:
Key Ideas and Challenges

- **Exploit characteristics (a.k.a. FINGERPRINTS) of physical layer**
  - Waveform, RF and hardware peculiarities
  - Embed artificial and stealthy ‘fingerprints’
- **Distribute assurance/trust function across software and hardware (increases difficulty to attacker significantly)**
- **Physically Unclonable Functions (PUFS)**
- **Trusted Platform Modules (TPM) and derivative technologies**
- **Secure Biometrics and Sensor Fingerprints**
- **Key Idea: Security Integration on the Portable Device**
- **Challenges:**

  (a) How to use informative time varying pieces of the biometric?

  (b) Develop anti-spoofing techniques using the sensor signature?

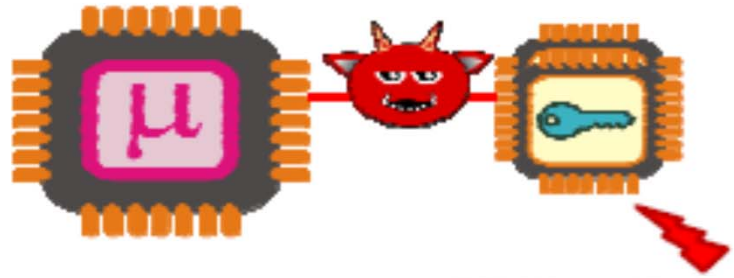
  (c) System integration and validation of the various fingerprints and physical layer techniques

  (d) Proof methods that security is improved – Information theoretic methods
- **Transformational concept: Authenticate the device to the network and then the user to the device** $\Rightarrow$ reduces attack risk (fewer times via the net)
- **“Push” security defense to the boundary**

New Ideas: Hardware-Based Security

Using an external TPM?

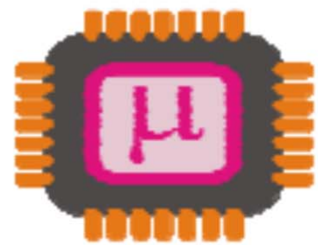
- Initial idea: Use an existing component-of-the-shelf like a TPM or SmartCard as root-of-trust
  - But…



Microcontroller TPM/SmartCard

- Cost, PCB area,
- Quality requirements, availability of suitable components (e.g. temperature range) and

Microcontroller with integrated HSM!



Solution

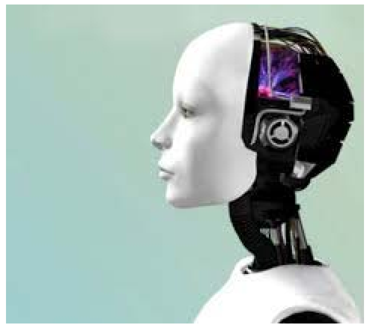
- Sensitivity to valid attacks
  - Reset attack (TPM is reset, manipulated µC continues operation)
  - Data exchange between µC and TPM not protected

Latest: Adaptive Component-Based MANET Security

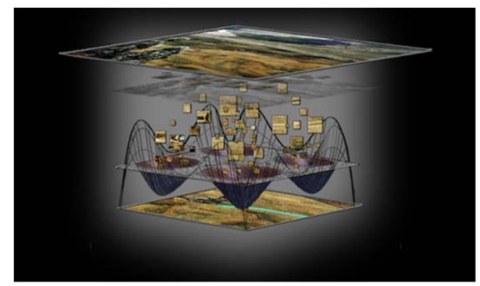
- **Components of MANET Routing Protocols**
- Neighborhood Discovery Component (NDC)
  - Status of nodes that are close to me (2-hop neighborhood)
- Selector of Topology Information to Disseminate Component (STIDC)
  - What information should be broadcasted in the network
- Topology Information Dissemination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

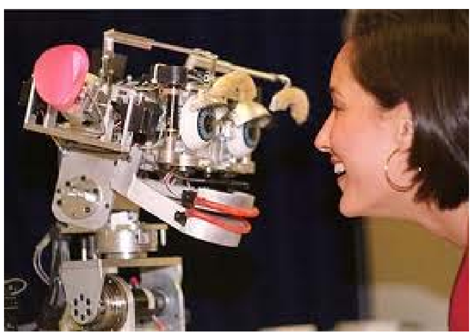
- **Cross-layer – MAC and Routing**
- **Detect attacks – mitigation strategies – adaptively change protocol component parameters and structure**
- **Distributed trust an integral part**
- **Treat it as a Feedback Control System!**
- **Part of the DARPA WND program**

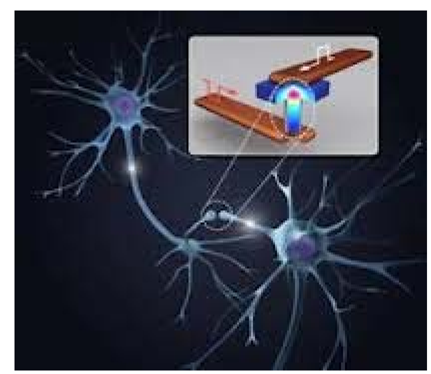
Perception-Cognition and Co-Robots



The pressure of P on C
The return of analog computation?
Non-von Neumann Architectures?
Physics of computation?
Beyond Turing?







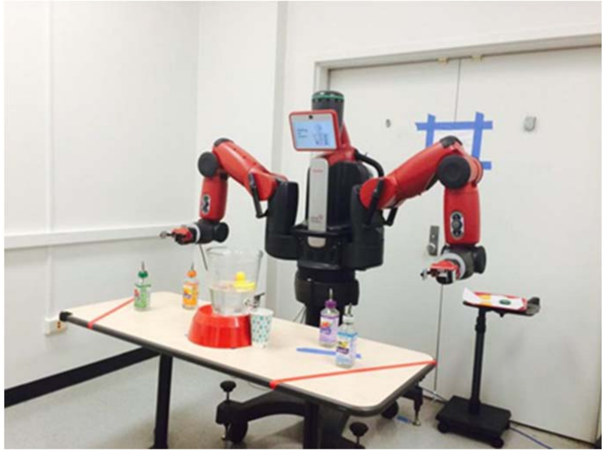
Cognition and knowledge generation from sensory perception – communicating with humans – collaboration
Not just obeying commands – the inverse problem

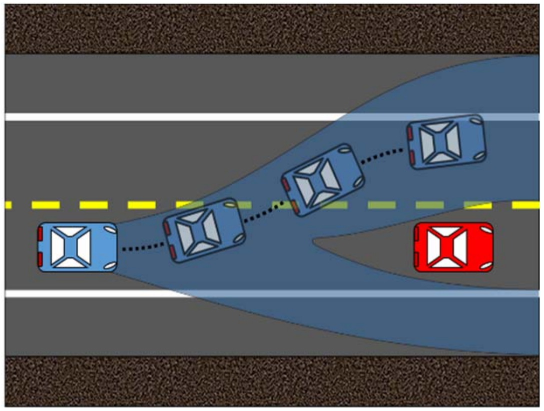
Learning Tasks, Changing Environments


- Teach through demonstrations
  - Easy training, hard to generalize to new constraints
- Program planning techniques
  - Generalize to constraints, manually design objectives

Temporal Logic, Robots, Human-Robot Teams

- Finite time logical constraints arise due to:
  - ✓Task description
  - ✓Decision making process
  - ✓Inherent inter–system interactions
  - ✓Other (a)causal dependencies



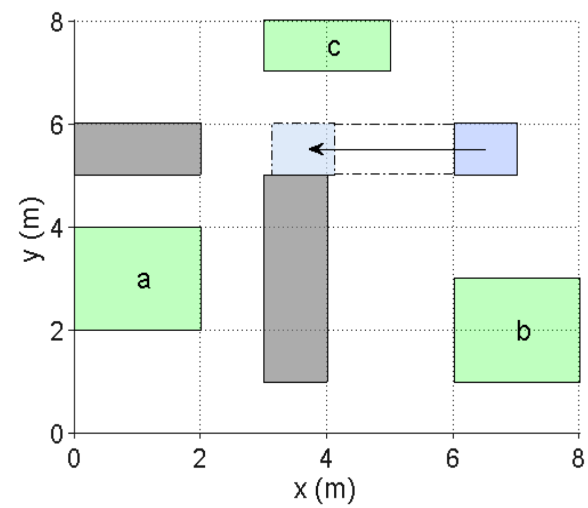


Constraints:

- Safety
- Human involvement
- Physical limitation

Path Planning with Temporal Specifications

- Q: How to generate trajectory/path based on temporal specifications such as ordering between actions, repetition of tasks, safety of the motions?
- State of the art: motion planning with temporal constraints without duration, such as Linear Temporal Logic (LTL).
- We have proposed a method for timed temporal logics, such as Metric Temporal Logic(MTL) for motion planning problem based on optimization[1].
- A timed-automata based method is proposed here.



Task: Always visiting area a,b,c and stay there for at least 2s. Always avoiding obstacles

1. Y. Zhou, D. Maity and J. S. Baras, “Optimal Mission Planner with Timed Temporal Logic Constraints", Proceedings of 2015 European Control Conference, Linz, Austria, pp. 759-764, July 15-17,2015.

Robotic Motion Planning Problem

Given:

A dynamic workspace (environment),

A **time constrained task (φ)**,

A cost function.

Objective:

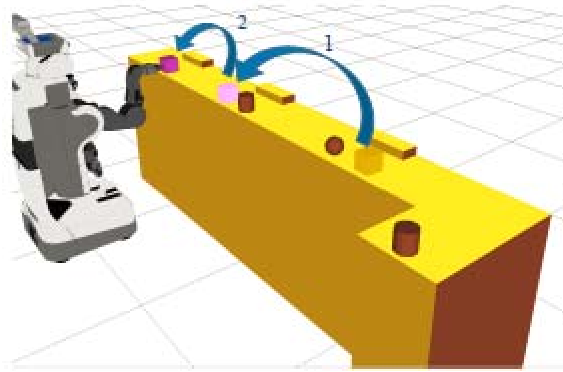
Find the suitable control input such that the robot completes the **given task** and **minimizes** the cost function.

Constraints:

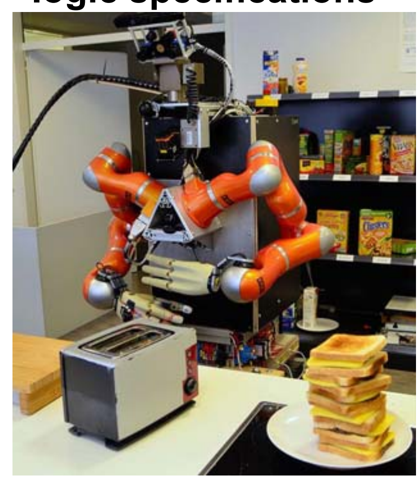
Avoiding collisions with all **static and moving obstacles** in the workspace.

A Robotic Motion Planning Example

- Manipulation task planning[2]
  - First, take food to customers and bring the empty plates back to the preparation area. Next, show the tip jar to the ones whom have already finished eating.
- The question is how fast to take the food to the customers, or what is a good time to ask for the tips from the customers. So timing aspects are important.
- Many robotic tasks require finite time constraints.
- LTL is unable to address finite time constraints and hence we need MITL.

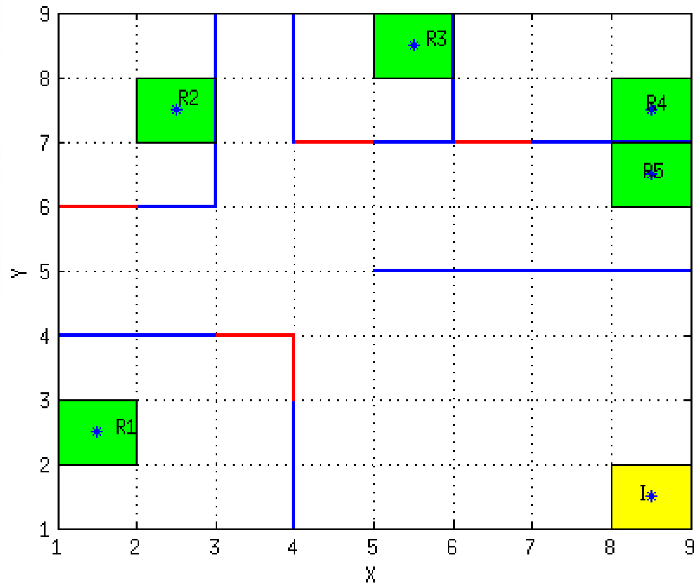


Towards manipulation planning with temporal logic specifications[2]

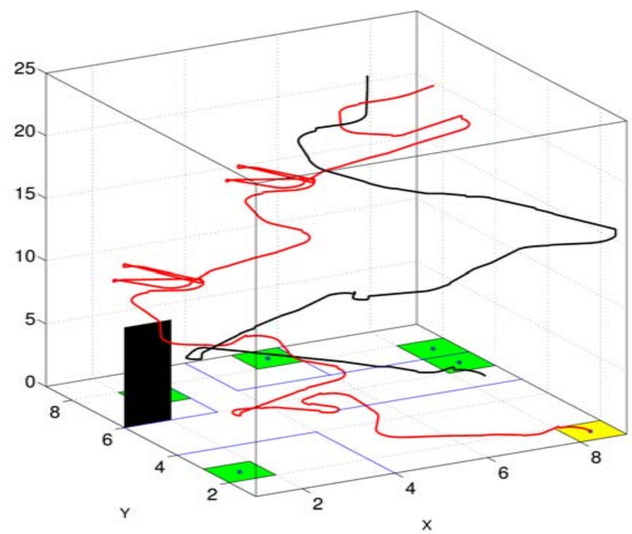


2. K. He, M. Lahijanian, L. E. Kavraki, and M. Y. Vardi, "Towards manipulation planning with temporal logic specifications," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, 2015,

Collaborative Planning and Re-planning with Finite-Time Task Constraints



Starting from I, visit R3 within the time Interval I1, visit R4 within time interval I2; before visiting R3 or R4, robot must Visit R2 . Eventually visit R1 and R5, and Complete the whole task in least time.



