UTRC Perspective on Controls: Integration for Commercial & Critical Infrastructure

Mihai Huzmezan, Ph.D., P.Eng.

Control and Embedded Systems Group Leader
United Technologies Research Centre
United Technologies Corporation

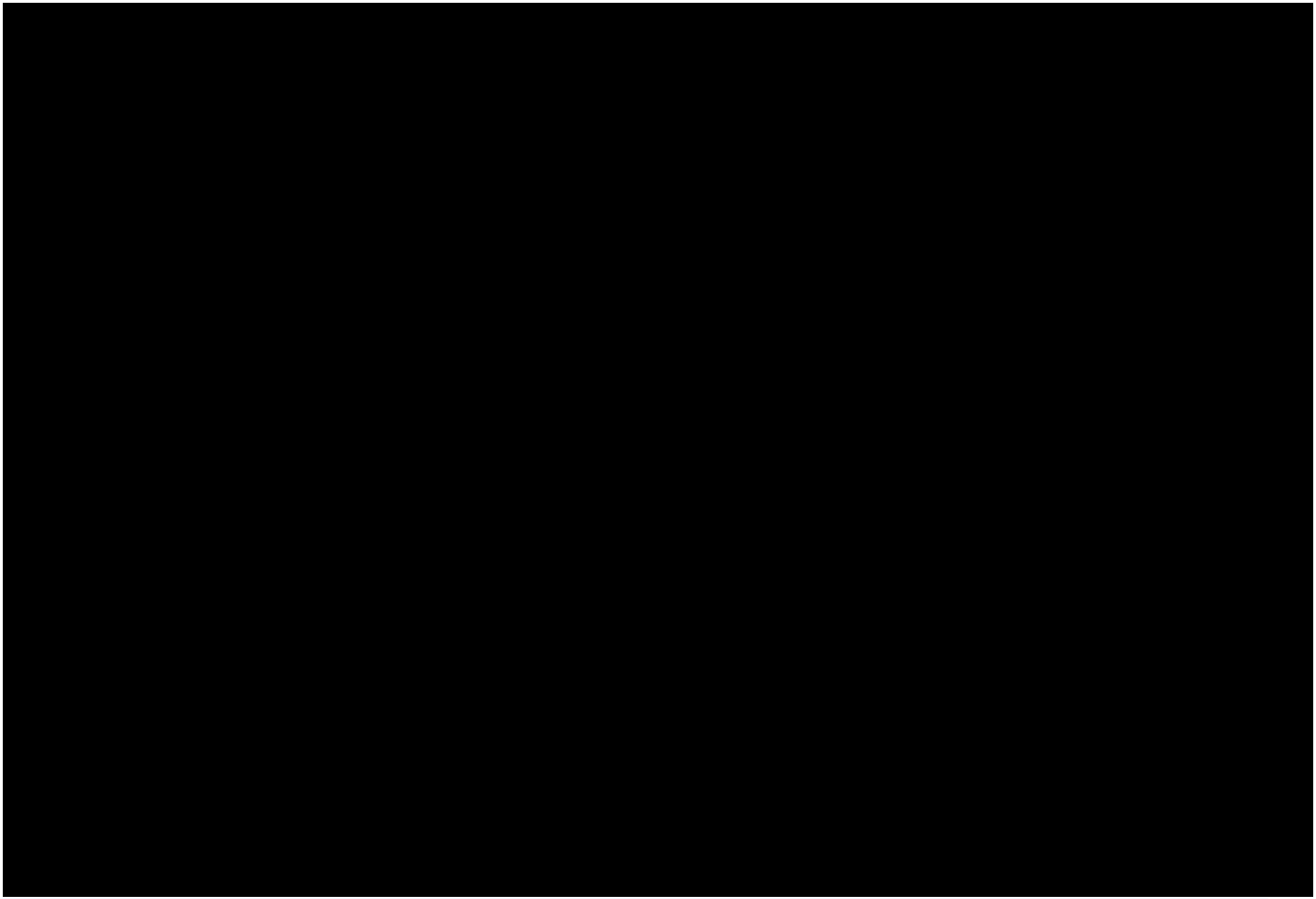
411 Silver Lane, East Hartford, CT-06415, USA
Tel: +1-860-610 7620, Fax: +1-860-660 0619, Mobile: +1-860-794 8373
huzmezm@utrc.utc.com

Integration for Commercial & Critical Infrastructure

Outline

- **UTC / UTRC overview**
- **The Challenge: Integration Through Controls**
- **The IBECS Example**
- **From Requirements and Modeling to Implementation**
- **Conclusion: Innovation Across the Design Cycle**

UTC: This is Momentum



United Technologies Corporation

Pratt & Whitney

UTC Power

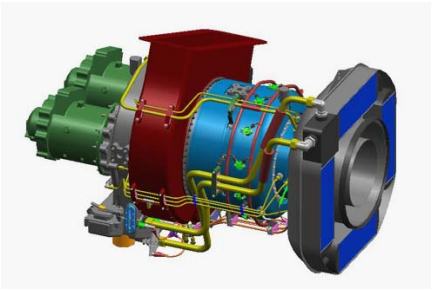
Carrier

United Technologies

- Aerospace Systems
- Power Systems
- Building Systems

Sikorsky

Otis

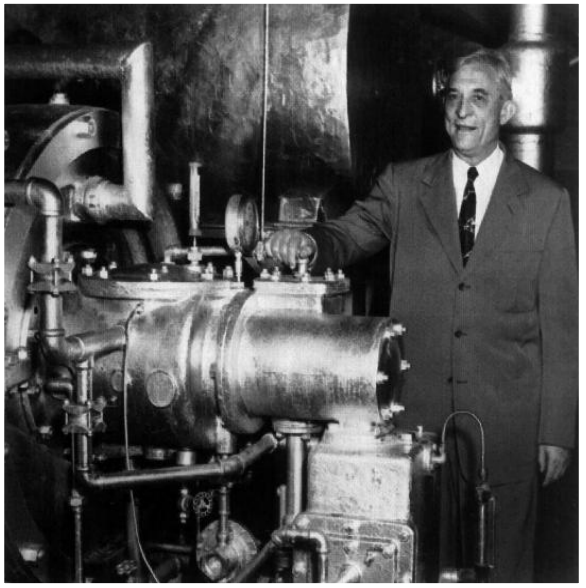


Hamilton-Sundstrand

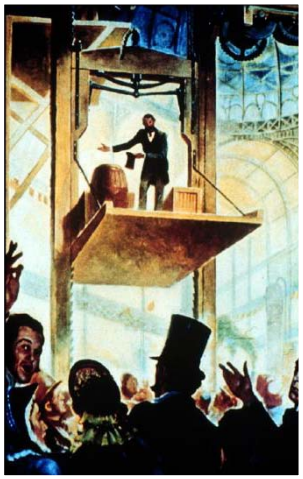
UTC Fire & Security (Kidde & Chubb)

United Technologies Corporation

A History of Innovation



Willis Carrier



Frank Rentschler

Thomas Hamilton

Elisha Otis

Igor Sikorsky

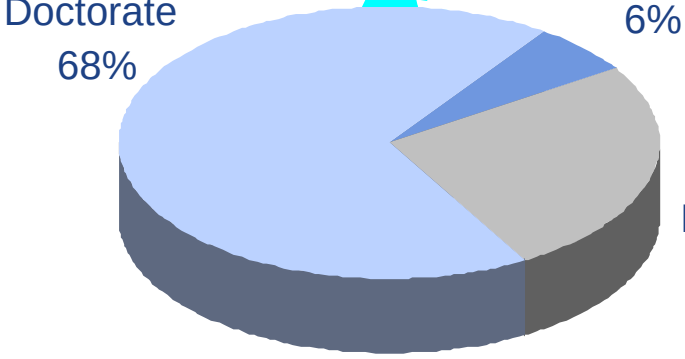
United Technologies Research Center

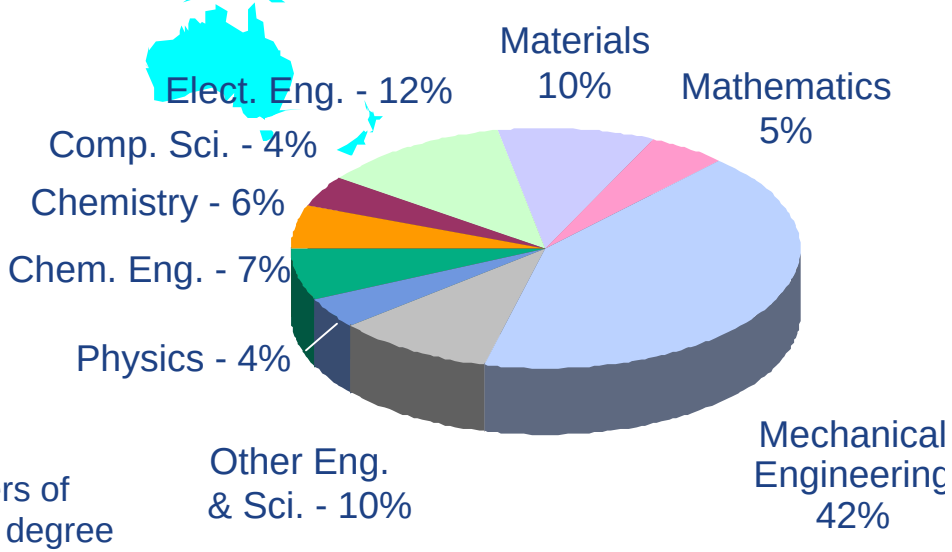
R&D Facilities

UTRC Departments:
Systems
Components
Physical Sciences
Product Qualification & Innovation Support

