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Equation-based Modeling and Control of Industrial Processes

A Global Leader in Power and Automation Technologies
Leading Market Positions in Main Businesses

- 135,000 employees in about 100 countries
- $38 billion in revenue (2011)
- Formed in 1988 merger of Swiss and Swedish engineering companies
- Predecessors founded in 1883 and 1891
- Publicly owned company with head office in Switzerland

How ABB is organized
Five global divisions



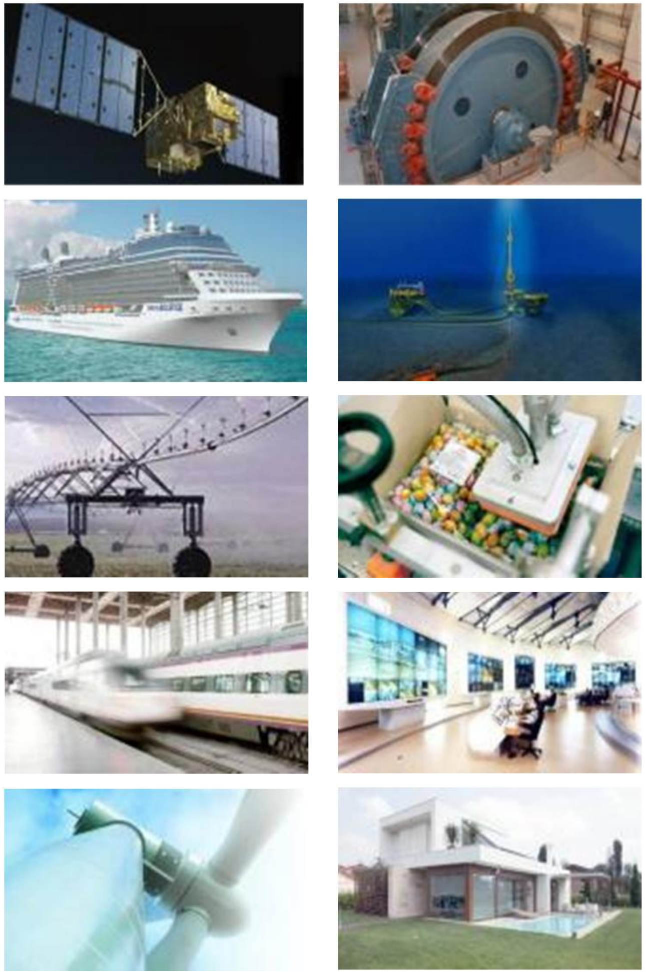


Power Products	Power Systems	Discrete Automation and Motion	Low Voltage Products	Process Automation
$10.3 billion 35,000 employees	$7.7 billion 19,500 employees	$8.4 billion 27,500 employees	$5.0 billion 21,000 employees	$7.8 billion 28,500 employees

(2011 revenues, consolidated)

- **ABB's portfolio covers:**
  - Electricals, automation, controls and instrumentation for power generation and industrial processes
  - Power transmission
  - Distribution solutions
  - Low-voltage products
  - Motors and drives
  - Intelligent building systems
  - Robots and robot systems
  - Services to improve customers productivity and reliability

