



R. Franke, PSP-A24, 02.02.2015

OpenModelica Annual Workshop 2015

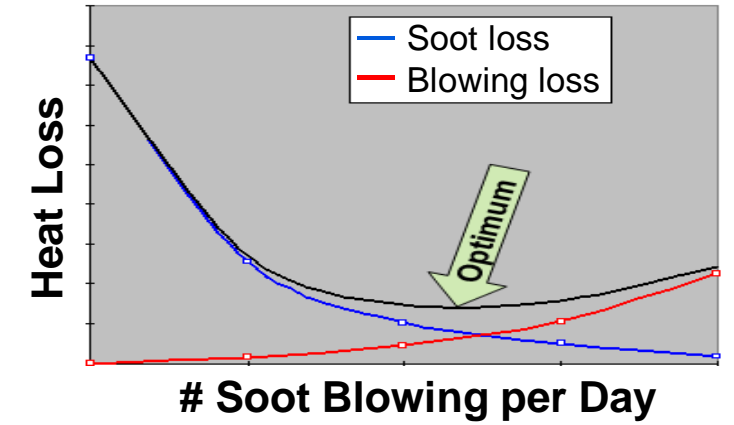
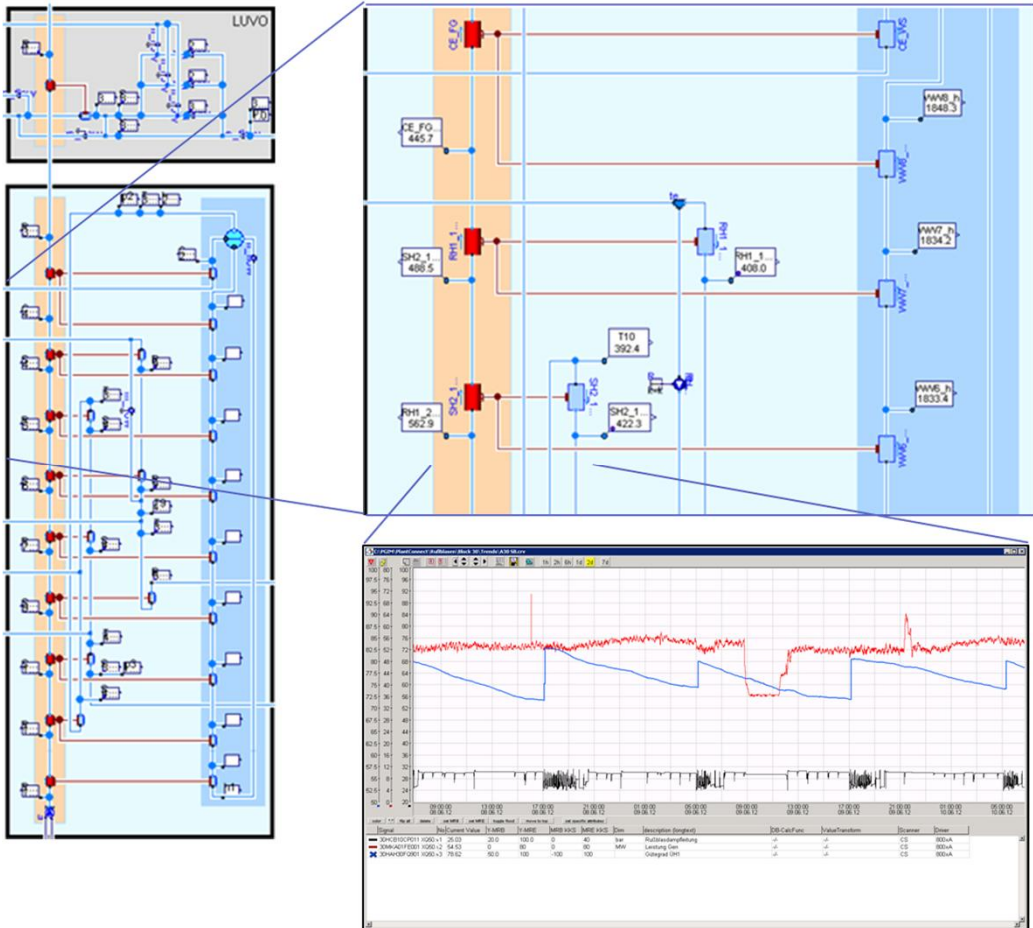
Mathematical Optimization of Dynamic Systems with OpenModelica

Overview

- Introduction to ABB OPTIMAX
- DrumBoiler example
 1. Setpoint optimization
 2. Startup optimization
- Formulation of optimization programs in Modelica
- FMI
- Industrial applications
 - Industrial power plant exploiting FMI 2.0
 - Large-scale virtual power plant exploiting OpenModelica with FMI 2.0

OPTIMAX[®] SootBlowMax

Sootblowing optimization boiler



Task

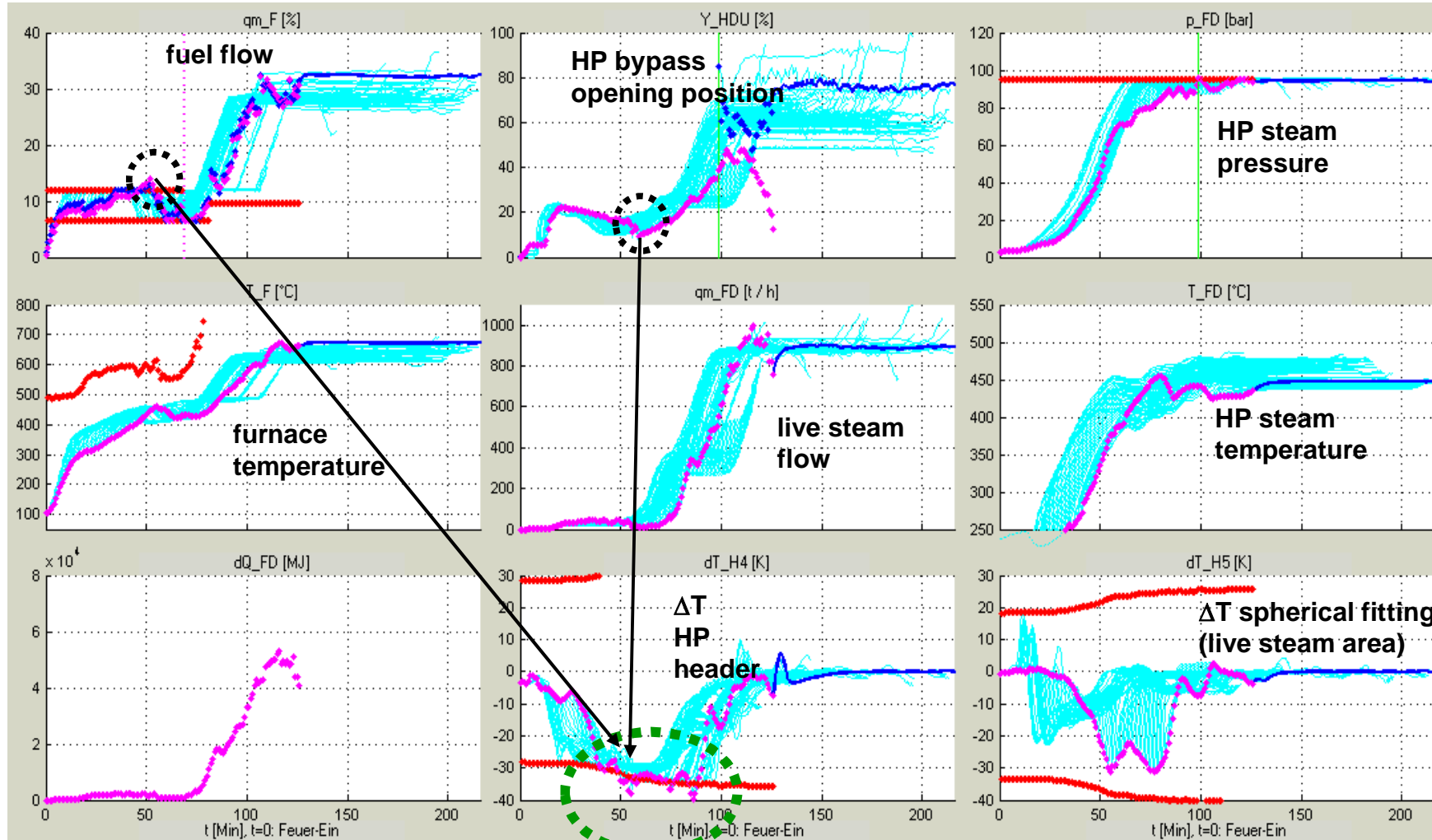
- Decide on optimal sootblowing sequences maximizing efficiency