East Hartford, CT

Shanghai, China





7% also hold a Masters of Business Administration degree

www.utrc.utc.com

Integration for Commercial & Critical Infrastructure

Outline

- **UTC / UTRC overview**
- **The Challenge: Integration Through Controls**
- **The IBECS Example**
- **From Requirements and Modeling to Implementation**
- **Conclusion: Innovation Across the Design Cycle**

Challenge - Integrated Product Offerings

Complexity Managed Through Systems Engineering and Supervisory Controls

UTC Power

Carrier

Hamilton Sundstrand

Pratt & Whitney

Chubb

Otis

Kidde

Sikorsky

Buildings

Infrastructure

Transportation

Aerospace

Key Points

- Innovation in ***building system design*** and operation is an area of opportunity for ***efficiency, safety and comfort***
- ***Innovation*** can be found in ***integration***
- Progress in the design of ***integrated systems*** requires:
  (1) focus on ***modeling and analysis of dynamics and control***;
  (2) a design methodology and tools for ***embedded systems***;
- ***Model based systems engineering*** is an ***enabler*** for the design and implementation of ideas

Why Now?

"Fourth broad trend I'll note is the increased system integration. Products are smarter. Controls play a larger role…. We believe that system integration trends will continue in homes, office and supermarkets"

Geraud Darnis

Carrier President
Remarks made on July 1, 2004

Systems Integration for Infrastructure Automation and Security

Effectively shape the behavior of products and services, which may involve human decision making, through controls and model and data-driven processes.

Enablers

Systems engineering – risk assessments, requirements, critical parameter management

System level modeling – multi-scale modeling, analysis and control design.

Control and Embedded system design tools and processes – speed development time and reduce risk.

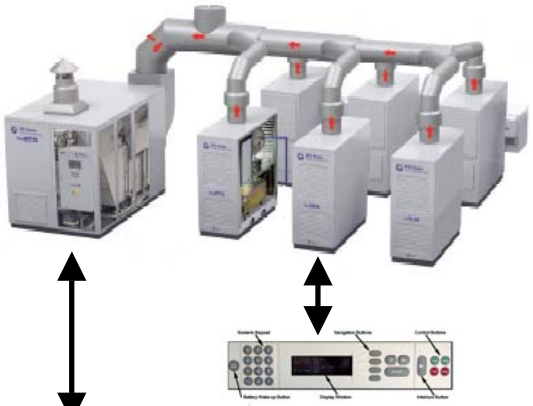
Monitoring – wireless sensor networks and video to enable information acquisition and analysis.

Decision Making –enable energy efficiency, comfort and security, and decision support for first responders

Integrated Cooling, Heating and Power (CHP) Generation

Supervisory Controls Virtual Qualification Speeds Integration

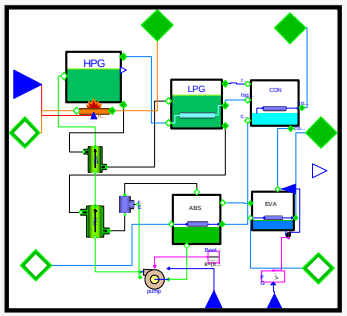
Problem
Controller Integration



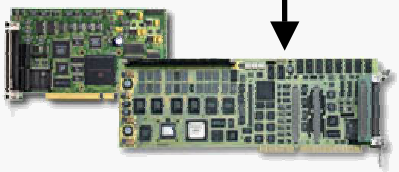
Capstone Controller

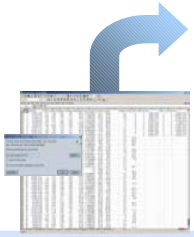
Carrier Controller

PureComfort Model



PureComfort system-level dynamic model





Carrier controller with modified software

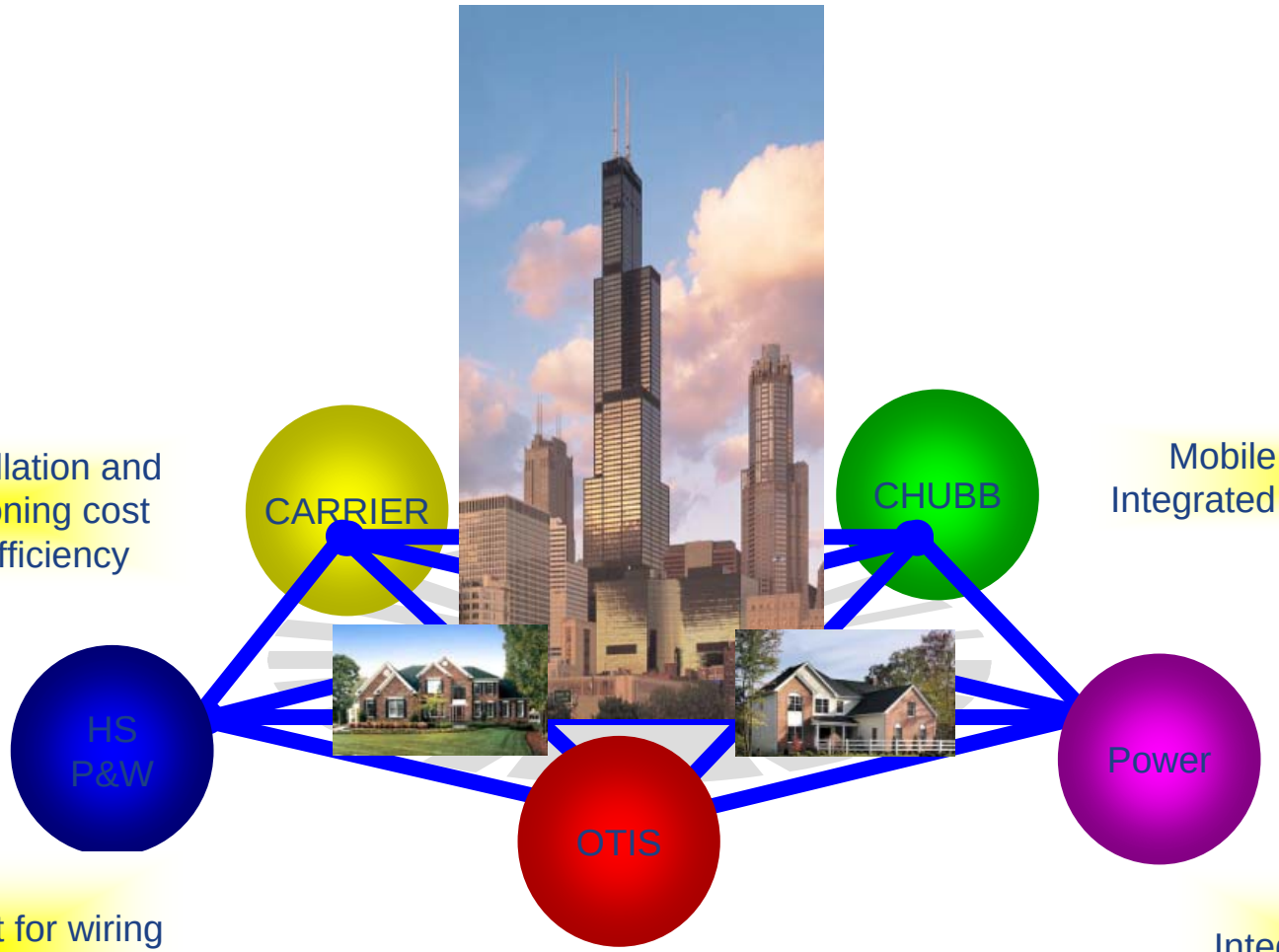
Integrated Solution

New Carrier Controller

- Accelerated Software Qualification 2X
- Risk Reduction – Virtual testing of extreme conditions

Integrated Solutions Through Wireless Sensor Networks (WSN)