Power and automation are all around us
You will find ABB technology…



orbiting the earth and working beneath it,

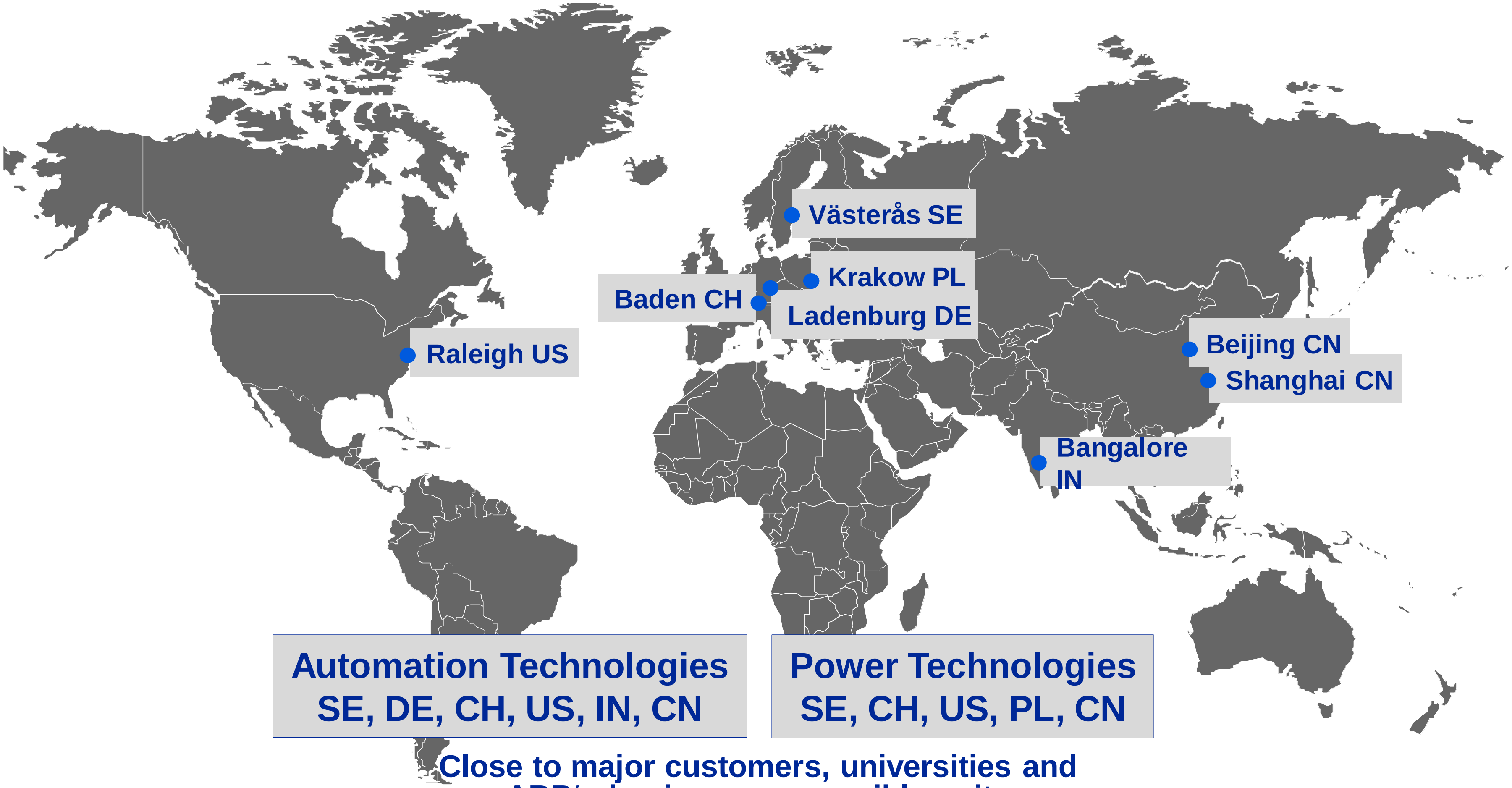
crossing oceans and on the sea bed,

in the fields that grow our crops and packing the food we eat,

on the trains we ride and in the facilities that process our water,

in the plants that generate our power and in our homes, offices and factories

Global Labs…
… and Local Lab Locations



Automation Technologies
SE, DE, CH, US, IN, CN

Power Technologies
SE, CH, US, PL, CN

Close to major customers, universities and ABB‘s business responsible units

Global Labs, Corporate Programs and Locations
700 Researchers World-Wide – 250 in Västerås/Oslo