Multiple fires, diverse conditions
Need to assess and plan/allocate

Resulting Continuous path In 3D space and time

Metric Interval Temporal Logic (MITL) and Time Constrained Task

Definition: The syntax of MITL[3] formulas are defined according to the following grammar rules:

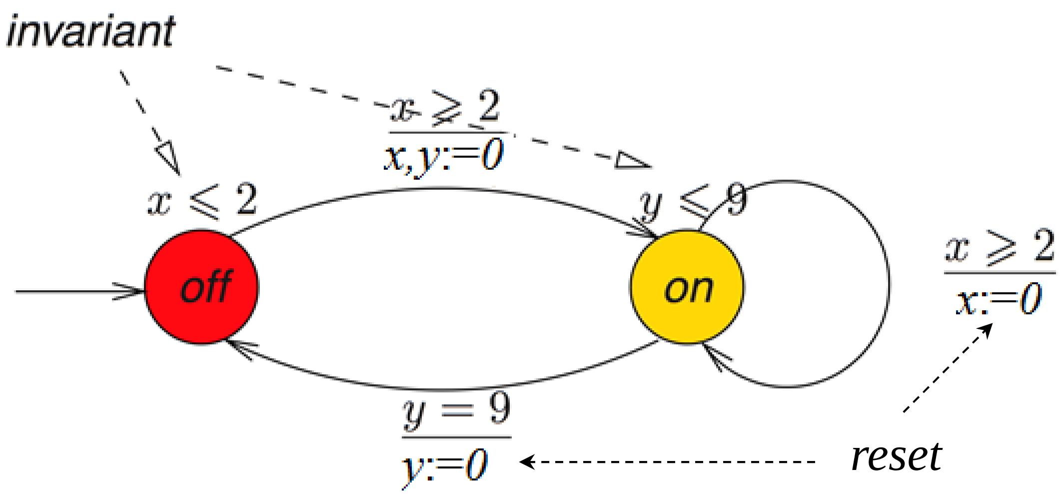
$$\phi ::= \top \mid \pi \mid \neg\phi \mid \phi \vee \phi \mid \phi U_I \phi$$

where $I \subseteq [0, \infty]$ is an interval with end points in $\mathbb{N} \cup \{\infty\}$ and the end points have to be distinct. $\pi \in \Pi$ is the atomic proposition.

More sophisticated MITL operators can be derived using the grammar defined above; such as: always in $I_1 \equiv \perp U_{I_1}$, eventually always $\Diamond_{I_1} \Box_{I_2}$ etc.

3. R. Alur, T. Feder, and T. A. Henzinger, “The benefits of relaxing punctuality,” Journal of the ACM (JACM), vol. 43, no. 1, pp. 116–146, 1996.

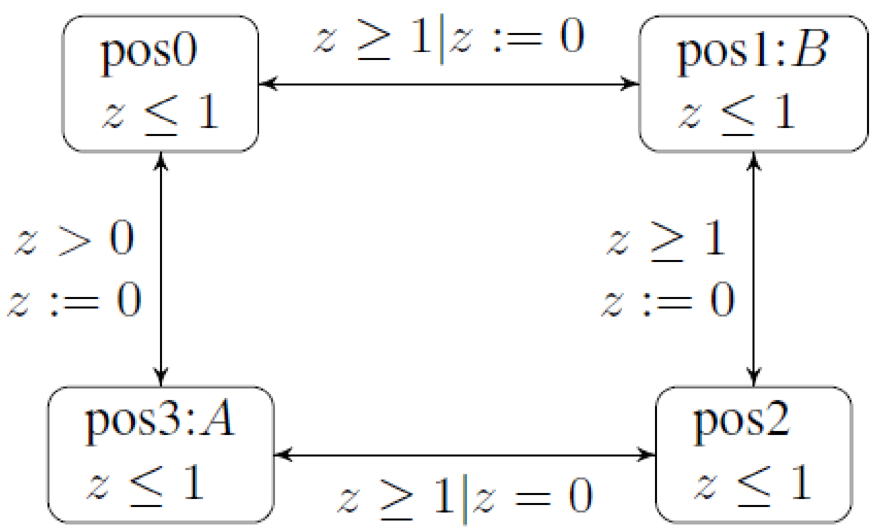
Timed Automata

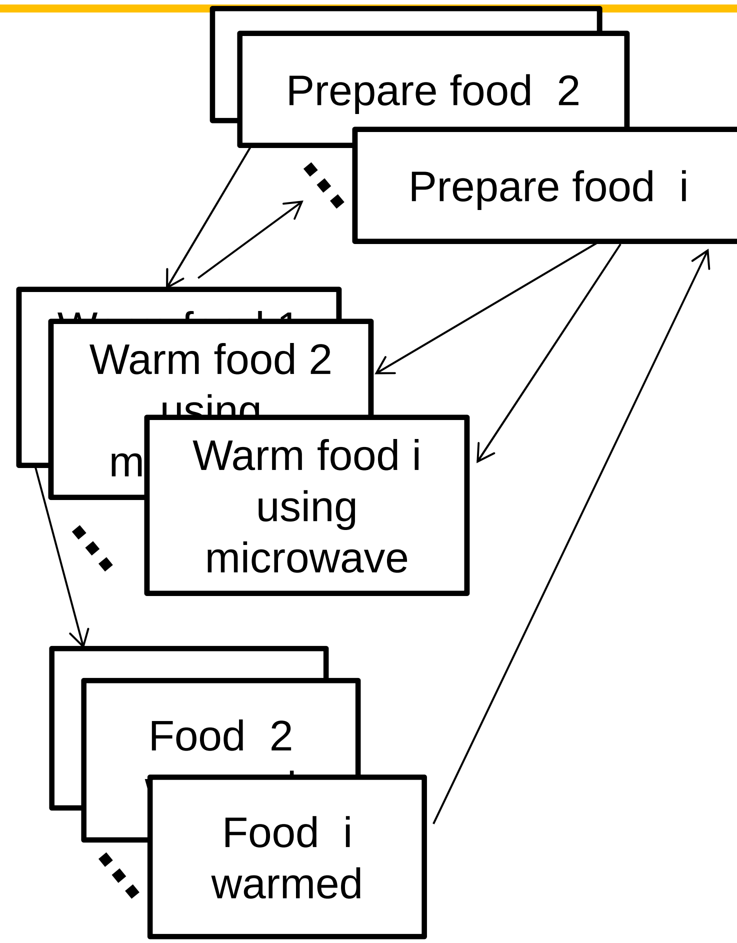


- Clocks can be **reset** when taking an edge
- Assumption: all clocks are **zero** when entering the initial location initially
- A location invariant specifies the **amount of time that may be spent in a location**

Remark: An MITL formula can equivalently represented by a Timed Automaton

Timed Automata and Robotic Action





Robotic motion including manipulation task can be captured in timed automata

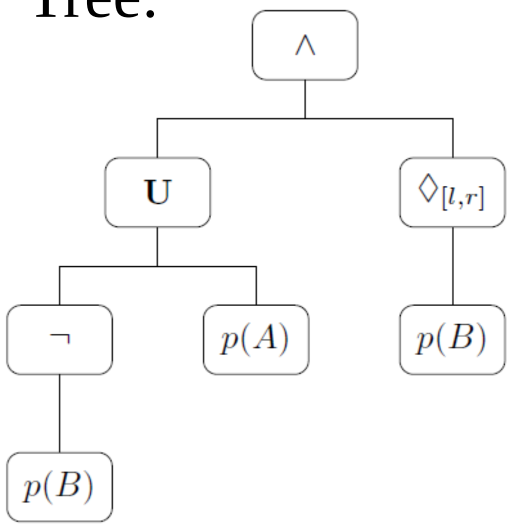
Timed Automata Based Planning Example

- Convert temporal logic formula to a timed automaton
  - Represent temporal logics as a tree structure
  - Every operator in the tree can be represented as a timed automaton with input and output
  - The product of them results into a timed automaton again

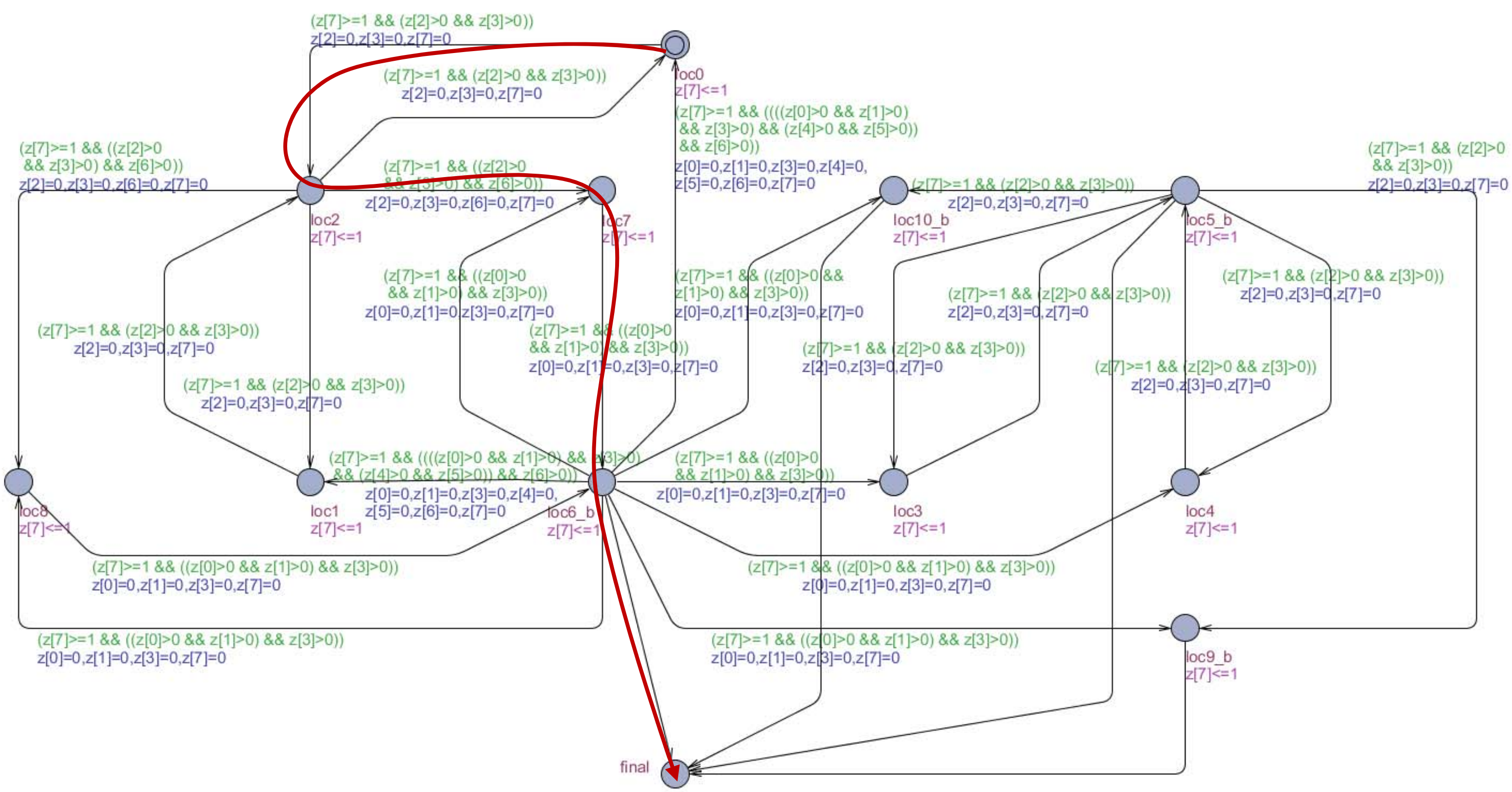
- Specs:
  Visit A before B and visit B within [l,r]
- MTL:

$$\phi = (\neg B \mathbf{U} A) \wedge (\Diamond_{[l,r]} B)$$

- Tree:



Path on the Automaton

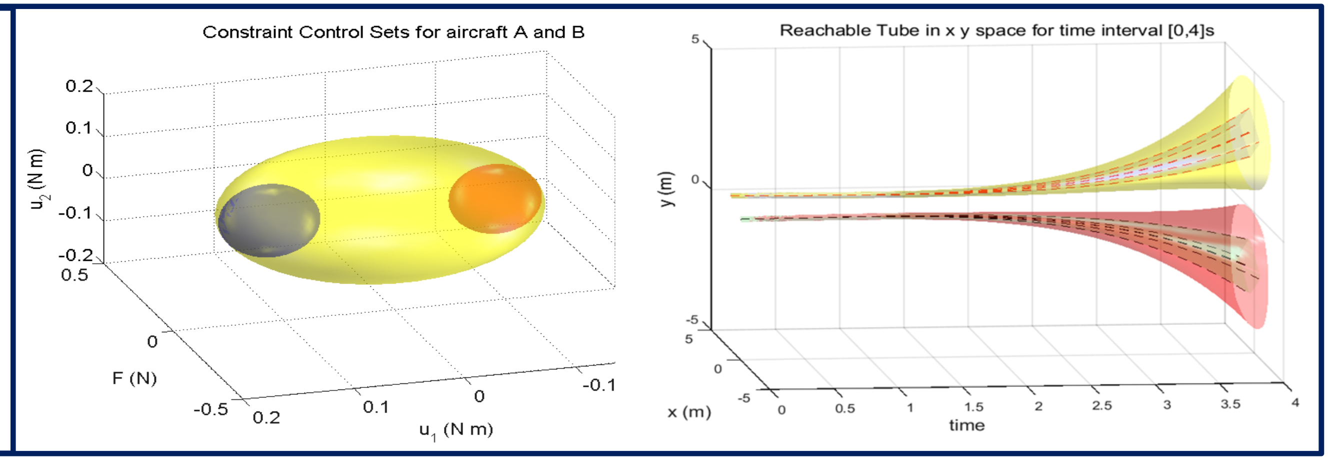


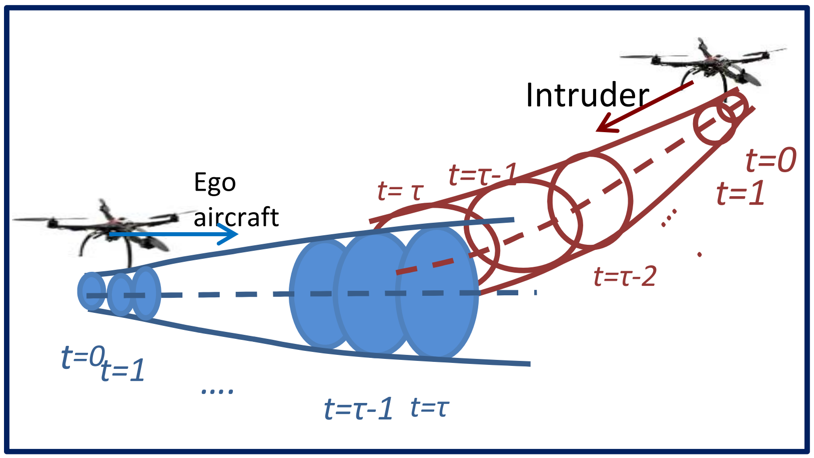
Generated timed automata and the fastest path using UPPAAL[4]

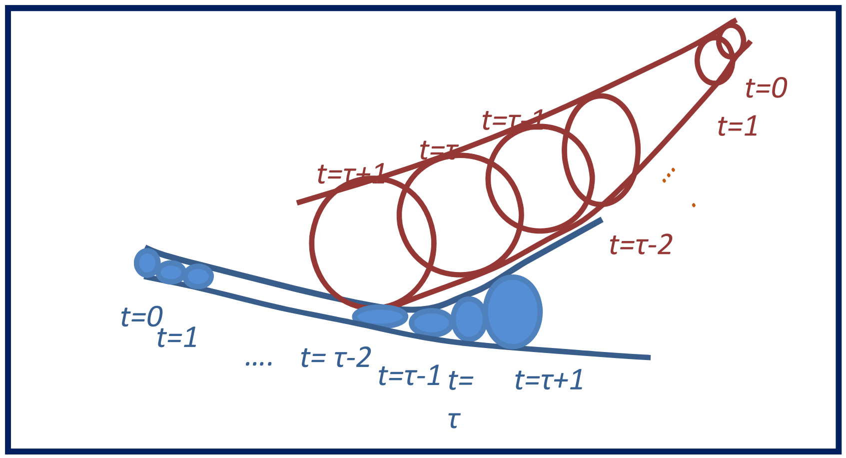
4. G. Behrmann, A. David, K. G. Larsen, J. Hakansson, P. Petterson, W. Yi, and M. Hendriks, “UPPAAL 4.0,” in *Third International Conference on Quantitative Evaluation of Systems, 2006. QEST 2006.*, 2006, pp. 125–126.

Safety Guarantees via Reachability Analysis

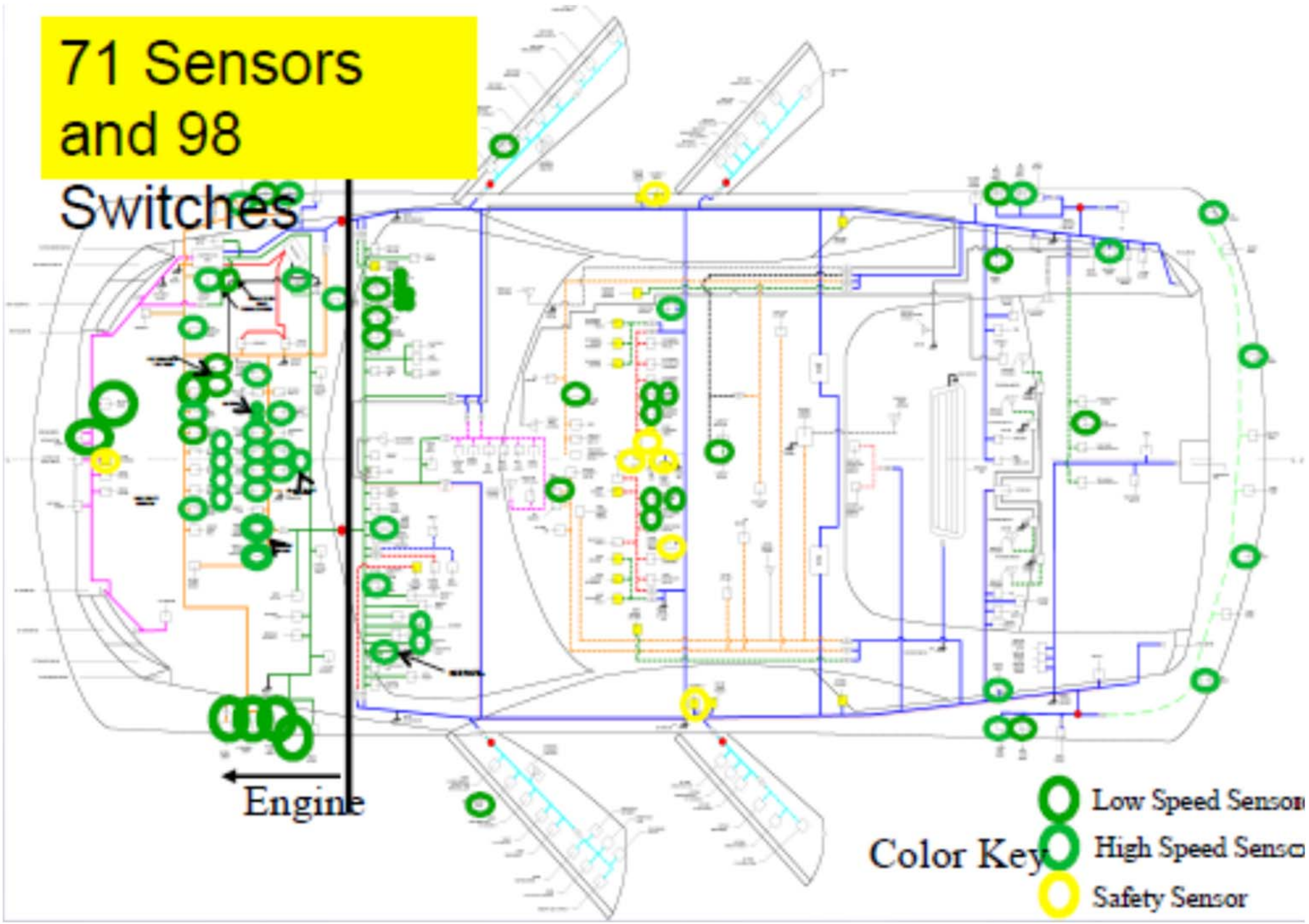
$$\dot{\xi} = v$$
$$\dot{v} = -g\mathbf{e_3} + \frac{F}{m}R\mathbf{e_3}$$
$$\dot{R} = R\hat{\Omega}$$
$$\dot{\Omega} = J^{-1}(-\Omega \times J\Omega + M)$$



