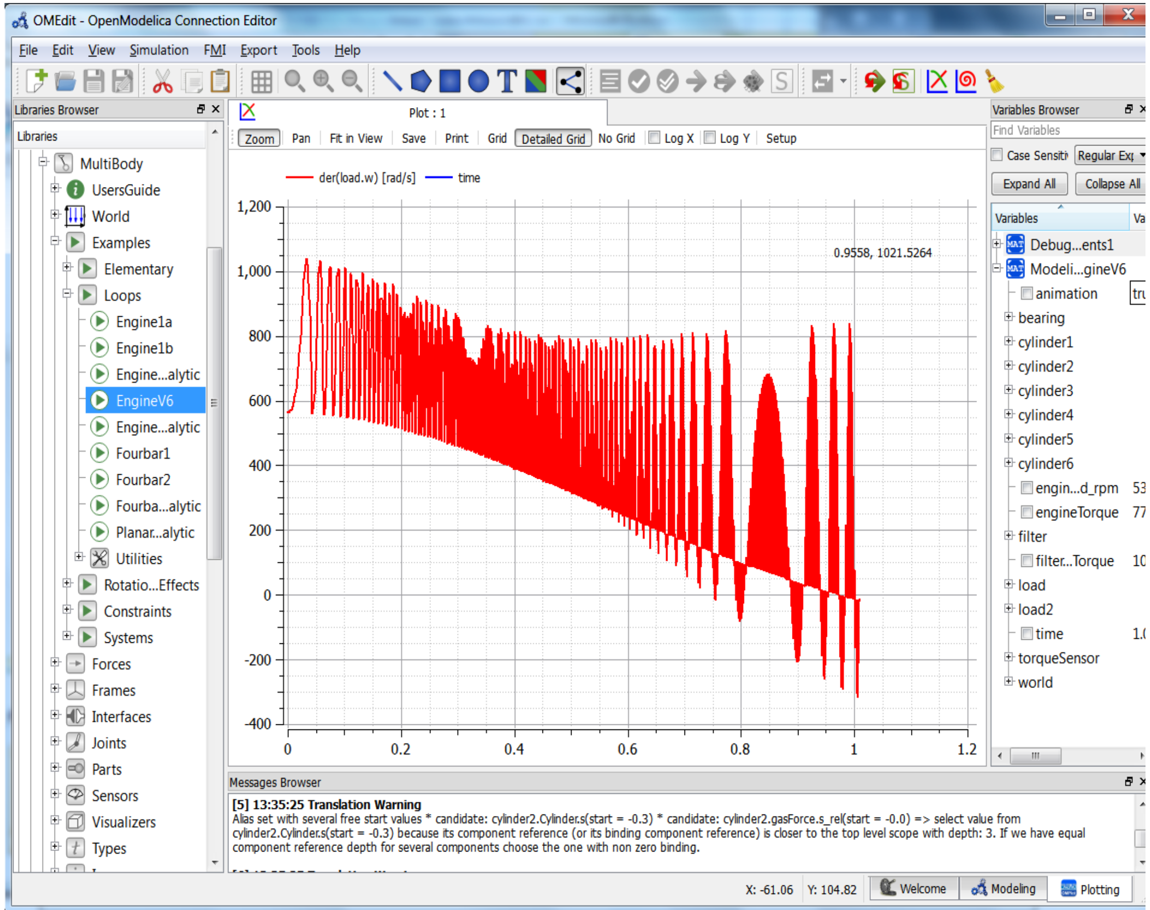
Modeling, Simulation, and Development of Cyber-Physical Systems with OpenModelica and FMI



Presentation at
RISE SICS East, Sweden

October 6, 2018

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Vice Chairman of Modelica Association

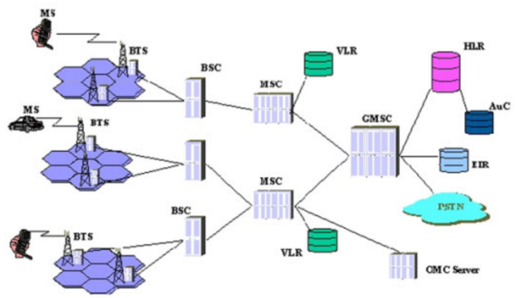
Director of the MODPROD Center for model-based development

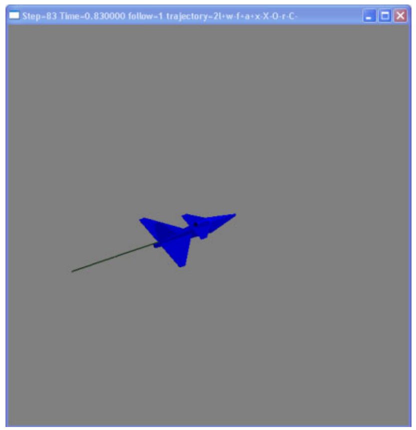
LINKÖPING UNIVERSITY

MODELICA

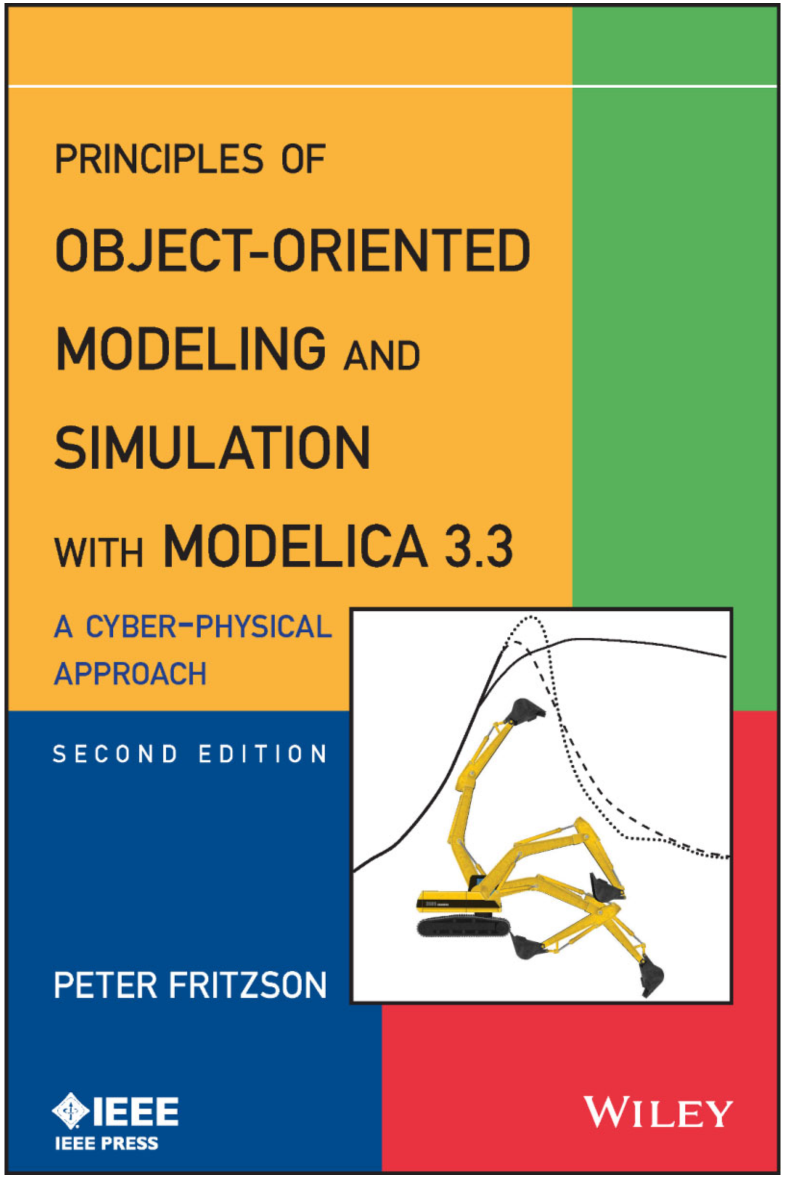
Industrial Challenges for Complex Cyber-Physical System Products of both Software and Hardware

- Increased **Software** Fraction
- **Shorter** Time-to-Market
- Higher demands on effective strategic **decision** making
- **Cyber-Physical** (CPS) – Cyber (software) Physical (hardware) products





Big Book on Modelica and Technology, Dec 2014
Download Free OpenModelica Software



Peter Fritzson

Principles of Object Oriented Modeling and Simulation with Modelica 3.3

A Cyber-Physical Approach

Can be ordered from Wiley or Amazon

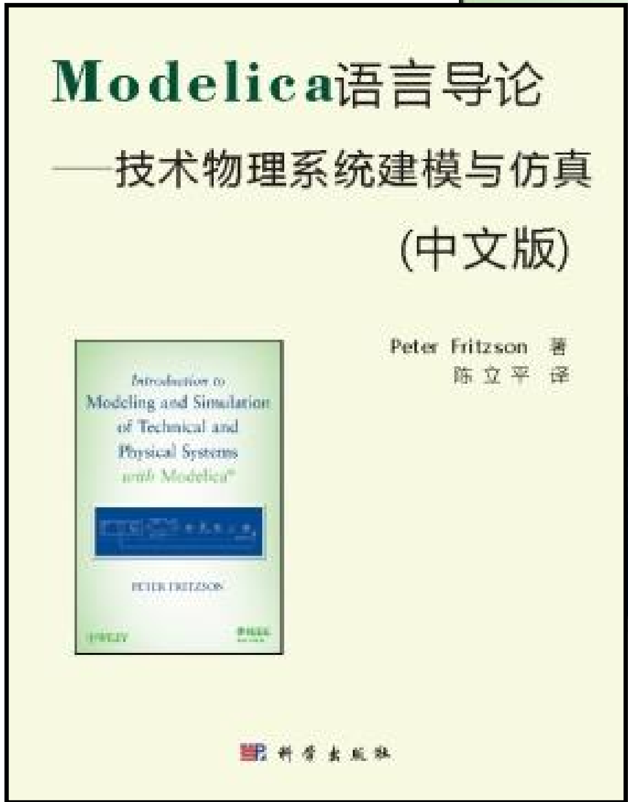
Wiley-IEEE Press, 2014, 1250 pages

- OpenModelica
  - www.openmodelica.org
- Modelica Association
  - www.modelica.org

