Dynamical models for industrial controls: use cases and challenges

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LCCC workshop: Systems Design Meets Equation-Based Languages

Lund, September 2012

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Outline

- Overview of controls at General Electric
- Train trip optimization example
- Power plant predictive control example
- From control system challenge to model challenge
- Conclusions

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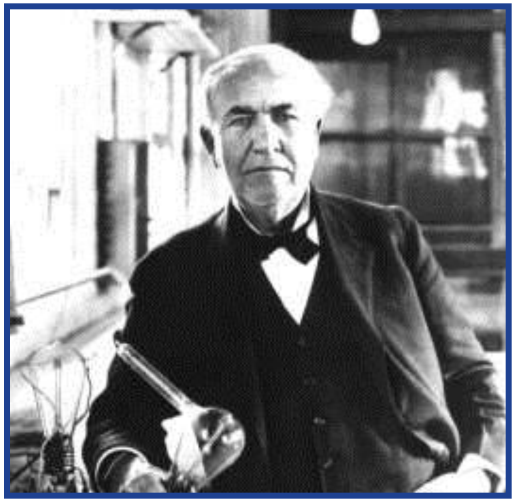
GE ... a heritage of innovation

- Founded in 1892
- 300,000 employees worldwide
- $150 billion in annual revenues
- Only company in Dow Jones index originally listed in 1896



GE today

System Design & Equation-based Languages
LCCC - Lund Sep 20, 2012

Aligned for growth

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Expanding global presence in research

3000 technologists worldwide

AMSTC
Ann Arbor, MI

Global Research HQ
Niskayuna, NY

Global Research - Europe
Munich, Germany

China Technology Center
Shanghai, China

Brazil Technology Center
Rio de Janeiro, Brazil

John F. Welch Technology Center
Bangalore, India

Products with Controls

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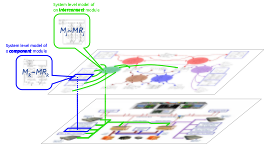
Controls at GE Research Labs

Supervisory Control & Systems Integration

- System Integration & Simulation
- Optimal Dispatch
- System validation & Verification


Real-Time Optimization & Controls

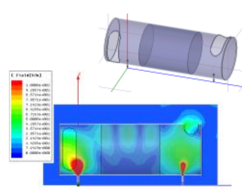
- Operation Critical Controls
- Dynamic Plant Optimization
- Predictive Controls


Model Based Controls

- Safety Critical Controls
- Advanced Multivariable Controls
- Estimation

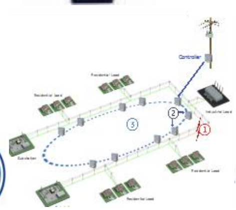
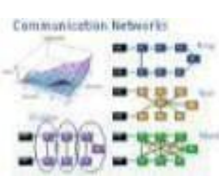

Real-Time Embedded Systems

- Hardware Architectures
- Real-Time Performance
- Hardware in the loop

Radio Freq. Instrumentation & Systems

- Electromagnetic Systems
- Integrated Instrumentation
- Novel Sensing Systems

Advanced Communication Systems

- Communication System Networks
- Software Defined Radio
- Signal Processing
- Source Coding and Compression

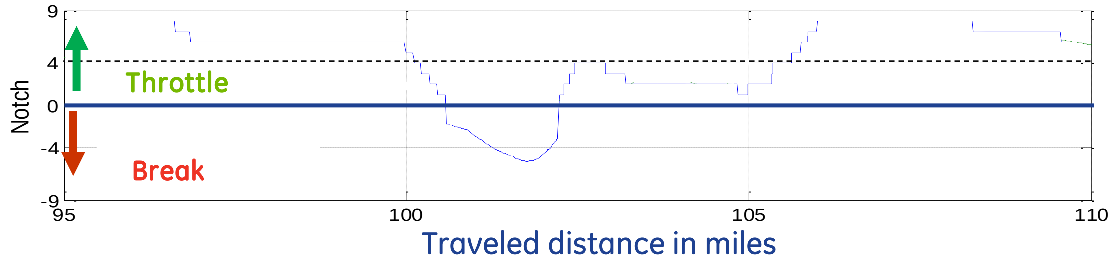
Transportation: Optimal train control

Optimize fuel utilization in every trip

The Problem

Online calculation of optimal acceleration and breaking

for fuel efficiency



Constraints

- Arrival timing
- Speed limits (mile per mile)
- Fuel reserves
- Maximum internal forces

Uncertainty/Variability

- Train weight
- Track conditions
- Other trains operation

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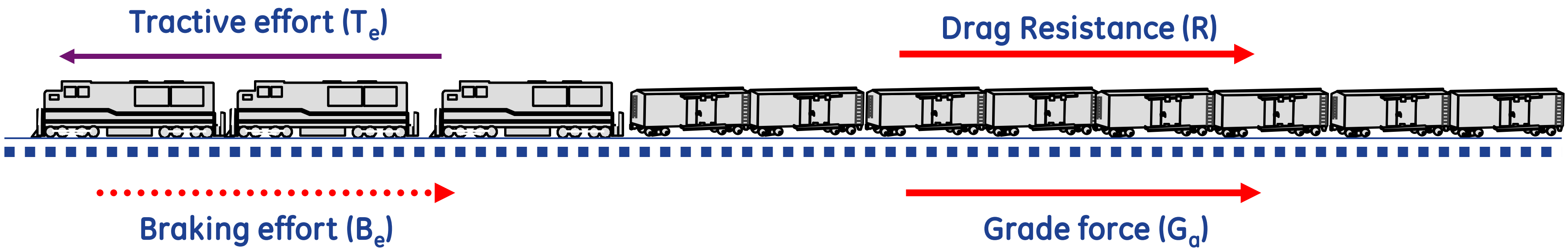
Approach: Online optimal control