WSN enables integration of capabilities



Integration for Commercial & Critical Infrastructure

Outline

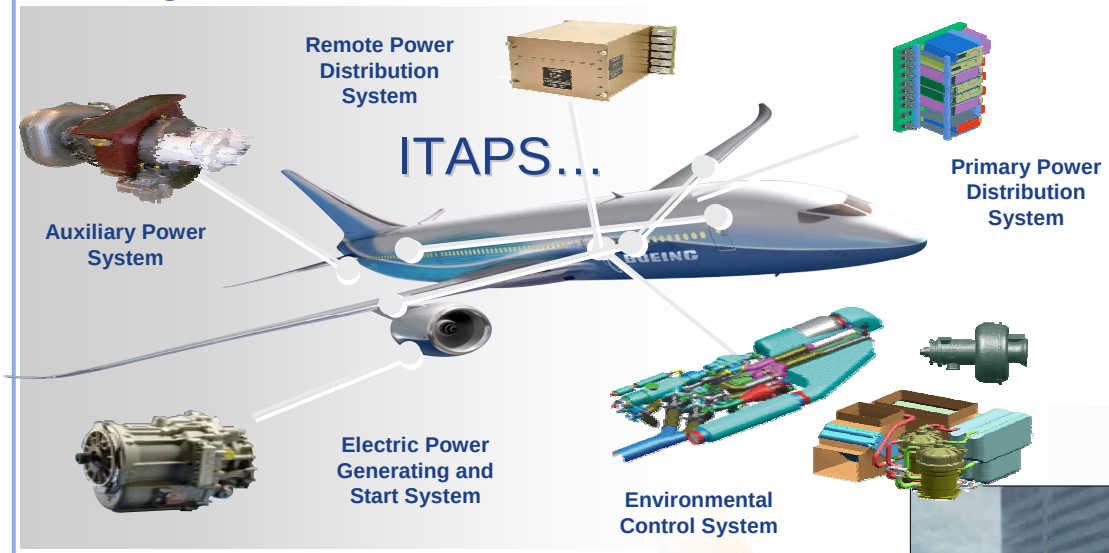
- **UTC / UTRC overview**
- **The Challenge: Integration Through Controls**
- **The IBECS Example**
- **From Requirements and Modeling to Implementation**
- **Conclusion: Innovation Across the Design Cycle**

Integrated Concurrent Design Processes

From ITAPS to IBECS

Integrated Products - A unique offering of which value is significantly higher than the individual components value.

Boeing 7E7 *Complete Power, Fuel and Thermal Management Solutions*



Integrated Concurrent Design Processes

IBECS …

Integrated Building Energy and Control Systems

HVAC including Indoor air quality

Cooling, heating and power systems

Integrated Design of High Efficiency Commercial Buildings

Current and Desired States

"A model-based systems design methodology to enable development of integrated HVAC and CHP solutions and advanced controls tailored to needs of specific commercial building market segments."

	Current State	**Desired State**
Design Process	▪ Build and test, sequential. ▪ Component - oriented ▪ Rated, steady state "design point" performance	▪ Model-based, concurrent. ▪ Systems - oriented ▪ Performance quantified throughout dynamic envelope.
Controls	▪ Proprietary scripting language – multiple versions. ▪ Proprietary *physical layers (CCN)* ▪ Sequential development process ▪ Qualified only at commissioning time	▪ Model-based, industry-standard best-in-class tools. ▪ Proprietary *behaviors and algorithms*. ▪ Concurrent development process. ▪ Qualify over entire design cycle.
Sizing & Specification Tools	▪ Component oriented ▪ Rated "design point" metrics ▪ Detached from industry-standard tools ▪ Prescriptive	▪ Systems oriented ▪ Operating envelope metrics ▪ Integrated into emerging construction industry standards ▪ Proscriptive

Integrated Building Energy & Control Systems (IBECS)

IBECS -> NIST-funded project

Year 1
"Modeling Infrastructure"

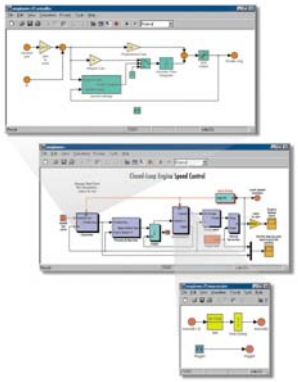
- IBECS facility
- Integration Enabled Model Library
- Top down software prototype
- Prototype building study
- Requirements – metrics for building classes

Year 2
"Lead with Controls"

- Advanced control capability
- Hardware-in-the-loop
- Optimization Tool prototype
- Prototype studies

Year 3
"Integrated value chain"

- CHP model library
- Sizing, specification tools
- Capstone CHP study including optimization & top down tool.

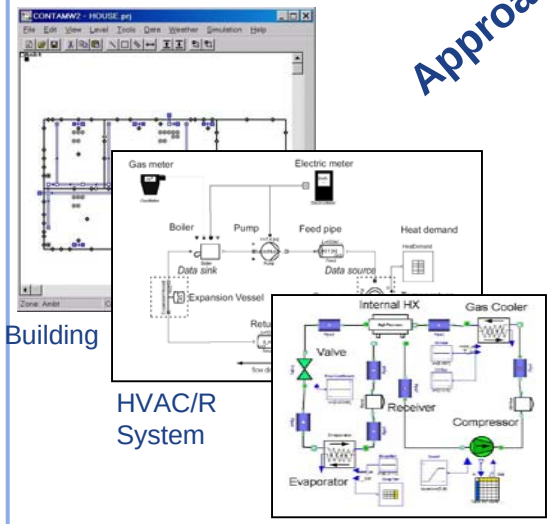


Integrated Building Energy & Control Systems (IBECS)

A model-based systems design methodology for development of integrated HVAC/R and CHP solutions and advanced controls tailored to commercial building market segments.