Solution

- Model of complete boiler (basing on Modelica.Fluid)
- Exploit overall mass and energy balance to replace missing measurements on flue gas side
- Online calculation of heat transfer coefficients between flue gas side and water/steam side

OPTIMAX[®] BoilerMax

Startup optimization boiler



Task

- Minimize fuel costs and startup time subject to thermal stress constraints

Solution

- NMPC for boiler startup

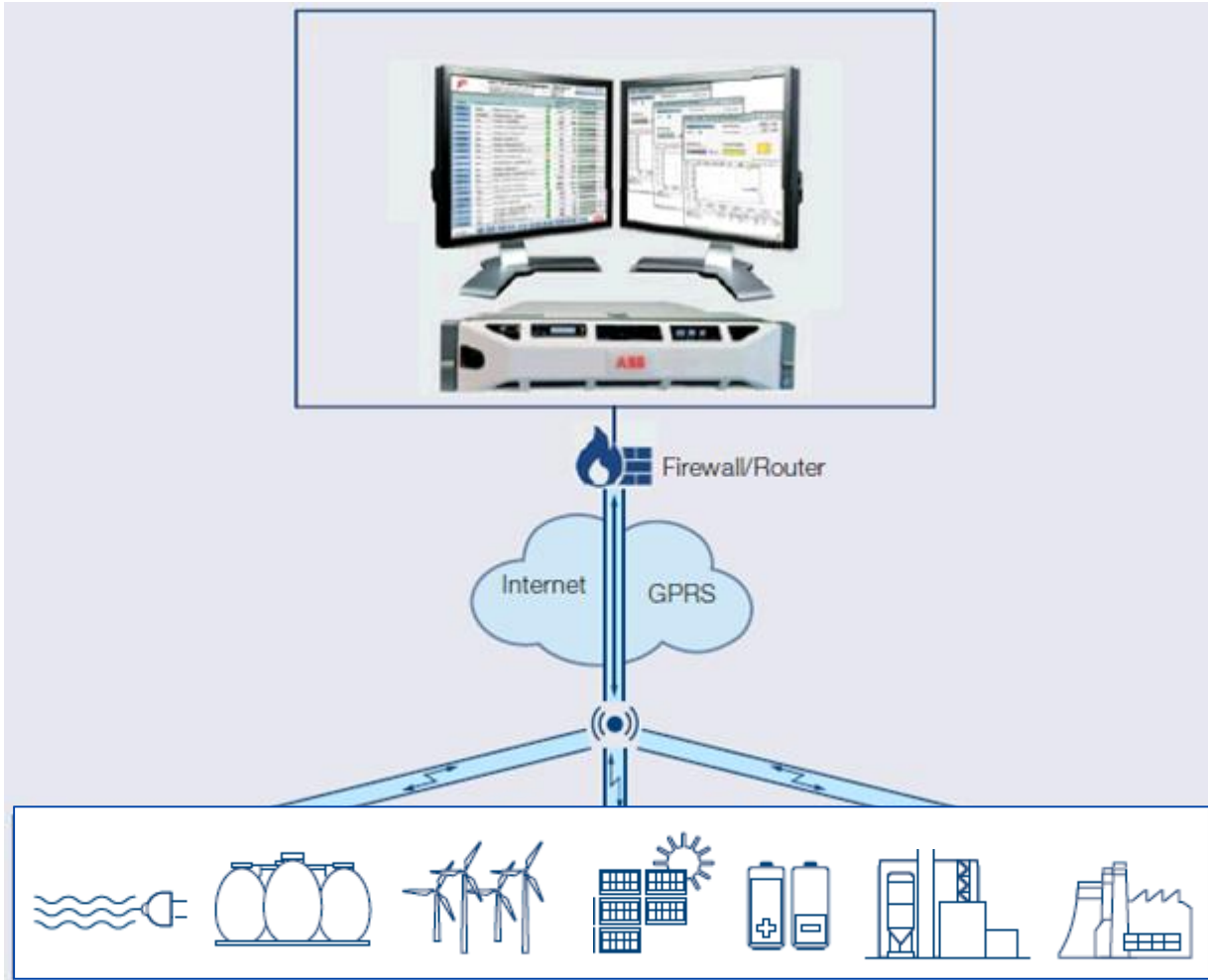
Graphics:

- Blue lines: optimized predictions, updated every minute
- Magenta points: actual operating points

See: <https://www.modelica.org/events/modelica2006/Proceedings/sessions/Session3c2.pdf>

OPTIMAX[®] PowerFit

Optimizing control of Virtual Power Plants and MicroGrids



Task

- Aggregate many small production units and treat them like one big power plant
- Exploit multiple forms of energy (e.g. el and heat) and storages