Input Data

1. Trip details
- Departure and arrival locations
- Objective: min time or set pace
- Train manifest (load, consist)

2. Track database
- Speed restrictions
- Grade & Curvature
- GPS coordinates

3. Loco and Train Physics
- Power: TE, SFC, Braking
- Train: Weight, length, drag
- Equations of motion

Physics based optimization

$$\min_{u(t)} \alpha_1 \int_0^{t_f} Fuel(u(t))\,dt + \alpha_2 \int_0^{t_f} \dot{u}(t)^2\,dt + \alpha_3 t_f$$

subject to:

$$\dot{x}(t) = v(t)$$
$$\dot{v}(t) = \frac{1}{M}\left(T_e(u,v) - B_e(u,v) - G_a(x) - R(v)\right)$$
$$\dot{u}(t) = \frac{du(t)}{dt}$$
$$x(0) = x_0;\; x(t_f) = x_f$$
$$v(0) = v_0;\; v(t_f) = v_f$$
$$u(0) = u_0$$
$$0 \le v \le \text{speed limit}$$
$$0 \le t \le t_f$$

T_e : Tractive Effort
B_e : Braking Effort
R : Drag Resistance
G : Gradient Force

x_0, x_f : initial and final distance
v_0, v_f : initial and final speed
u_0 : initial notch
tf : maximum trip time

Calculated magnitudes

Driving plan vs. distance
- Optimal speed
- Optimal notch
- Expected arrival time
- Expected fuel use

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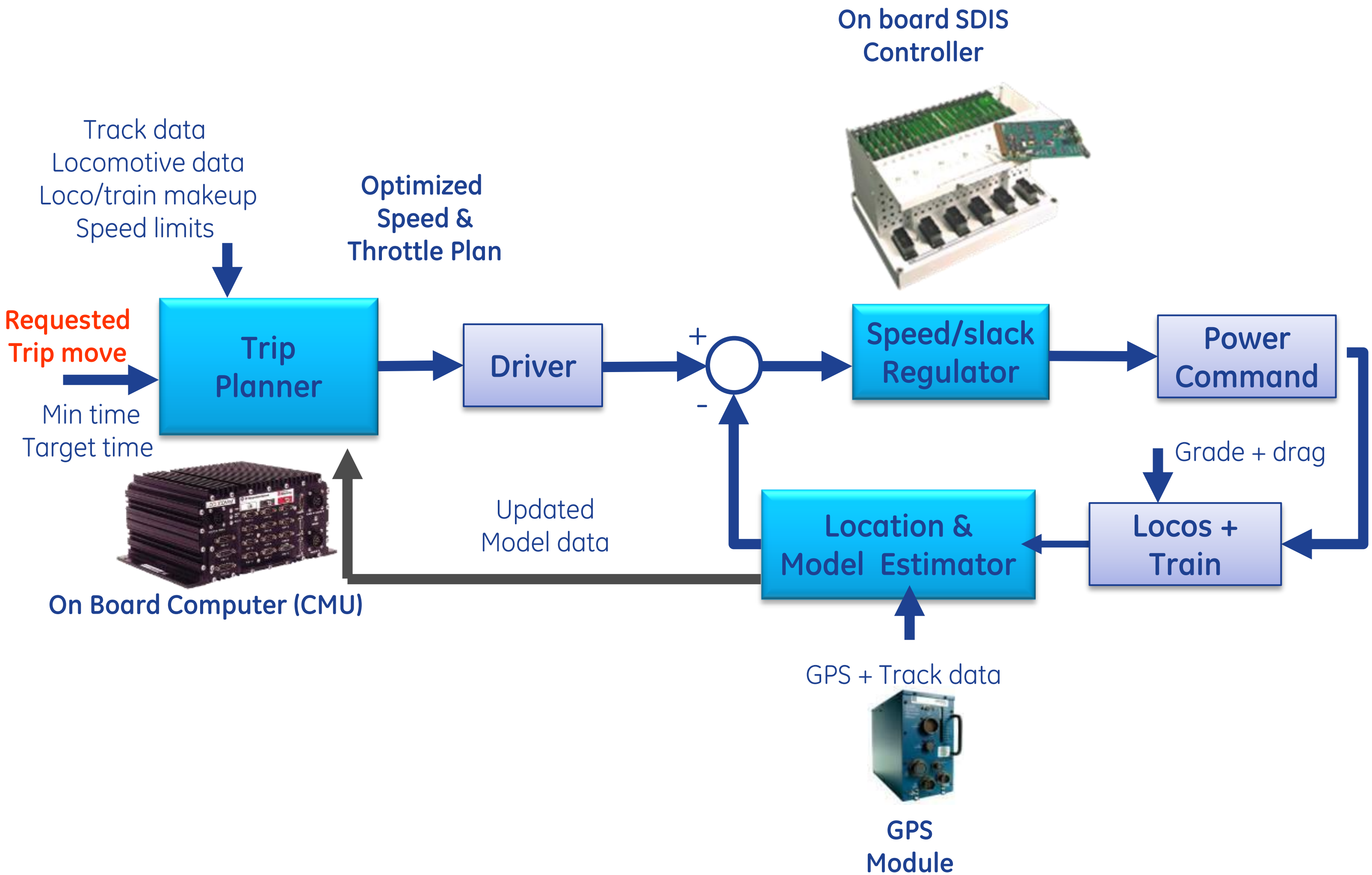
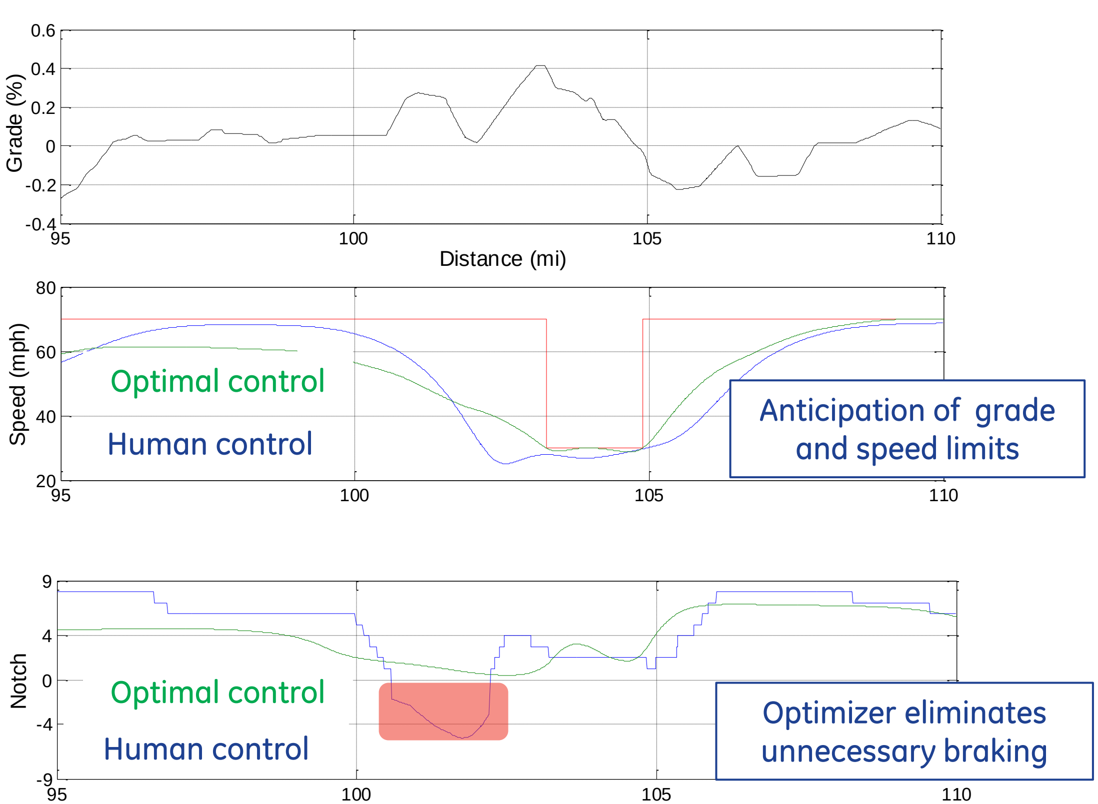
Implementation