System-Level Model Hierarchy

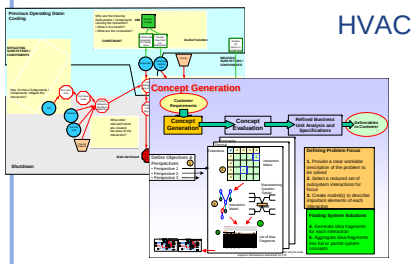
Approach



Building

HVAC/R System

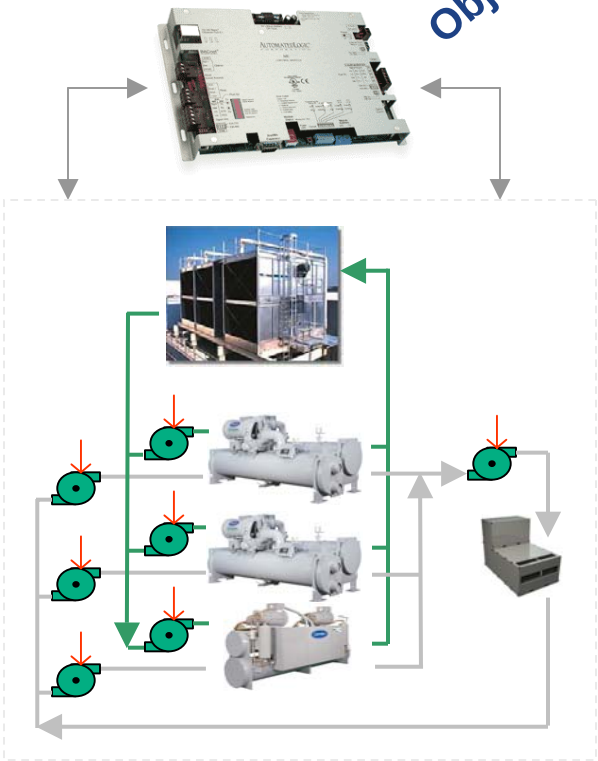
HVAC Equipment



Systems Engineering Process

Optimal Control

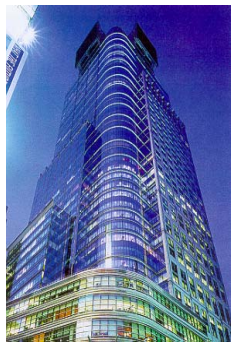
Objectives



Optimal Configuration

Commercial building segments

Scope



Requirements

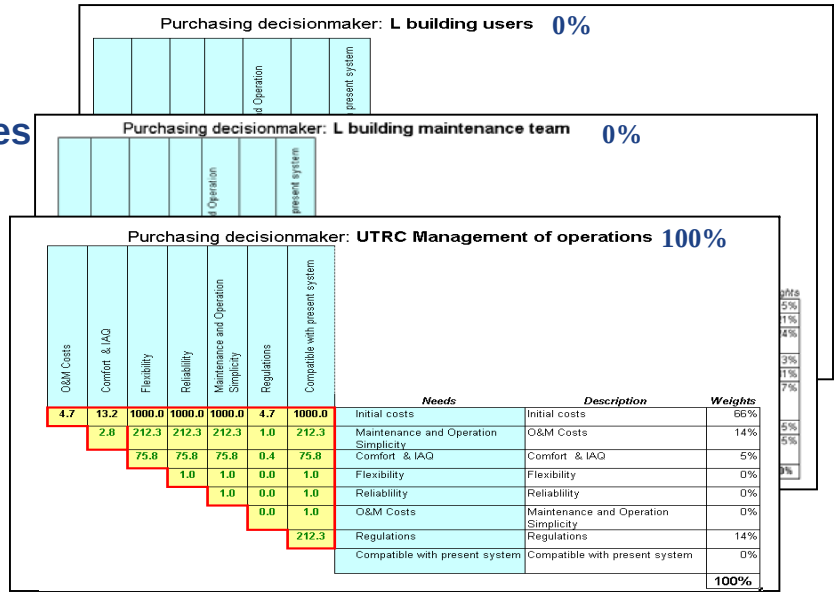
Value-Based Gauge

Weighted customer needs for stakeholders

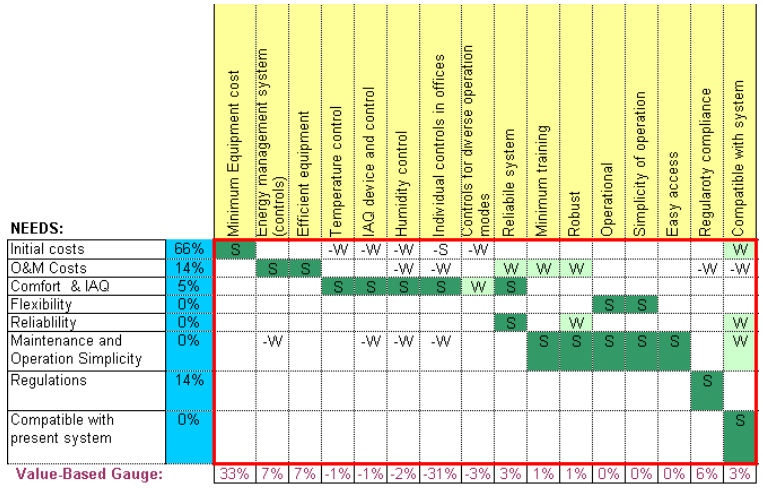
Users

Facilities Team

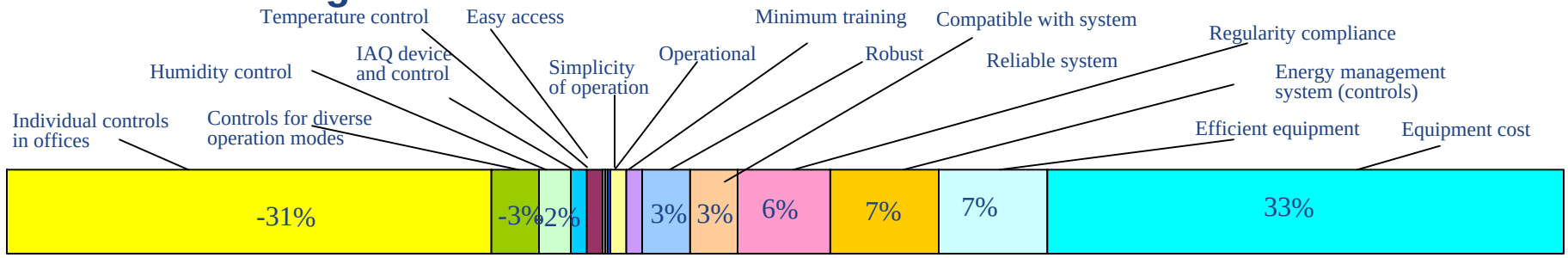
Owners



Concept screening matrix: Requirements vs. Characteristics



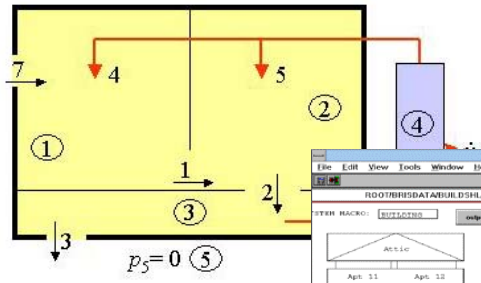
Value-Based Gauge



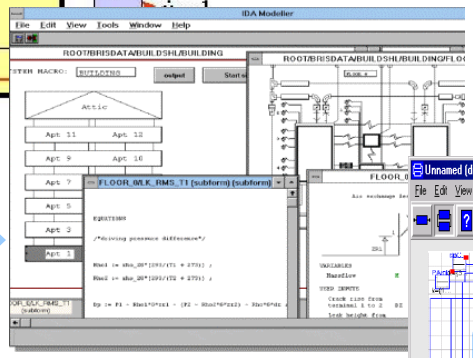
The IBECS Integrated Tool Chain

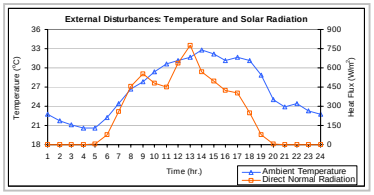
Dynamic modeling & economic analysis of integrated HVAC/R solutions

Physical Description

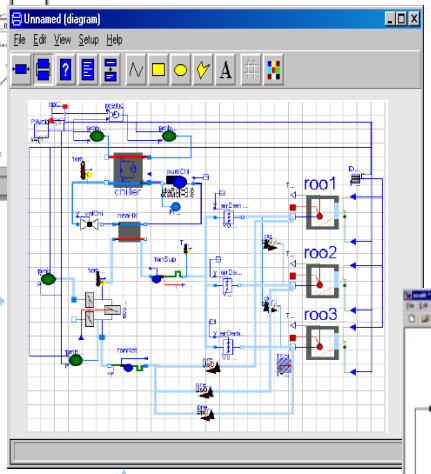


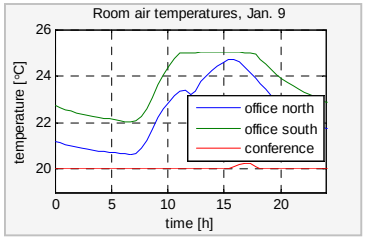
IDA - *Building Envelope Physics*



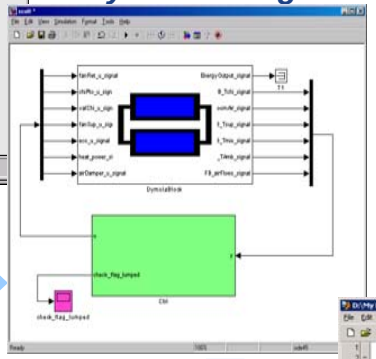


Dymola - *HVAC & Airflow Performance*

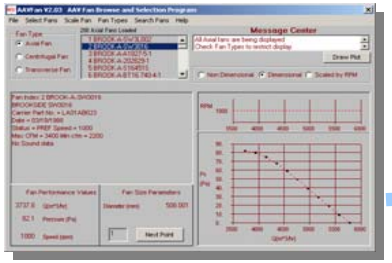




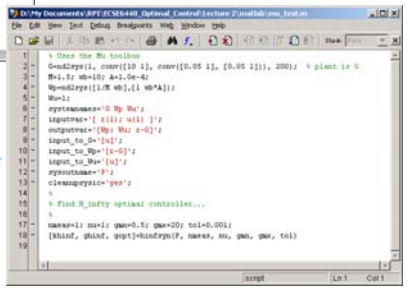
Simulink – *Controls Analysis & Design*



AVVFan Database



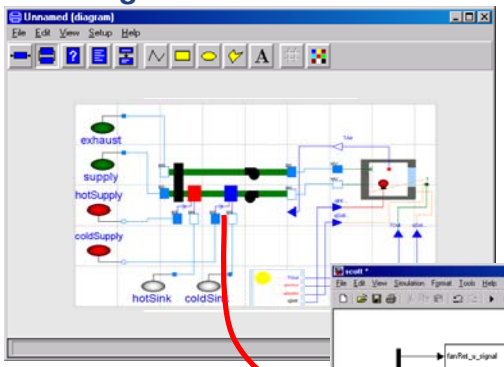
Matlab – *Economic Analysis*



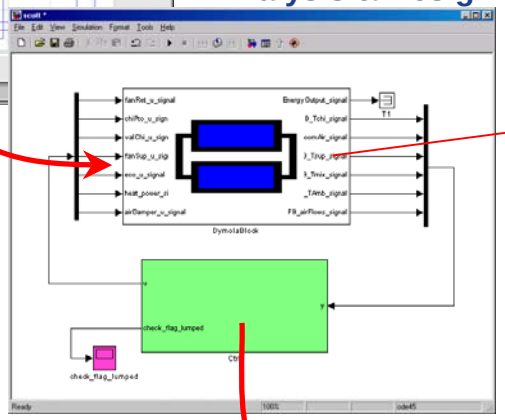
Envisioned IBECS Integrated Tool Chain

Automated Code Generation & HIL Simulation

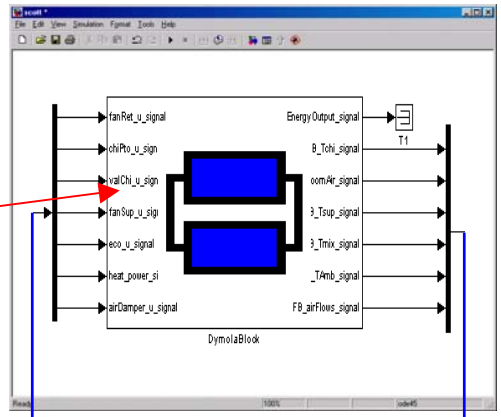
Dymola: HVAC + Building Model



Simulink – Controls Analysis & Design

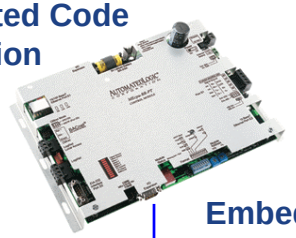


Dymola / Simulink – "Virtual Building"