Solution

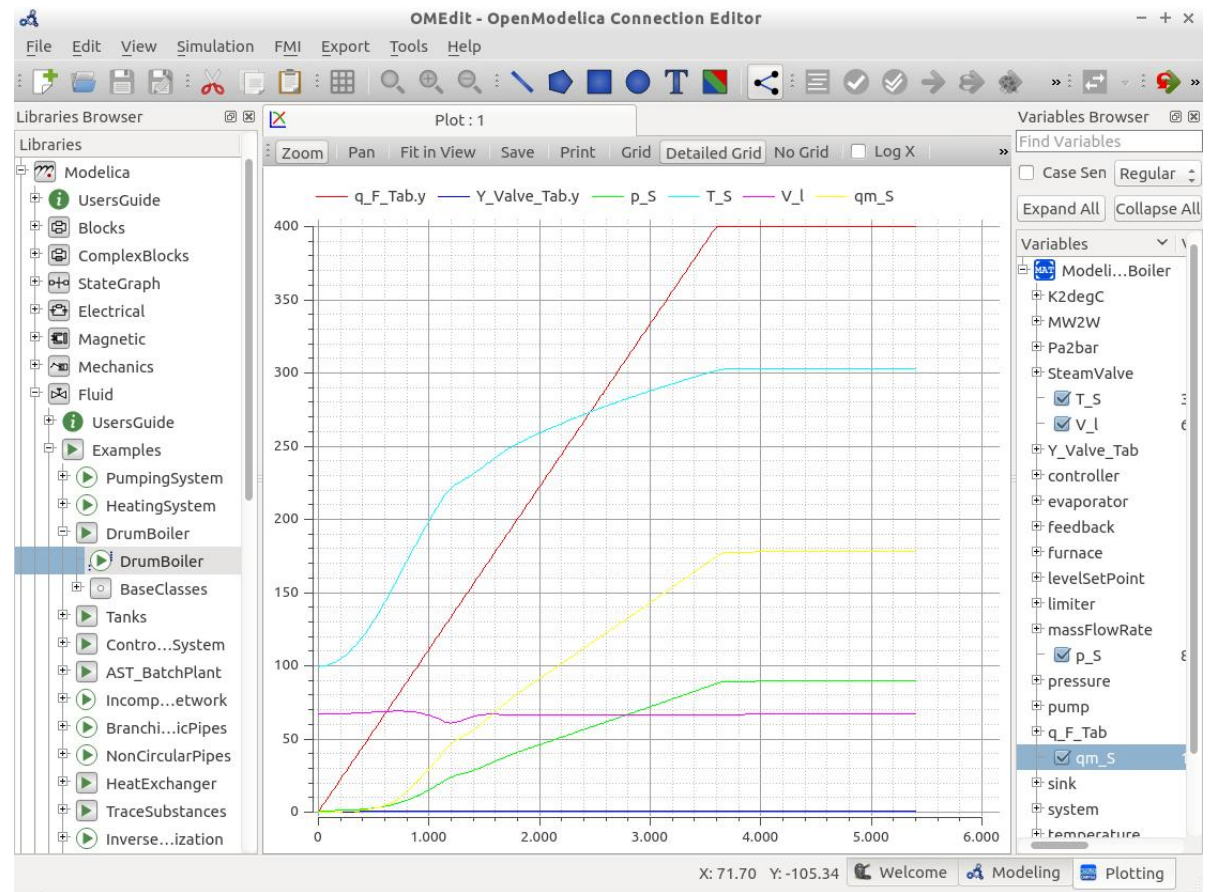
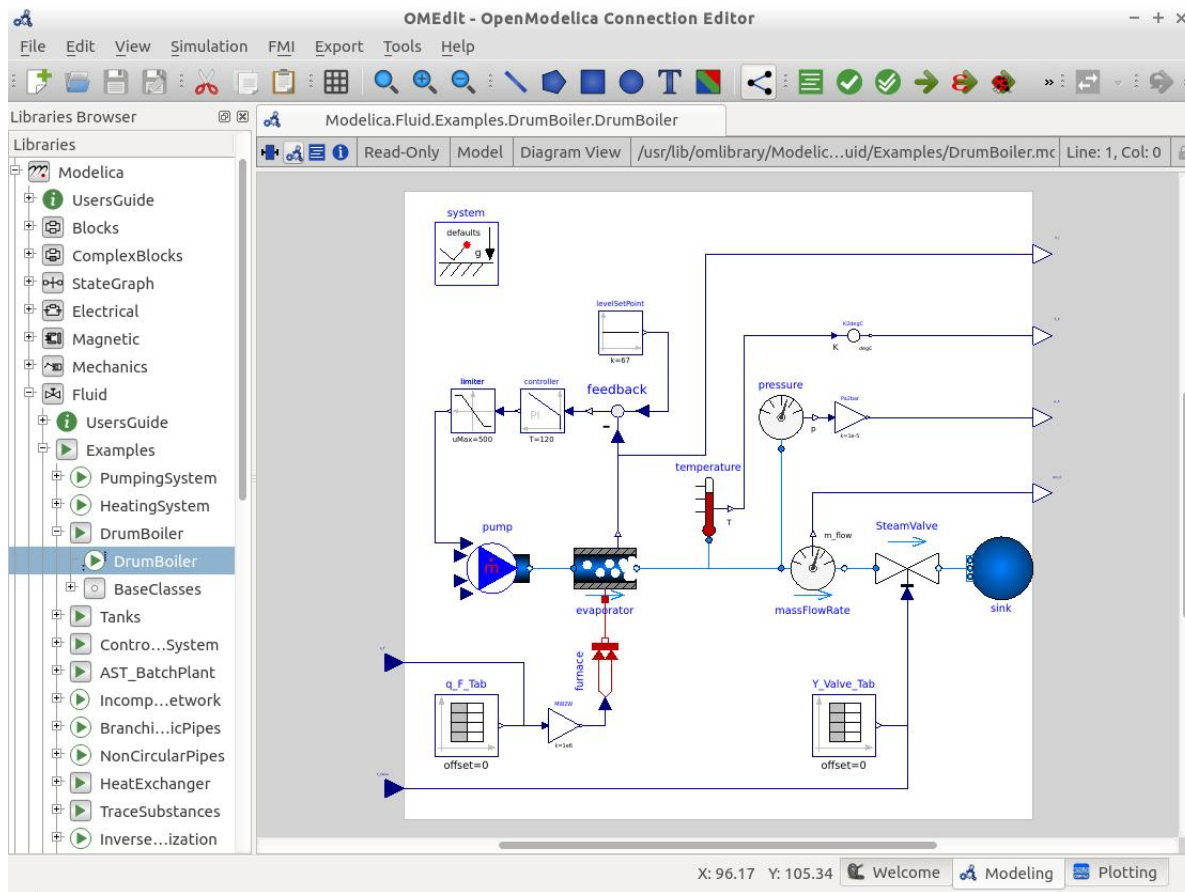
- Build overall plant model (exploiting Modelica multi-physics)
- Formulate optimizing control task as mathematical program
- Online optimization of set points and plant schedules

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DrumBoiler Example

Open in OMEdit (left) and simulate until steady-state reached (right)



See: R. Franke, M. Rode, K. Krüger: On-line Optimization of Drum Boiler Startup, Modelica 2003, https://www.modelica.org/events/Conference2003/papers/h29_Franke.pdf

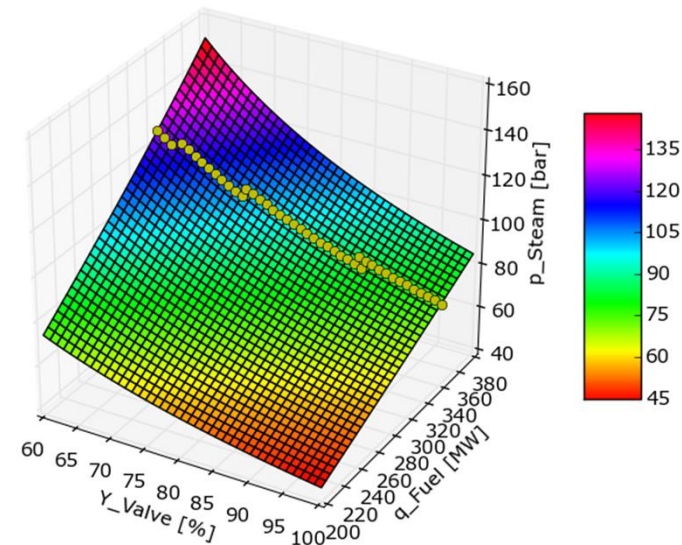
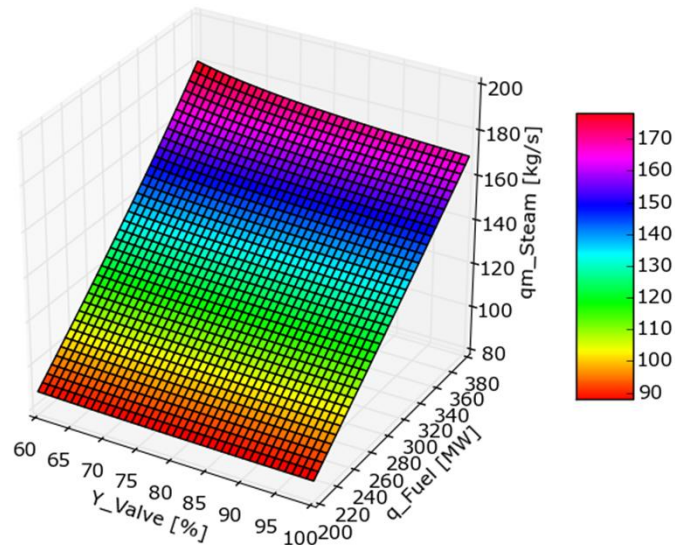
DrumBoiler setpoint optimization example

Simulation studies

Task: find steady-state operating point minimizing fuel q_F such that:
 $qm_{Steam} = 150 \text{ kg/s}$, $100 \text{ bar} \leq p_{Steam} \leq 120 \text{ bar}$

Simulation approach:

- obtain steady-state for inputs: $60 \leq Y_{Valve} \leq 100$, $200 \leq q_F \leq 380$
- plots show of $41 \times 37 = 1517$ steady-state values
- select best point



Nonlinear programming (NLP)

Nonlinear Programming (NLP)