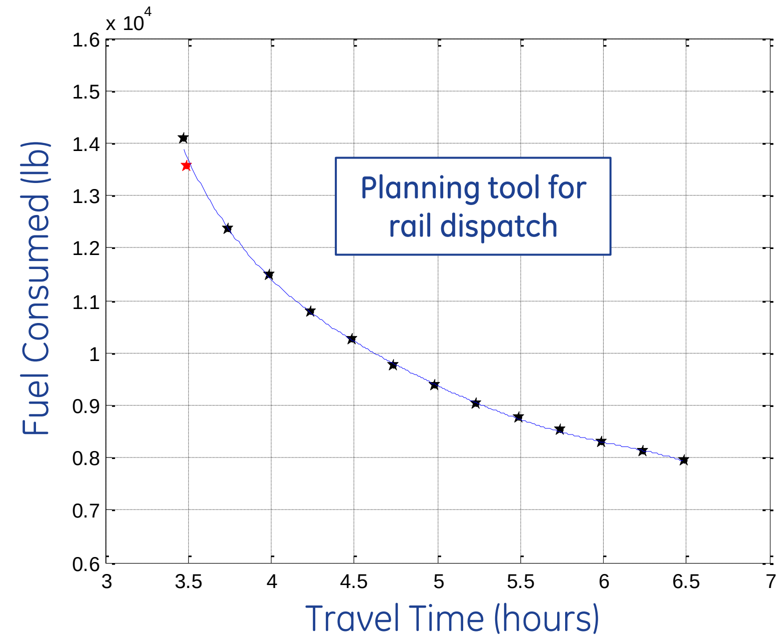


Results

Improvements from optimal control



Entitlement curve



Impact

- Runs on BSNF, CP, CSX, CN, coal, grain & general merchandise
- 97 Subdivisions, 17000 Track Miles
- **10+ % system-wide average fuel savings, no velocity impact**