Introductory Modelica Book

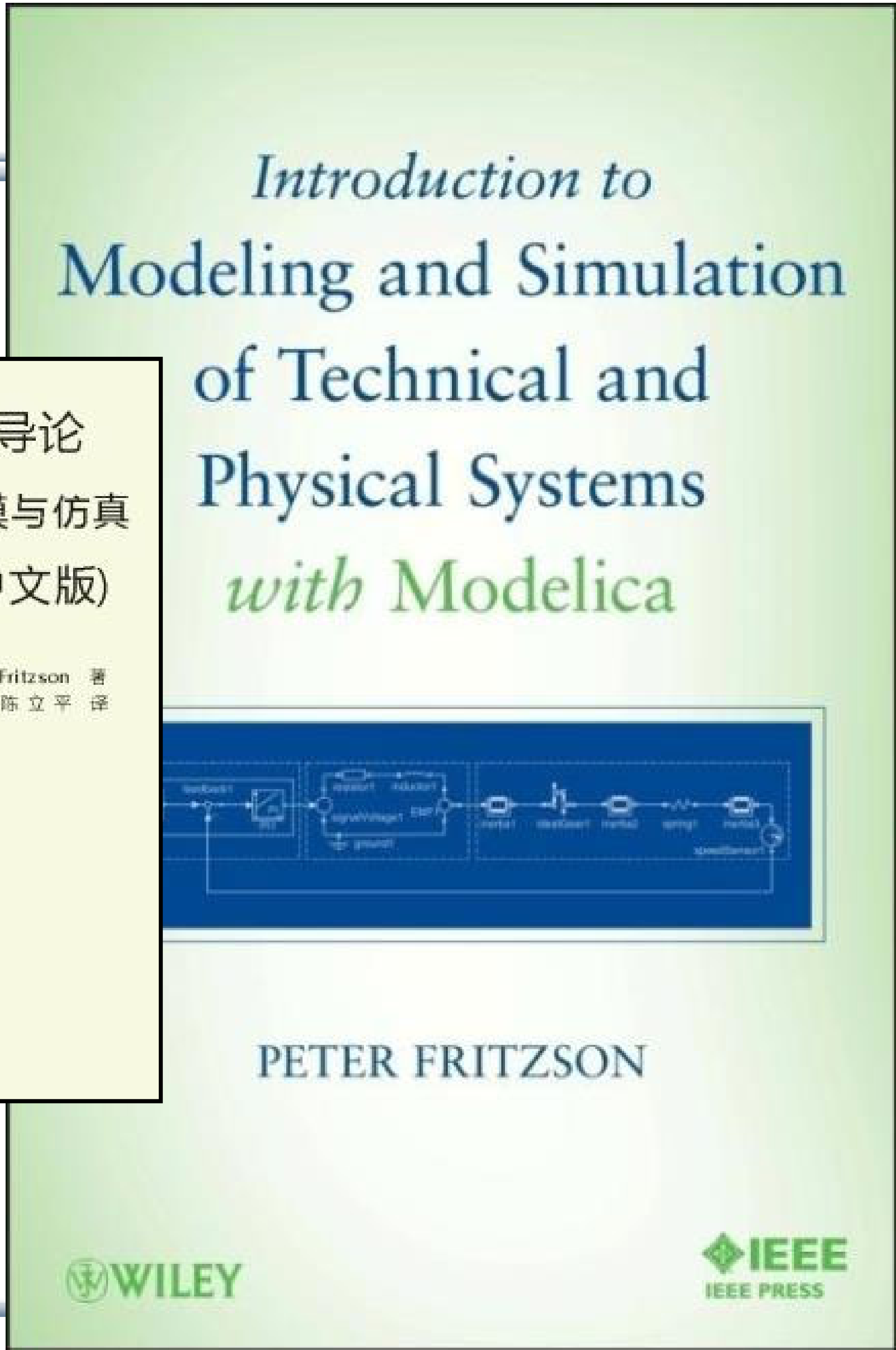
September 2011
232 pages

Translations available in **Chinese, Japanese, Spanish**



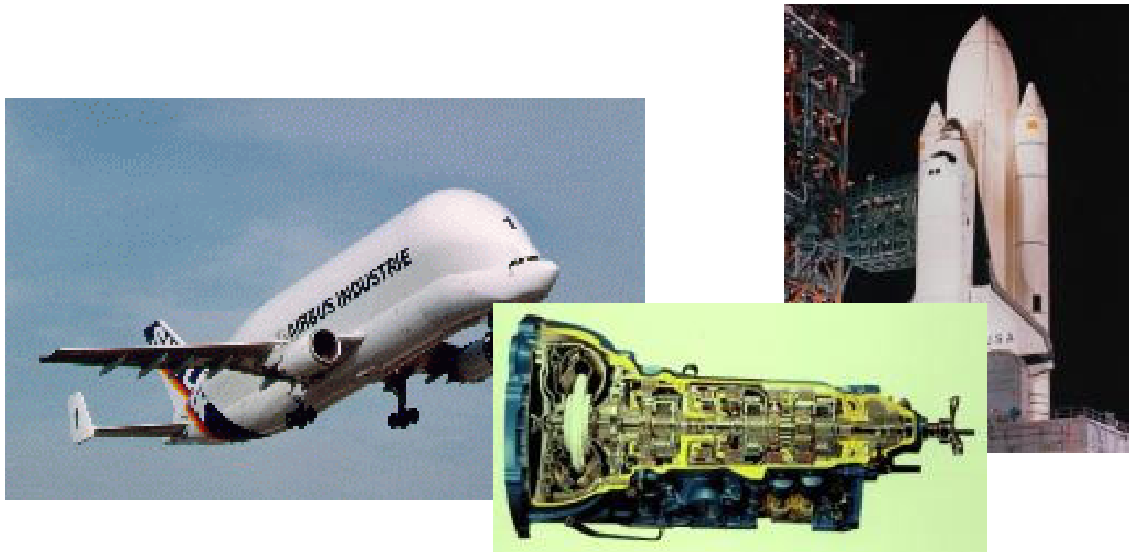
Wiley
IEEE Press

For Introductory Short Courses on Object Oriented Mathematical Modeling



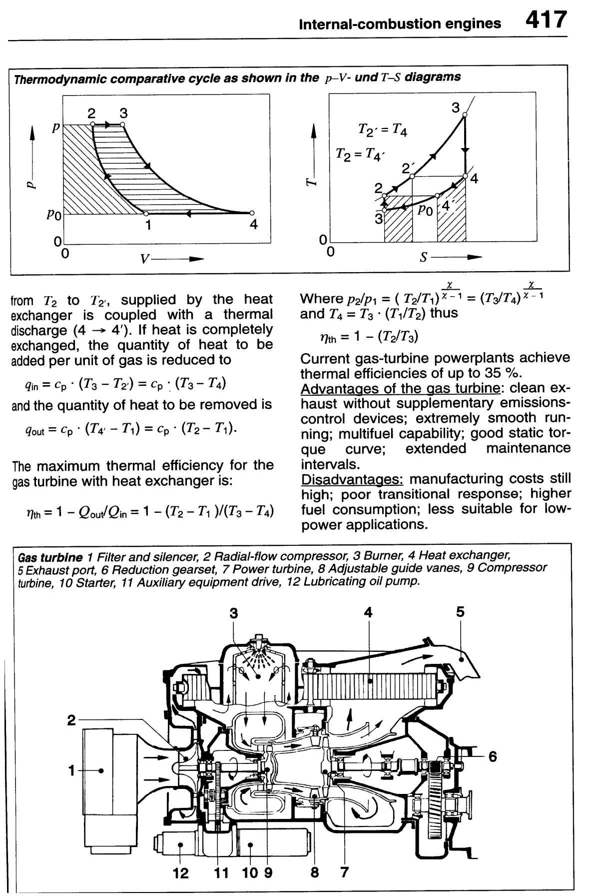
Part I

Introduction to Modelica



Modelica Background: Stored Knowledge

Model knowledge is stored in books and human minds which computers cannot access


Internal-combustion engines 417

Thermodynamic comparative cycle as shown in the p–V- und T–S diagrams

from T_2 to $T_{2'}$, supplied by the heat exchanger is coupled with a thermal discharge (4 → 4′). If heat is completely exchanged, the quantity of heat to be added per unit of gas is reduced to

$q_{in} = c_p \cdot (T_3 - T_{2'}) = c_p \cdot (T_3 - T_4)$

and the quantity of heat to be removed is

$q_{out} = c_p \cdot (T_{4'} - T_1) = c_p \cdot (T_2 - T_1)$.

The maximum thermal efficiency for the gas turbine with heat exchanger is:

$\eta_{th} = 1 - Q_{out}/Q_{in} = 1 - (T_2 - T_1)/(T_3 - T_4)$

Where $p_2/p_1 = (T_2/T_1)^{\frac{\chi}{\chi-1}} = (T_3/T_4)^{\frac{\chi}{\chi-1}}$ and $T_4 = T_3 \cdot (T_1/T_2)$ thus

$\eta_{th} = 1 - (T_2/T_3)$

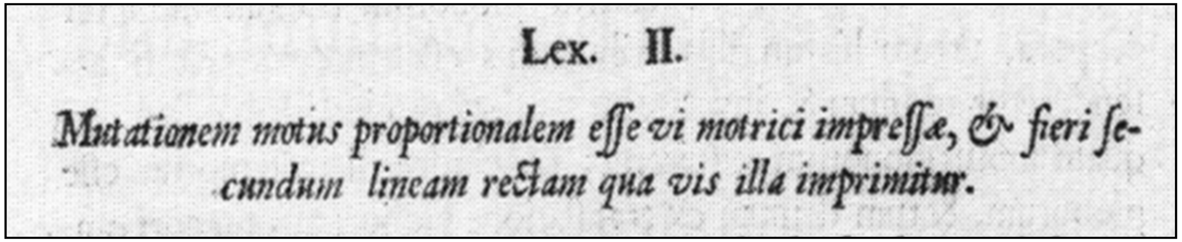
Current gas-turbine powerplants achieve thermal efficiencies of up to 35 %.

Advantages of the gas turbine: clean exhaust without supplementary emissions-control devices; extremely smooth running; multifuel capability; good static torque curve; extended maintenance intervals.

Disadvantages: manufacturing costs still high; poor transitional response; higher fuel consumption; less suitable for low-power applications.

Gas turbine 1 Filter and silencer, 2 Radial-flow compressor, 3 Burner, 4 Heat exchanger, 5 Exhaust port, 6 Reduction gearset, 7 Power turbine, 8 Adjustable guide vanes, 9 Compressor turbine, 10 Starter, 11 Auxiliary equipment drive, 12 Lubricating oil pump.

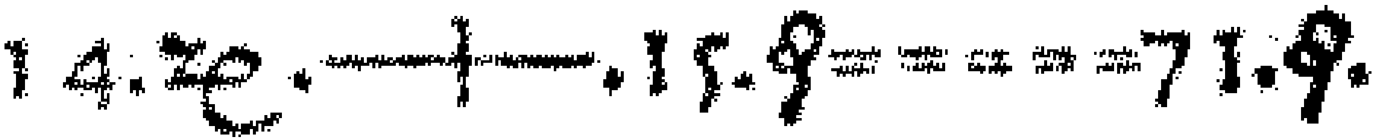
"The change of motion is proportional to the motive force impressed"
– Newton


Lex. II.

Mutationem motus proportionalem esse vi motrici impressæ, & fieri secundum lineam rectam qua vis illa imprimitur.

Modelica Background: The Form – Equations

- Equations were used in the third millennium B.C.
- Equality sign was introduced by Robert Recorde in 1557



Newton still wrote text (Principia, vol. 1, 1686)
“*The change of motion is proportional to the motive force impressed*”
CSSL (1967) introduced a special form of “equation”:

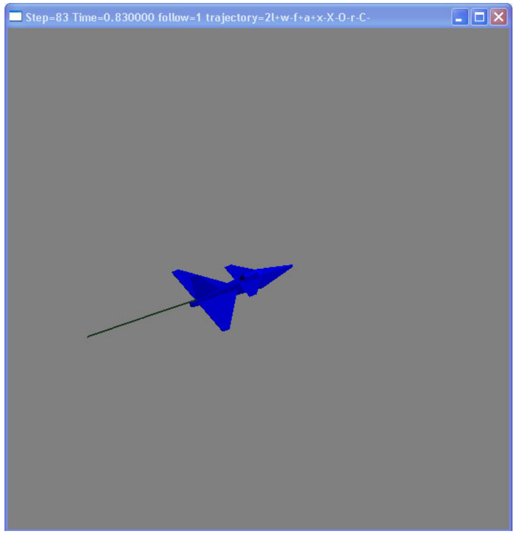
```
variable = expression
v = INTEG(F)/m
```

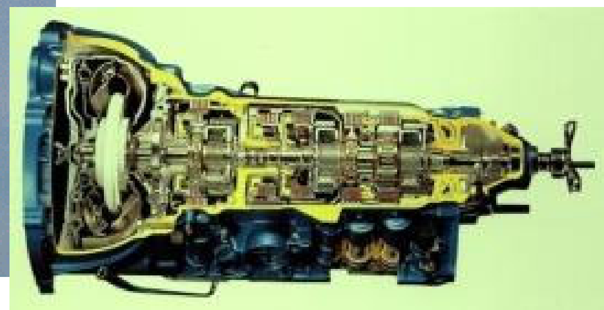
Programming languages usually do not allow equations!

What is Modelica?

A language for modeling of complex cyber-physical systems

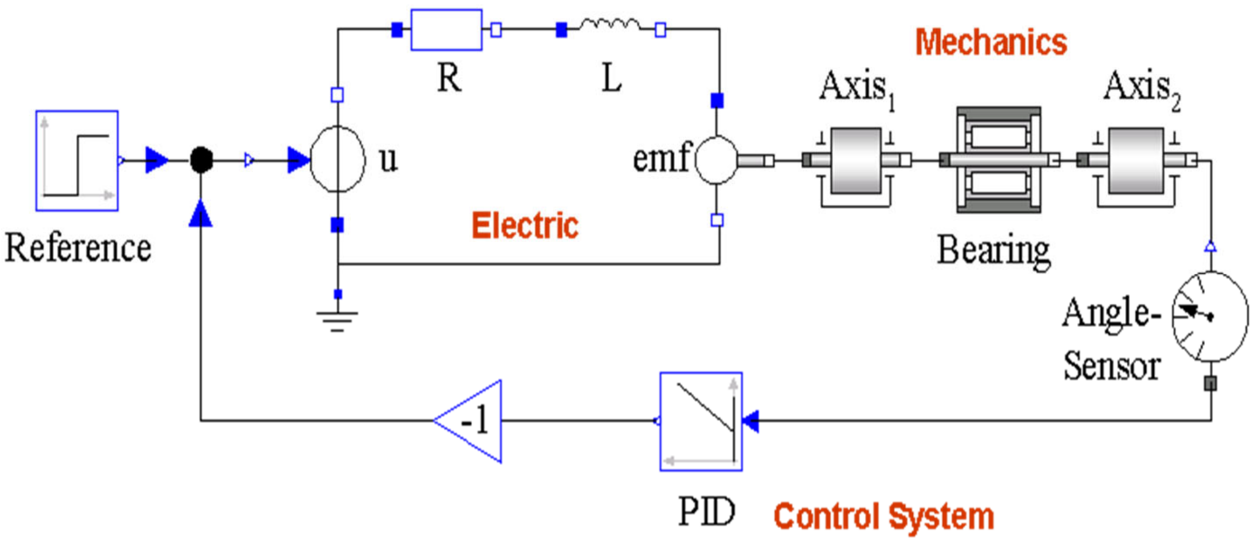
- Robotics
- Automotive
- Aircrafts
- Satellites
- Power plants
- Systems biology





What is Modelica?

A language for modeling of complex cyber-physical systems



Primary designed for **simulation**, but there are also other usages of models, e.g. optimization.

What is Modelica?

A language for modeling of complex cyber-physical systems

i.e., Modelica is **not** a tool

Free, open language specification:

Available at: www.modelica.org

Developed and standardized by Modelica Association

There exist several free and commercial tools, for example:

- **OpenModelica from OSMC**
- Dymola from Dassault systems
- Wolfram System Modeler fr Wolfram MathCore
- SimulationX from ITI – ESI Group
- MapleSim from MapleSoft
- AMESIM from LMS
- JModelica.org from Modelon
- MWORKS from Tongyang Sw & Control
- IDA Simulation Env, from Equa

Modelica – The Next Generation Modeling Language

Declarative language

Equations and mathematical functions allow acausal modeling, high level specification, increased correctness

Multi-domain modeling

Combine electrical, mechanical, thermodynamic, hydraulic, biological, control, event, real-time, etc...

Everything is a class

Strongly typed object-oriented language with a general class concept, Java & MATLAB-like syntax

Visual component programming

Hierarchical system architecture capabilities

Efficient, non-proprietary

Efficiency comparable to C; advanced equation compilation, e.g. 300 000 equations, ~150 000 lines on standard PC

Modelica Acausal Modeling

What is *acausal* modeling/design?

Why does it increase *reuse*?

The acausality makes Modelica library classes *more reusable* than traditional classes containing assignment statements where the input-output causality is fixed.

Example: a resistor *equation*:

R*i = v;

can be used in three ways:

i := v/R;

v := R*i;

R := v/i;

What is Special about Modelica?