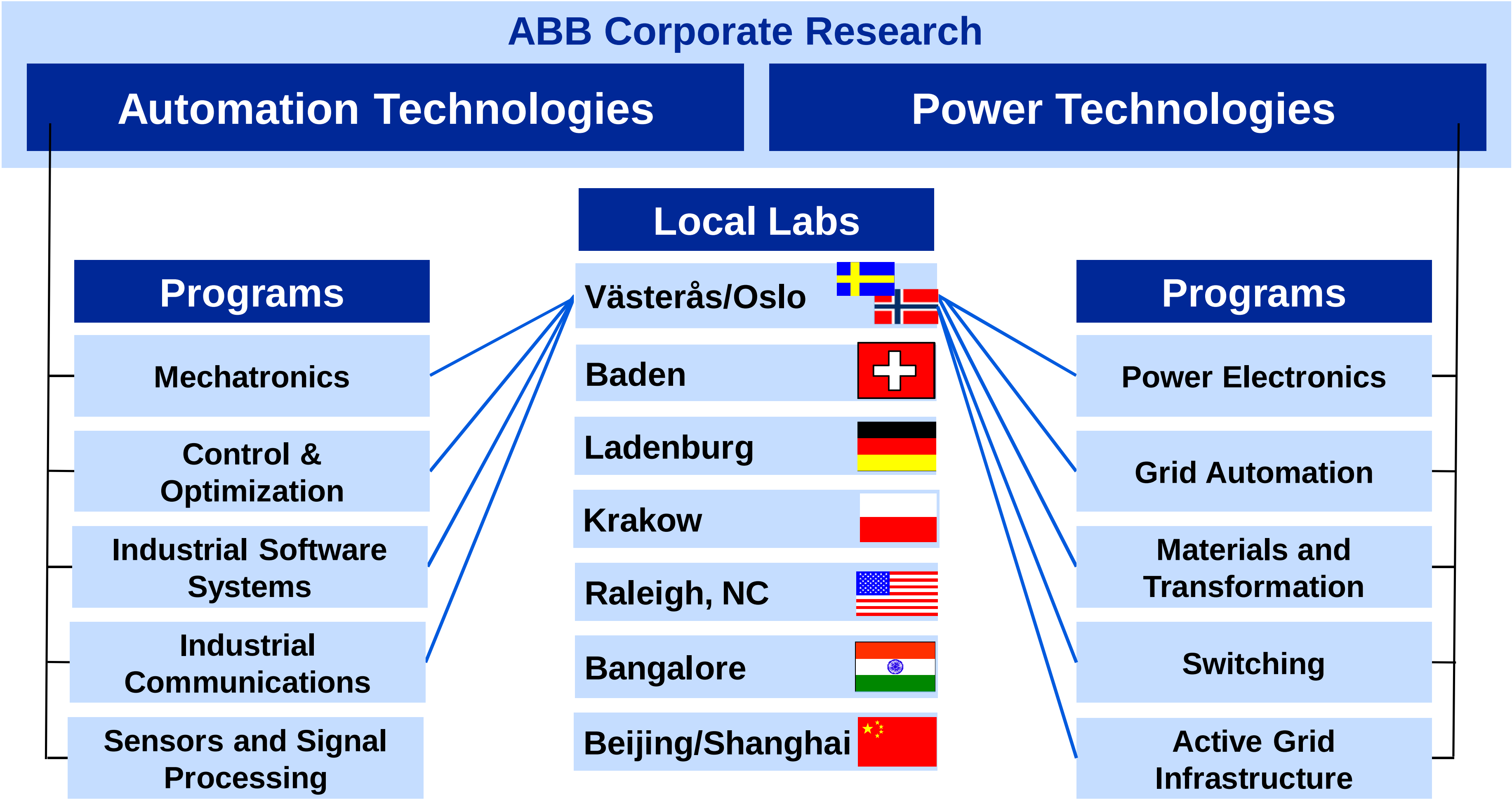


ABB Corporate Research

Automation Technologies

Power Technologies

Local Labs
- Västerås/Oslo
- Baden
- Ladenburg
- Krakow
- Raleigh, NC
- Bangalore
- Beijing/Shanghai

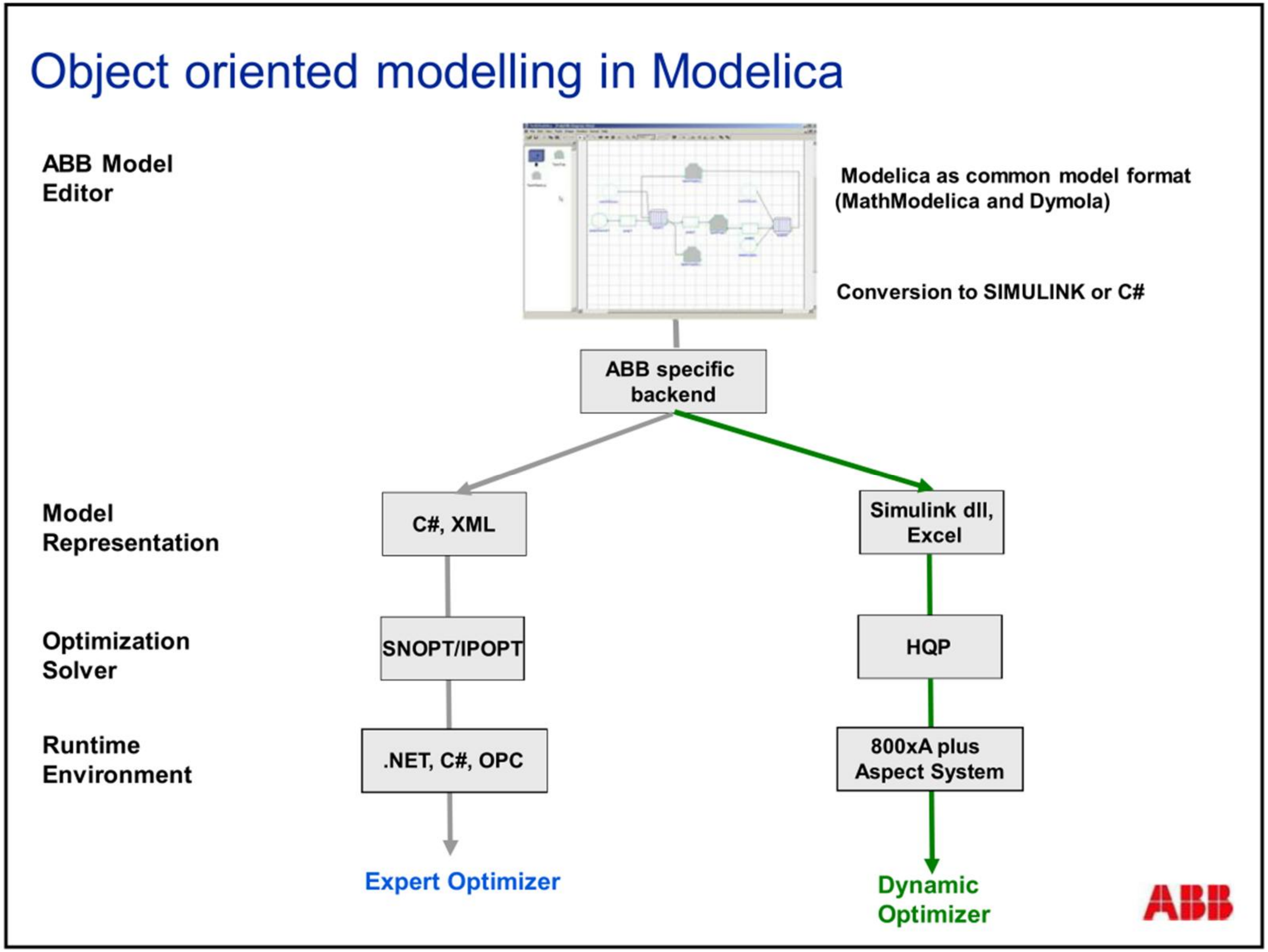
Programs (Automation Technologies)
- Mechatronics
- Control & Optimization
- Industrial Software Systems
- Industrial Communications
- Sensors and Signal Processing