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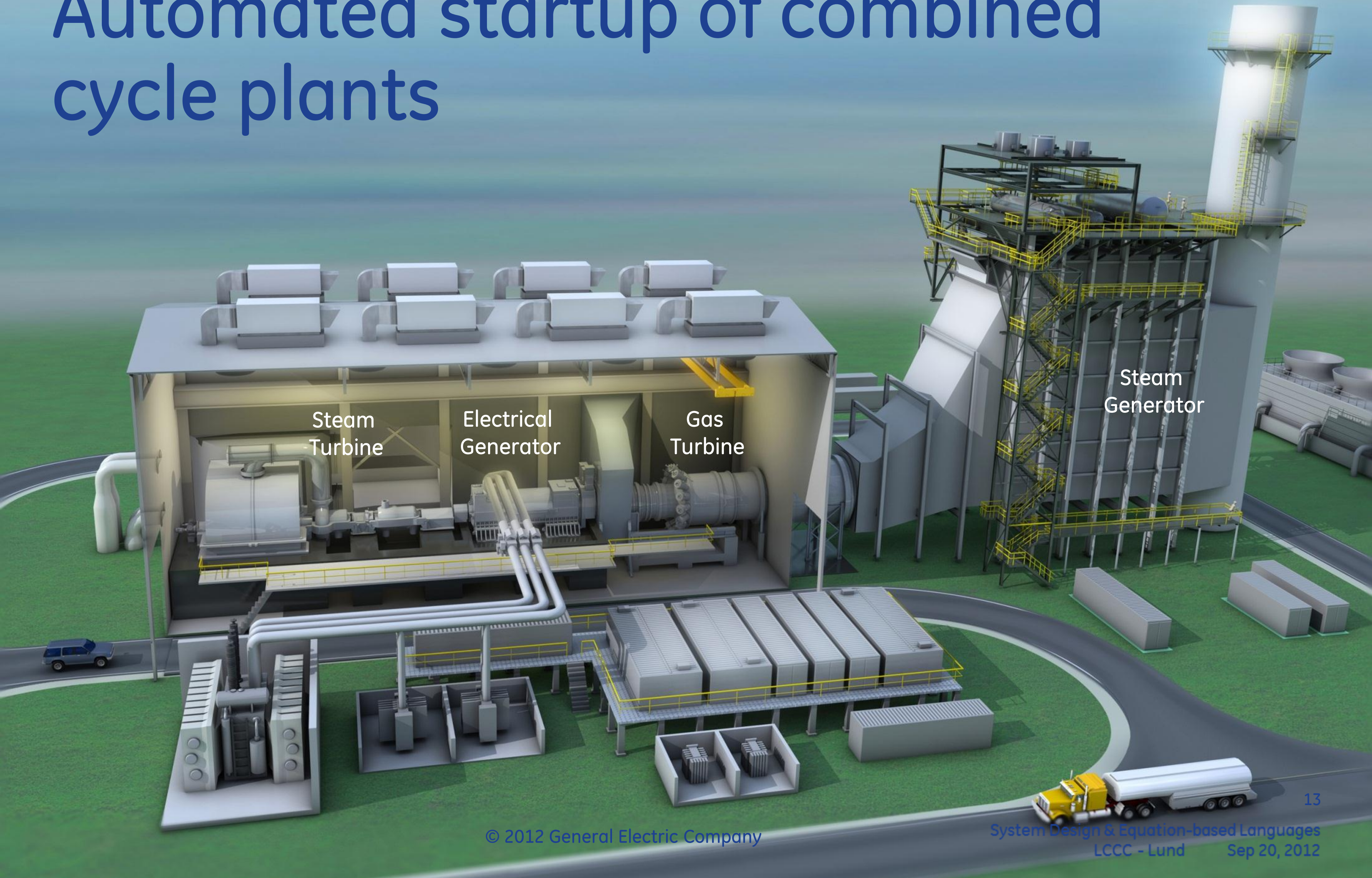
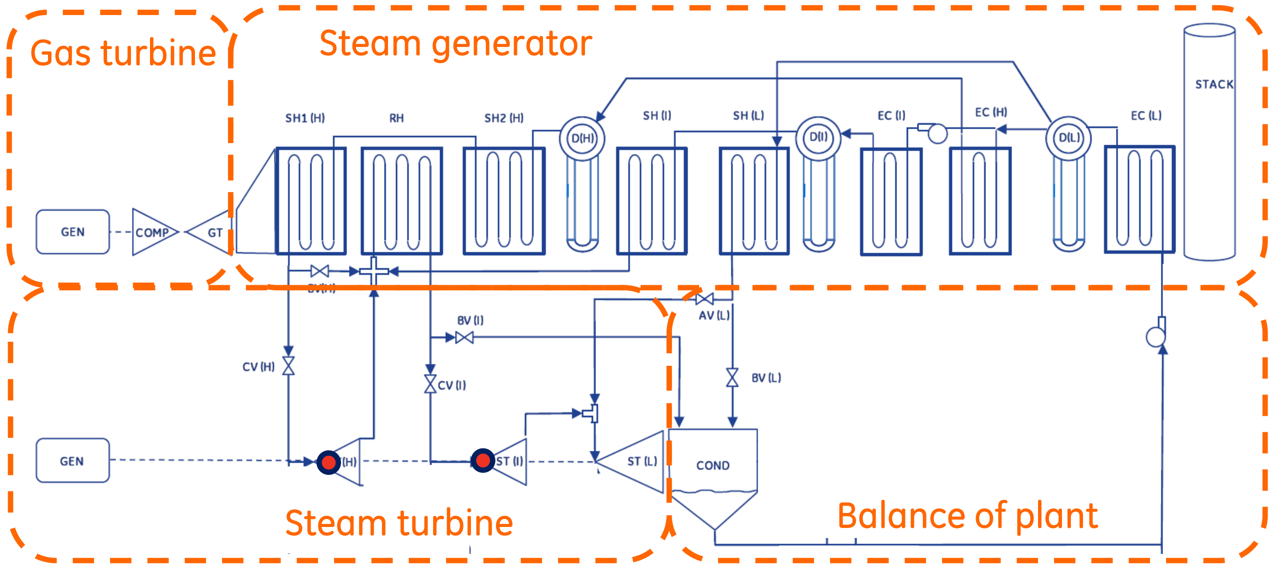
Power Generation: Automated startup of combined cycle plants