Hardware-in-the-Loop Simulation

Automated Code Generation



Embedded Platform

New algorithms

Building Management Systems

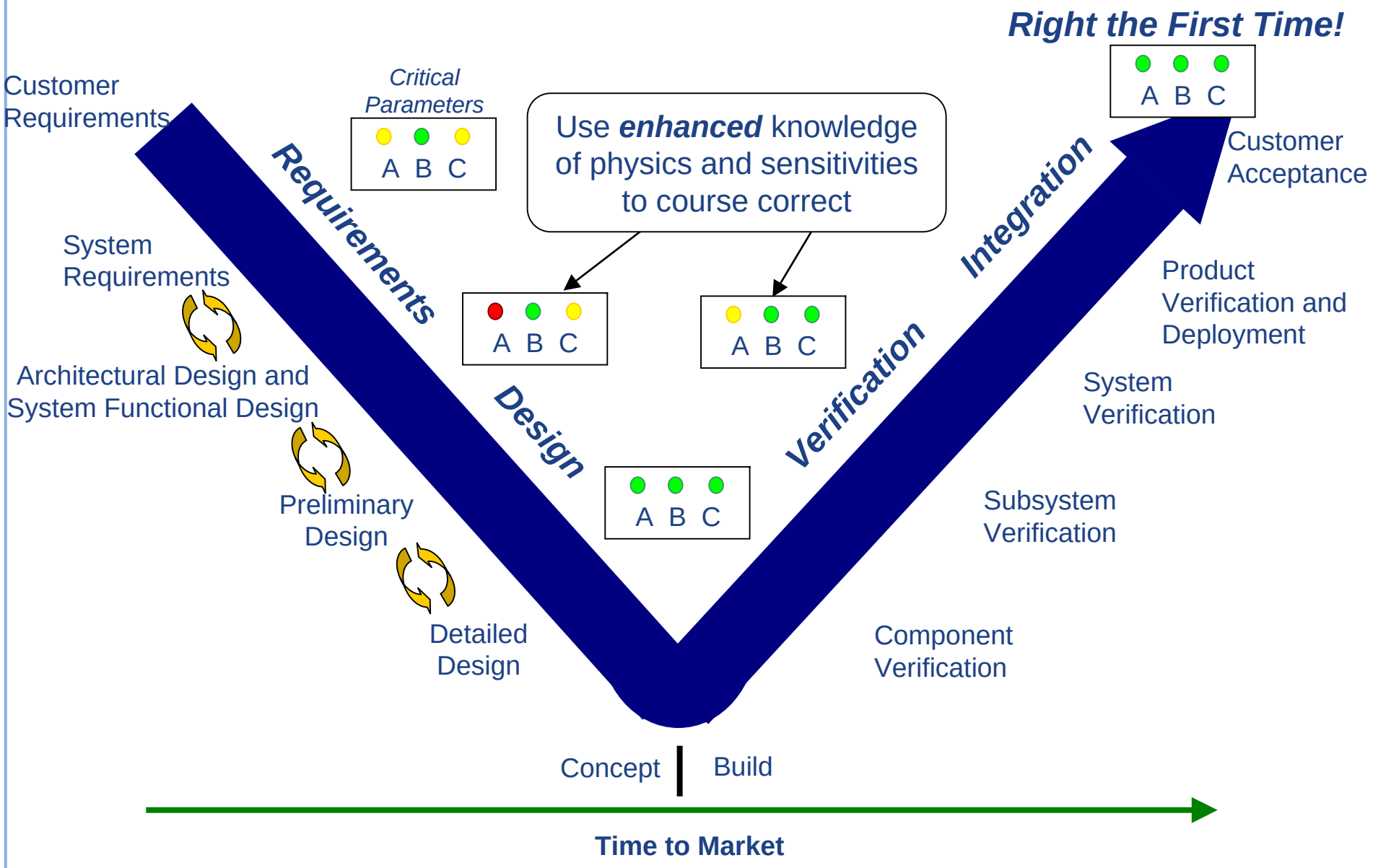
Integration for Commercial & Critical Infrastructure

Outline

- **UTC / UTRC overview**
- **The Challenge: Integration Through Controls**
- **The IBECS Example**
- **From Requirements and Modeling to Implementation**
- **Conclusion: Innovation Across the Design Cycle**

Model-Based Systems Engineering

System Modeling and Analysis in Design Phase enables Robust Solutions



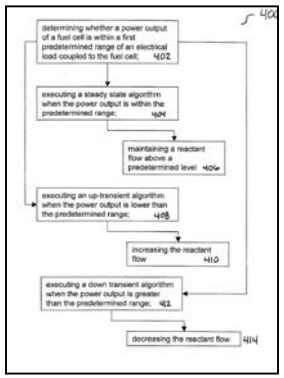
Typical Embedded Controls Opportunity

Address Issues in the Product Development Process

Product Differentiation

Monitoring

Requirements Management



Paper Requirements Documents

Product Quality

Truck Trailer Container Applications

Avoid Obsolescence

```
00118     for (tok = s;;) {
00119         c = *s++;
00120         spanp = delim;
00121         do {
00122             if ((sc = *spanp++) == c) {
00123                 if (c == 0) {
00124                     s = NULL;
00125                 } else {
00126                     s[-1] = 0;
00127                 }
00128                 *stringp = s;
00129                 return (tok);
00130             }
00131         } while (sc != 0);
00132     }
00133 }
```