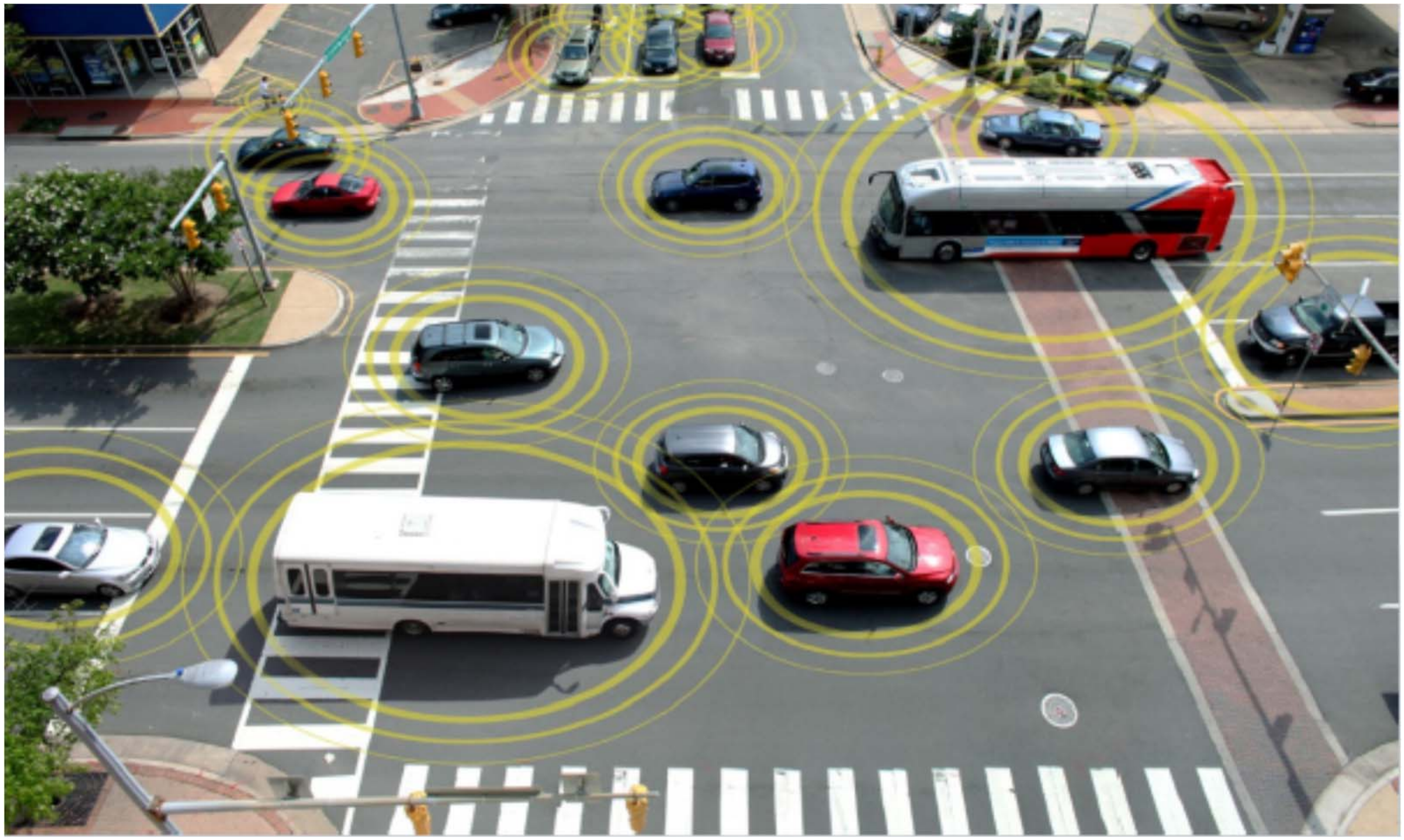




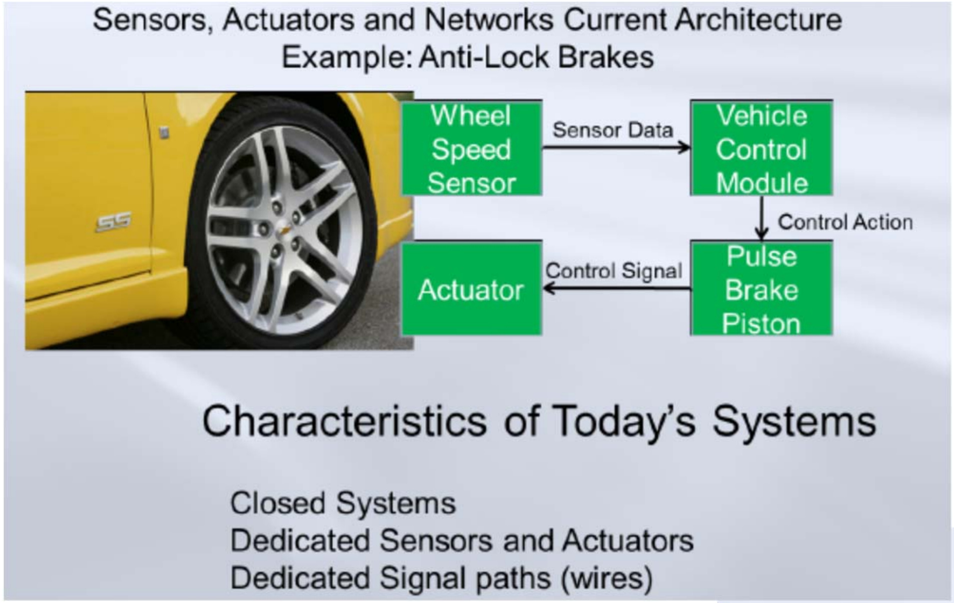
Connected Cars: Internal



Connected Cars: External

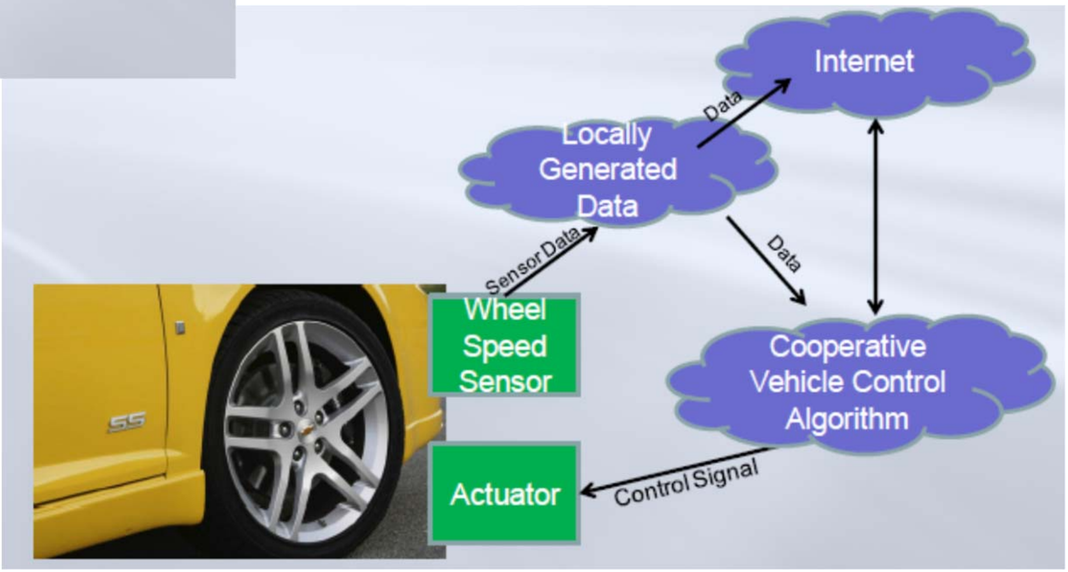


Connected Cars:
Cognitive and Collaborative

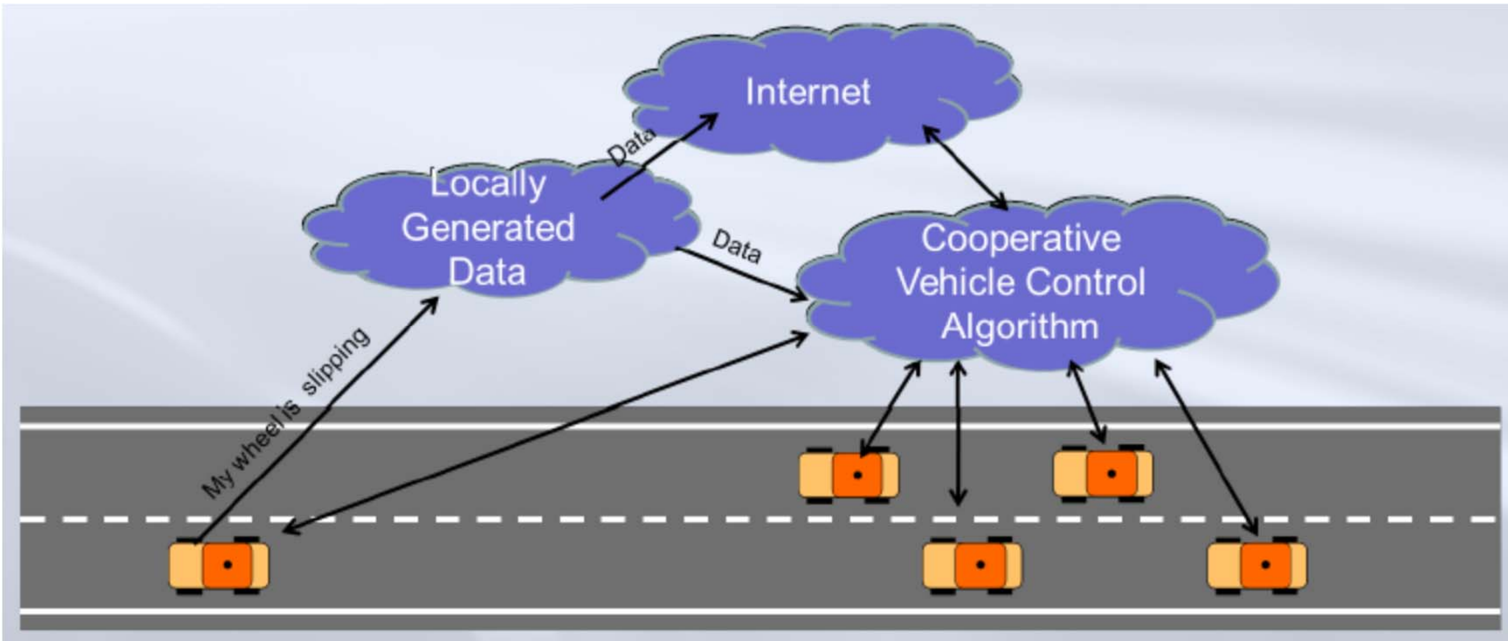


Current

Future



Connected Cars:
Cognitive and Collaborative



Key Challenge: **Humans**

We are developing novel frameworks to include humans in this collaborative networked CPS environment

SYSTEMS BIOLOGY – THE ULTIMATE SYSTEMS CHALLENGE

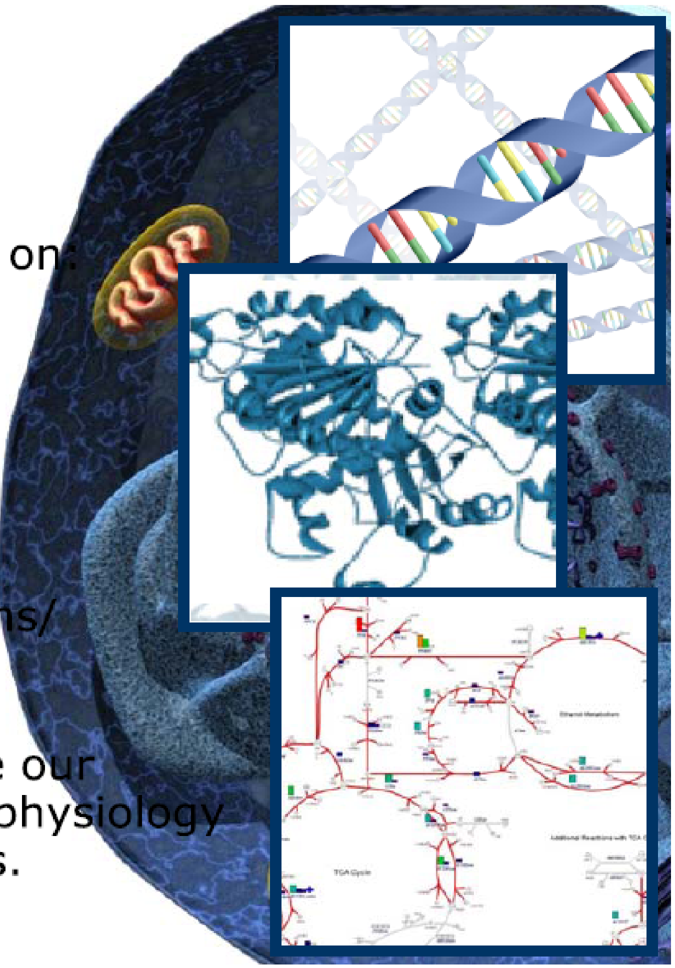
Systems Biology

Goal of systems biology:

To integrate information on:

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

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



SYSTEMS BIOLOGY

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

Requires

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

A Systems Biology Model for Alzheimer's Disease

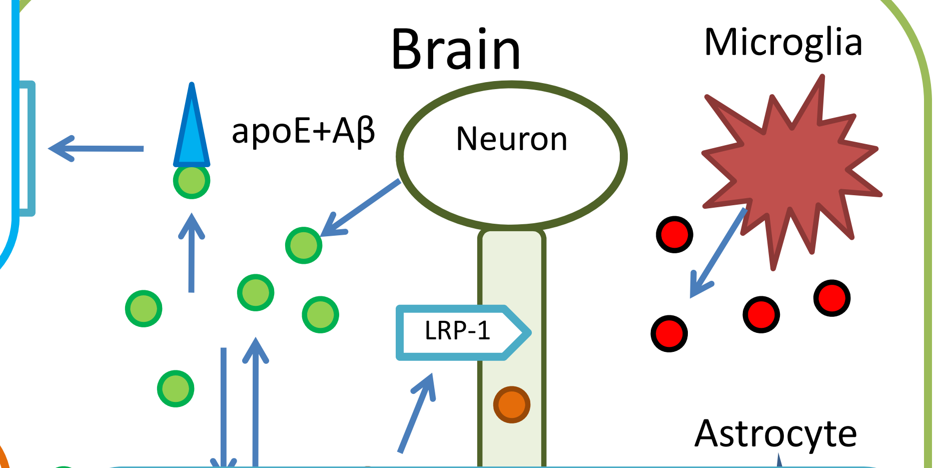
- **Study the roles of cholesterol, LRP, ApoE and inflammation in disease pathogenesis**
- Studied effect of simvastatin treatment on LRP and ApoE levels, in addition to changes in Aβ
- Developed a mathematical model that integrates energy & lipid metabolism, the inflammatory response & expression of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

Forefront of AD research:

Interplay between lipid metabolism & inflammation

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

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



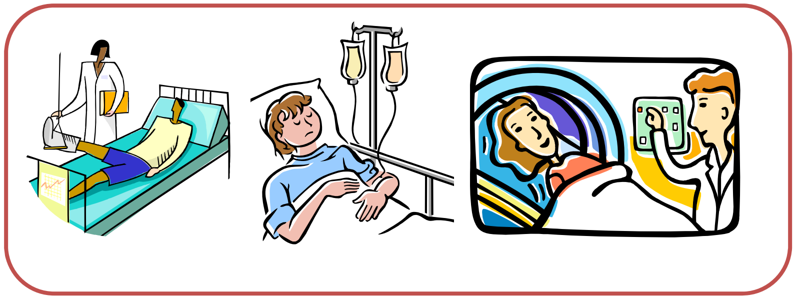
ion

- Synapse formation
- Co-localizes w/ Aβ plaques

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

Aβ Cholesterol ApoE

Model-Based Systems Engineering for ITU Management

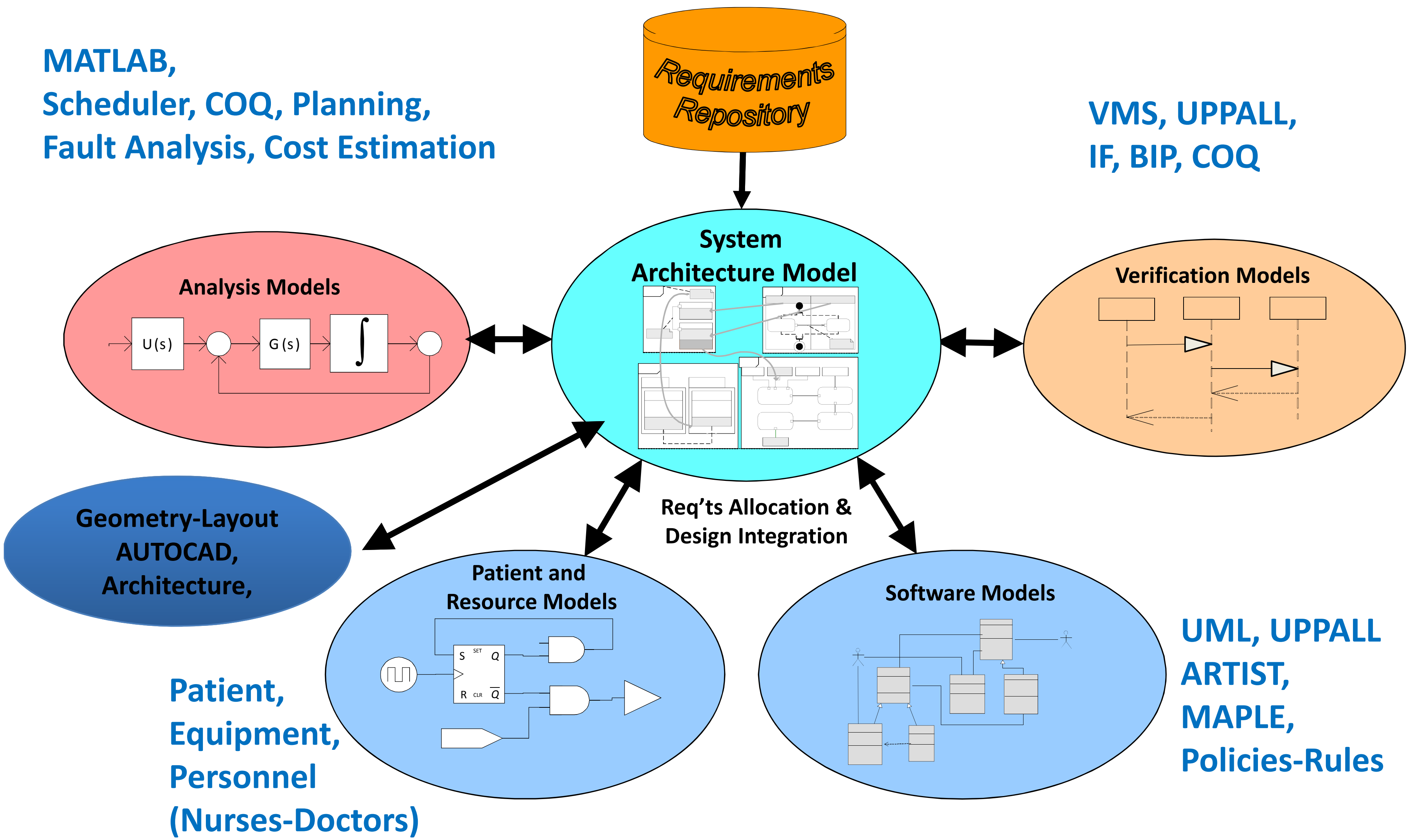


Healthcare operations

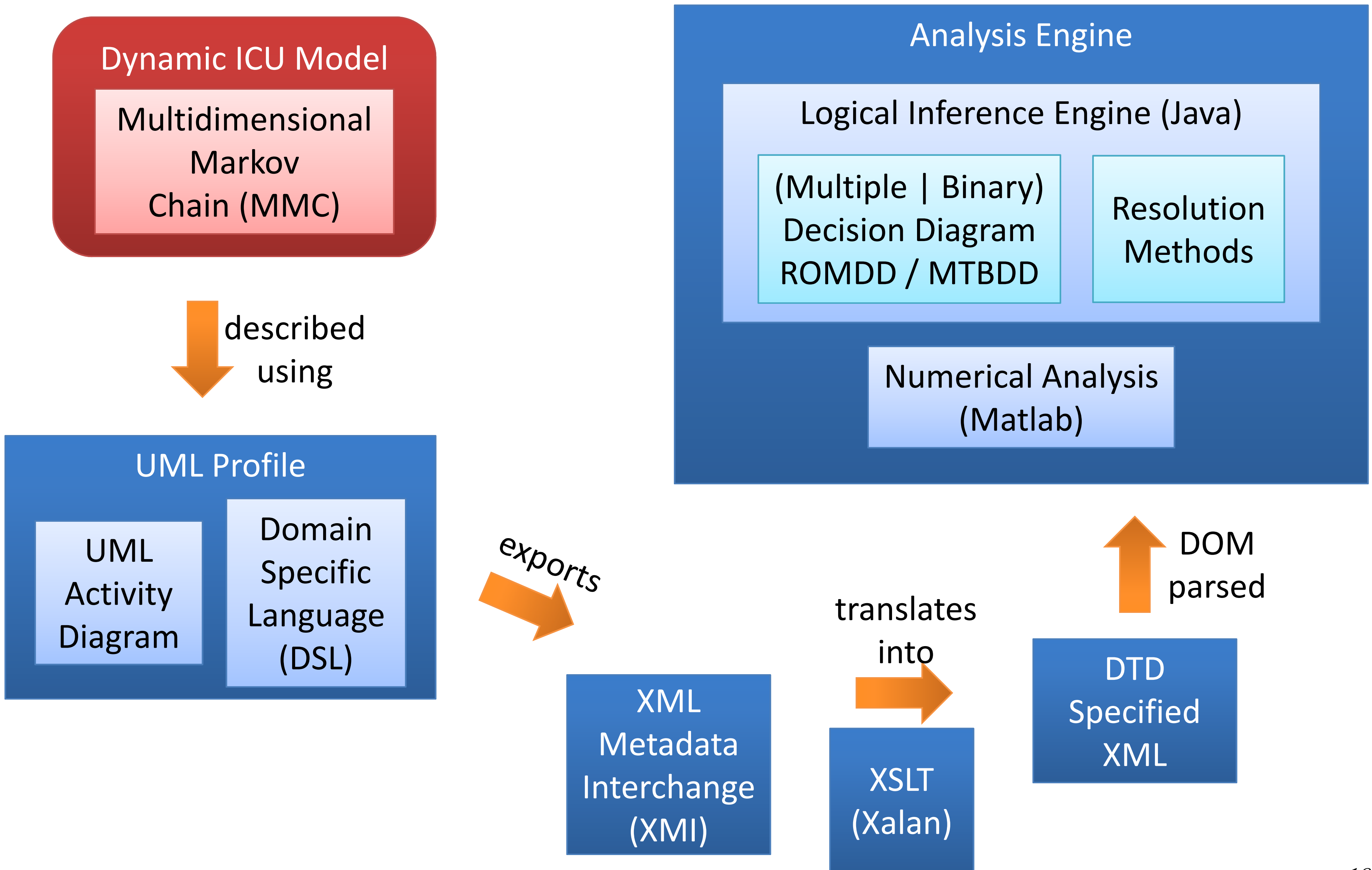
Monitor performance,
generate ideas,
implement changes

Build models,
analyze operations,
predict changes

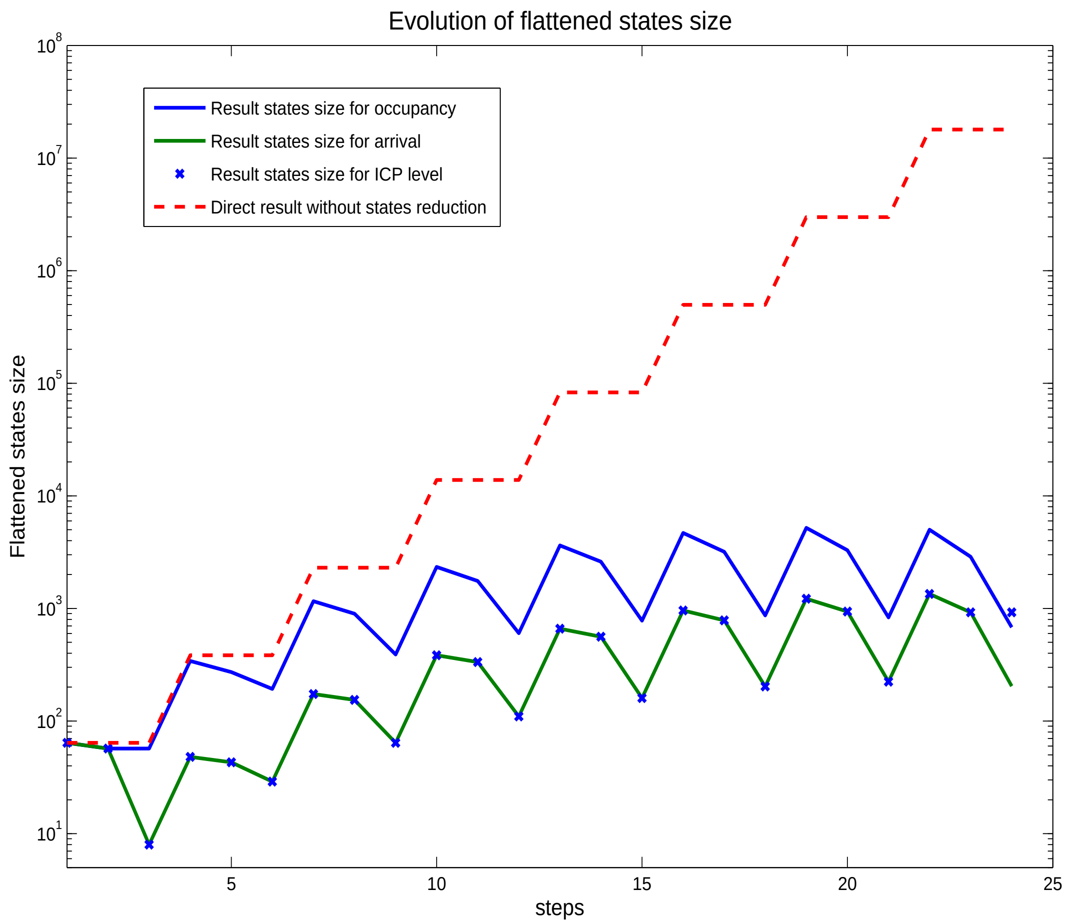
Using *System Architecture Model* as a MODEL Integration Framework