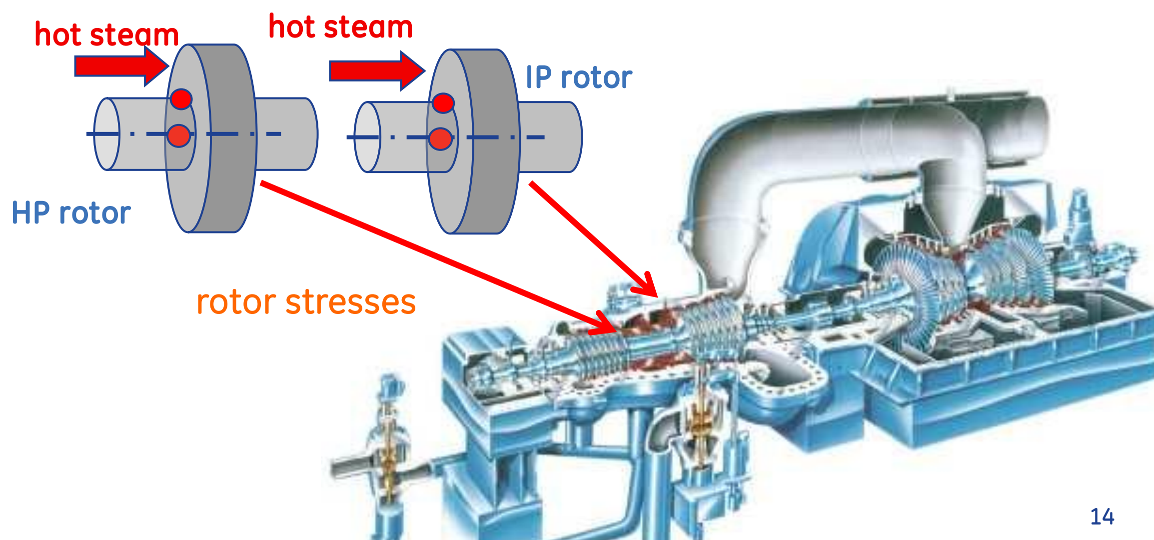
The startup problem

Online calculation of
optimal startup trajectories



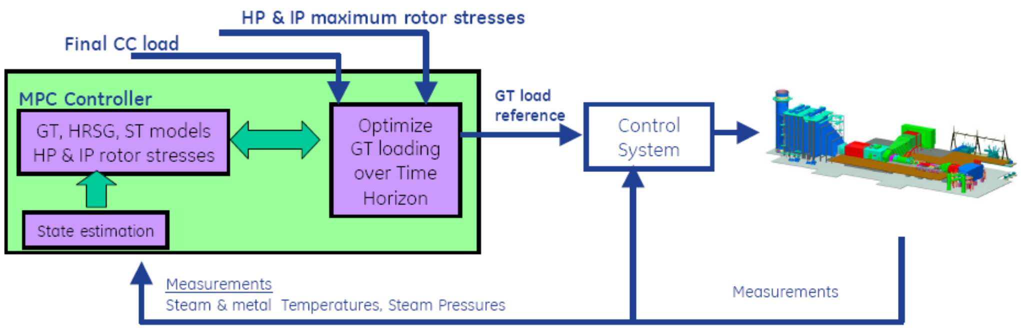
Constraints

- Thermal stresses (multiple)
- Turbine clearances
- Material temperatures
- Valve slew rates
- Drum levels
- Bearing thrust
- Emissions
- …

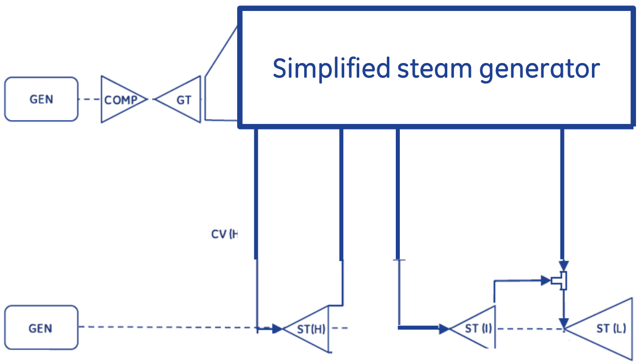


Approach: Model Predictive Control

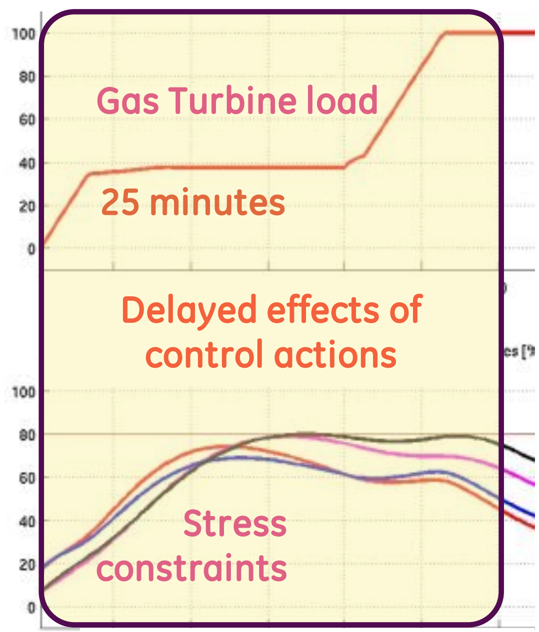
MPC framework



Simplified plant model



- Prediction horizon include dominant dynamics
- Receding horizon to address variation and uncertainty