Programs (Power Technologies)
- Power Electronics
- Grid Automation
- Materials and Transformation
- Switching
- Active Grid Infrastructure

Examples of Industrial Systems modeled using an Equation-based Approach at ABB

- Pulp & paper
- Metals & minerals
- Mechatronical systems
- Power generation
- Power products
- Power systems
- …

Tools for Equation-based Simulation and Control
Modelica



Object oriented modelling in Modelica

ABB Model Editor

Modelica as common model format (MathModelica and Dymola)

Conversion to SIMULINK or C#

ABB specific backend

Model Representation

C#, XML

Simulink dll, Excel

Optimization Solver

SNOPT/IPOPT

HQP

Runtime Environment

.NET, C#, OPC

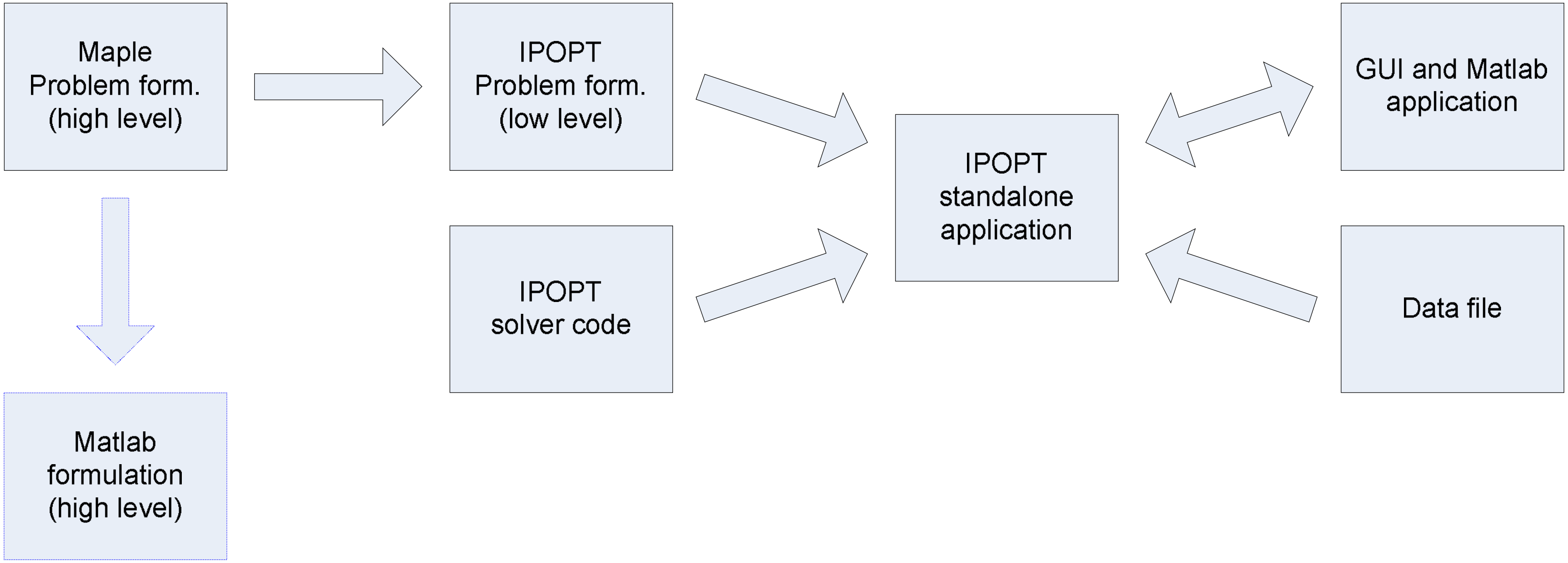
800xA plus Aspect System

Expert Optimizer

Dynamic Optimizer

Tools for Equation-based Simulation and Control

Maple to IPOPT



Maple
Problem form.
(high level)