Implementation

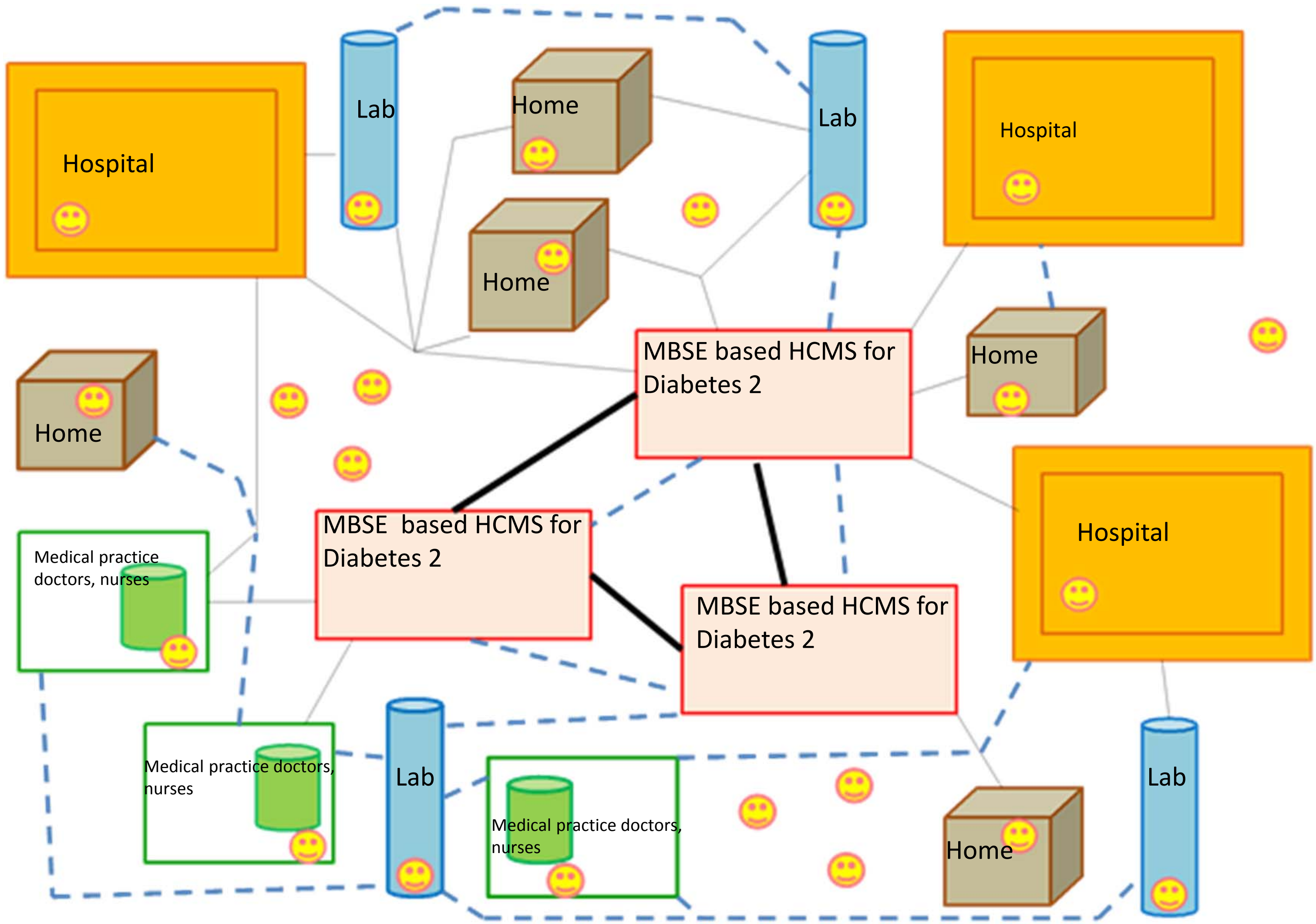


State Reduction Achieved



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

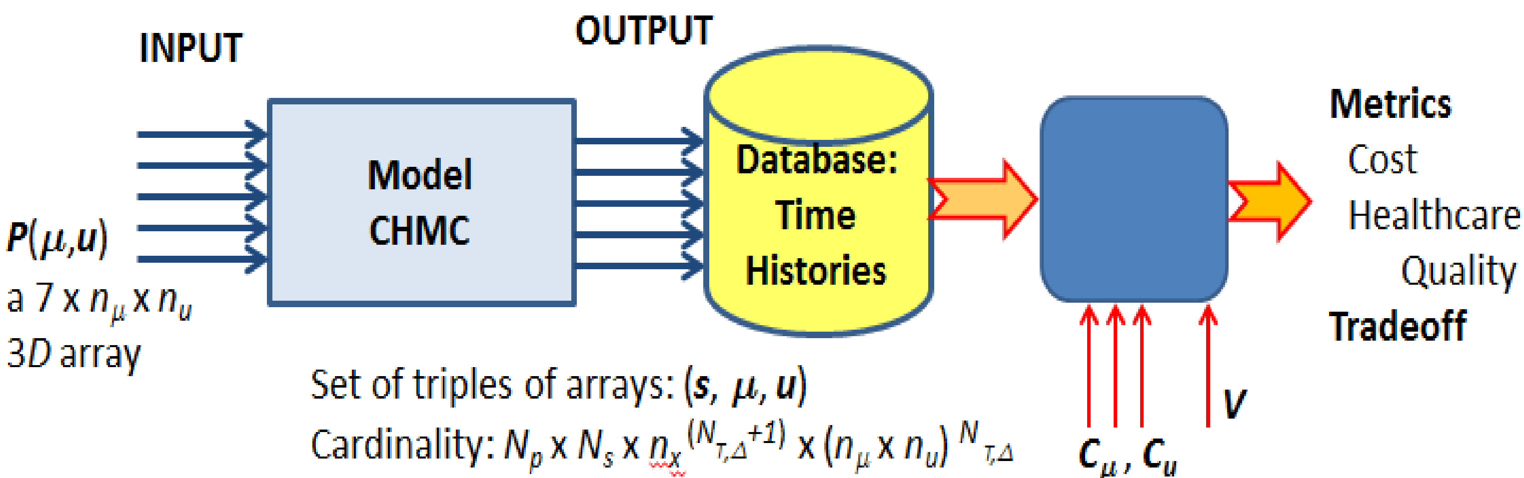
MBSE based HCMS for Diabetes II and its functional connectivity



Reasoning Engine through MBSE Framework

Health Quality Metric combines patient health risk behavior and patient time history counting

$$J_{hc}(i,m_i) = V_1^i * O_1^i(m_i) + V_2^i * O_2^i(m_i) + V_3^i * O_3^i(m_i)$$



Set of triples of arrays: ($\boldsymbol{s}$, $\boldsymbol{\mu}$, $\boldsymbol{u}$)

Cardinality: $N_p \times N_s \times n_x^{(N_{T,\Delta}+1)} \times (n_\mu \times n_u)^{N_{T,\Delta}}$

Each triple size: $3 \times N_{T,\Delta} + 1$

Set of triples $\boldsymbol{O}$

Cardinality: $N_p \times N_s \times n_x^{(N_{T,\Delta}+1)} \times (n_\mu \times n_u)^{N_{T,\Delta}}$

Reasoning Engine through MBSE Tradeoff Analysis

- Developed Reasoning Engine of the HCMS, based on these disease models and metrics of health state time history: focus in these evaluations are systematic Tradeoffs (Pareto points)
- Three computational methods developed and used
- First method, **Evaluation by Monte Carlo Simulation (EMCS),** uses the model in an exhaustive generation of all possible sample paths (time histories) for any number of patients
- The second method **Fully Observable Multi- Criteria Optimization (FOMCO)** and the third **Partially Observable Multi-Criteria Optimization (POMCO),** employ multi-criteria optimization to directly compute the Pareto points and associated selection of tests and interventions

  Both use Dynamic Programming for computations

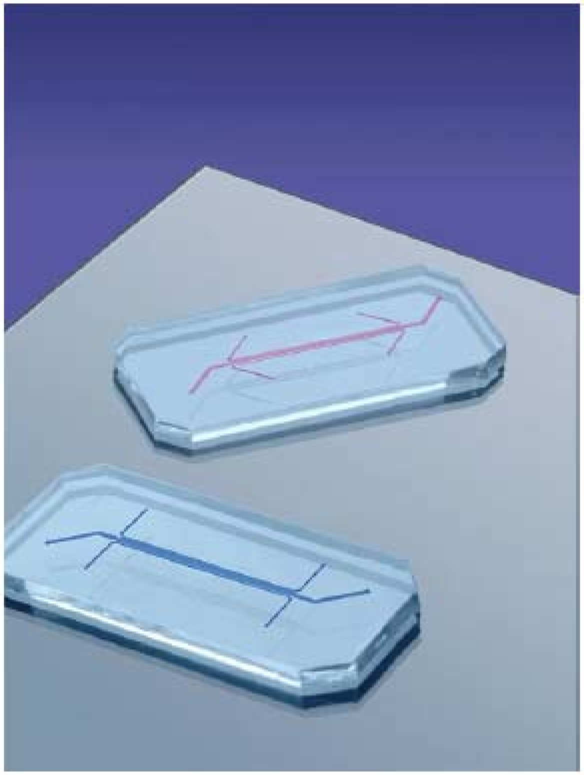
Reasoning Engine: Decision Making & Analytics Capabilities

Can provide answers to many practical questions, queries, problems, from health care management perspective

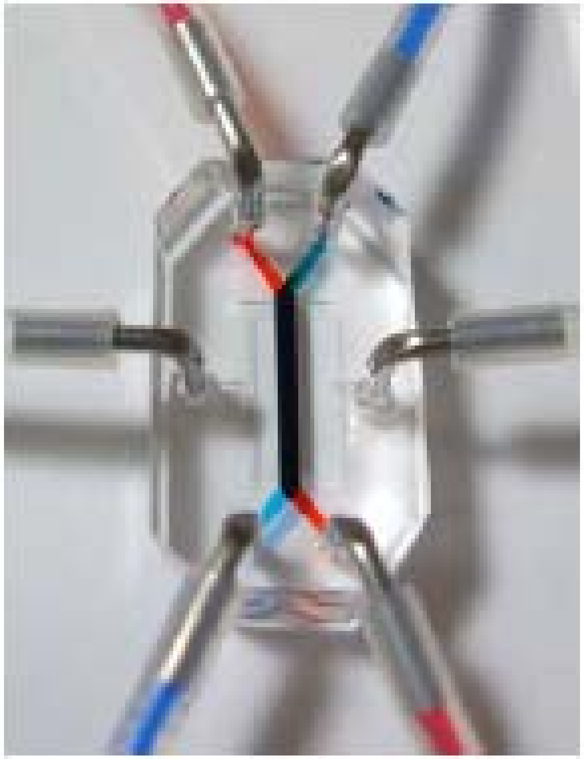
- Evaluate patient risk behavior impact on health care quality
- Evaluate "best" health care achievable
- Can learn from new data, treatment results, improve models
- Evaluate "value" of new proposed tests and interventions
- Provide aggregate statistics for insurance policies calibration
- Find best tests and interventions for patient type, disease state
- Evaluate effects of incentives and rewards for health "maintenance"
- Evaluate sequences of tests and treatments for reversing disease