- Reduced validity range due to model simplifications

Variation

- Plants with 1, 2 and 3 gas turbines
- Site specific temperature constraints
- Combinatorial start types with multiple turbines

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Approach: Optimization formulation

Input Data

1. Plant details
- Plant configuration
- Type of start
- Main controller algorithms
- Allowed stress

2. End of start
- Desired plant load

3. Combined cycle physics
- Turbine design parameters
- Steam generator time constants
- Allowable stress levels

Physics based optimization

$$\frac{1}{2}\sum_{k=1}^{N-1}\left[(x_k - x_{\text{ref}})^T Q_k (x_k - x_{\text{ref}}) + (u_k - u_{\text{ref}})^T R_k (u_k - u_{\text{ref}})\right] + \frac{1}{2}(x_N - x_{\text{ref}})^T Q_N (x_N - x_{\text{ref}})$$

subject to

$$x_{k+1} = A_k x_k + B_k u_k + F_k$$

dynamics

$$\begin{aligned} \sigma_{HP}^{\text{bore}} &\leq \sigma_{HP\ \max}^{\text{bore}} \\ \sigma_{HP}^{\text{surf}} &\leq \sigma_{HP\ \max}^{\text{surf}} \\ \sigma_{IP}^{\text{bore}} &\leq \sigma_{IP\ \max}^{\text{bore}} \\ \sigma_{IP}^{\text{surf}} &\leq \sigma_{IP\ \max}^{\text{surf}} \end{aligned}$$

stresses

$$0\% \leq u \leq 100\%$$

$$0 \leq \frac{du}{dt} \leq \dot{u}_{\max}$$

GT limits

$$A_k = \left.\frac{\partial f}{\partial x}\right|_{\bar{x}_k,\bar{u}_k} \quad B_k = \left.\frac{\partial f}{\partial u}\right|_{\bar{x}_k,\bar{u}_k}$$

Calculated magnitudes

Gas turbine load references
- Reference MW and exhaust temperature for 1, 2 or 3 turbines

Computational approach
- Euler discretization scheme
- Finite differencing sensitivities
- SQP optimization

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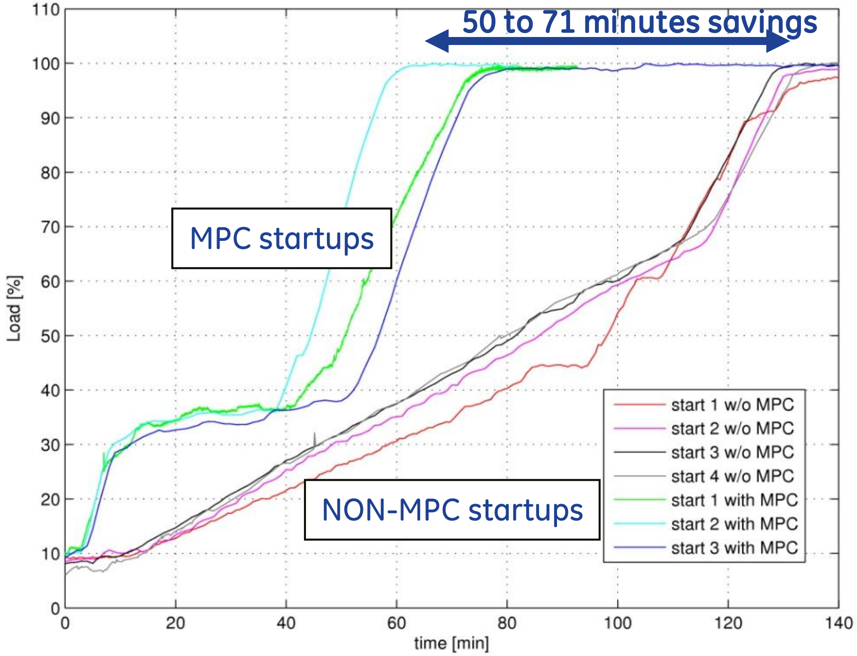
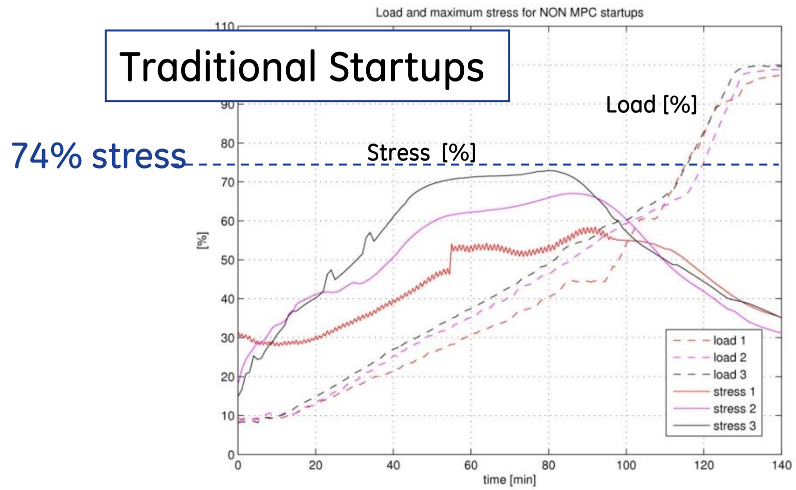
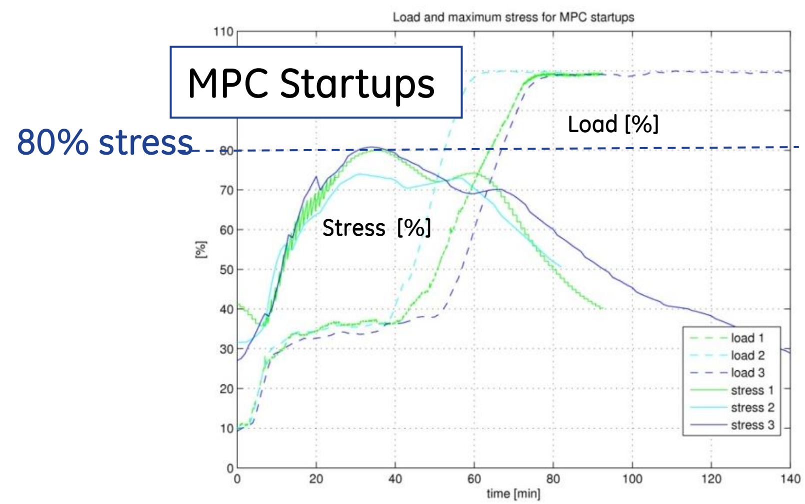
Implementation