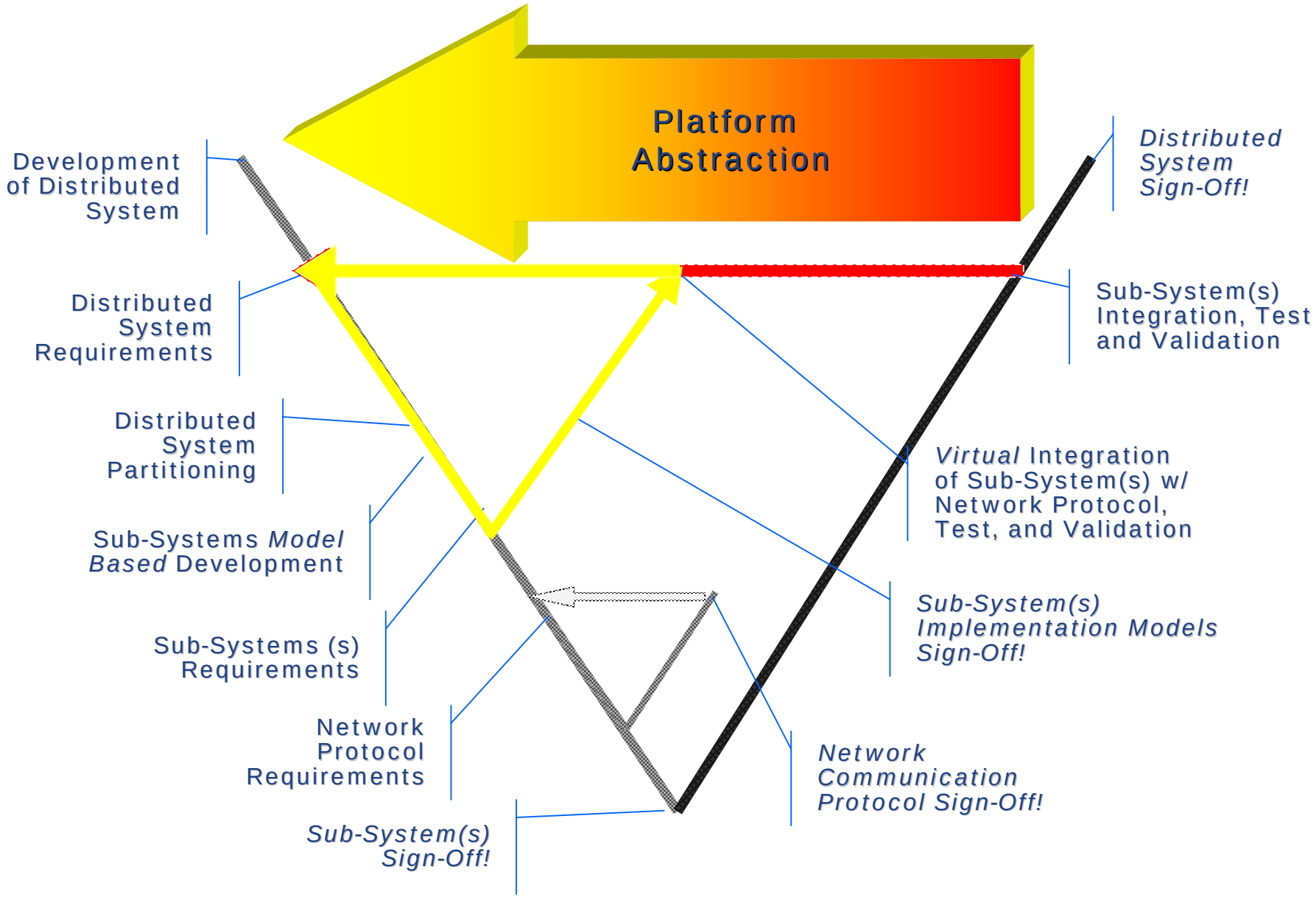
C Code

Embedded System

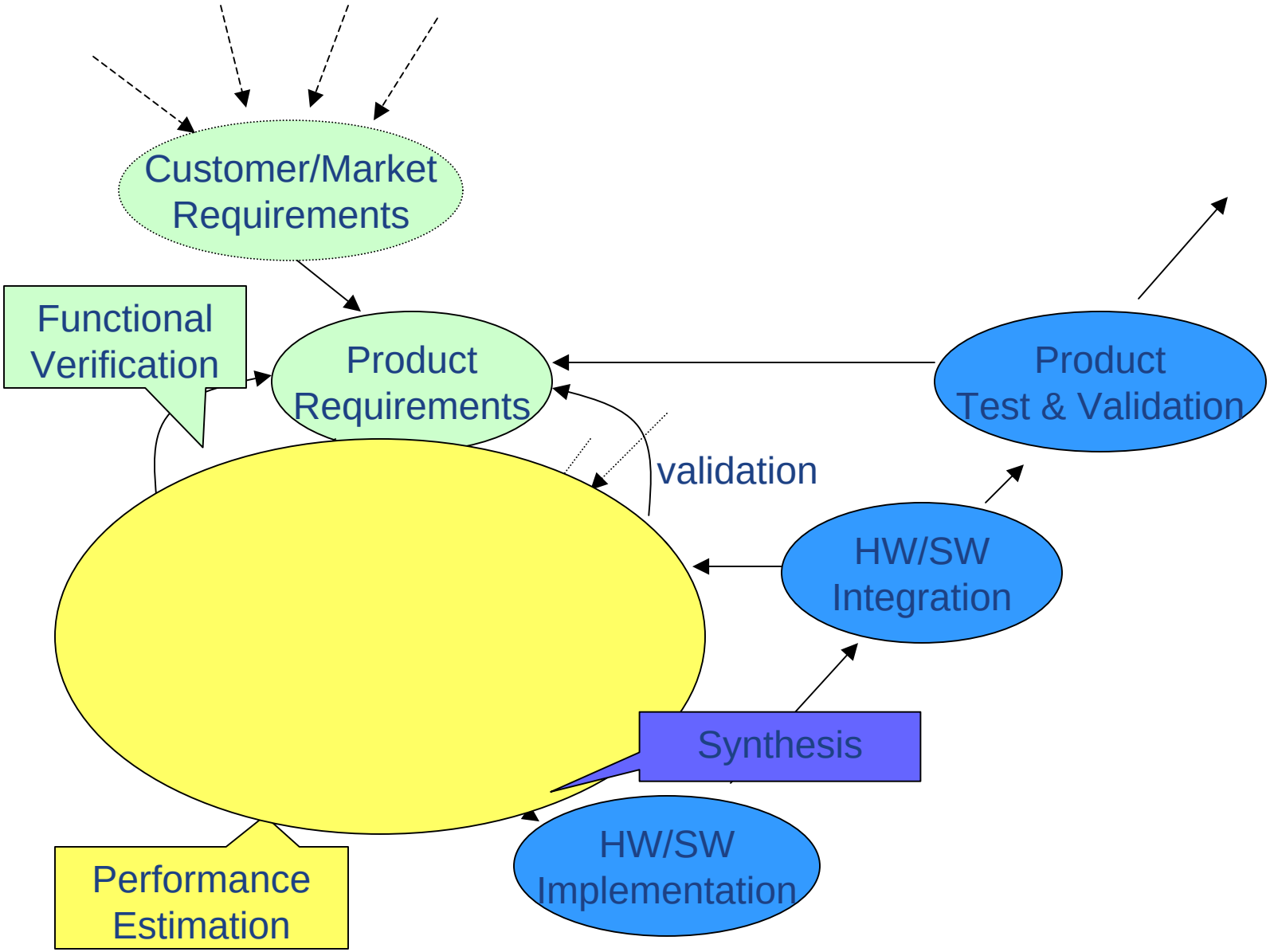
Circuit Board

Minimized Rework

Platform Based Design

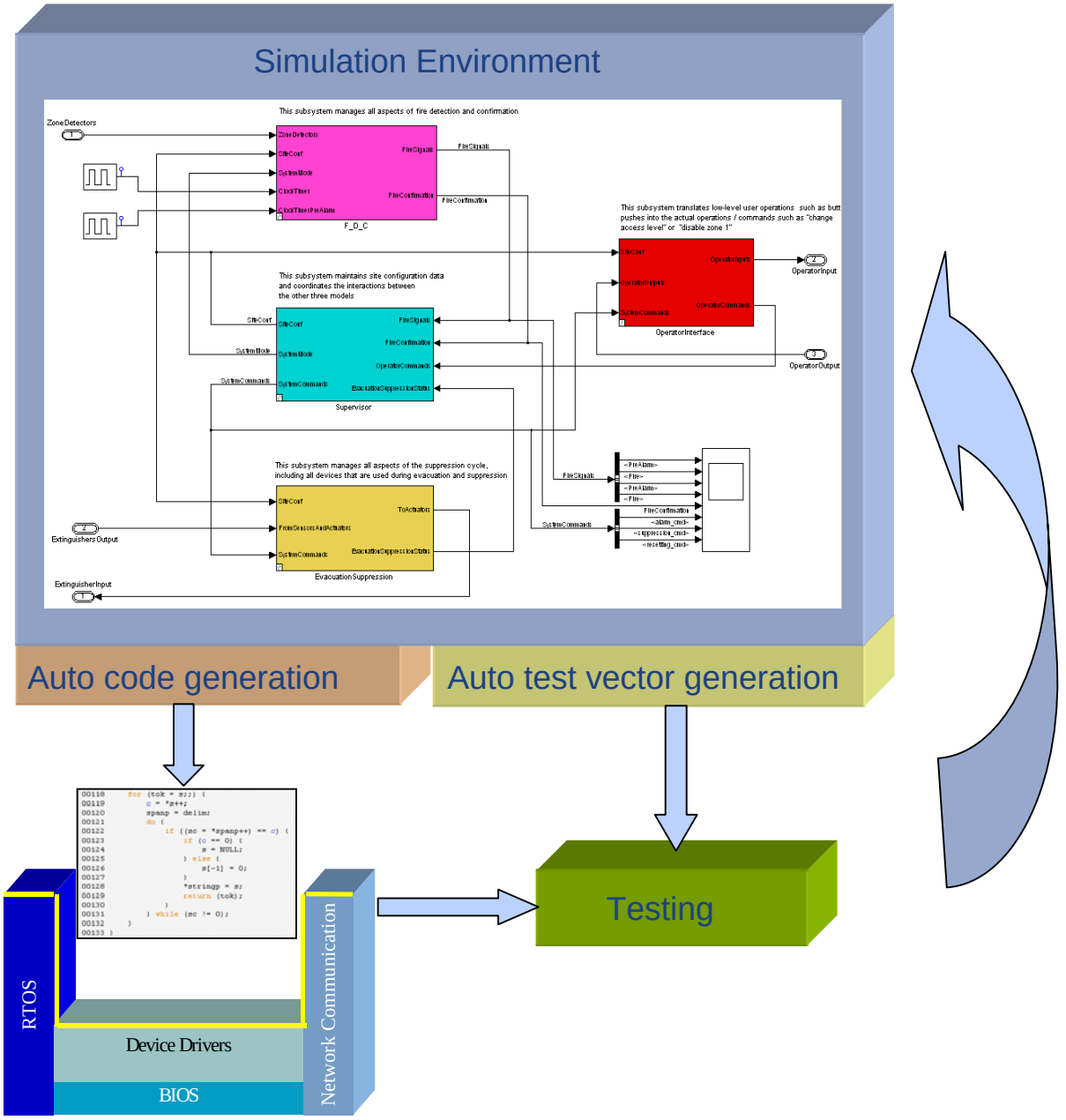


Platform and Model Based Design Methodology



Embedded Control System Modeling, Analysis, Design,Testing

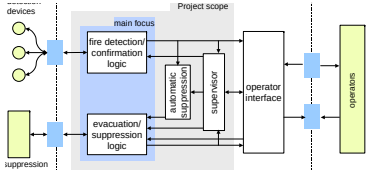
Bird Eye View

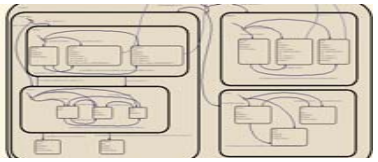


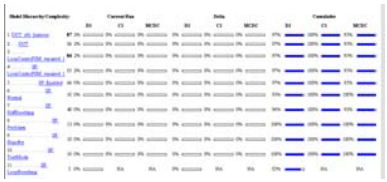
Model-Based Embedded Systems Development

Outline of the Process

1	Define scope for modeling; define separation of application and platform	High-level functional decomposition (Pencil, PPT, Simulink)
2	Define all external I/O, internal signals, & events; create abstractions	Data dictionary (Simulink busses)
3	Decompose top-level functions into 1 or more State Machines	State Machine(s) (Pencil, Stateflow)
4	Simulate & refine State Machines	Basic test cases (Signal Builder, Stateflow)
5	Generate test vectors and perform coverage analysis; check assertions	Test cases & Cov. report (Reactis, TNI-Valiosys, Simulink V&V)
6	Automatic code generation; verify code using test vectors	ANSI C code, html report (RTW or TL, Simulink)
7	Verify generated code on target	Test results performance measurements