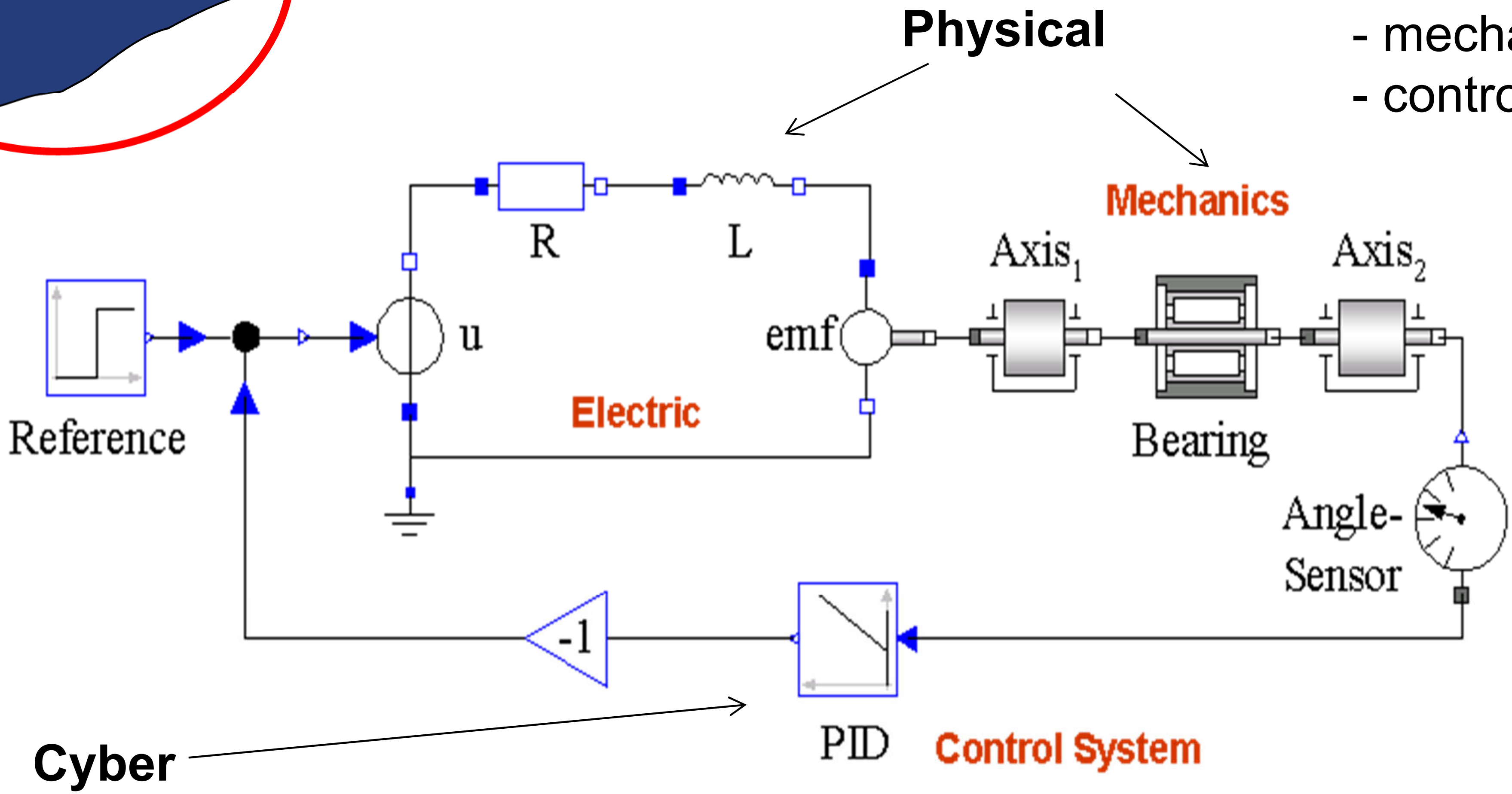
- Multi-Domain Modeling
- Visual acausal hierarchical component modeling
- Typed declarative equation-based textual language
- Hybrid modeling and simulation

What is Special about Modelica?

Multi-Domain Modeling

Cyber-Physical Modeling

3 domains
- electric
- mechanics
- control



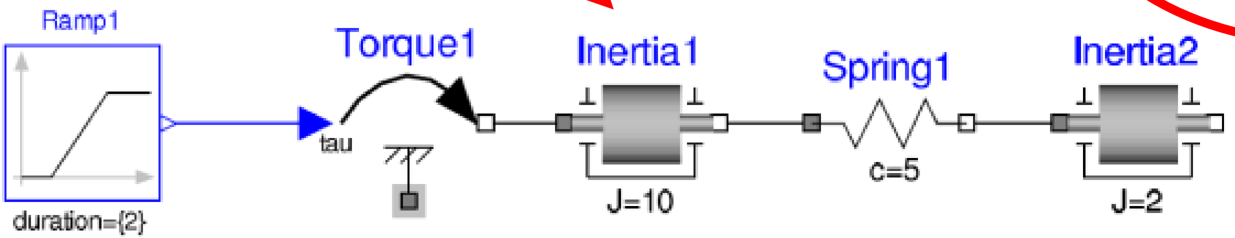
What is Special about Modelica?

Multi-Domain Modeling

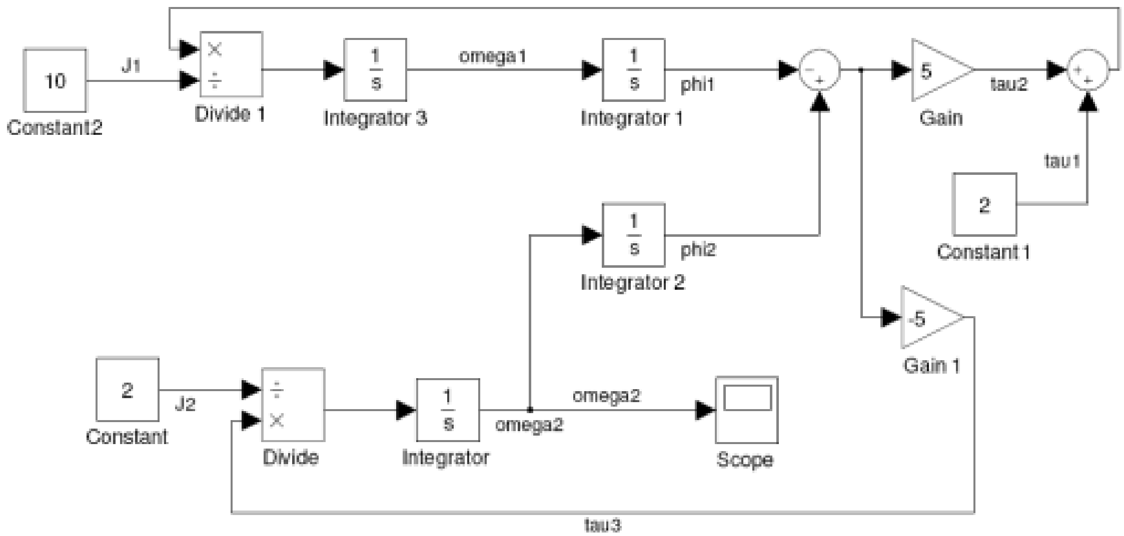
Keeps the physical structure

Visual Acausal Hierarchical Component Modeling

Acausal model (Modelica)



Causal block-based model (Simulink)



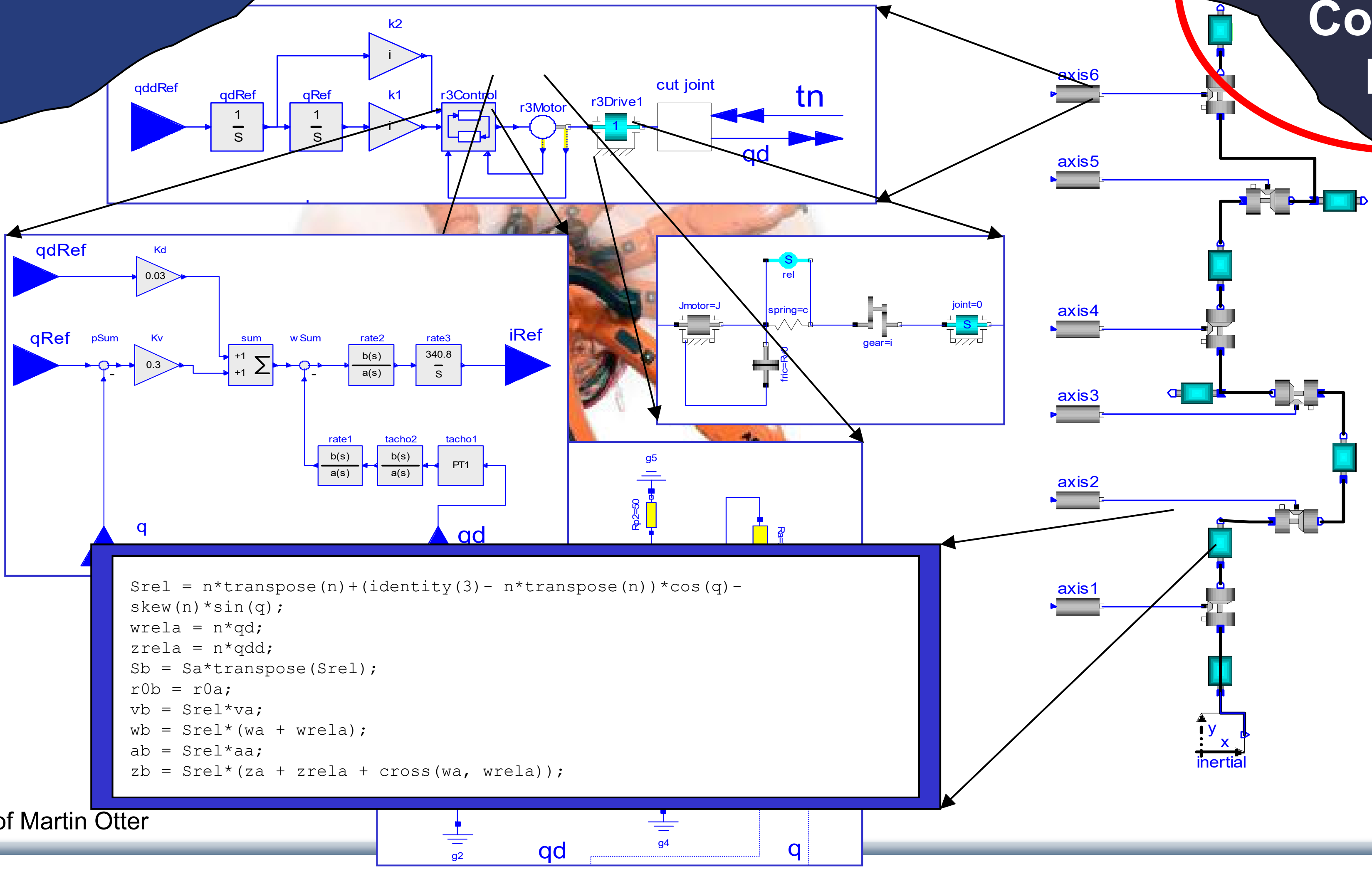
MODELICA

What is Special about Modelica?

Multi-Domain Modeling

Hierarchical system modeling

Visual Acausal Hierarchical Component Modeling




```
Srel = n*transpose(n)+(identity(3)- n*transpose(n))*cos(q)-
skew(n)*sin(q);
wrela = n*qd;
zrela = n*qdd;
Sb = Sa*transpose(Srel);
r0b = r0a;
vb = Srel*va;
wb = Srel*(wa + wrela);
ab = Srel*aa;
zb = Srel*(za + zrela + cross(wa, wrela));
```

Courtesy of Martin Otter

What is Special about Modelica?

Multi-Domain Modeling

Visual Acausal Hierarchical Component Modeling

A textual *class-based* language
OO primary used for as a structuring concept

Behaviour described declaratively using

- Differential algebraic equations (DAE) (continuous-time)
- Event triggers (discrete-time)

Variable declarations

```
class VanDerPol   "Van der Pol oscillator model"
  Real x(start = 1)   "Descriptive string for x";
  Real y(start = 1)   "y coordinate";
  parameter Real lambda = 0.3;
equation
  der(x) = y;
  der(y) = -x + lambda*(1 - x*x)*y;
end VanDerPol;
```

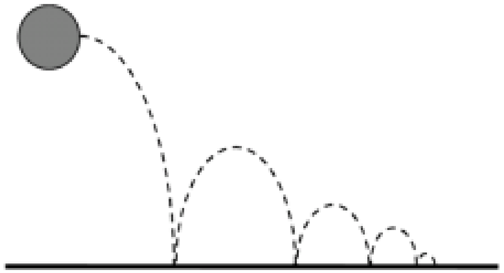
Differential equations

Typed Declarative Equation-based Textual Language

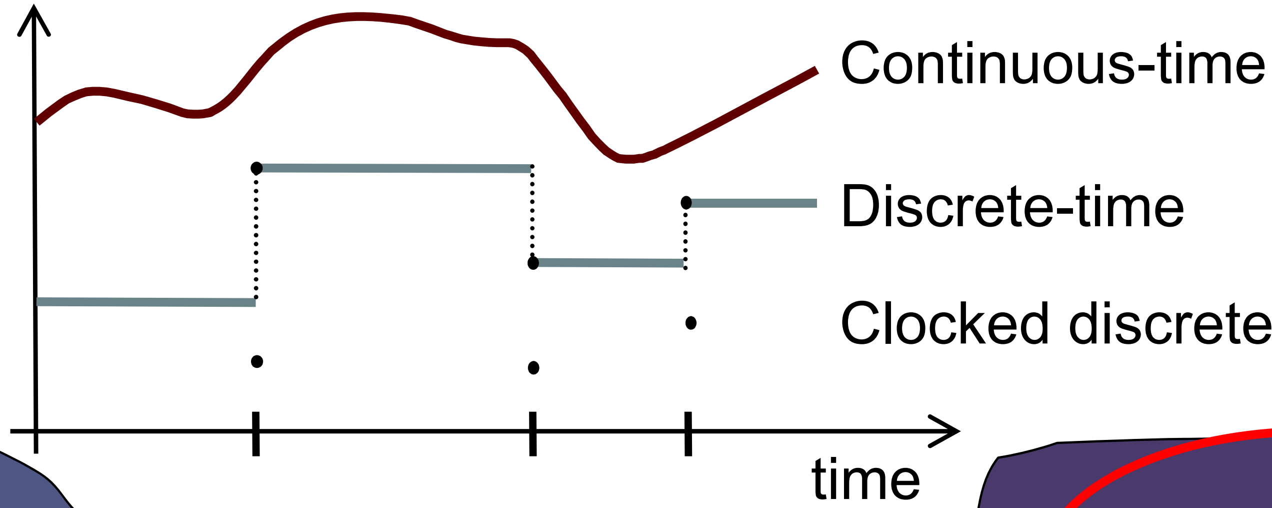
What is Special about Modelica?