Minimize optimization objective J
subject to equality constraints h and
inequality constraints g :

$$J(v) \xrightarrow{v} \min \quad J: R^n \rightarrow R^1$$

$$h(v) = 0 \quad h: R^n \rightarrow R^{m_e}$$

$$g(v) \geq 0 \quad g: R^n \rightarrow R^m$$

Setpoint optimization example

$$v = \begin{pmatrix} x \\ u \end{pmatrix}$$

$$x = (x_{PI}, p_{Steam}, V_{Liquid})$$

$$u = (q_F, Y_{Valve})$$

$$J(v) = q_F \xrightarrow{x,u} \min$$

$$J: R^5 \rightarrow R^1$$

$$h(v) = \begin{pmatrix} f(x, u) \\ qm_S - 150 \end{pmatrix} = 0$$

$$h: R^5 \rightarrow R^4$$

$$g(v) = \begin{pmatrix} 120 - p_S \\ p_S - 100 \\ 500 - q_F \\ q_F \\ 1 - Y_{Valve} \\ Y_{Valve} \end{pmatrix} \geq 0$$

$$g: R^5 \rightarrow R^6$$

Treatment of nonlinear programs (NLP)

Lagrangian, KKT conditions, Newton method

Lagrange function

$$L(v, \lambda, \mu) = J(v) - \lambda^T h(v) - \mu^T g(v)$$
$$L: R^n \times R^{m_e} \times R^m \rightarrow R^1$$

Karush Kuhn Tucker conditions

Stationarity

$$\nabla_v L(v, \lambda, \mu) = \nabla J(v) - \nabla h(v)^T \lambda - \nabla g(v)^T \mu = 0$$

Feasibility

$$\nabla_\lambda L(v, \lambda, \mu) = -h(v) = 0$$
$$g(v) \geq 0$$
$$\mu \geq 0$$

Complementarity

$$g(v)^T \mu = 0$$

Lagrange Newton iteration ($m=0$)

$$\nabla^2 L(v, \lambda) \begin{pmatrix} \Delta v \\ \Delta \lambda \end{pmatrix} = -\nabla L(v, \lambda)$$

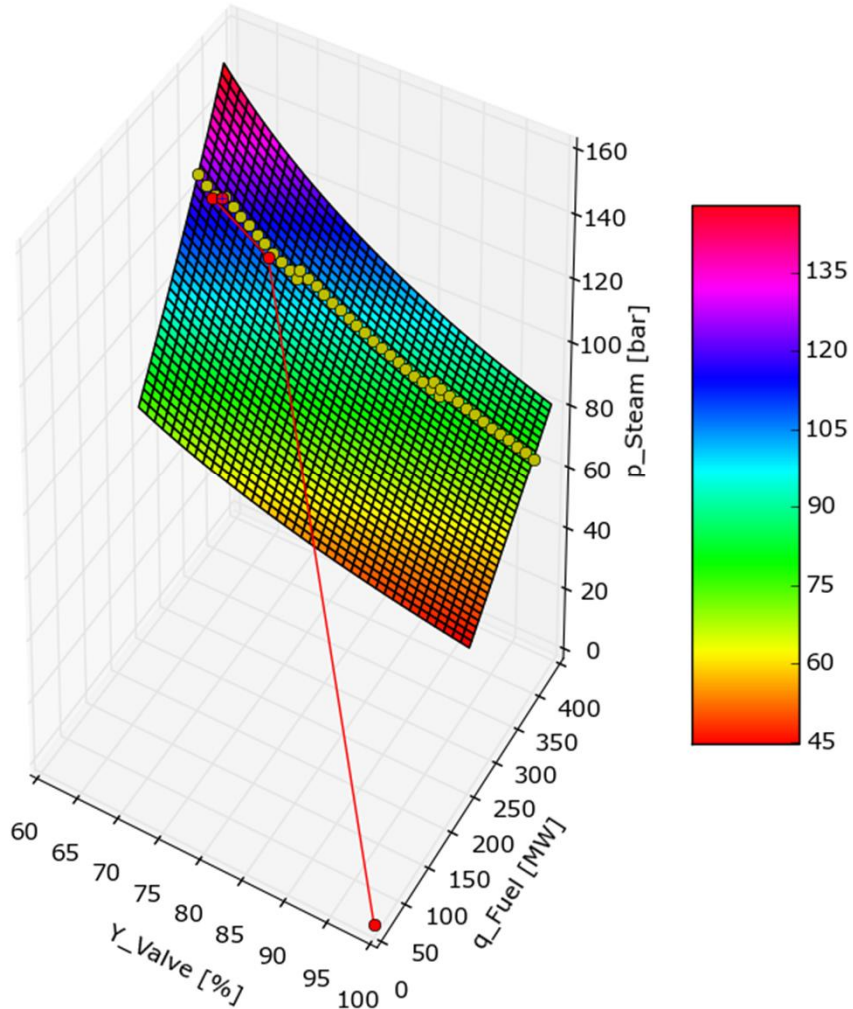
$$\begin{pmatrix} v^+ \\ \lambda^+ \end{pmatrix} := \begin{pmatrix} v + \Delta v \\ \lambda + \Delta \lambda \end{pmatrix}$$

Specific Lagrange Newton methods

- Active Set Method:
convert to equality constrained problems
- Interior Point Method:
augment Lagrange function for inequalities
- Sequential Quadratic Programming (SQP)
fully solve constraints in each iteration
- Quasi Newton Method:
numerical update/approximation of Hessian

DrumBoiler setpoint optimization

Application of mathematical programming



Starting point:

- $q_F = 0 \text{ MW}$
- $Y_{\text{Valve}} = 100\%$
- $x = (0, 1 \text{ bar}, 65 \text{ m}^3)$

Solution after 5 iterations:

- $q_F = 328 \text{ MW}$
- $Y_{\text{Valve}} = 62.8 \%$
- $x = (15, 120 \text{ bar}, 67 \text{ m}^3)$

See red solution path in figure left

Dynamic Optimization

Numerical treatment

$$J = f_0(x^K) + \sum_{k=0}^{K-1} f_0(x^k, u^k) \longrightarrow \min_{x^0, u^k}$$

s.t.

$$c^k(x^k, u^k) \geq 0, \quad k = 0, \dots, K-1$$

$$c^K(x^K) \geq 0$$

$$0 = \begin{cases} \text{Collocation:} \\ f^k(x^k, u^k, x^{k+1}) \\ \text{Multistage/shooting:} \\ f^k(x^k, u^k) - x^{k+1} \end{cases}, \quad k = 0, \dots, K-1$$

- Optimize over time horizon $t \in [t_0, t_f]$
- Degrees of freedom: optimal control $u(t)$ and possibly initial states $x(t_0)$
- Numerical treatment:
 - parameterize control trajectories: $u(t) = u(u^k), k=0,1,\dots,K-1$
 - Treat constraints and state equations in discrete time
 - Collocation: implicit state equations
 - Multistage: explicit state equations
 - Collect all discrete-time control and state variables in one large vector of optimization variables

$$v = (x^0, u^0, x^1, u^1, \dots, x^{K-1}, u^{K-1}, x^K)$$
- Alt. simple treatment: $\check{v} = (u^0, u^1, \dots, u^{K-1})$

DrumBoiler startup optimization

Minimize

- quadratic deviation from set point

subject to

- control bounds
- rate of change bounds
- state/output constraints
(thermal and membrane stress)

$$J = \int_{t=t_0}^{t_f} w^T \left\{ \begin{array}{l} [p_S(t) - p_{ref}]^2 \\ [q_{m,S}(t) - q_{m,ref}]^2 \\ \left[\frac{dq_F(t)}{dt} \right]^2 \end{array} \right\} dt \xrightarrow{u(t)} \min$$

$$0 \leq q_F \leq 500 \text{ MW}$$

$$0 \leq Y_{valve} \leq 1$$

$$-24 \text{ MW/min} \leq \frac{dq_F}{dt} \leq 24 \text{ MW/min}$$

$$-150 \frac{N}{mm^2} \leq \sigma_{Drum} \leq 150 \frac{N}{mm^2}$$

$$\sigma_{Drum} = 10^{-3} \frac{dT_{Drum}}{dt} + 10^{-5} p_{Drum}$$

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Formulation in Optimica – see JModelica.org