IPOPT
Problem form.
(low level)

IPOPT
solver code

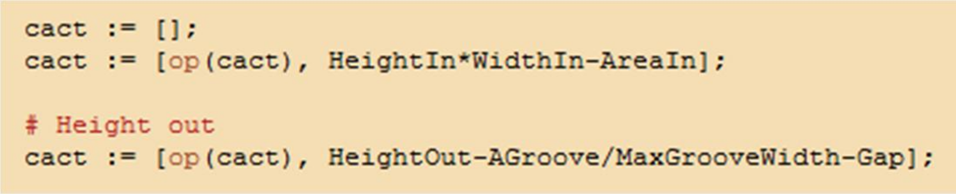
IPOPT
standalone
application

GUI and Matlab
application

Data file

Matlab
formulation
(high level)

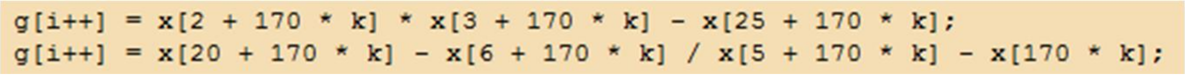
- **Maple (high level description)**



```
cact := [];
cact := [op(cact), HeightIn*WidthIn-AreaIn];

# Height out
cact := [op(cact), HeightOut-AGroove/MaxGrooveWidth-Gap];
```

- **IPOPT (low level description)**



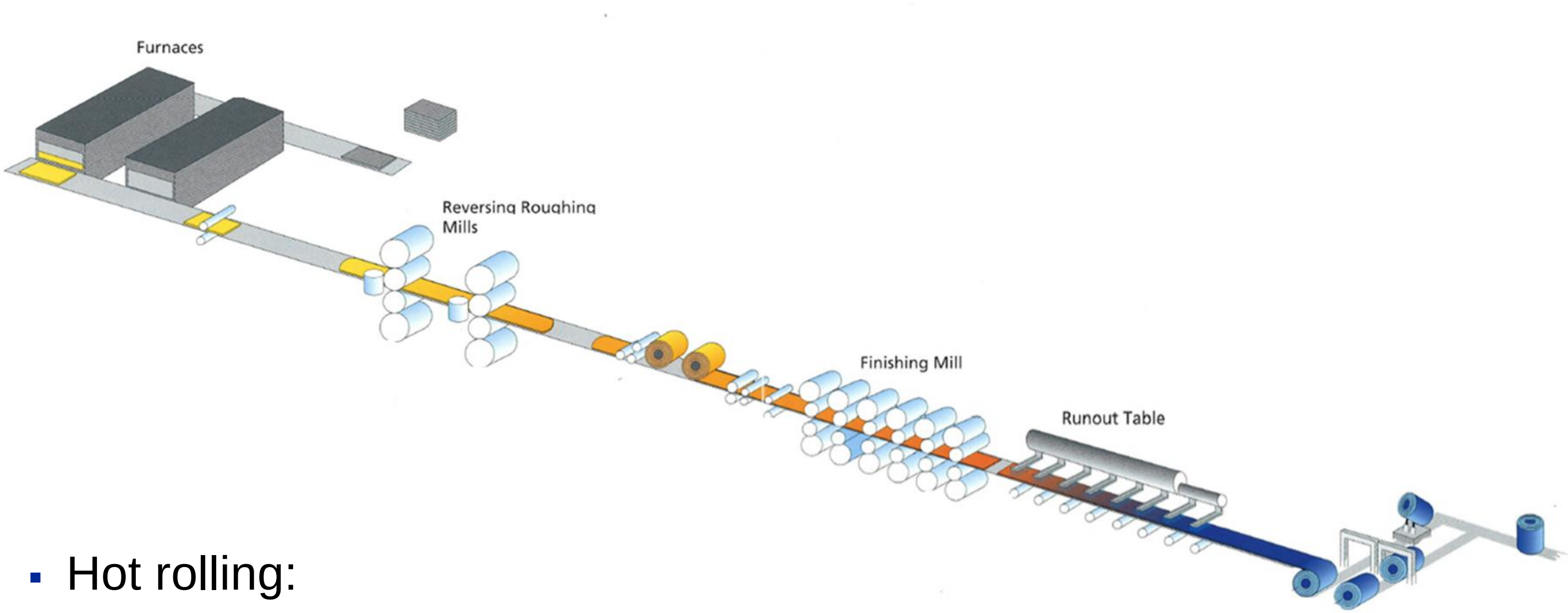
```
g[i++] = x[2 + 170 * k] * x[3 + 170 * k] - x[25 + 170 * k];
g[i++] = x[20 + 170 * k] - x[6 + 170 * k] / x[5 + 170 * k] - x[170 * k];
```