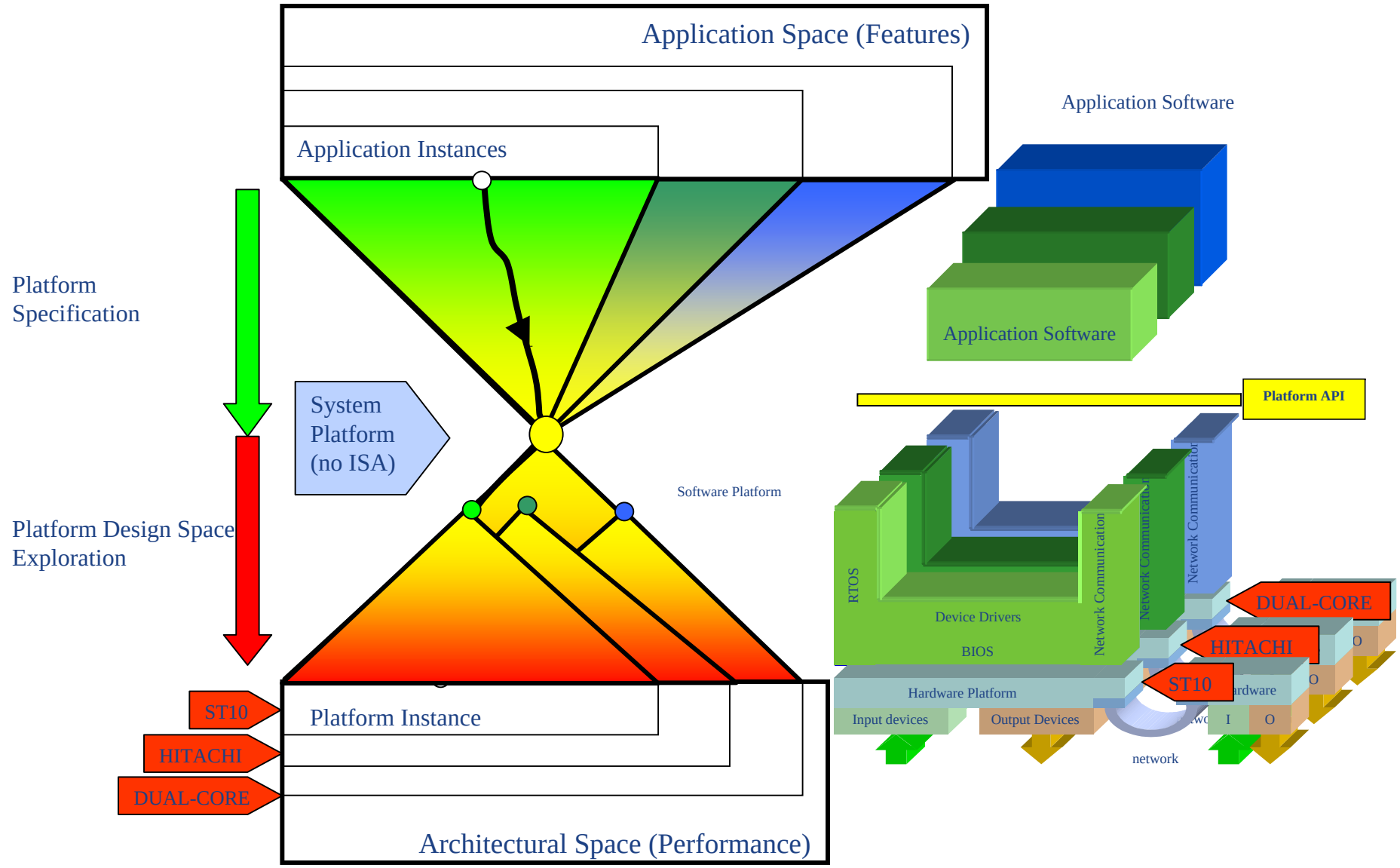




```
00122                if ((sc = *spanp++) == c
00123                    if (c == 0) {
00124                        s = NULL;
00125                    } else {
00126                        s[-1] = 0;
00127                    }
00128                    *stringp = s;
00129                    return (tok);
```

Platform Based Design Enables Platform Selection

Berkeley and PARADES driven initiatives



Integration for Commercial & Critical Infrastructure

Outline

- **UTC / UTRC overview**
- **The Challenge: Integration Through Controls**
- **The IBECS Example**
- **From Requirements and Modeling to Implementation**
- **Conclusion: Innovation Across the Design Cycle**

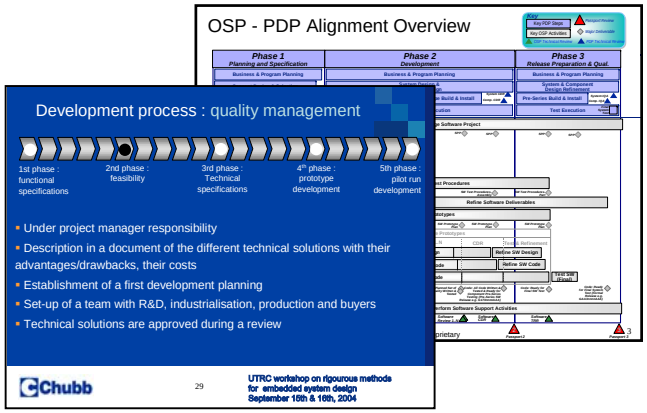
UTRC: Dr. John Cassidy – UTC Senior VP Science & Technology

Integration for Commercial & Critical Infrastructure

Backup Slides

The Key to Integration: Project Planning and Execution

Achieving Competitive Excellence (ACE) Through Adequate Processes



Business Unit Passport Process

Phase 0	Phase 1	Phase 2	Phase 3	Phase 4
Opportunity Analysis	Concept Development	Design & Dev't	Validation	In Service

0 1 2 3 4 5

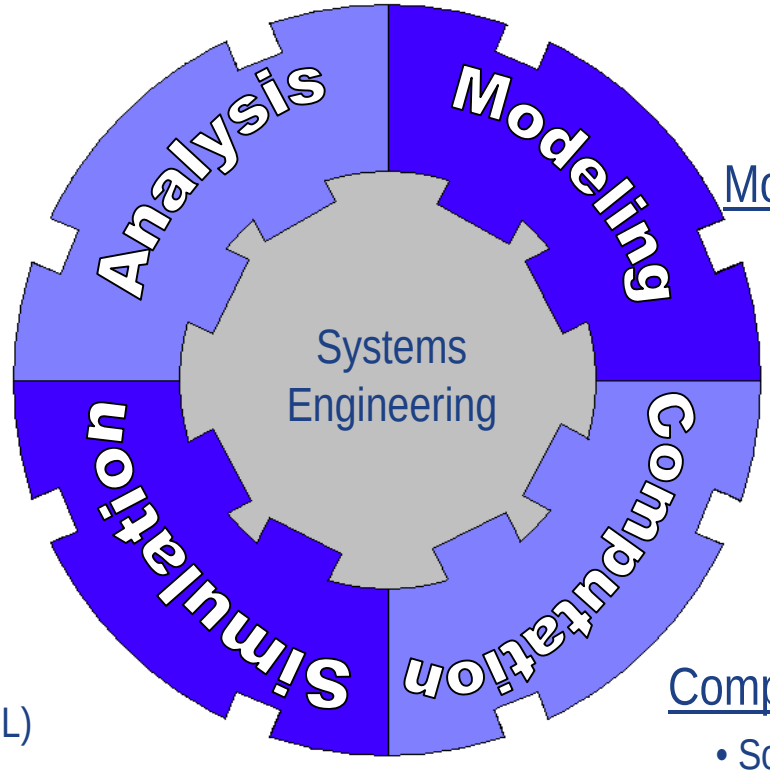
Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Opportunity Identification	Opportunity Analysis	Concept Synthesis	Critical Risk Reduction	Feasibility Demonstration	Technology Readiness

-1 0 1 2 3 4 5

UTRC Project Planning & Execution Process

Modeling, Analysis, Simulation, & Computation (MASC)

Enhancing the UTC Engineering Effectiveness



Analysis

- Dynamical Systems
- Control Design
- Fundamental Limits
- Sensitivity & Uncertainty

Modeling

- Equation-based model construction
- Model verification & validation
- Model maturation

Simulation

- Hardware-in-Loop (HIL)
- Embedded Systems
- Shared, Distributed Computation
- Protected External Participation