Extending Modelica syntax (see red text)

```
optimization DrumBoilerStartup(  
  objective = 1e-7 * (p_S - 110)^2 + 1e-8 * (qm_S - 180)^2 + 1e-4 * dq_F^2,  
  startTime = 0,  
  finalTime = 3600)  
  extends DrumBoiler(  
    q_F = integrated_q_F,  
    Y_Valve(free = true, initialGuess = 1),  
    use_inputs = true  
  );  
  Real sigma_D = (-1.0e3 * der(evaporator.T_D)) + 1.0e-05 * evaporator.p;  
  input Real dq_F(free = true, initialGuess = 400/3600);  
  Real integrated_q_F;  
equation  
  der(integrated_q_F) = dq_F;  
constraint  
  0 <= q_F; q_F <= 500;  
  -24/60 <= dq_F; dq_F <= 24/60;  
  0 <= Y_Valve; Y_Valve <= 1;  
  -150 <= sigma_D; sigma_D <= 150;  
end DrumBoilerStartup;
```

Formulation in OpenModelica (provided by Vitalij Ruge)

Inside Modelica model using standard attributes and new annotations

```
model optDrumBoiler
  extends DrumBoiler(use_inputs = true,
    Y_Valve(min = 0, max = 1, nominal = 1, start = 0.5),
    q_F(min = 0, max = 500, start = 0, fixed = true, nominal = 400),
    controller.x(nominal = 10));

  Real cost_p_S(nominal = 1e7) annotation(isLagrange = true);
  Real cost_qm_S(nominal = 1e8) annotation(isLagrange = true);
  Real cost_dq_F(nominal = 1e4) annotation(isLagrange = true);
  Real sigma_D(min = -150, max = 300) = (-1.0e3 * der(evaporator.T_D)) + 1.0e-05 * evaporator.p;
  Real conSigma(min = -150, max = 150) annotation(isConstraint = true);
  input Real dq_F(min = -24/60, max = 24/60, start = 400/3600);

equation
  cost_p_S = (p_S - 110)^2;
  cost_qm_S = (qm_S - 180)^2;
  cost_dq_F = dq_F^2;
  conSigma = sigma_D;
  der(q_F) = dq_F;
end optDrumBoiler;
```


Formulation with parameter records and custom annotations

Generic approach that nicely applies to optimization

```
import DO = DynamicOptimization.Types; // parameter records for custom annotations

model DrumBoiler_StartupOptimization
  extends DrumBoiler(
    use_inputs = true,
    q_F
      annotation(DO.Input(u_active = true, u_start = 0, der_u_start = 400/3600,
        u0_max = 0, u_min = 0, u_max = 500,
        der_u_min = -24/60, der_u_max = 24/60, der_u_weight2 = 1e-4)),
    Y_Valve
      annotation(DO.Input(u_active = true, u_start = 1,
        u0_max = 0, u_min = 0, u_max = 1)),
    p_S
      annotation(DO.Output(y_ref = 110, y_nominal = 100, y_weight2 = 1e-3)),
    qm_S
      annotation(DO.Output(y_ref = 180, y_nominal = 100, y_weight2 = 1e-4)));

  output Real sigma_D = -1e3 * der(evaporator.T_D) + 1e-5 * evaporator.p
    annotation(DO.Output(y_min = -150, y_max = 150));
end DrumBoiler_StartupOptimization;
```

ABB Dynamic Optimization

Use Excel GUI automating import of model and upload to runtime

Microsoft Excel - Drum Boiler_Startup Optimization.xls

File Edit View Insert Format Tools Data Window Help Dynamic Optimization

C7 = DrumBoiler

	A	B	C	D
1				
2	Object	String	Drum Boiler	
3	Aspect	String	Startup Optimization	
4				
5				
6	SOH	Type	Value	
7	ModelName	String	DrumBoiler	
8	SolverName	String	HQP	
9	SolverVersion	String	1.9.8	
10	SolverState	String	Ready	
11	SolverIteration	Integer	0	
12	SolverMessage	String	.	
13	Service.Enable	Boolean	FALSE	
14	Service.Trigger	Integer	0	
15	Service.Quit	Integer	0	
16	Data.LogName	String		
17	Data.StartTime	DateTime	+00:00:00	
18	Data.EndTime	DateTime	+01:00:00	
19	Data.SampleTime	TimeSpan	0:01:00	
20	Results.LogName	String	ResultsLog	

Microsoft Excel - Drum Boiler_Startup Optimization.xls

File Edit View Insert Format Tools Data Window Help Dynamic Optimization

A1 = SOH

	A	B	C	D	E	F	G	H	I
1	SOH	varname	y	y_nominal	y_ref	y_min	y_max	y_weight1	y_weight2
2	Type	String	Real	Real	Real	Real	Real	Real	Real
3		T_S	0	100					
4		p_S	0	100	110				1.00E-03
5		qm_S	0	100	180				1.00E-04
6		sigma_D	0	100		-150	150		
7		V_I	0	100					

Ready

Microsoft Excel - Drum Boiler_Startup Optimization.xls

File Edit View Insert Format Tools Data Window Help Dynamic Optimization

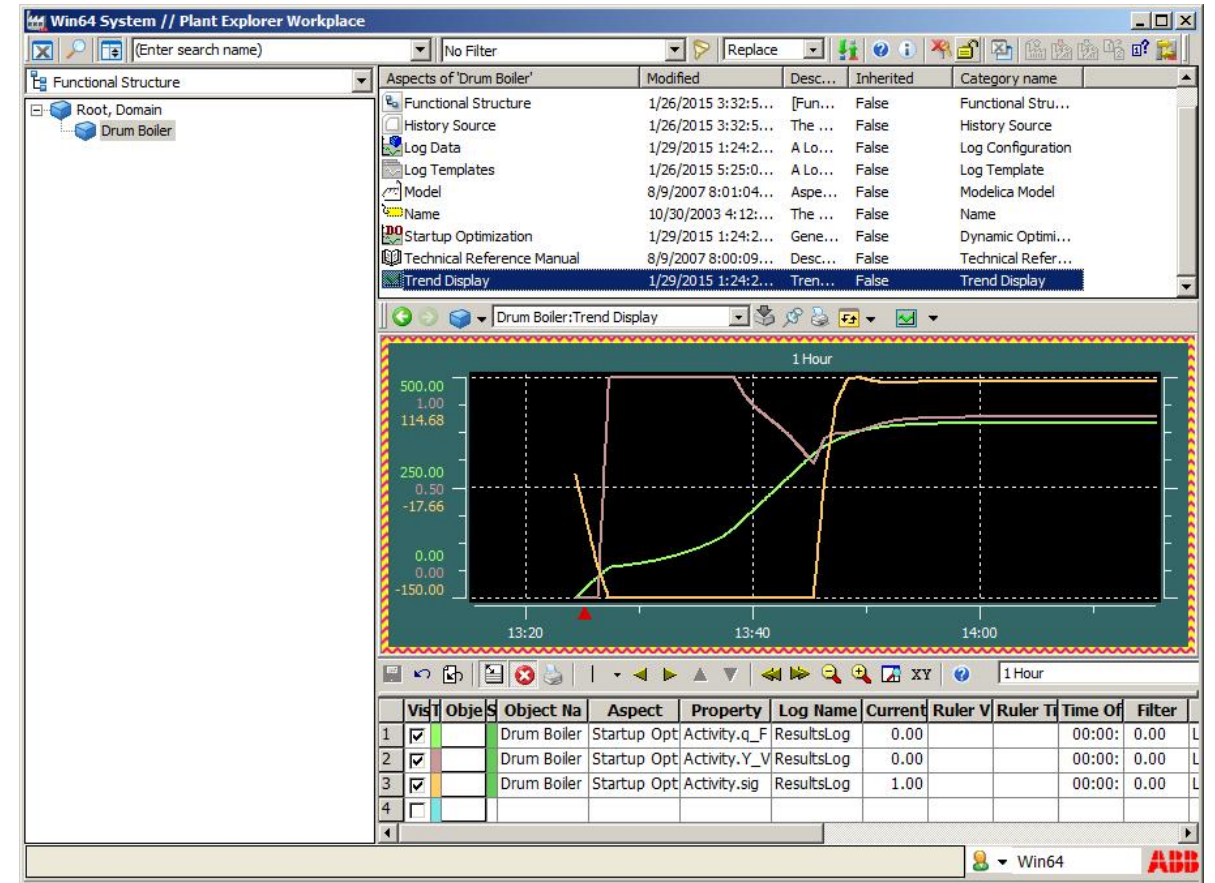
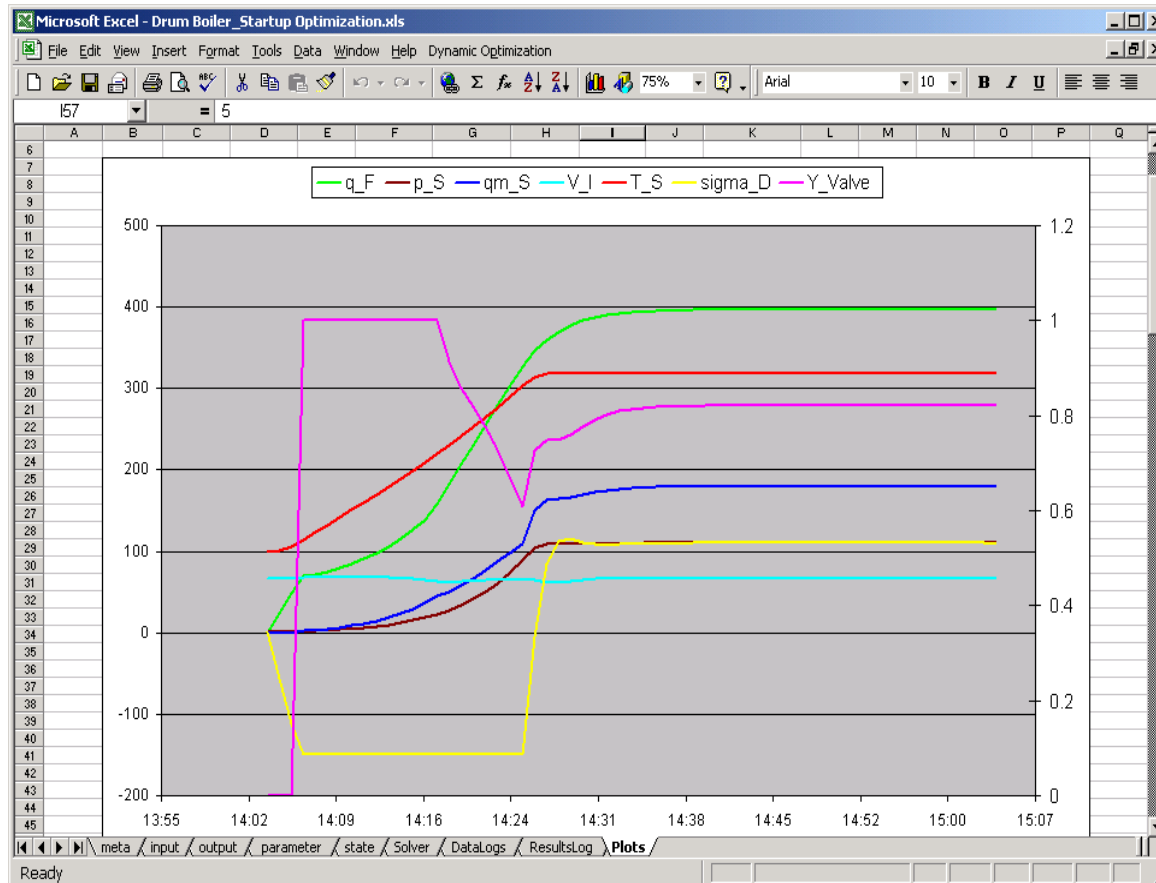
A1 = SOH