Multi-Domain Modeling

Visual Acausal Component Modeling



Hybrid modeling =
continuous-time + discrete-time modeling



Typed Declarative Equation-based Textual Language

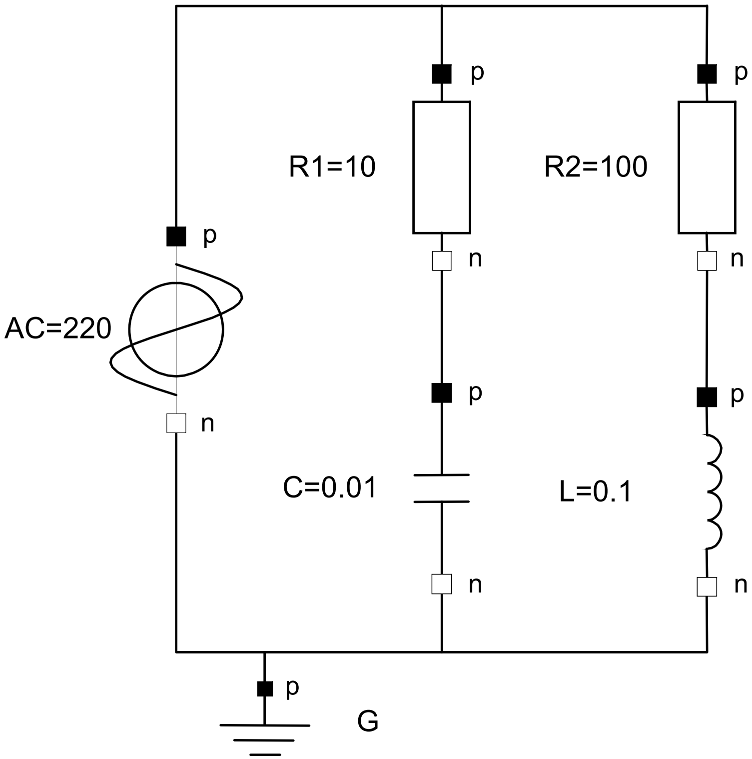
Hybrid Modeling

MODELICA

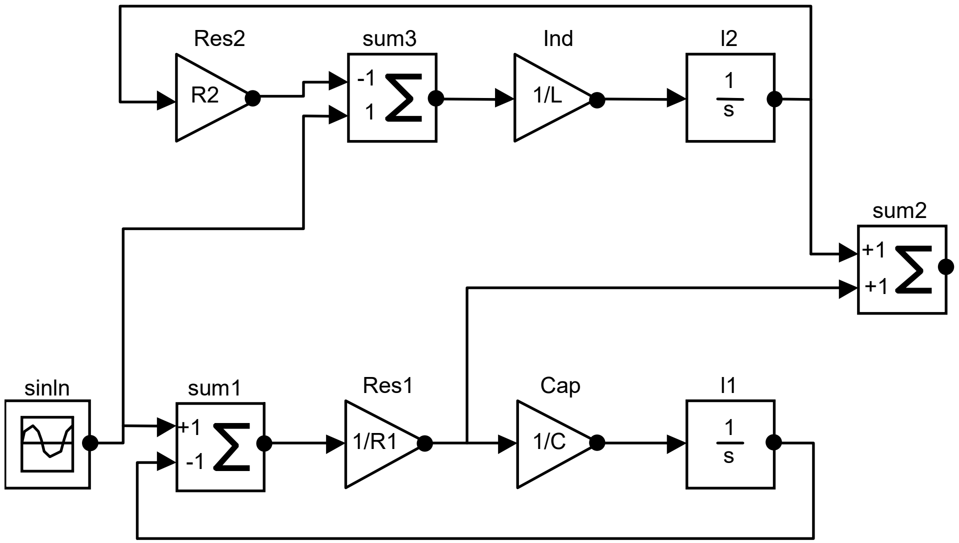
Modelica vs Simulink Block Oriented Modeling Simple Electrical Model

Modelica:
Physical model – easy to understand

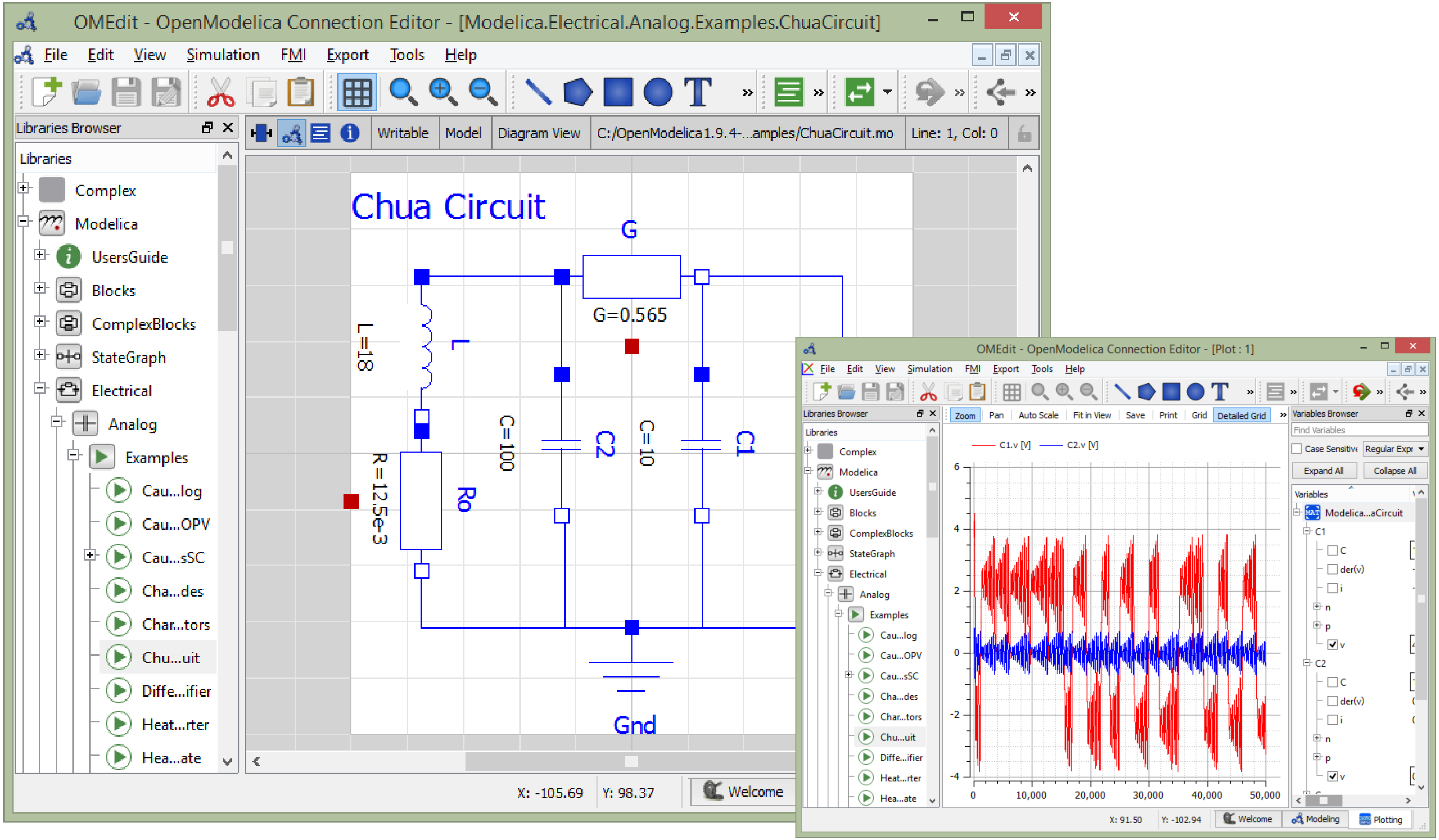
Keeps the physical structure



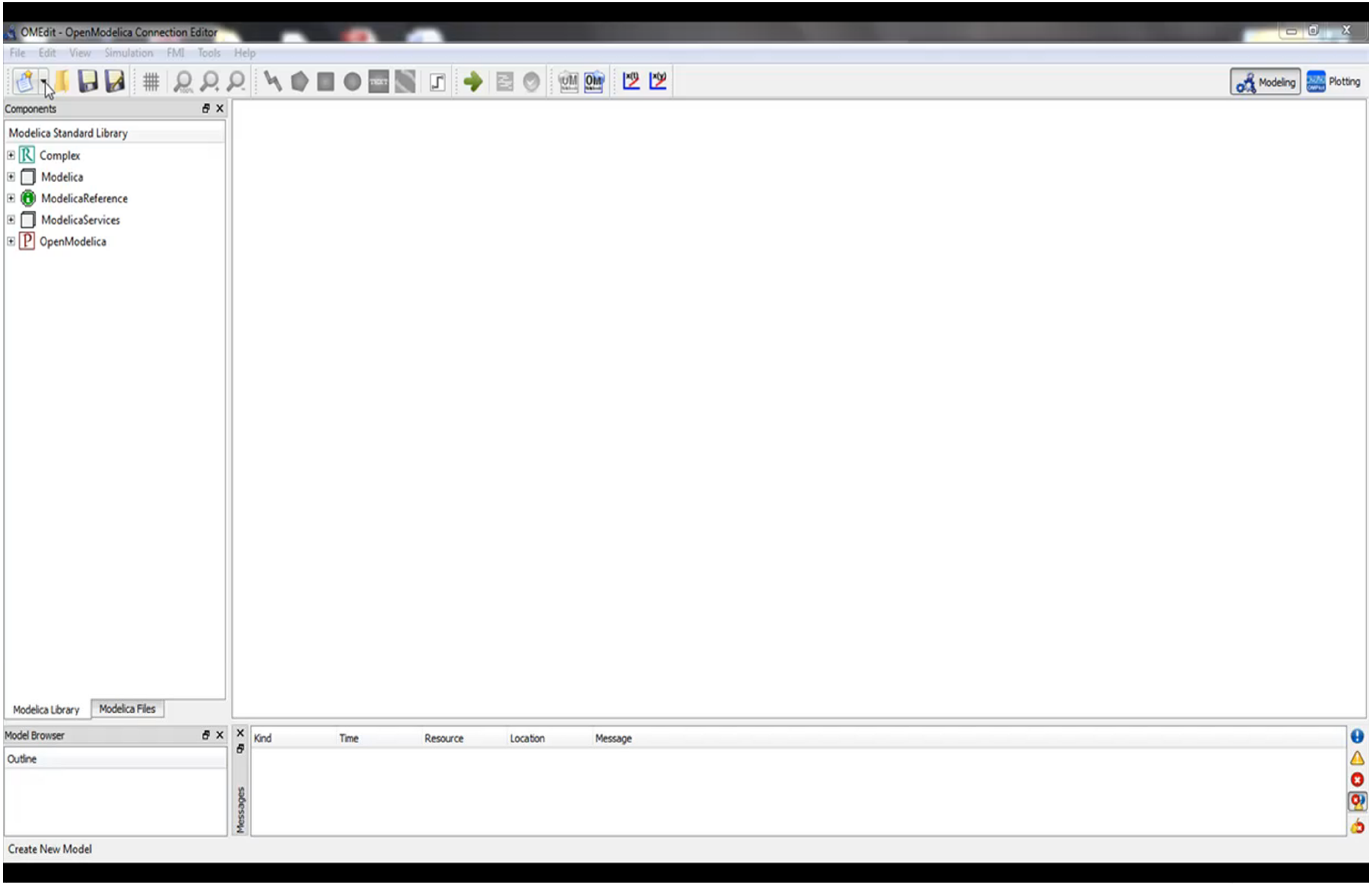
Simulink:
Signal-flow model – hard to understand



OpenModelica Tool Graphical Editor and Plotting
Graphical Modeling Using Drag and Drop