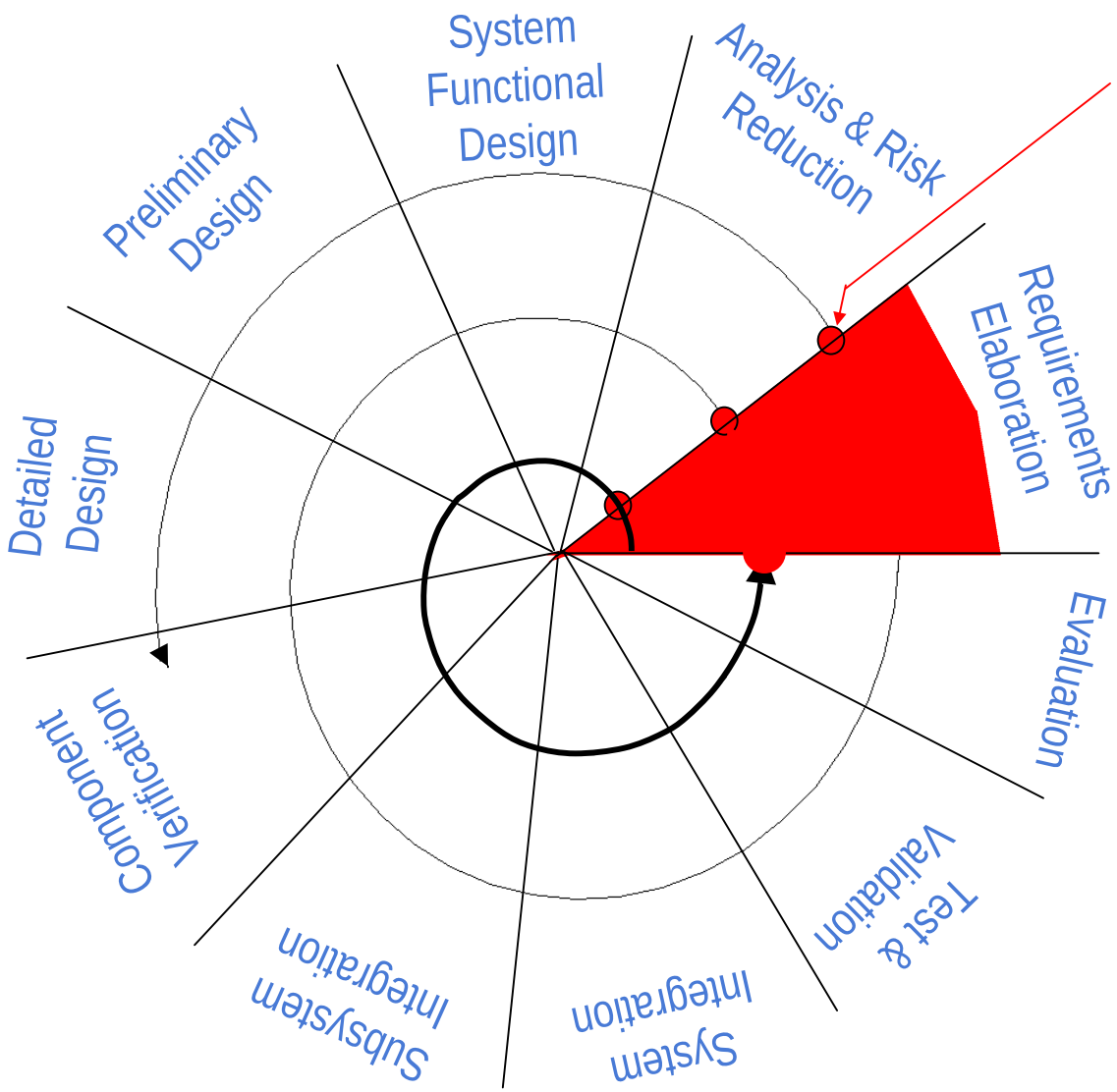
Computation

- Solution Architecture Design
- Multi-scale, multi-fidelity integration
- Multi-Domain integration
- Algorithmics & Numerical Analysis

Make United Technologies a world leader in the effective use of modeling and analysis for competitive differentiation of our products and processes, as measured by development time and costs, system performance and robustness, and product quality and reliability.

Model-Based Systems Engineering

Iteration Through Systems Engineering Process For Design Objectives



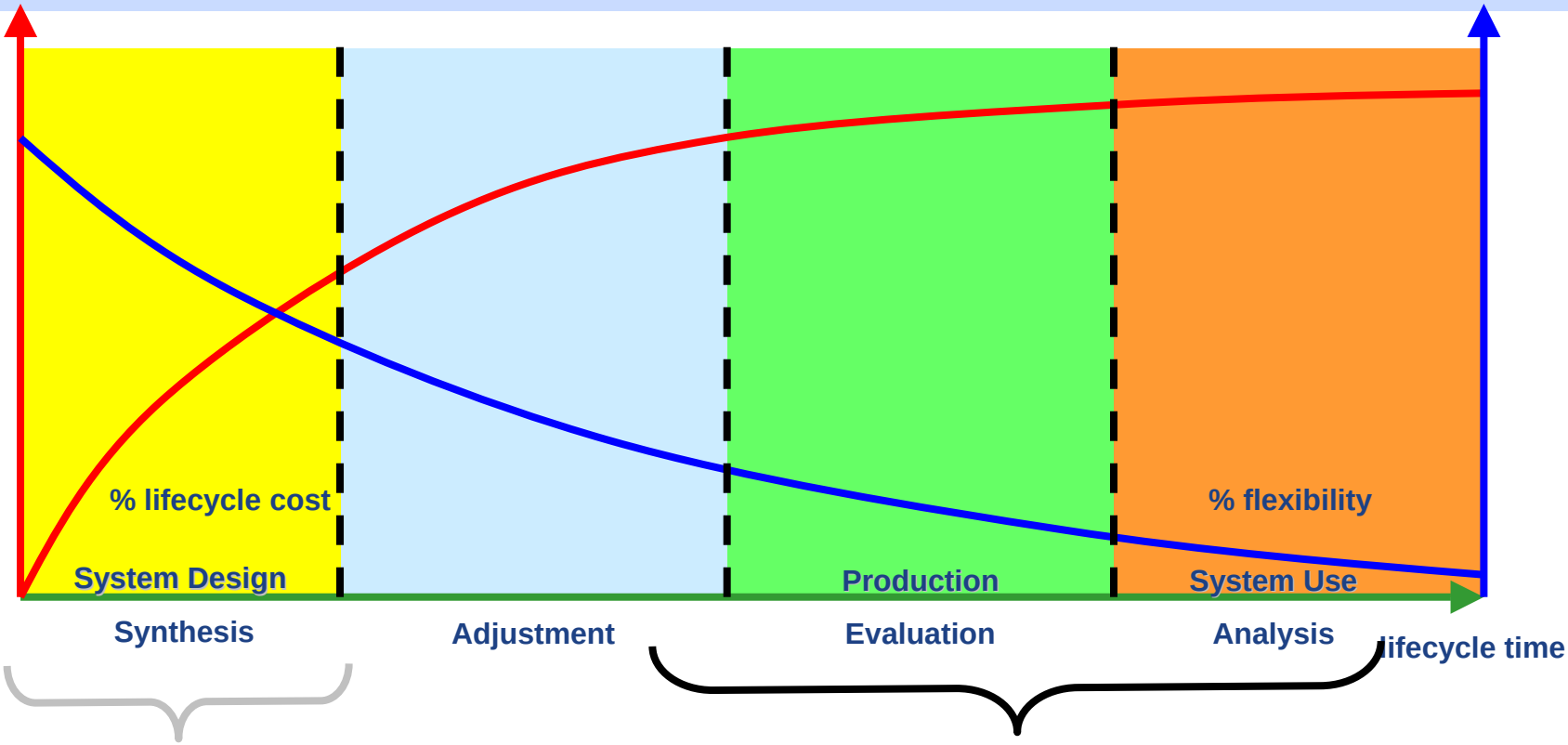
Stages in the iterative design process are separated by key *Decision Points*

Decisions are based on information subject to:

- *Imprecision*
- *Uncertainty*
- *Negotiation*
- *Misinterpretation*

Use *model-based* design and analysis of *dynamics*, *imprecision*, and *uncertainty* to reduce decision *risk*

How to increase impact of Control Theory on Design?



Future: design beneficial dynamics => exploit flexibility at low cost

Today: attempt to fix detrimental dynamics late in design cycle

Success Stories ⇦ Education ⇦ Credibility ⇦ Problem

Management

Technical personnel

Uncertainty Propagation in Networks of Dynamical Components

Robust design process

Reduce Complexity

System Model

Create Models

Advanced Engine

Interconnected system models

Graph Partition

Decomposition of network into weakly connected sub-networks and density mapping facilitates computation of uncertainty propagation

Directed acyclic graph

Weakly/strongly coupled subsystems

- *New graph theoretic methods*
- *Vertical-horizontal decomposition for hierarchical networks facilitates uncertainty propagation*
- *Demonstrated in fuel cell and DNA examples (~20 states)*

$g(u)$

f_x

$f_u(u)$

Uncertainty Propagation

Subsystem output uncertainty model

Direct sum of densities

System output uncertainty model

Iterate

Basic convergence theory for propagating uncertainty in dynamical systems introduced

System architecture

Reduce Sensitivity

Direction of Increasing Detuning

stable

unstable

unstable

Stability Boundary

G_{i-1} G_i G_{i+1} ...

Design Criteria

Assess Robustness

Decision Making in the Face of Uncertainty