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	SOH	varname	u	u_start	u_order	u_active	u0_min	u0_max	u_min	u_max	der_u	der_u_start	der_u_min	der_u_max	der_u_weight2
2		String	Real	Real	Integer	Boolean	Real	Real	Real	Real	Real	Real	Real	Real	Real
3		q_F	0	0	1	TRUE	0	0	0	500	0	1.11E-01	-0.4	0.4	1.00E-04
4		Y_Valve	0	1	1	TRUE	0	1	0	1					

Ready

ABB Dynamic Optimization

Offline engineering in Excel / Online optimization in control system



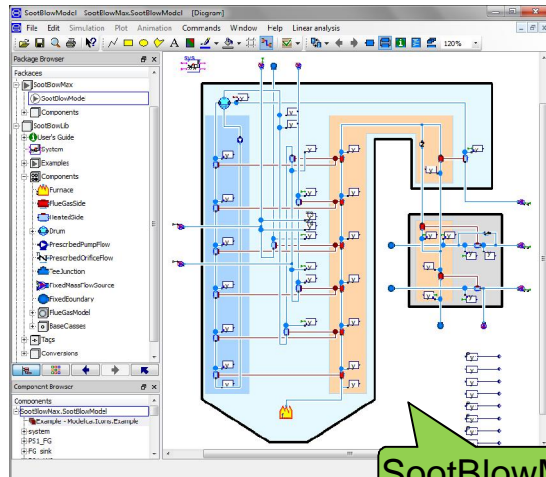
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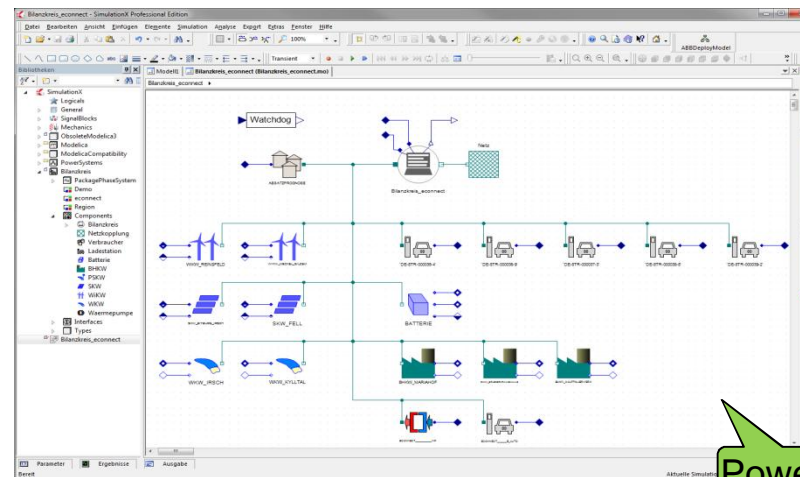
ABB Dynamic Optimization

Standardized engineering and deployment of control&optimization apps

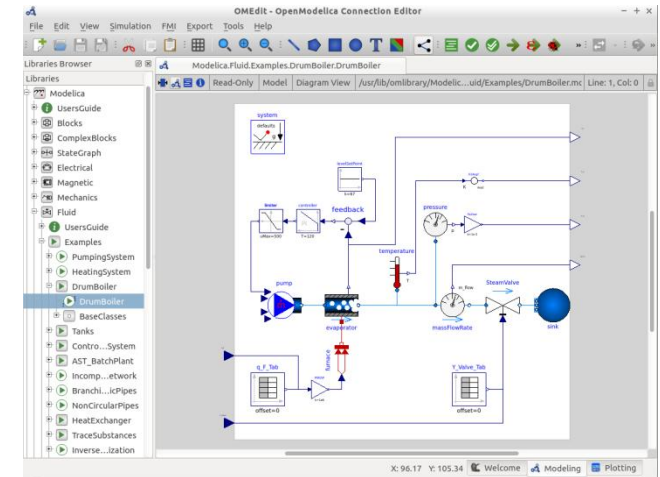
Modelica for application engineering (www.modelica.org)



SootBlowMax



PowerFit



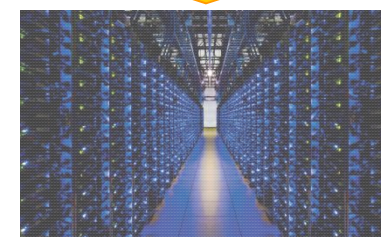
FMI (Functional Model Interface) for deployment (www.fmi-standard.org)