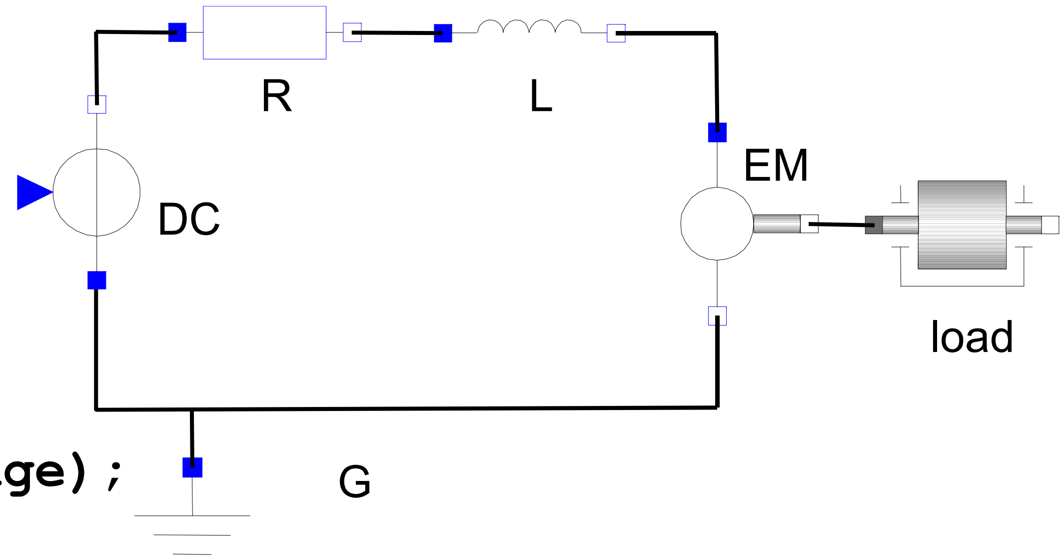
Graphical Modeling with OpenModelica Environment



Multi-Domain (Electro-Mechanical) Modelica Model

- A DC motor can be thought of as an electrical circuit which also contains an electromechanical component

```
model DCMotor
    Resistor R(R=100);
    Inductor L(L=100);
    VsourceDC DC(f=10);
    Ground G;
    ElectroMechanicalElement EM(k=10,J=10, b=2);
    Inertia load;
equation
    connect(DC.p,R.n);
    connect(R.p,L.n);
    connect(L.p, EM.n);
    connect(EM.p, DC.n);
    connect(DC.n,G.p);
    connect(EM.flange,load.flange);
end DCMotor
```



Corresponding DCMotor Model Equations

The following equations are automatically derived from the Modelica model:

```
0 == DC.p.i + R.n.i
DC.p.v == R.n.v

0 == R.p.i + L.n.i
R.p.v == L.n.v

0 == L.p.i + EM.n.i
L.p.v == EM.n.v

0 == EM.p.i + DC.n.i
EM.p.v == DC.n.v

0 == DC.n.i + G.p.i
DC.n.v == G.p.v
```

```
EM.u == EM.p.v - EM.n.v
0 == EM.p.i + EM.n.i
EM.i == EM.p.i
EM.u == EM.k * EM.ω
EM.i == EM.M / EM.k
EM.J * EM.ω == EM.M - EM.b * EM.ω

DC.u == DC.p.v - DC.n.v
0 == DC.p.i + DC.n.i
DC.i == DC.p.i
DC.u == DC.Amp * Sin[2 π DC.f * t]
```

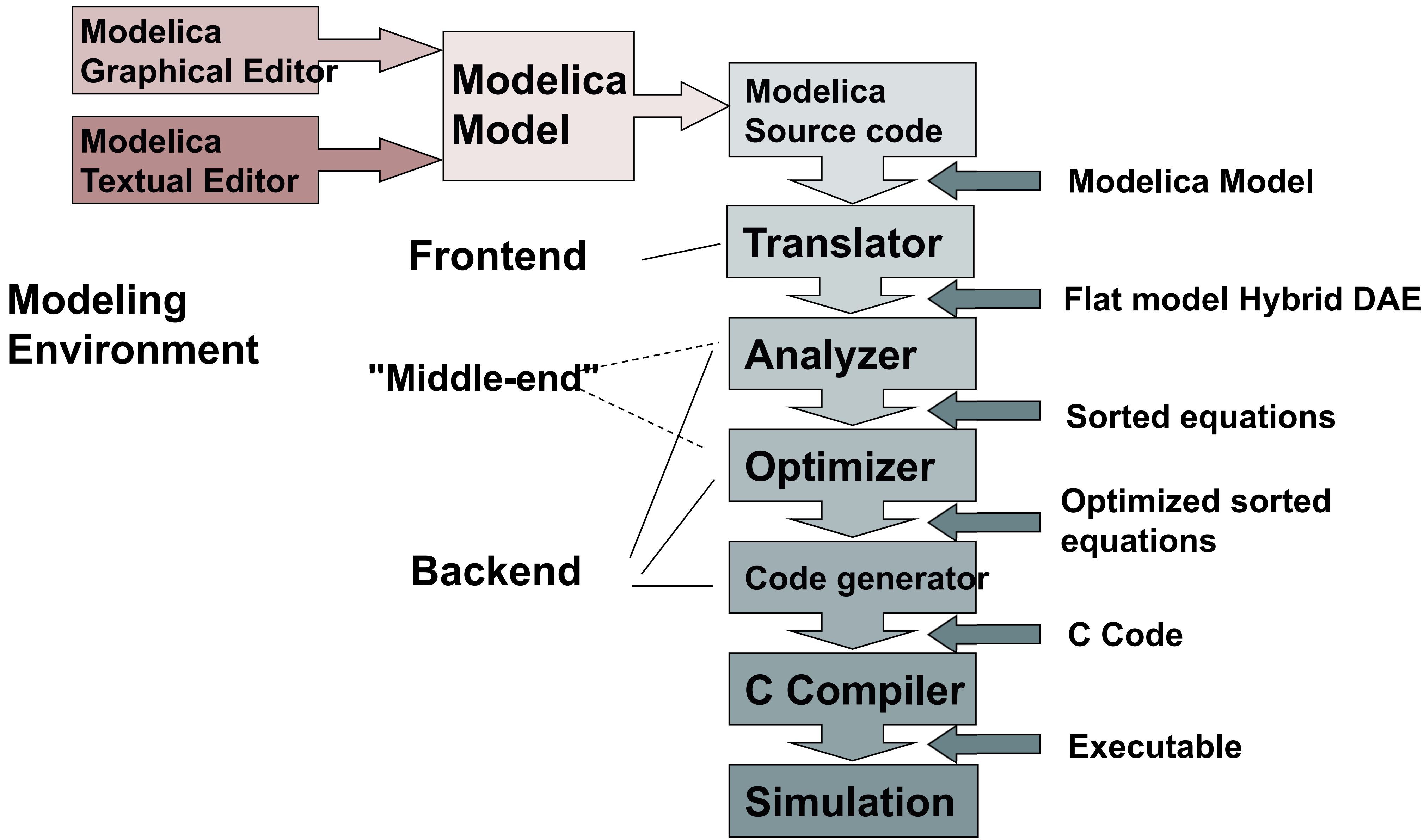
```
R.u == R.p.v - R.n.v
0 == R.p.i + R.n.i
R.i == R.p.i
R.u == R.R * R.i

L.u == L.p.v - L.n.v
0 == L.p.i + L.n.i
L.i == L.p.i
L.u == L.L * L.i'
```

(`load` component not included)

Automatic transformation to ODE or DAE for simulation:

$$\frac{dx}{dt} == f[x, u, t] \qquad g\left[\frac{dx}{dt}, x, u, t\right] == 0$$

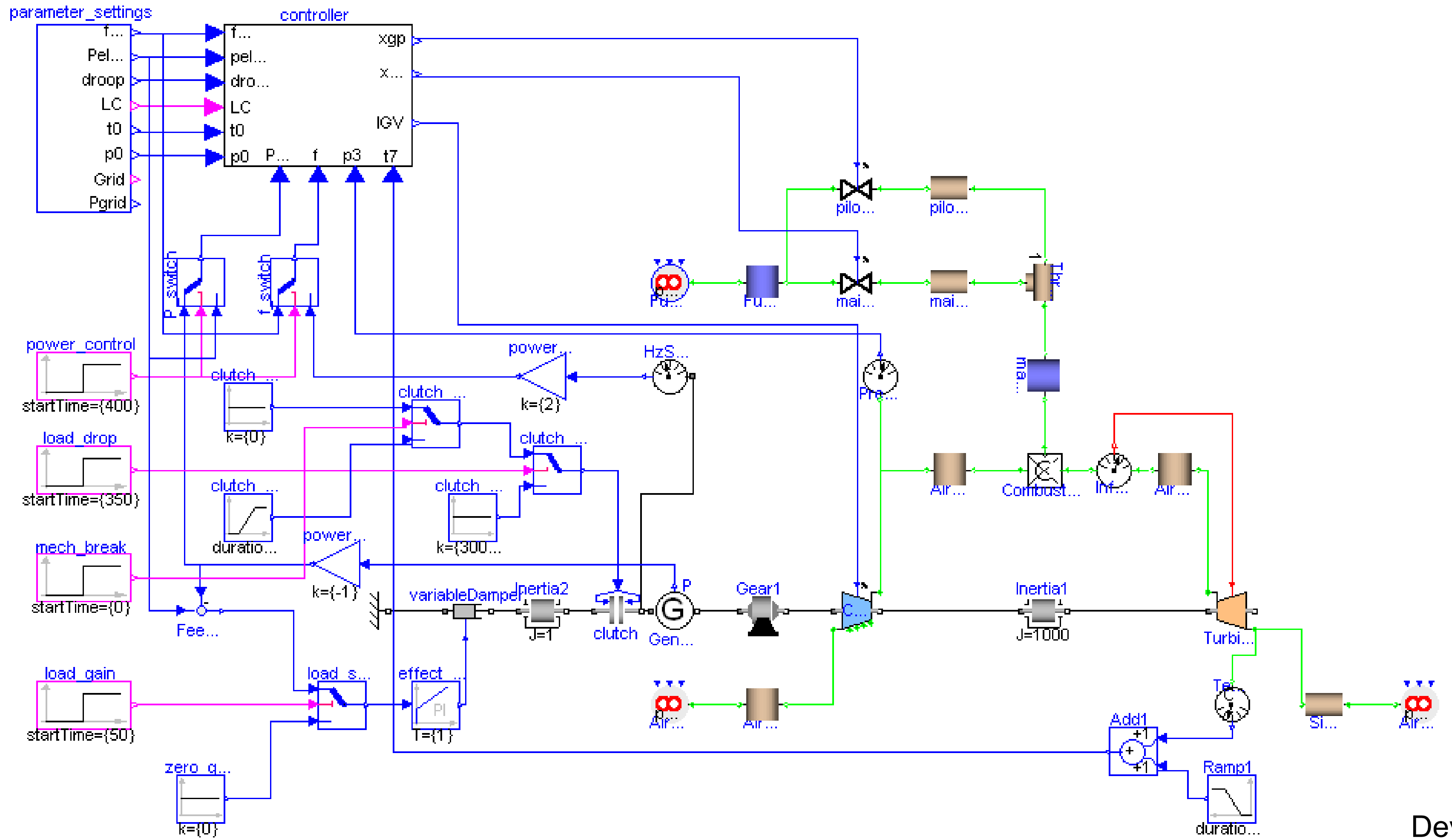
Model Translation Process to Hybrid DAE to Code



Brief Modelica History

- First Modelica design group meeting in fall 1996
  - International group of people with expert knowledge in both language design and physical modeling
  - Industry and academia
- Modelica Versions
  - 1.0 released September 1997
  - 2.0 released March 2002
  - 2.2 released March 2005
  - 3.0 released September 2007
  - 3.1 released May 2009
  - 3.2 released March 2010
  - 3.3 released May 2012
  - 3.2 rev 2 released November 2013
  - 3.3 rev 1 released July 2014
  - 3.4 released May 2017
- Modelica Association established 2000 in Linköping
  - Open, non-profit organization

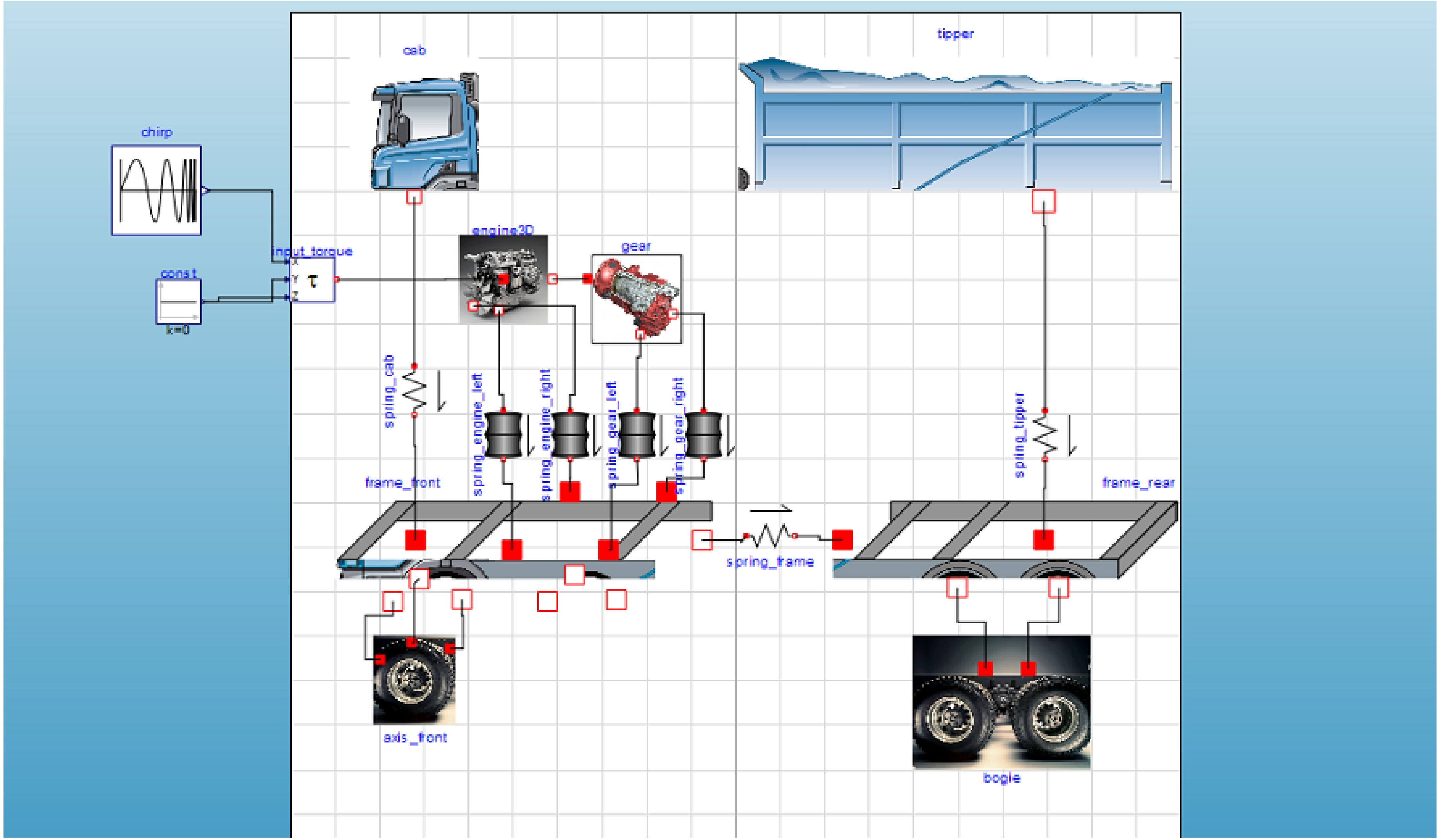
Modelica in Power Generation
GTX Gas Turbine Power Cutoff Mechanism