Revolutionizing Drug Manufacturing: Organ-on-a Chip -- Biochips

Wyss-Lung on a chip -- 2010



Wyss-Gut on a chip -- 2012



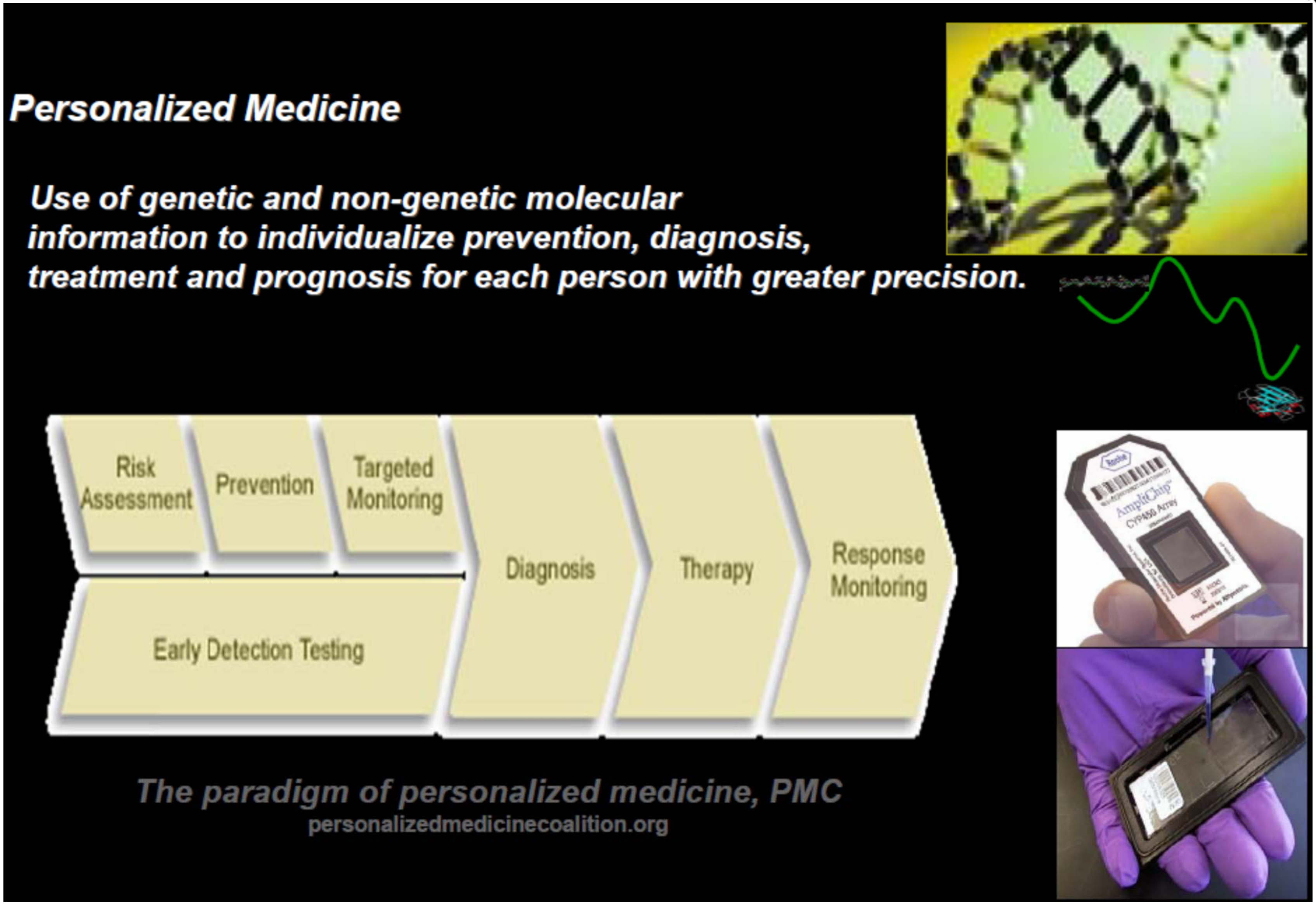
The Institute for Systems Research

REVOLUTIONIZING DRUG TESTING

University of Maryland 1856

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

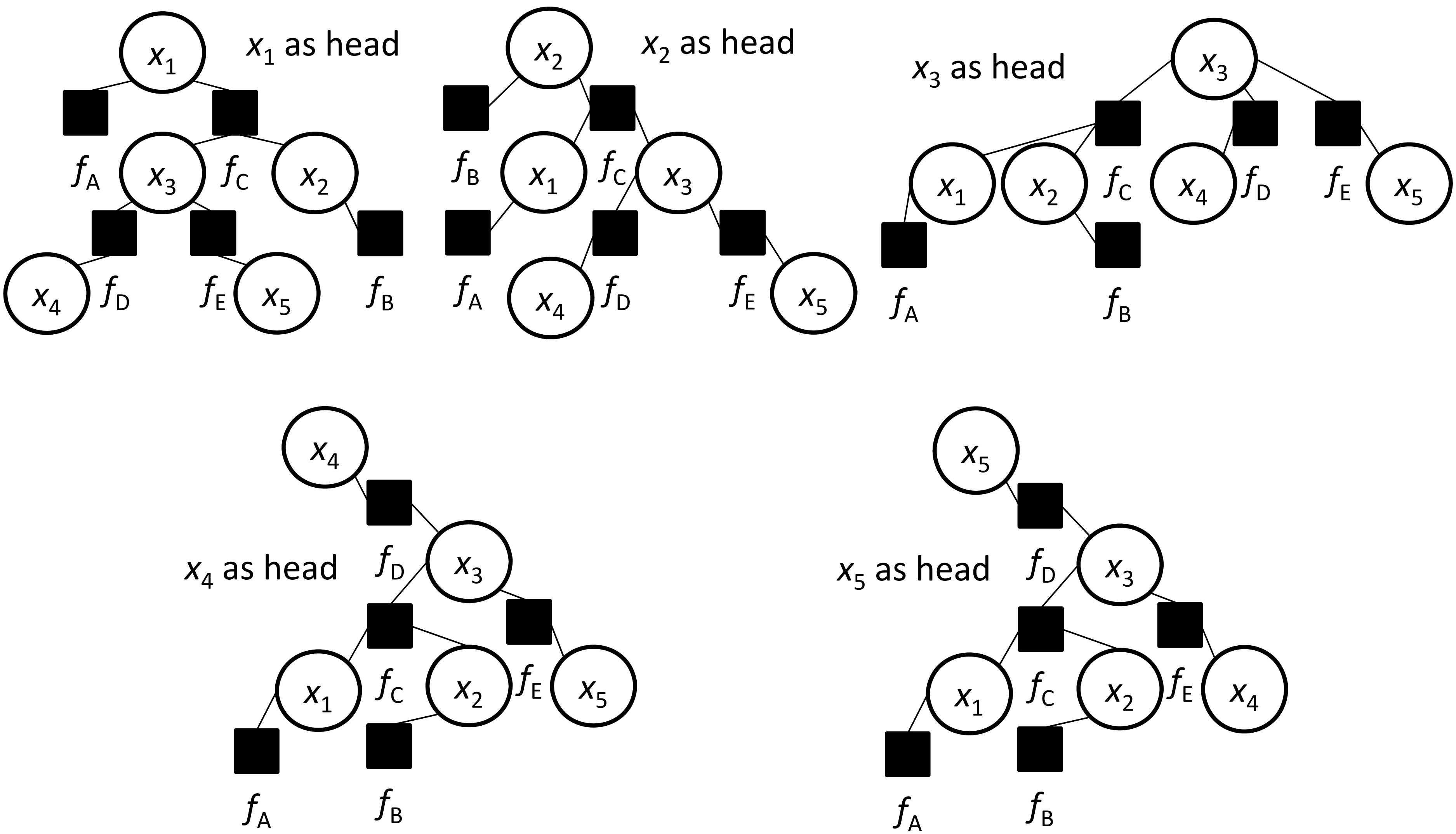
Personalized Medicine



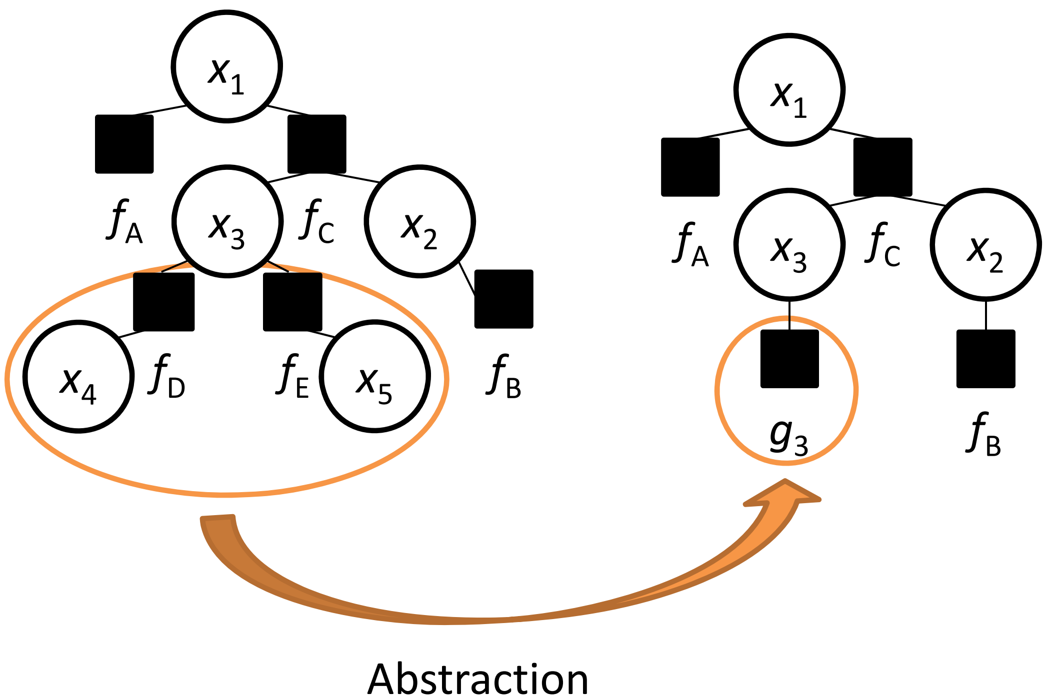
Design Space Exploration: Queries and Complexity

- Large, complex systems have many tunable parameters
- To perform **tradeoff analysis at system level**, a simplified view of the underlying components must be available
- **Challenge**: create an abstract, tractable representation of underlying components.
- **Hypothesis**: Although components are not perfectly decoupled, structure provides useful information for parametric decomposition
- The query itself influences the shape of the resulting graph
- A query that is not local can create links between non-local variables
- The resulting graph and *analysis complexity is dependent on the query*

Query Induced Hierarchies



Abstraction as Summation/ Aggregation



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

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

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

Summation remains local!

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

Factor Join Trees in Systems Design Space Exploration and Decomposition

- **Results/Contributions:**
- Starting from an undirected graph representation of the system developed a “divide and conquer” methodology and tool to choose subsets of nodes that completely separate the graph
- Separation produces interfaces -- leads to system decomposition in trees; “width” of a decomposition the size of the largest system component while “treewidth” is the minimum possible width over all tree decompositions
- Decomposition complexity is exponential in treewidth and linear in problem size
- By using novel organization of tradeoff queries for design space exploration, the method leads to chordal systems – decomposition performed in **linear time**

Tradeoff Queries

- The query itself influences the shape of the resulting graph
- A query that is not local can create links between non-local variables
- The resulting graph and *analysis complexity is dependent on the query*

Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph

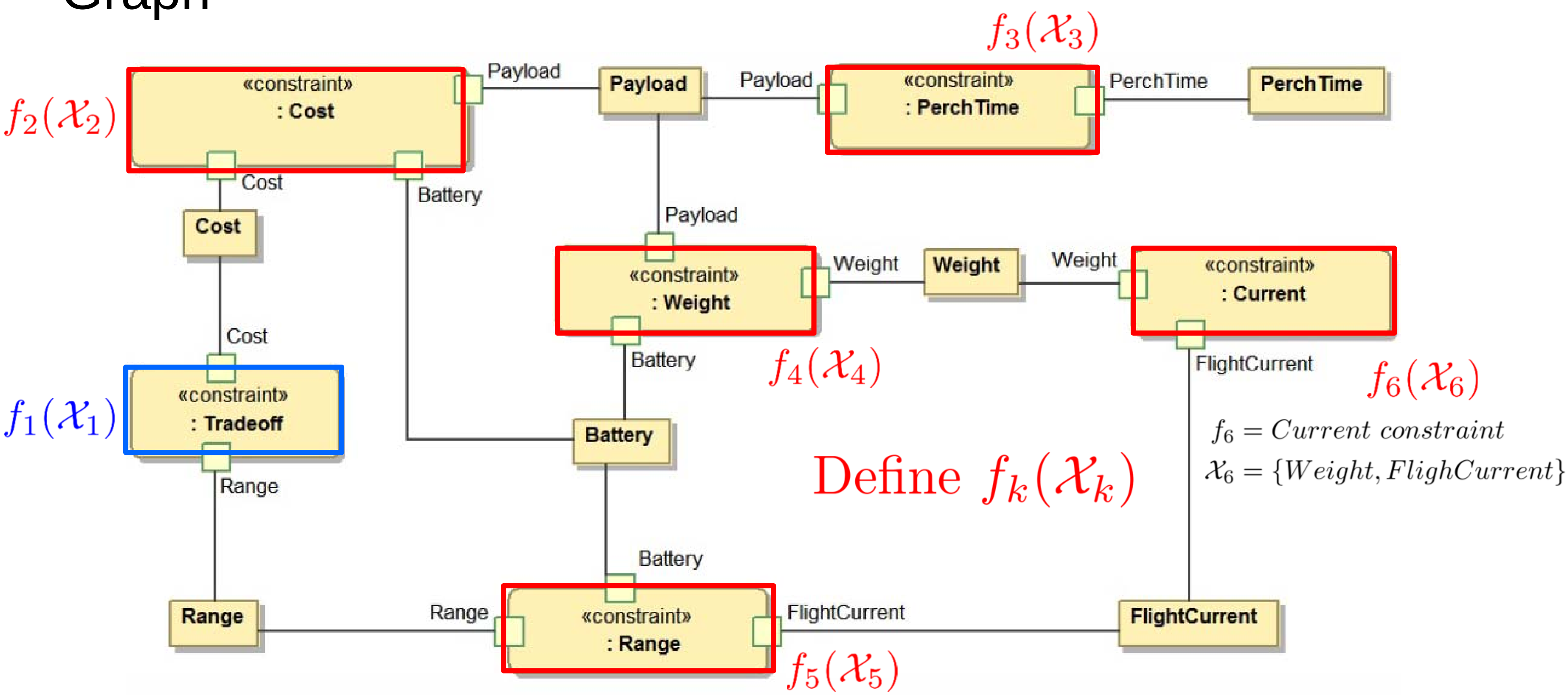


Figure: SysML Parametric Diagram (Factor Graph)

Example: Quadrotor

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

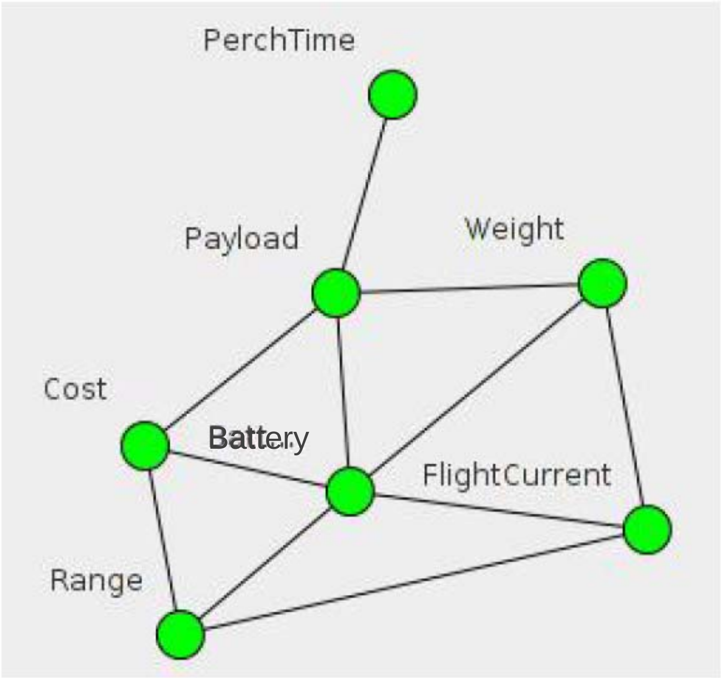


Figure: Functional Dependence Graph (step 1)