Embedded



Server



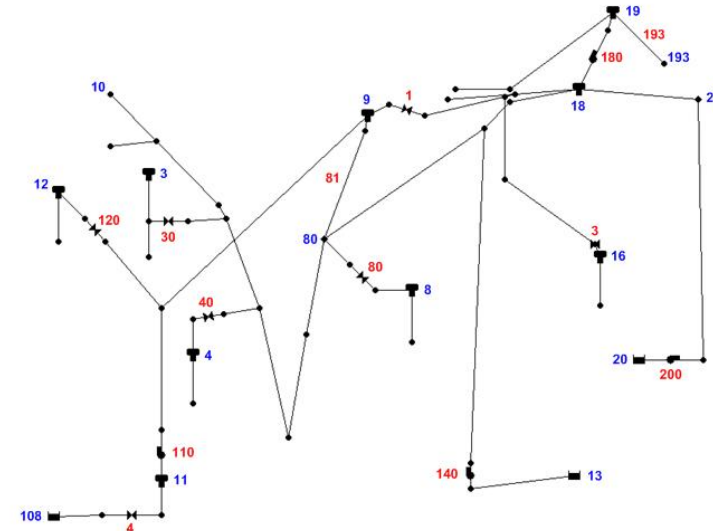
Cloud

Exploitation of sparse structures

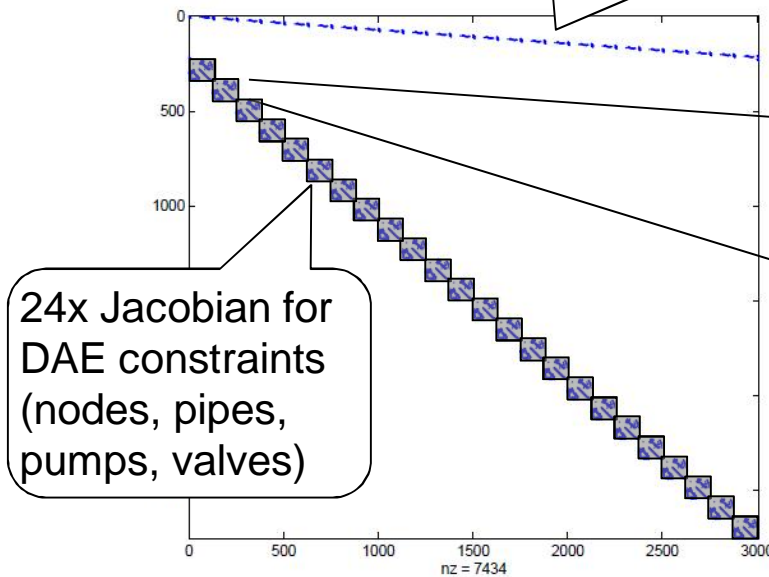
Example: water distribution network

S-function, FMI 1.0: can exploit sparsity resulting from time staging (left spy plot)

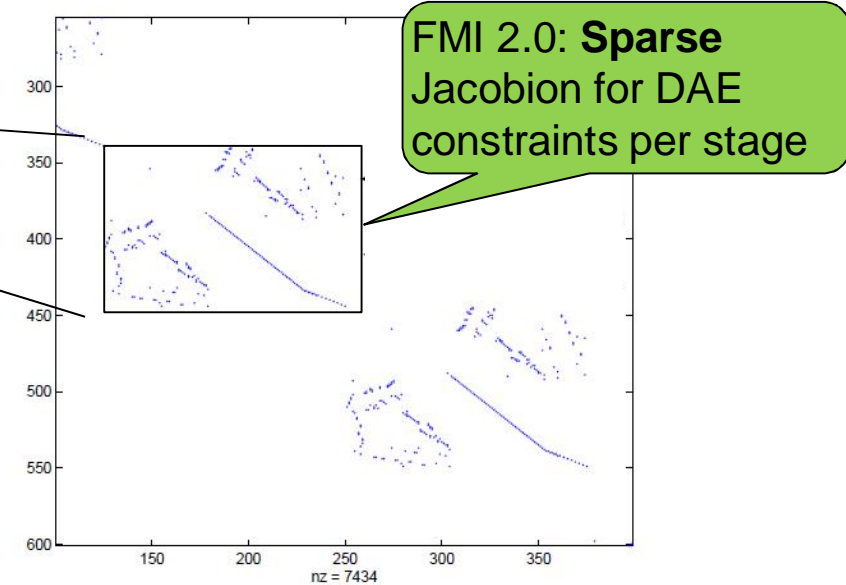
FMI 2.0: additionally exploit sparse models (right spy plot)



Jacobian for state equations (tanks) over 24 stages



24x Jacobian for DAE constraints (nodes, pipes, pumps, valves)

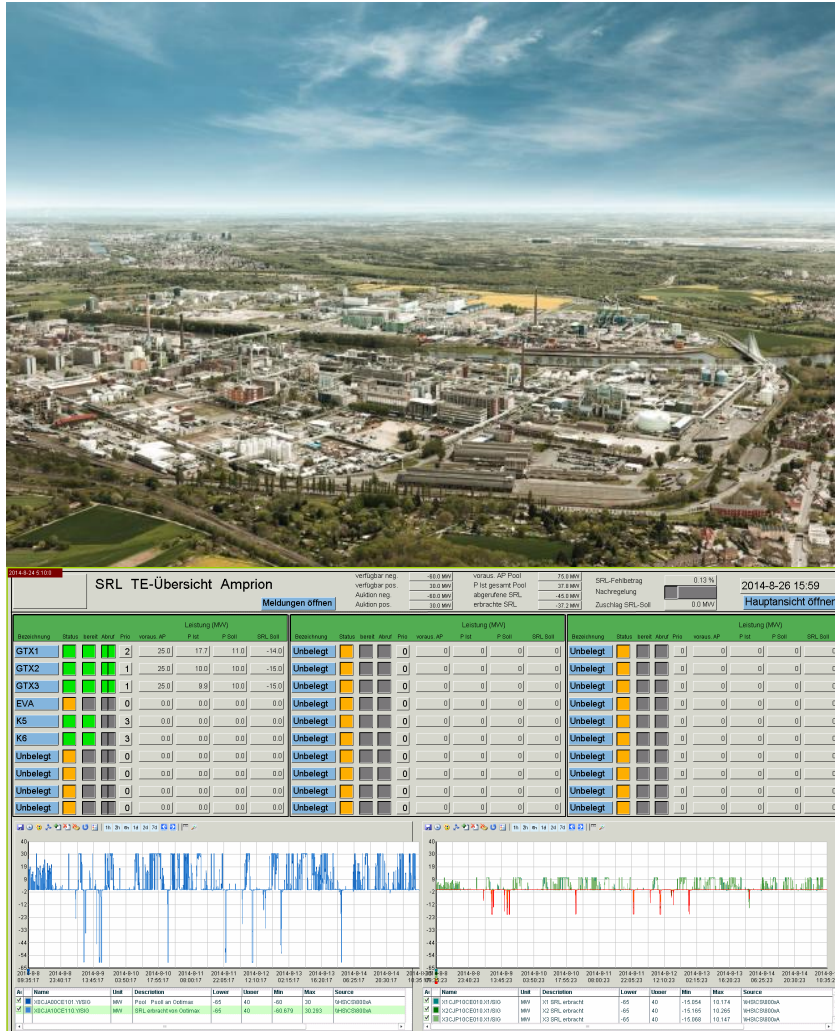


FMI 2.0: Sparse Jacobian for DAE constraints per stage

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Reference OPTIMAX PowerFit Industrial power plant / active site



Site

- 800 buildings, 120 production facilities
- 90 companies (chemical, pharmaceutical)
- 22.000 employees

OPTIMAX PowerFit

- Software extension of regular plant control system
- Providing secondary frequency control with 3 GTs and 2 E-Boilers
- To be extended
- Connect plant control to energy management

First industrial application of FMI 2.0

- Running 7/24 since June 9, 2014 00:00:00

Thank's to Your support ... 26 tickets later ...