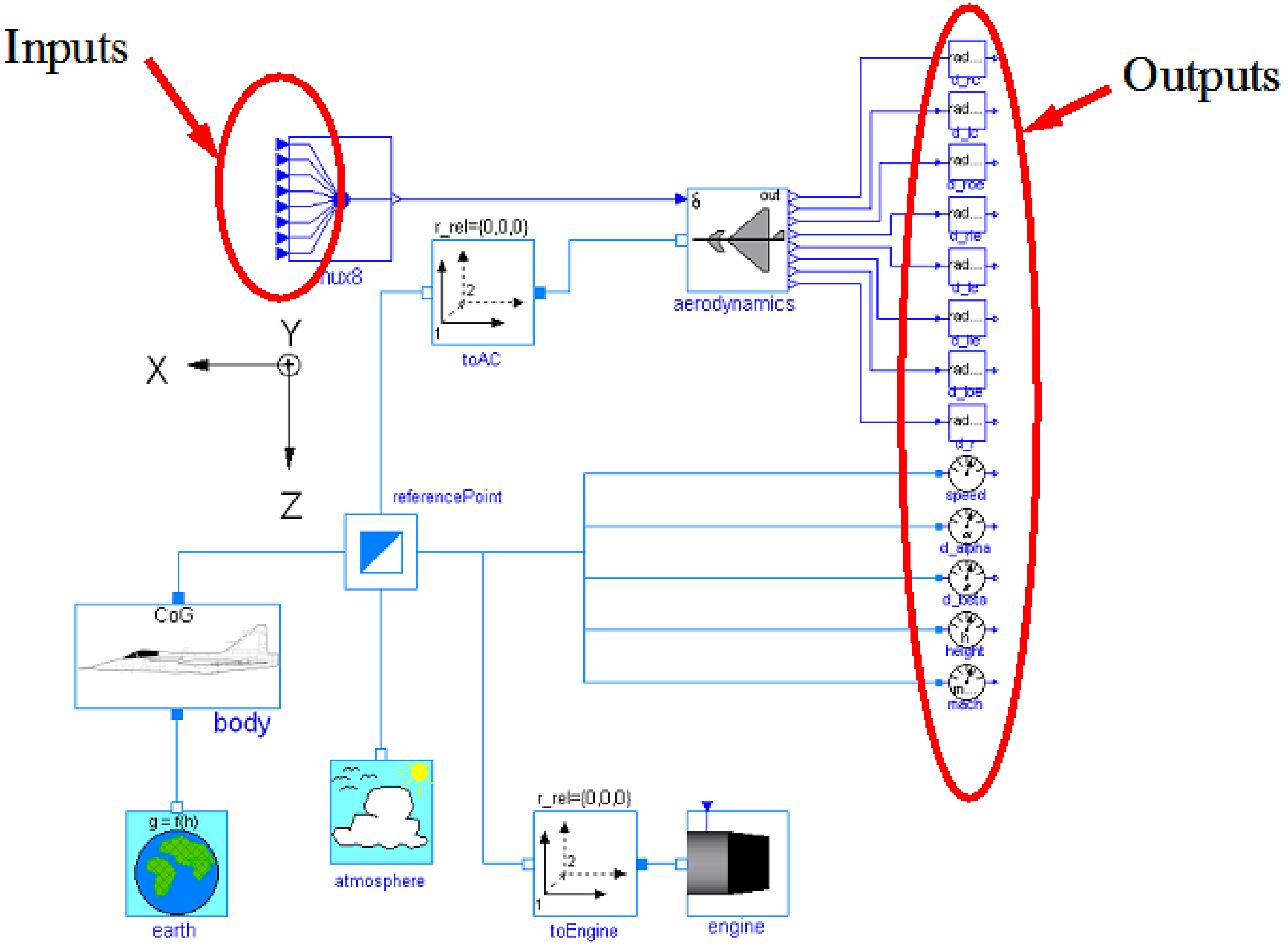
Developed by MathCore for Siemens

Courtesy of Siemens Industrial Turbomachinery AB

Modelica in Automotive Industry

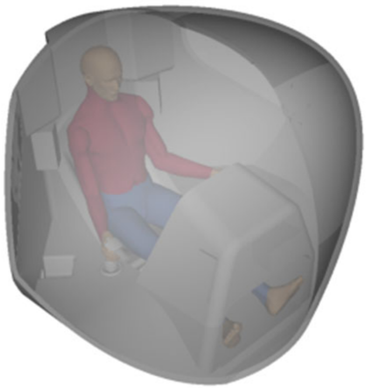


Modelica in Avionics



Application of Modelica in Robotics Models
Real-time Training Simulator for Flight, Driving

- Using Modelica models generating real-time code
- Different simulation environments (e.g. Flight, Car Driving, Helicopter)
- Developed at DLR Munich, Germany
- Dymola Modelica tool



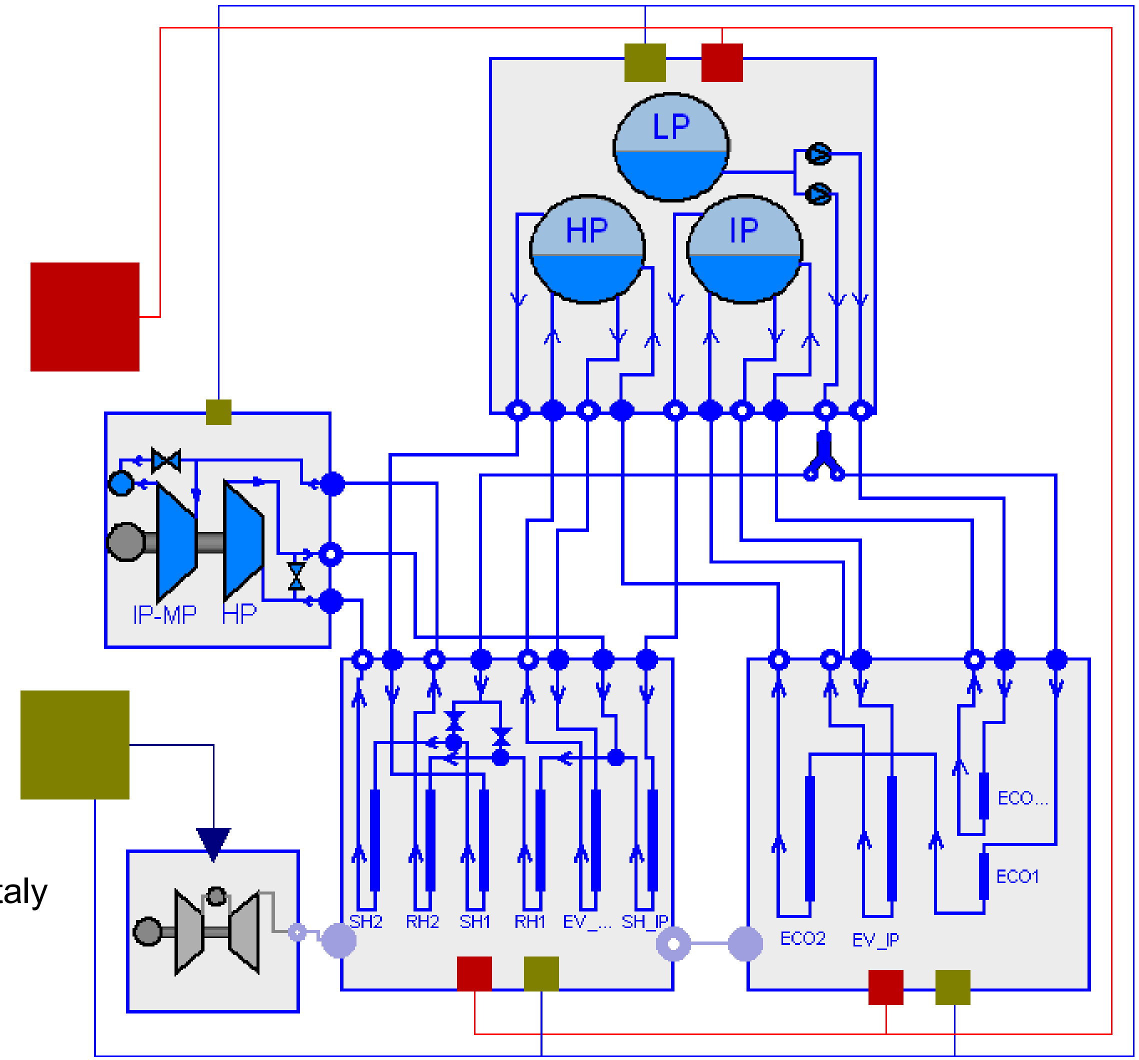
Courtesy of Tobias Bellmann, DLR, Oberphaffenhofen, Germany

Large Robotic Flight Simulator (Demo)

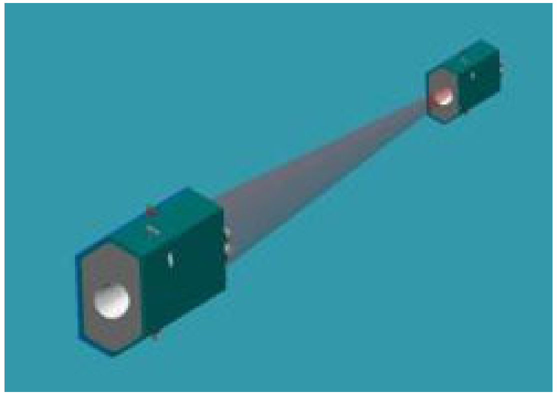
Combined-Cycle Power Plant
Plant model – system level

- GT unit, ST unit, Drum boilers unit and HRSG units, connected by thermo-fluid ports and by signal buses
- Low-temperature parts (condenser, feedwater system, LP circuits) are represented by trivial boundary conditions.
- GT model: simple law relating the electrical load request with the exhaust gas temperature and flow rate.

Courtesy Francesco Casella, Politecnico di Milano – Italy and Francesco Pretolani, CESI SpA - Italy