Optimization of Hot Rolling

(Energy) Optimization in Hot Rolling Mills
Huge Potential

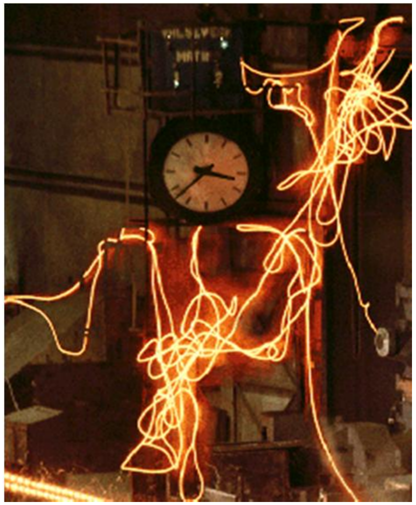
- Profile mills:
  - 7% reduction => 1.2 GWh/yr (>1000 profile mills globally)
- Flat mills:
  - 0,5% reduction => 1.6 GWh/yr (~400 flat mills globally)

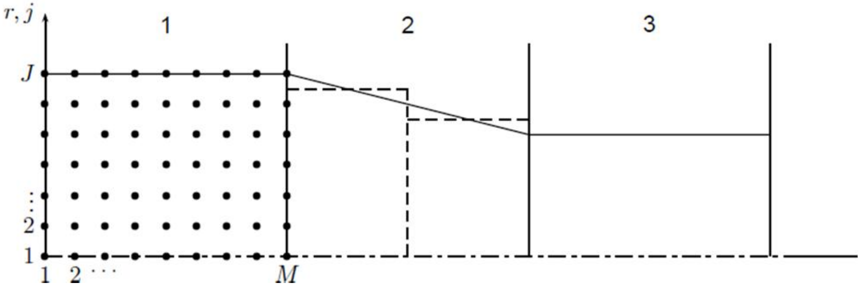
Introduction to Hot Rolling

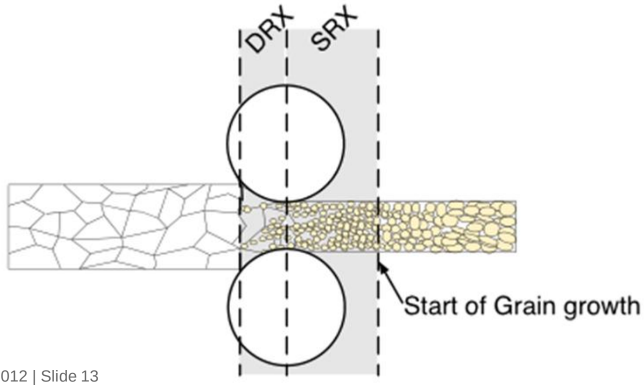


- Hot rolling:
  - Temperature above the recrystallization temperature. (otherwise cold rolling).
- Profile rolling
  - To produce rods, bars, wires, etc.

Process Model





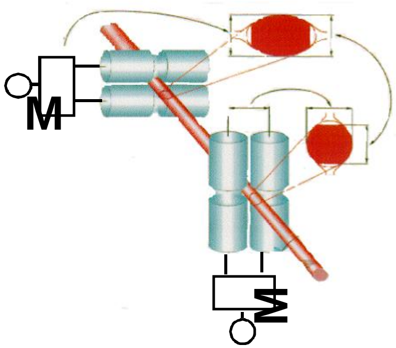


- Covers room temperature to room temperature

- The model includes for instance
  - Mass balance, rolling geometries, power, groove utilization, temperature field, microstructure of material

- Model properties:
  - Large but sparse
  - Discontinuities due to switching behavior
  - Bad numerical scaling of certain equations

Optimization Formulation



$$\min f(v, g, htc, T_0, \mathcal{X})$$

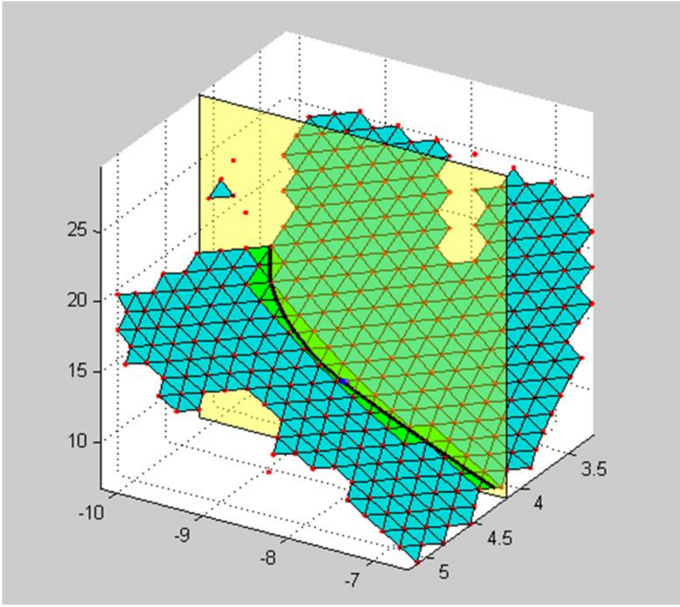
$$\text{s.t.} \quad \left.\begin{array}{l} c_i(v, g, htc, T_0, \mathcal{X}) = 0, \ i \in \mathcal{E} \\ c_i(v, g, htc, T_0, \mathcal{X}) \geq 0, \ i \in \mathcal{I} \end{array}\right\} \approx 700 + 45$$