MPC module **Main controller** **500 MW power plant**

Results







Typical benefits per start

- Time savings: **1 hour**
- Fuel (NG) savings: **70,000 lbm**
- Fuel cost reduction: **$10K**
- NOx reduction: **140 lbm**

Virtually no impact on life

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Trends

Calculations getting faster & cheaper

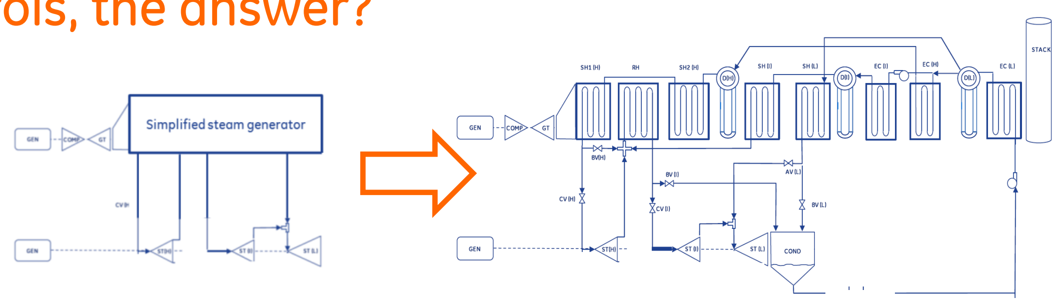
- Computing HW performance ↑
- Algorithms performance ↑
- Computing cost ↓

Increasing performance demands

- Competitiveness in market place
- Increased operation flexibility
- Transient efficiency
- Environmental regulations

Advanced Model Based Controls, the answer?

- More detailed physical models
- Rely more on optimization

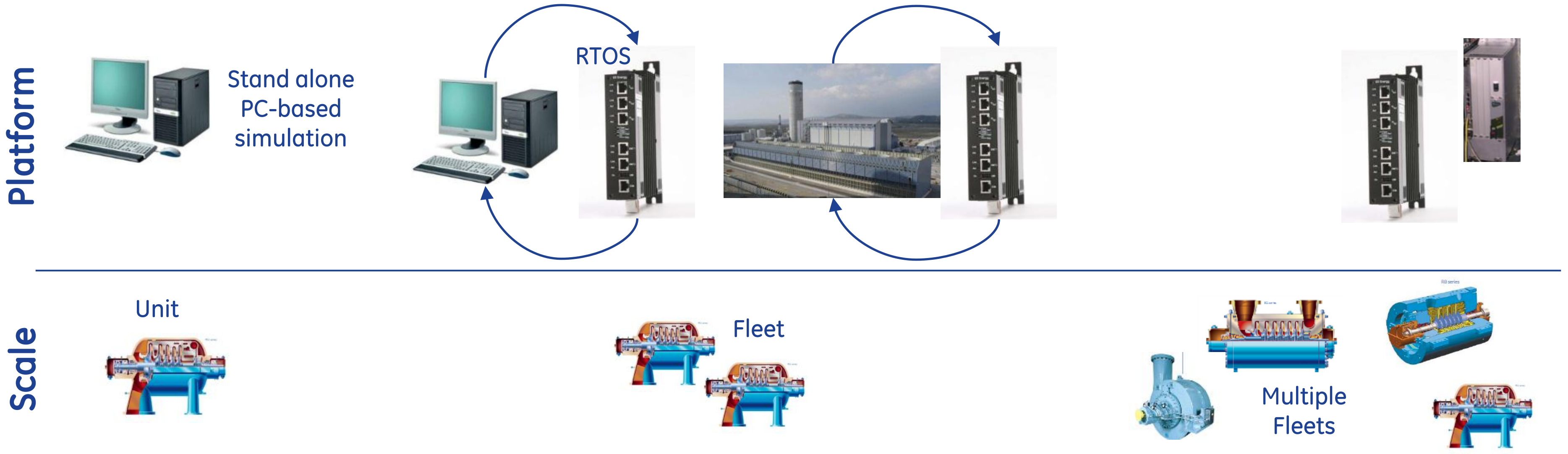


Significant challenges ahead …

Industrial Control Development

Idea → Feasibility analysis → Prototype development → Prototype field test → Product development → Commercialization