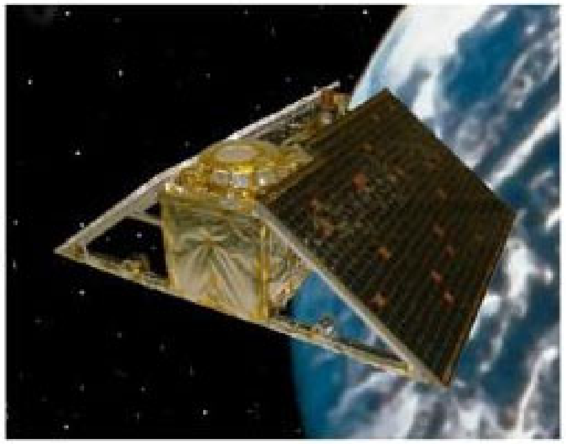


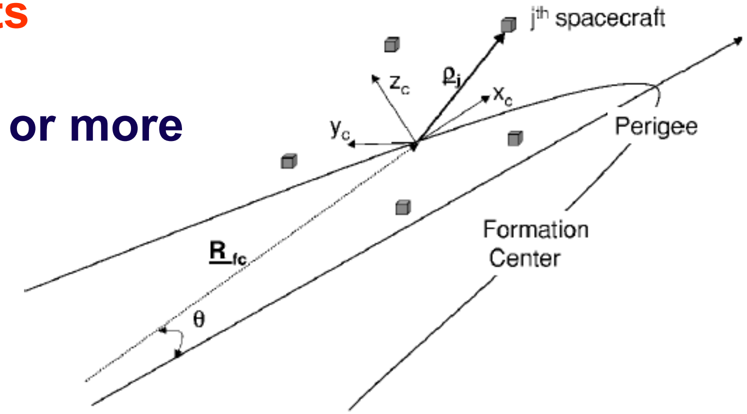
Modelica Spacecraft Dynamics Library



Formation flying on elliptical orbits

Control the relative motion of two or more spacecraft



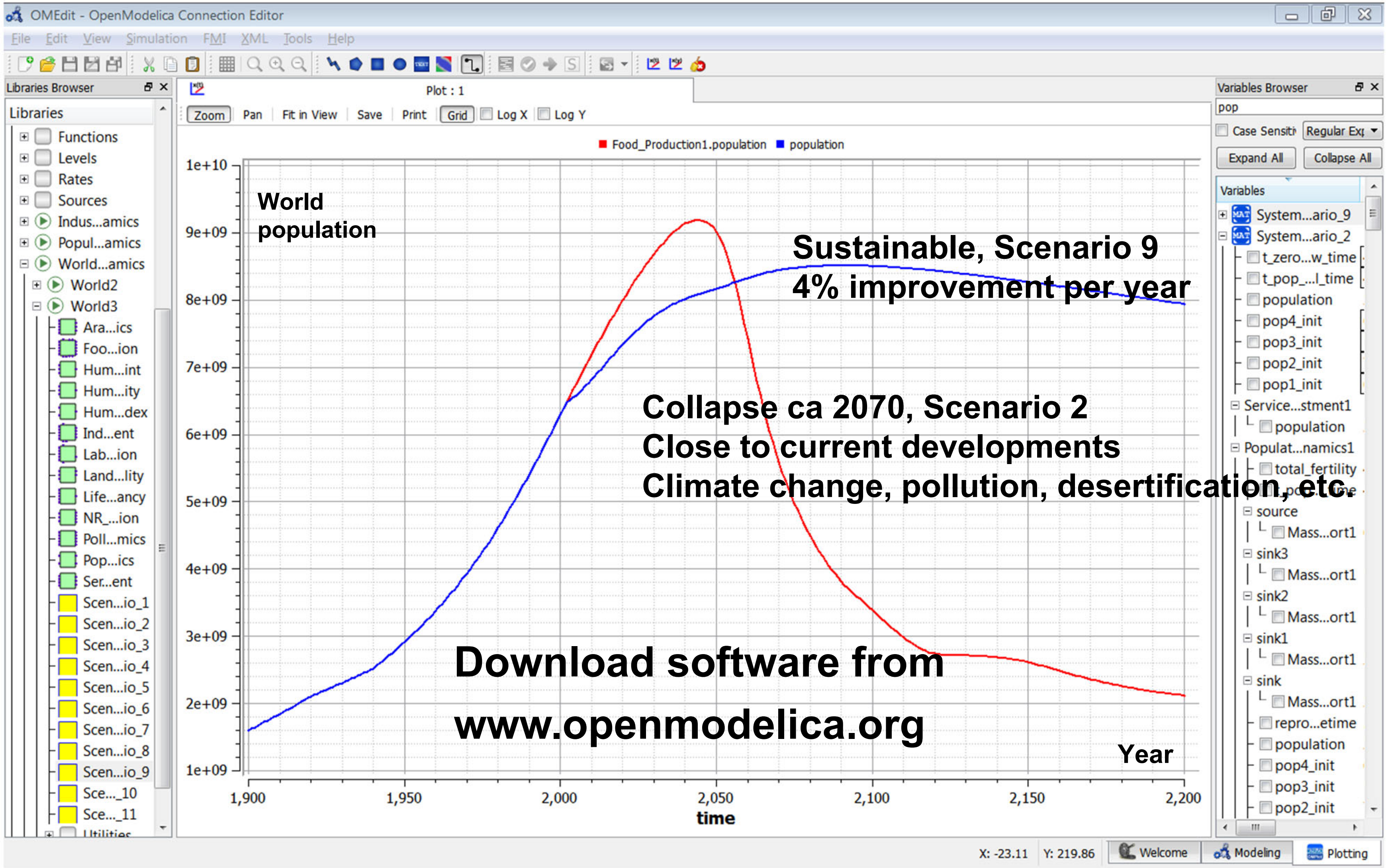


Attitude control for satellites using magnetic coils as actuators

Torque generation mechanism: interaction between coils and geomagnetic field

Courtesy of Francesco Casella, Politecnico di Milano, Italy

Biggest Immediate Challenge for Humanity –
Create a Sustainable Society – Avoid Global Collapse in 50 Years

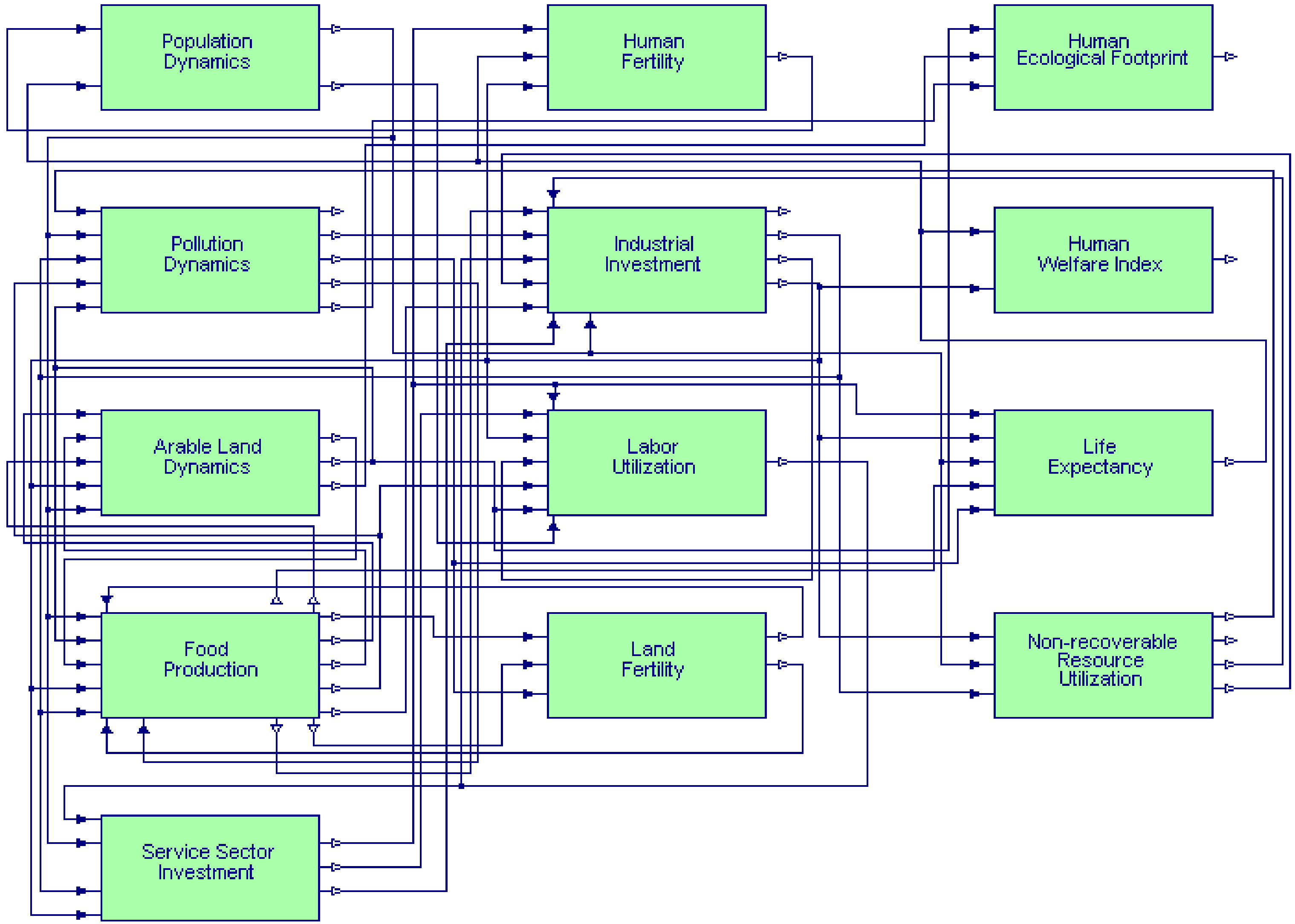


World System Dynamics Simulation with OpenModelica – World3 model, Meadows et al

MODELICA

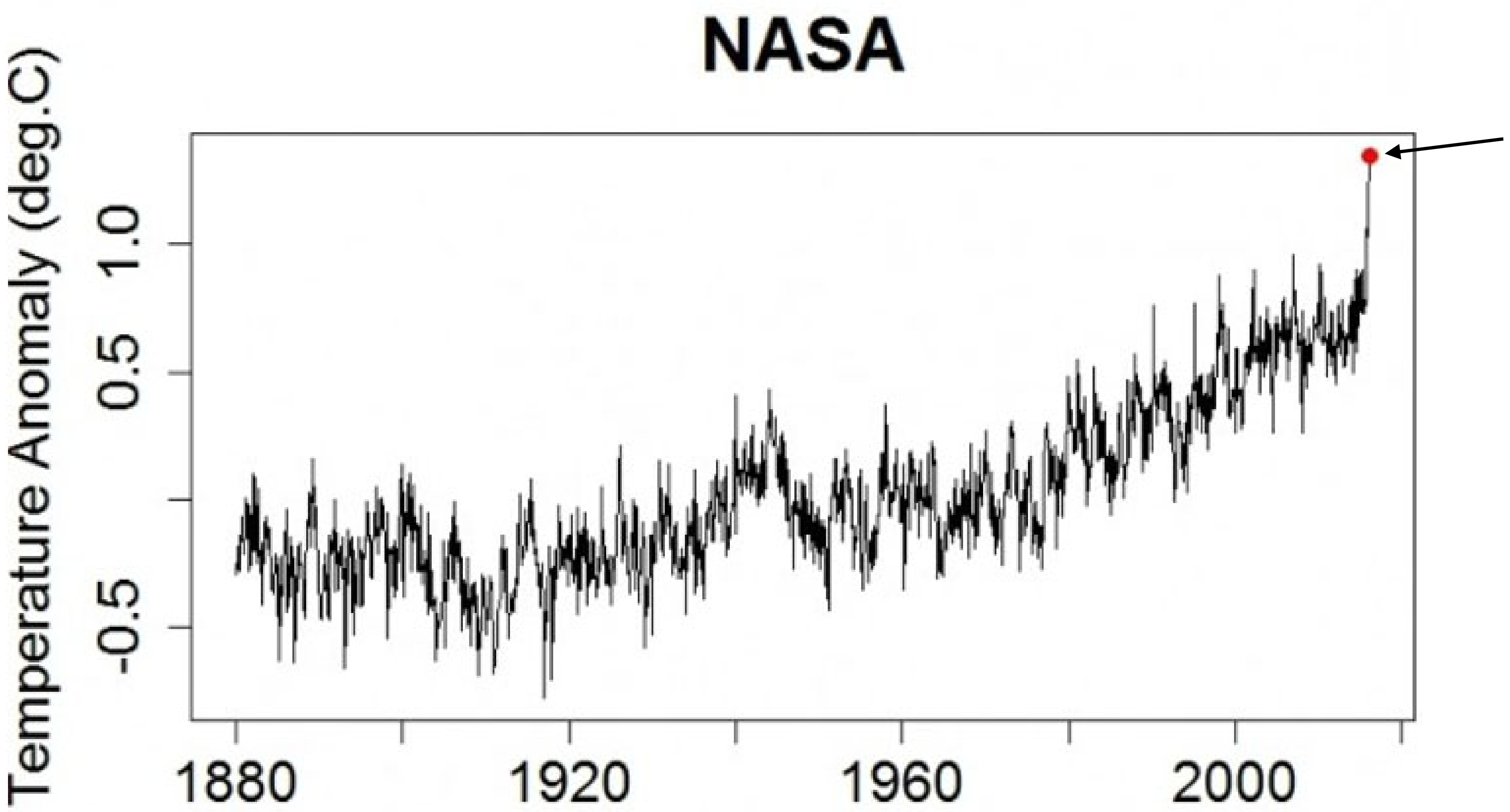
World3 Model in Modelica, Meadows et al, Cellier