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https://trac.openmodelica.org/OpenModelica/ Search

1 2 3 →

#3067: defect: Memory leak in FMI 2.0 (20 MB/min) (new)
Thanks to the solution of a couple of tickets during the last weeks the optimization basing on FMI is working quite well now! A remaining problem is a memory leak that can be seen in all examples to some extend. Here is an extreme case ...
By rfranke — 01/09/15 09:30:53

#3057: defect: Erronous FMI ModelStructure (closed: fixed)
In many cases the ModelStructure generated for FMI 2 is wrong. The following example triggers some of the problems: {{{ model ModelStructureTest parameter Integer switch = 1; parameter Real p = 1; input Real u1; input Real u ...
By rfranke — 01/05/15 09:59:46

#3055: defect: Wrong initialization of parameters in FMI2 (closed: duplicate)
Recently FMI version 2 sets parameters to their start values during `fmi2Enter/ExitInitializationMode`. This reverts possible custom values set beforehand by the calling environment. The problem was seen in r23881 and r23899; it was not th ...
By rfranke — 12/30/14 09:11:08

#3053: defect: Unimplemented derivatives for built-in Modelica operators (assigned)
Thank you for prompt fix to #3048. FMU export works now for my models that use max! Are there more unimplemented derivatives? `translateModelFMU(Rem, version="2.0")` for the model: {{{ model Rem input Real x; input Real y; ou ...
By rfranke — 12/23/14 08:17:25

#3051: defect: extends and modification of attributes (accepted)
The following model is motivated by some Modelica.Media models, which seems to have some issue with modification of the attributes like min, max, nominal and start. The following script {{{ loadString(" package p package types ...
By wbraun — 12/22/14 16:16:39

#3049: defect: FMI export of attributes of variables (closed: fixed)
OpenModelica r23881 does not include the attributes of model variables into modelDescription.xml, or it does it wrong. This is bad for numeric solvers that rely on appropriate nominal and start values for things like pressure in Pa. Her ...
By rfranke — 12/22/14 11:10:38

#3048: defect: FMI2 fails with max of more than 2 elements (closed: fixed)
The following model passes `translateModelFMU(Max2, version="2.0")`. The generated ModelStructure is correct, i.e. the output depends on both inputs. {{{ model Max2 constant Integer n=2; input Real[n] v; output Real max_ ...
By rfranke — 12/22/14 10:37:17

#3038: defect: omnotebook.desktop leads to corrupted start menu under Lubuntu (closed: fixed)
Installing OpenModelica under Lubuntu 14.10 with: {{{ sudo apt-get install openmodelica }}} leads to a corrupted start menu in lxpanel. After some trial&error and re-installations, finally a newline in the Comment of the desktop entry ...
By rfranke — 12/17/14 12:28:20

Foo.mo (Ticket #3033)
By rfranke — 12/15/14 20:31:50

#3033: defect: OMEdit does not seem to treat UTF-8 in its Text View (closed: fixed)
Localization of models requires doc strings with non-ASCII characters, like: {{{ model Foo Real mu = 1e-6 "Does OpenModelica treat UTF-8, like µ or ö in Linköping?"; end Foo; }}} Encoded with UTF-8, OMEdit opens the model, but scra ...
By rfranke — 12/15/14 07:53:55

Search Results - OpenModelica - Mozilla Firefox

Search Results - Op... x +

https://trac.openmodelica.org/OpenModelica/ Search

1 2 3 →

Results (11 - 20 of 26)

#2840: defect: Segmentation fault if assertion fails in FMU (closed: fixed)
The following model contains an assertion that fails during the simulation with a constant input u = -2 after 0.1 seconds. {{{ model DIC "Double Integrator Continuous-time" parameter Real p = 1 "gain for input"; parameter Real y1_s ...
By rfranke — 09/25/14 20:57:45

Calculations_PumpEfficiencyMeter.fmu (Ticket #2776)
the FMU 1.0 exported from Calculations.PumpEfficiencyMeter
By rfranke@... — 08/11/14 08:15:53

Calculations.mo (Ticket #2776)
By rfranke@... — 08/11/14 08:14:35

#2776: defect: Process crashed: Simulation process exited with code 0 on FMU import (closed: fixed)
... {{{ /tmp/OpenModelica_rfranke/OMEdit/Calculations_PumpEfficiencyMeter_me_FMU.mo:23:3-23:88) Warning: Parameter calculations_pumpefficiencymeter_me_fmu1.eta_o_D_deliver has no value, and is fixed during initialization (fixed=true), using available start value (st ...
By rfranke@... — 08/11/14 08:13:36

#2767: defect: fmi2GetDerivatives shifts value references by -1 when calling getReal of ... (closed: fixed)
First of all: thank you for the fast processing of #2762! Now the exported FMU version 2.0 shall run in another environment (github.com/omuses/hqp). According to modelDescription.xml the FMU has the following variables: {{{ valueRefer ...
By rfranke@... — 08/02/14 22:03:01

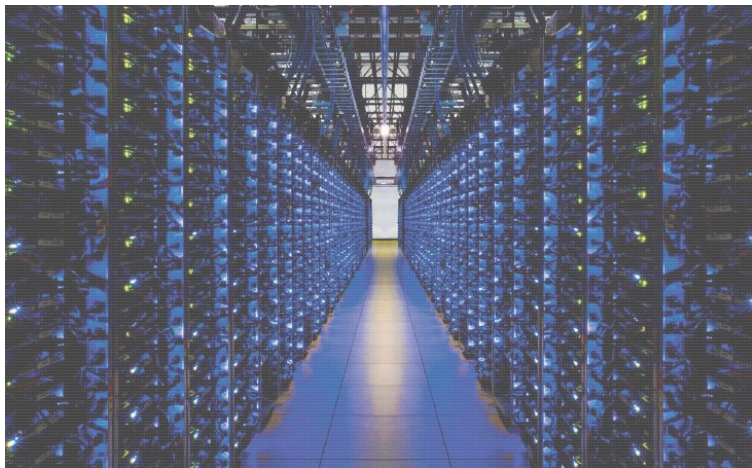
#2765: defect: Export of FMU 2.0 fails if parameters are used as start values (assigned)
Using the current nightly build 1.9.1+dev (r21649), the following model {{{ model DIC_start "Double Integrator Continuous-time" parameter Real p = 1 "gain for input"; parameter Real y1_start = 1 "start value for first state"; ...
By rfranke@... — 07/29/14 09:07:40

#2764: defect: ModelStructure with wrong dependencies for states and without dependencies ... (accepted)
Using the current nightly build 1.9.1+dev (r21649), the following model {{{ within ; model DIC "Double Integrator Continuous-time" parameter Real p = 1 "gain for input"; parameter Real y1_start = 1 "start value for first state"; ...
By rfranke@... — 07/29/14 08:53:58

#2763: enhancement: Propagation of start values for inputs to simulation (new)
If the model below is opened and simulated with OMEdit (1.9.1+dev (r21649)), the simulation assigns zero to the input u. Couldn't the simulation use the start value of -2 instead? How could one otherwise define values for external in ...
By rfranke@... — 07/29/14 08:27:29

#2762: defect: Process crashed -- Simulation process exited with code 0 (closed: fixed)
The model listed below uses the same variables as outputs and states (like some models from the MSL, see Modelica.Blocks.Continuous.Integrator). Opened and simulated with OMEdit, the compilation raises a lot of warnings and the simulat ...
By rfranke@... — 07/29/14 08:19:03

Reference OPTIMAX PowerFit Large-scale Virtual Power Plant



Customer

- Fast growing start-up company
- Pooling more than 1000 renewable plants in all 4 German grid areas

OPTIMAX PowerFit

- Stand-alone supervisory control system
- Geographically redundant with multiple high-performance virtual servers
- Providing secondary frequency control with large-scale Virtual Power Plant

Benefit of FMI 2.0

- Exploit sparse model structures to reduce required server capacity by 50%

Conclusions

Modelica

- unique technology for the implementation of technical process knowledge
- Modelica models provide constraints for optimization programs
- Additional specifications, like bounds and weights, can be treated with custom annotations – exploiting parameter records and Modelica parameter GUIs

FMI

- offers a standard interface for the deployment of executable models
- unique features: XML declaration file, sparse model structures, ...
- missing in FMI 2.0: DAE constraints, clocked equations for optimization

OpenModelica

- unique open development process; great progress during the last years
- some pioneering features – e.g. MetaModelica for library upgrades
- missing for commercial applications: encryption of Modelica libraries

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