Research — **Product**



Challenges for model-based control products

- Time to market
- Cost & complexity → development, deployment, maintenance

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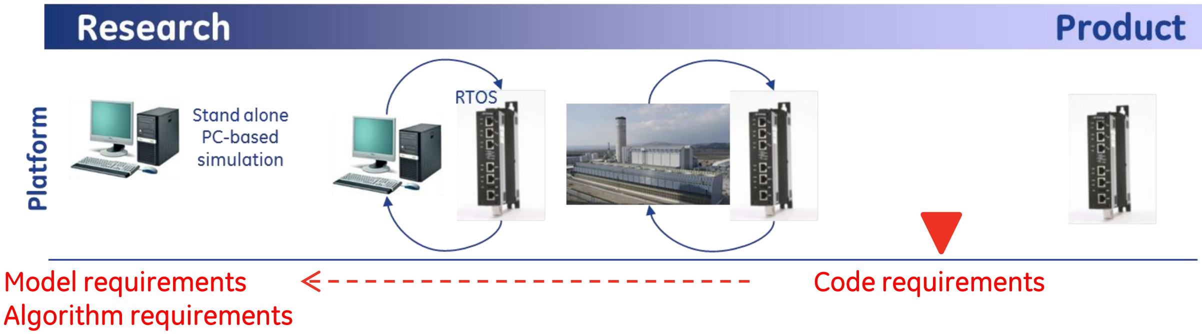
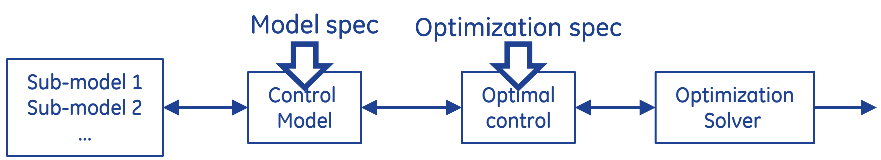
How can modeling help? SW reliability

WANT: Embed complex calculations
- Accurate models
- Online optimization process

NEED: Aids to get embedded code quality
- SW infrastructure
- Rigorous coding practice
- Testing as you go



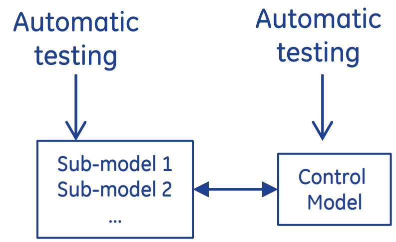


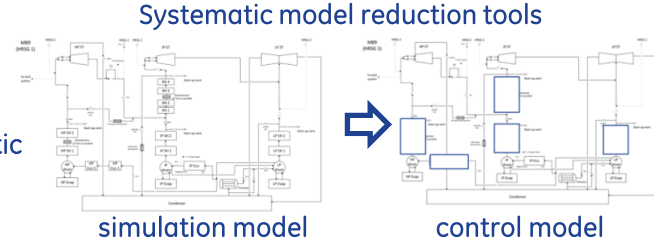
RTOS requirements	Modeling needs
Memory management	SW refactoring
Min math errors (i.e. MISRA compatible)	Code discipline (i.e., division by zero checks & handling)
	SW complexity analysis & policies
	SW test design (early, often)
Time consistency	Reduce/remove iterative calculations
	Profiling tools

How can modeling help? Function reliability & maintainability

WANT: Ensure physics is captured (always)
- Trust model in pre-defined operating envelope

NEED: Validation tools
- Test every branch ?
- Model compatibility checks
- Test vectors for every component & system models



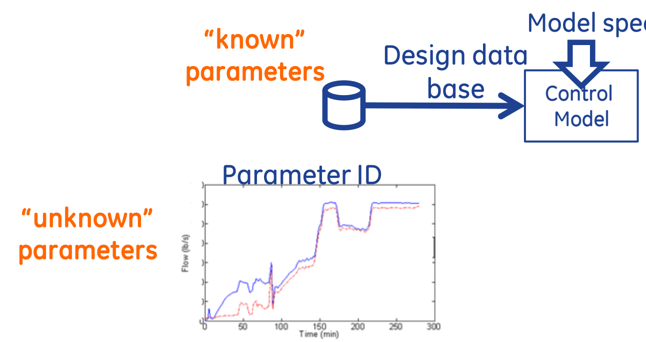


Maintainability requirements	Modeling needs
Physical correctness	Modeling discipline, assumptions tracking
	Functional verification during model development
	Continuity / smoothness of physical magnitudes
Low complexity	Integrated model reduction
	Tools for parameter reduction
	Tools to analyze/limit model complexity
Error diagnostics and traceability	Diagnostics capability in SW architecture
Consistency	Robust initialization tools

How can modeling help? Product dev. peed

WANT: Deployment speed
- Time to assemble, reconfigure system & validate system models

NEED: Requisition & tuning tools
- User skills << developer skills
- Remove the PhD out of the loop
- Finite commissioning time
- Execute with limited information



Productization requirements	Modeling needs
Ease for reconfiguration	Configuration tools based on requirements
Fast requisition	Integrated requisition tools with design dbase
	Model tuning tools, i.e. parameter ID
Functional test	Definition of system level test vectors
	Testing plan, auto-testing tools

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Summary

- Model Based Control to boost performance in industrial applications
- MBC solutions are as good as models allow
- For MBC to be competitive, models need to
  - Reduce development cost & time
  - Ensure maintainability
- Good modeling practices & tools are essential for viable products

Need tools to accelerate transfer of academic solutions into industrial products