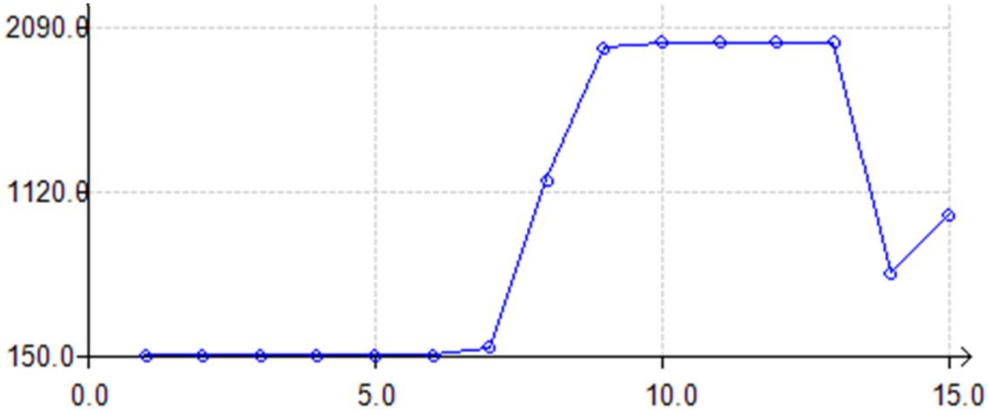
$$A(htc, \mathcal{X})T^{m+1} = b(T^m, htc, \mathcal{X})\} \approx 10000 - 100000$$

$$\begin{aligned} v &= \text{roll speed} \\ g &= \text{gap} \\ T_0 &= \text{furnace temperatures} \\ htc &= \text{heat transfer coefficients} \\ \mathcal{X} &= \text{intermediate variables and} \\ &\quad\ \text{parameters such as } T_j,\ \sigma, \ldots \end{aligned}$$

Multiobjective Optimization

- Real life: Compromise between different objectives:
  - Total power
  - Austenite grain size (related to strength of material)
  - Production speed
- Pareto front analysis yields many insights, for instance, for the cooling.
  - Grain size reduction requires cooling. For low energy consumption, start from behind.





Optimization & Optimal control are important but…
Hardware-in-the-loop

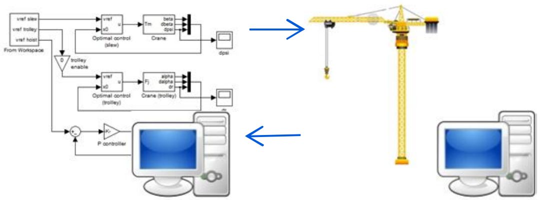

Winch


Deck crane


Indoor crane


Tower crane


Harbor crane

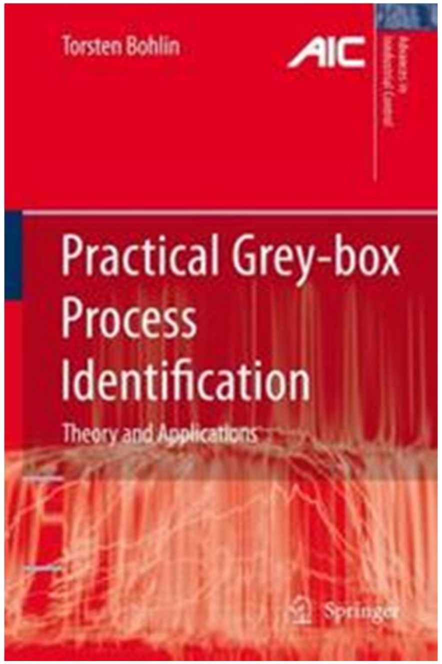

Control code development based on mathematical representation of application (e.g. tower crane) using Modelica


Control code verification using hardware (Drive, PLC) in the loop


Site test of new automation solutions

Optimization & Optimal control are important but…

System Identification - Grey-box identification



Book by Torsten Bohlin
Springer, 2006

- In an optimization project, modelling is by far the most time-consuming part
- Physical model should be gradually extended while testing statistical significance against experimental data
- Estimation of parameters using horizon estimation (HE) gives biased parameters without the right regularization in many cases.