Example: Quadrotor

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

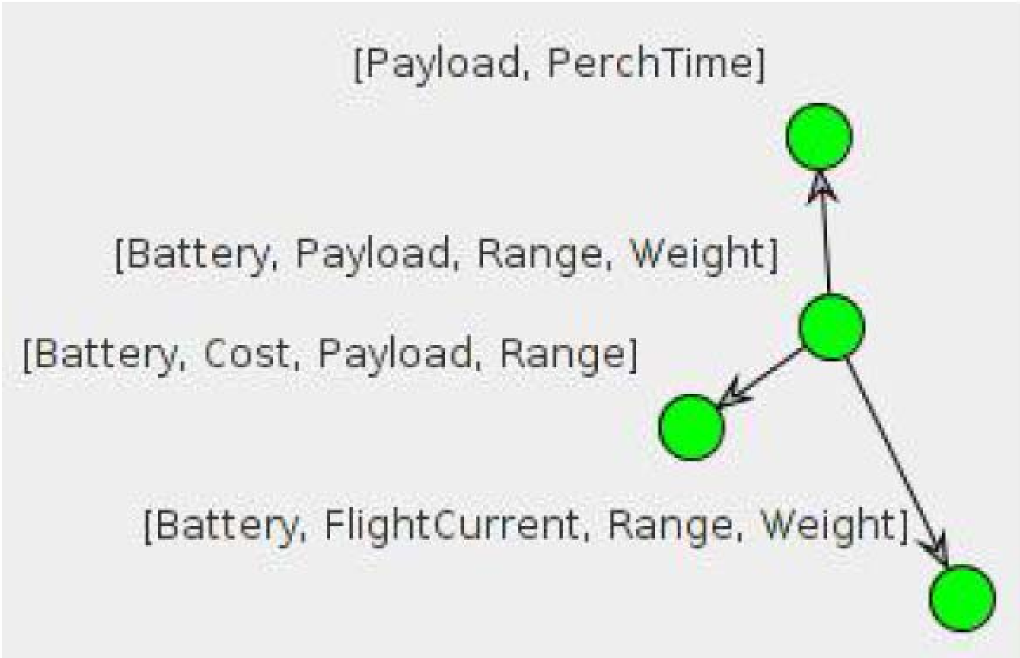


Figure: Join Tree (step 2)

Example: Quadrotor

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

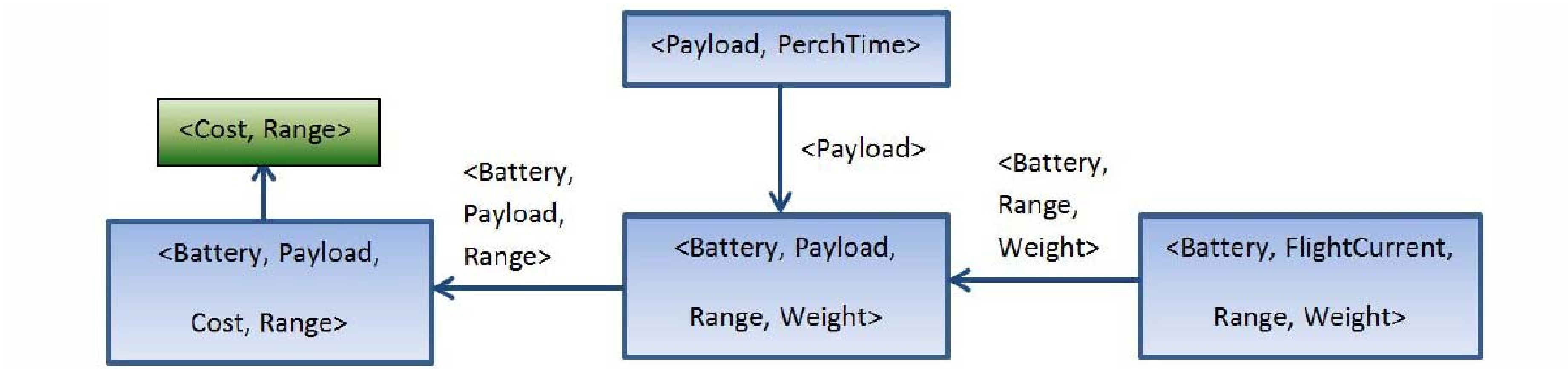
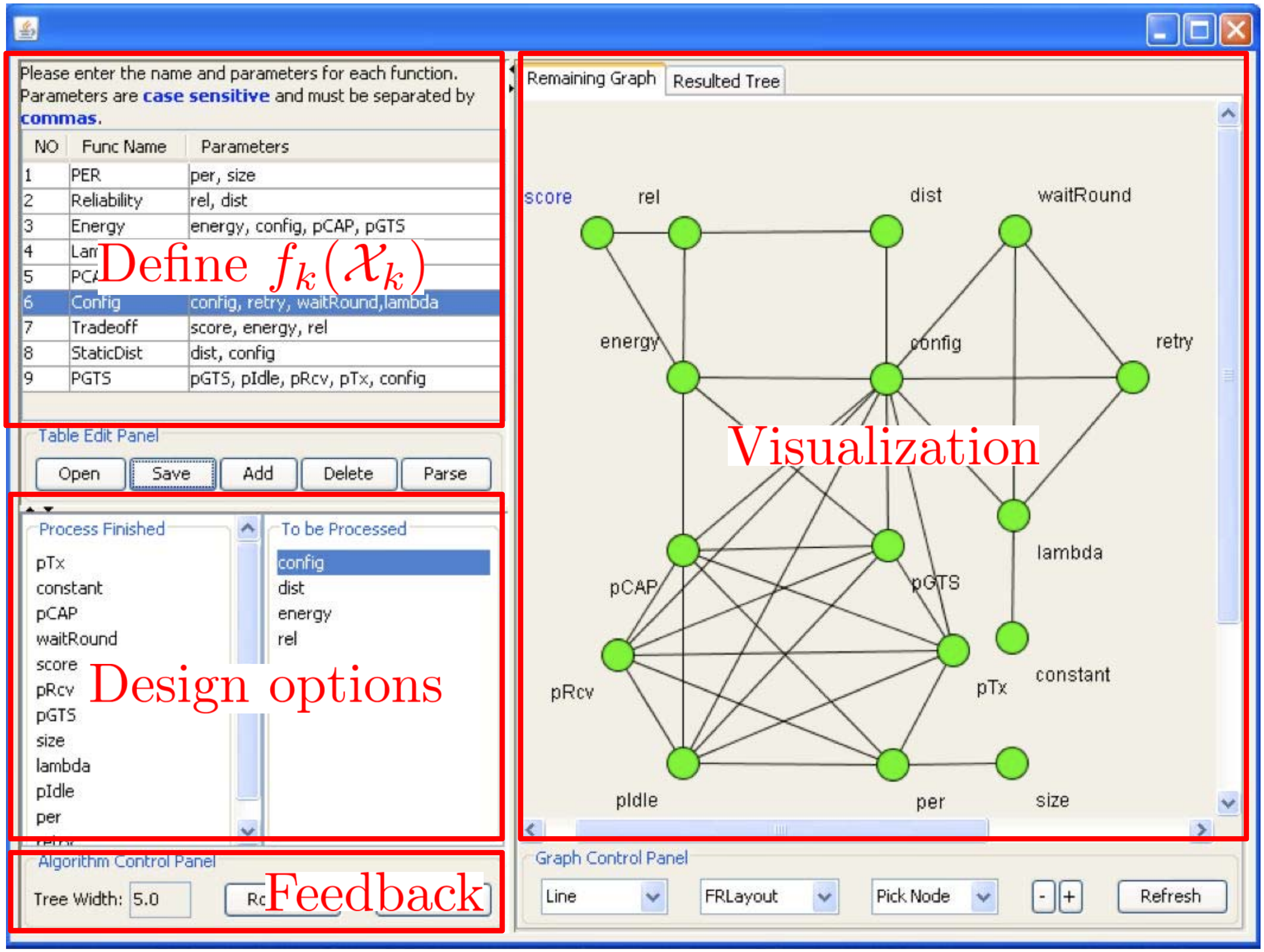


Figure: Summary Propagation (step 4): $\langle \oplus = \mathit{Projection}, \otimes = \mathit{Intersecion} \rangle$

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

GUI



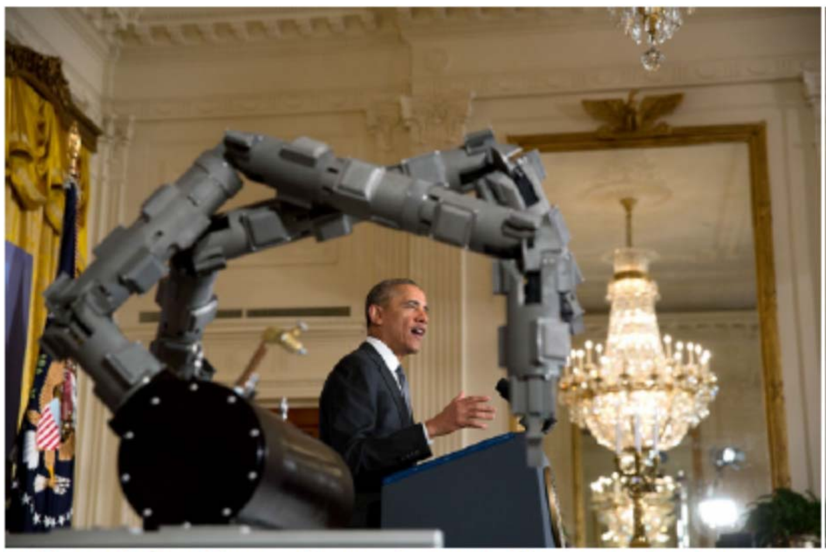
Please enter the name and parameters for each function. Parameters are case sensitive and must be separated by commas.
NO Func Name Parameters
1 PER per, size
2 Reliability rel, dist
3 Energy energy, config, pCAP, pGTS
6 Config config, retry, waitRound,lambda
7 Tradeoff score, energy, rel
8 StaticDist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

How to Use It?

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

Digital Manufacturing Design Innovation Institute (DMDII)

- Announced February 25, 2014, 2014 by President Obama
  http://www.whitehouse.gov/the-press-office/2014/02/25/president-obama-announces-two-new-public-private-manufacturing-innovatio



President Barack Obama delivers remarks announcing two new public-private Manufacturing Innovation Institutes, and launches the first of four new Manufacturing Innovation Institute Competitions, in the East Room of the White House, Feb. 25, 2014. (Official White House Photo by Lawrence Jackson)

- Headquartered in Chicago, Illinois
- Academic-Industry-Government "Mega Project" \$320M co-funding, 5 years
- **Goal**: Revitalize manufacturing along the lines described in this lecture

- "Infinite number of virtual factories and an open-source manufacturing platform"

“Democratizing” Manufacturing

- **Goal**: Transforming more ordinary people to “makers” of products and services
- Helping small and medium size companies to manufacture products and services – **bridge the “gap”** from innovation, prototyping, to manufacturing

- General Electric (GE) opens manufacturing fab lab to spark ideas and participation in manufacturing through making
- Several companies have also opened up similar “open” labs: Ford etc.

- Several regional manufacturing centers (industry-university-government) are being established in various regions of USA
- “Industrial Internet” (USA) and “Industrie 4.0” (GE-EU) arrive

Crowdsourcing Manufacturing

- ***Google's Project ARA***: Smartphones are composed of modules (of the owner's choice) assembled into metal frames

- ***Ubundu Edge Project***: crowdsourcing the most radical smartphone yet "Why not look for the best upcoming tech and throw it together to stay ahead of the competition?"
- ***Crowdsourcing*** the development and manufacturing of ***small unmanned aerial vehicles***

Need to Transform Engineering Education

- Move from a ***reductionist*** scientific approach to an ***integrative*** scientific approach
- **The challenge is to synthesize engineering systems so as to be able to generate predictable system behavior and performance by integrating behaviors and performance of system components**
- ***Compositional synthesis, manufacturing and life-cycle management*** of complex engineered systems
- This compositional synthesis advances engineering to the next frontier, **way beyond 'plug and play synthesis'**

THE ISR SE PROGRAMS IN BRIEF

MSSE

DEGREE REQUIREMENTS

The following courses are required:

Systems Engineering Core

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

Management Core

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

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

ENPM-SE

DEGREE REQUIREMENTS

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

Systems Engineering Core

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

Management Core

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

Both Supplemented by Technical Electives form many Technical Areas

A Bold Experiment

Starting early in the education chain

Undergraduates working with industry and government mentors on SE projects

Comparative Impact on Transforming Life-Work-Society

- Typography
- Microelectronic chips
- The PC
- The Internet
- MBSE

Concluding Remarks -- Challenges

- Further work on meta-models needed
- Create libraries with patterns of component models annotated by properties and metrics
- Develop a lot more uncertainty models and their composability; deterministic and stochastic
- Integrate multi-criteria optimization, constraint based reasoning, and logic
- Link the above to the integrated modeling hubs that allows return “values”
- Link to query management for design space exploration allowing many views
- Develop requirement representations for automatic verification: constraints, metrics, rules, semirings, soft semirings, automata, timed automata, Petri nets, process models, contracts, model-checking, automatic theorem proving, include uncertainties
- Develop automatic suggestions for feasibility or improvements
- Integrate all the above, especially composability and compositionality
- Provide users with ability to select “slices of tools” and integrate them
- Address the “front end” to make it affordable and easy to use

References

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Questions?