$$\min_{x_k,\theta} \frac{1}{2}\sum_{k=0}^{N} w_k^T Q^{-1} w_k + v_k^T R^{-1} v_k + \log(\det(S_k(\theta)))$$

$$\begin{aligned} \text{s.t. } x_{k+1} &= f(x_k, u_k) + w_k \\ y_k &= h(x_k, u_k) + v_k \\ x(0) &= x_0 \end{aligned}$$

Equation-based Modeling and Control for Industry
Conclusions

- Modeling
  - More and more use of first principle modeling
  - Requires considerable knowledge to succeed – process as well as theoretical
- Optimization
  - Optimization and decision support are slowly gaining ground
  - Increased competition will force more and more optimization solutions
  - More plant-wide & wider scope (production scheduling etc)
  - Optimal solution often used for comparison, not for the actual control

Equation-based Modeling and Control for Industry
Conclusions, cont’d.

- Identification
  - Parameter identification is not supported enough yet.
- Virtualization
  - Hardware-In-the-Loop / training simulators gain popularity
- Generally
  - Ease of use (incl. look-and-feel)
  - Model management
  - Integration (process, data, tool etc)

Power and productivity
for a better world™

Proposed grey-box scheme for nonlinear systems

1. Model process in Modelica
2. Discretize symbolically and export equations
3. Linearize model symbolically
4. Import and prepare data
5. Carefully introduce noise variables at equations motivated by physical insight
6. Solve by nonlinear programming (e.g. using IPOPT)

$$\min_{x_k,\theta} V = \frac{1}{2}\sum_{k=0}^{N}(w_k^T Q^{-1} w_k + v_k^T R^{-1} v_k + \log(\det(S_k(\theta)))$$

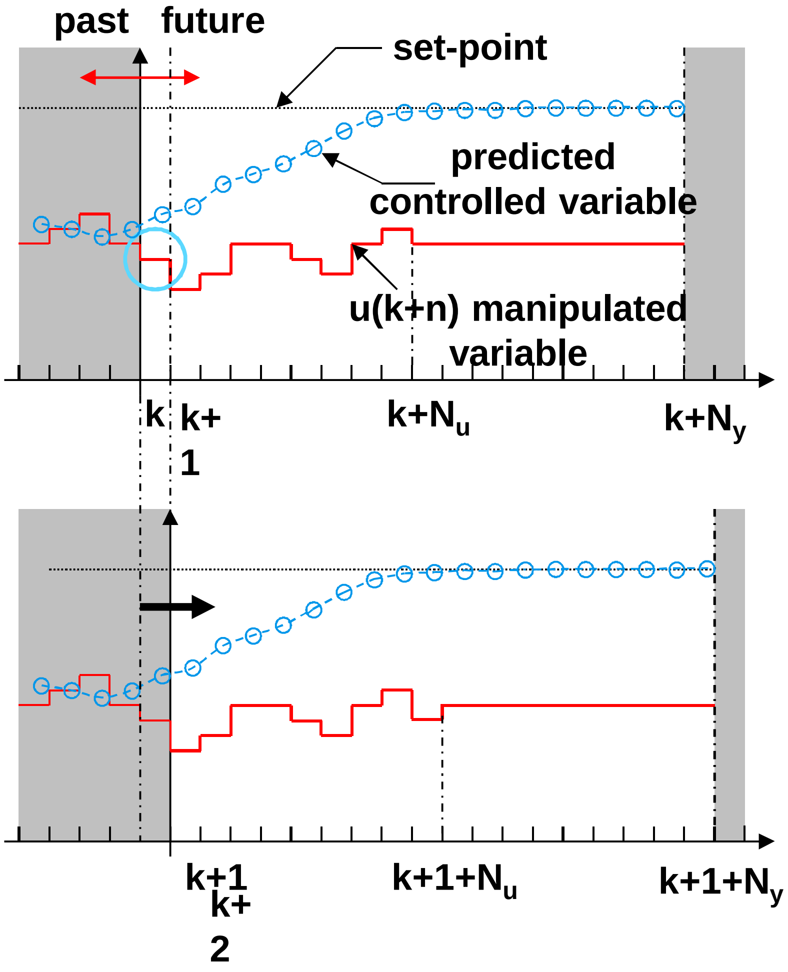
subject to

$$x_{k+1} = g(x_k, u_k) + w_k$$

$$y_k = h(x_k, u_k) + v_k$$

7. For every evaluation of V calculate the (time varying) linearized system along the trajectory to compute S_k
8. Test which parameters to make free (including noise parameters) by hypothesis testing using the chi-squared risk calculation
9. Repeat 5-8 until no further improvement

Model Predictive Control (MPC) Algorithm



Use model to

- Estimate where you are – state estimation
- Optimize future control signals over a time horizon

- Repeat at next sampling instant
- Shift horizon one step – receding horizon control