Comprehensive model – 13 areas

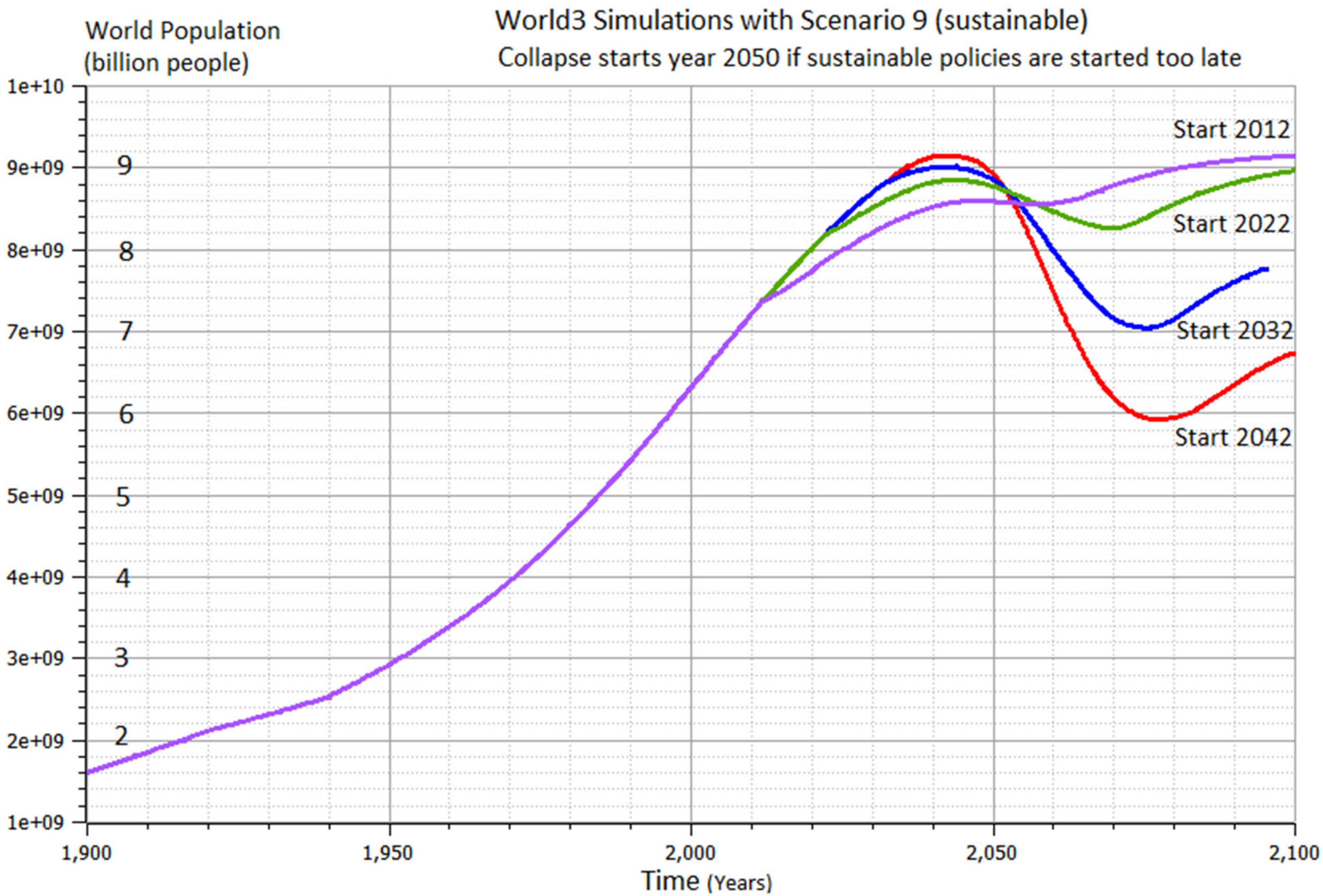


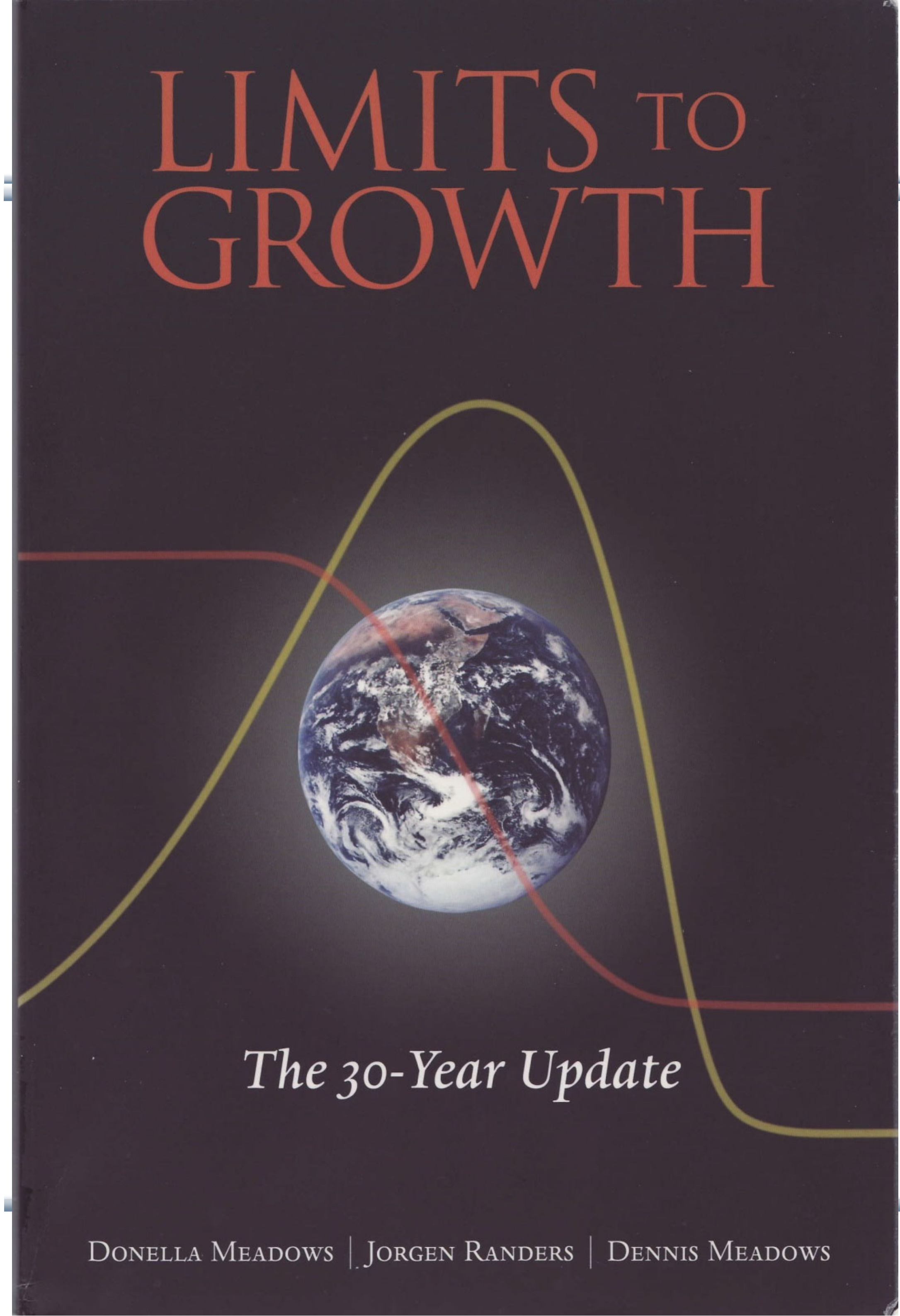
- Population dynamics
- Human fertility
- Human ecological footprint
- Pollution dynamics
- Industrial investment
- Human welfare
- Arable land
- Labor utilization
- Life expectancy
- Food production
- Land fertility
- Non-recover resource
- Service sector

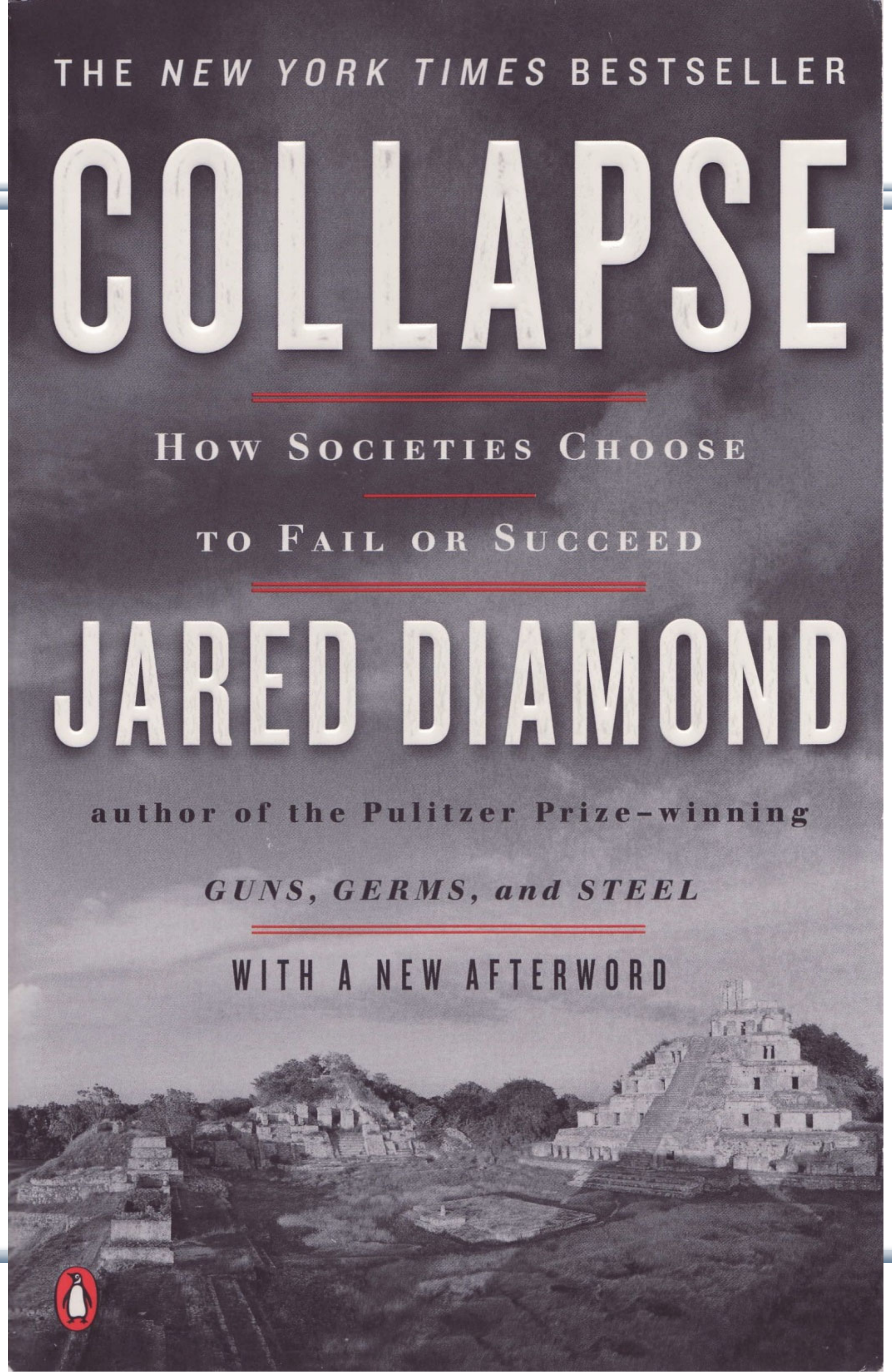
Each Year New Record for Global Mean Temperature
This is February 2016



World3 Simulations with Different Start Years for Sustainable Policies – Collapse if starting too late

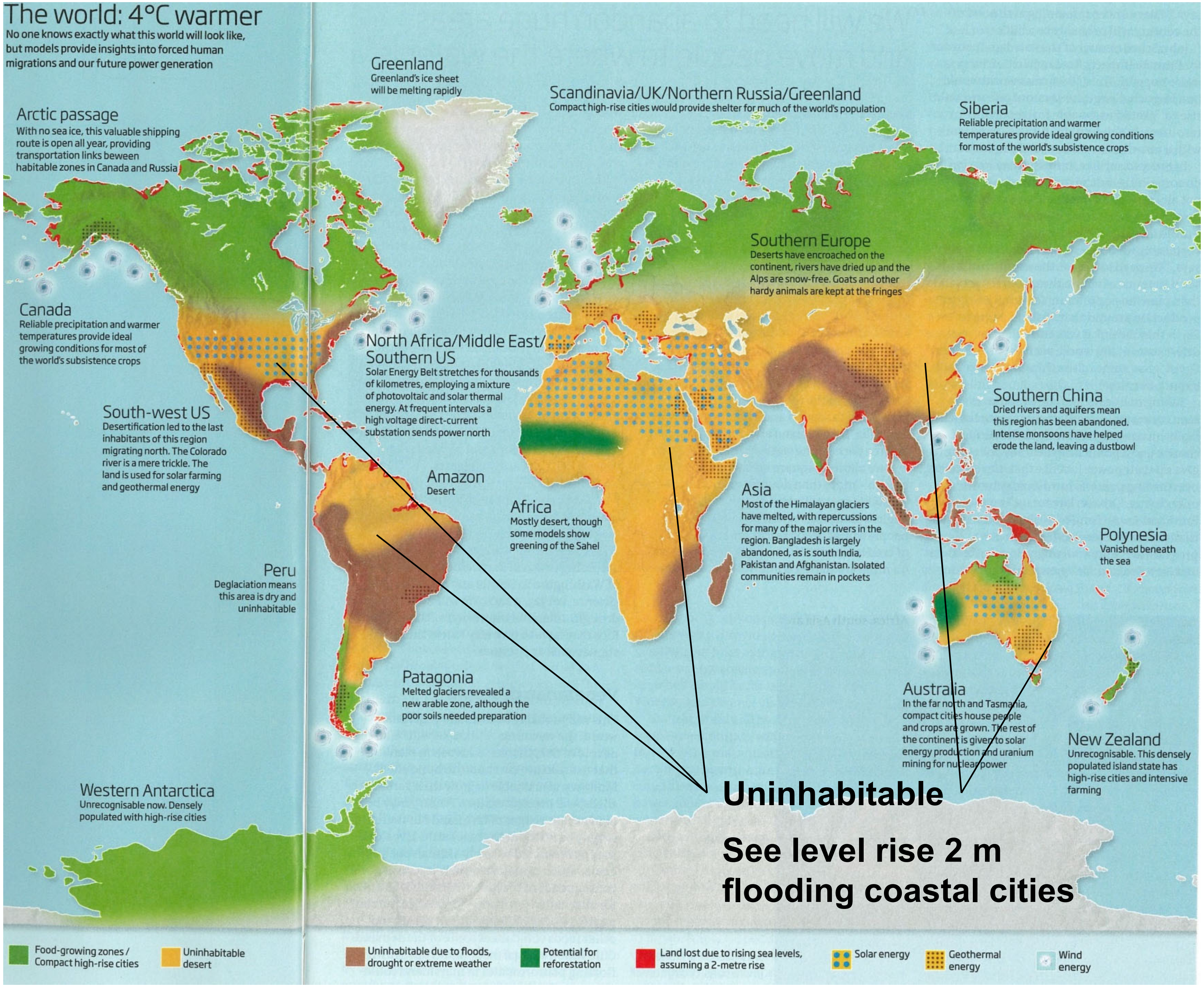



LIMITS TO GROWTH
The 30-Year Update
DONELLA MEADOWS | JORGEN RANDERS | DENNIS MEADOWS


THE NEW YORK TIMES BESTSELLER
COLLAPSE
HOW SOCIETIES CHOOSE
TO FAIL OR SUCCEED
JARED DIAMOND
author of the Pulitzer Prize-winning
GUNS, GERMS, and STEEL
WITH A NEW AFTERWORD

How the world could be in 80-100 years at a global warming of 4 degrees

Business-as-usual scenario, IPCC



- Cities, agriculture
- Uninhabitable desert
- Uninhabitable due to extreme weather
- Flooded

Massive migration to to northern Europe, Russia, and Canada

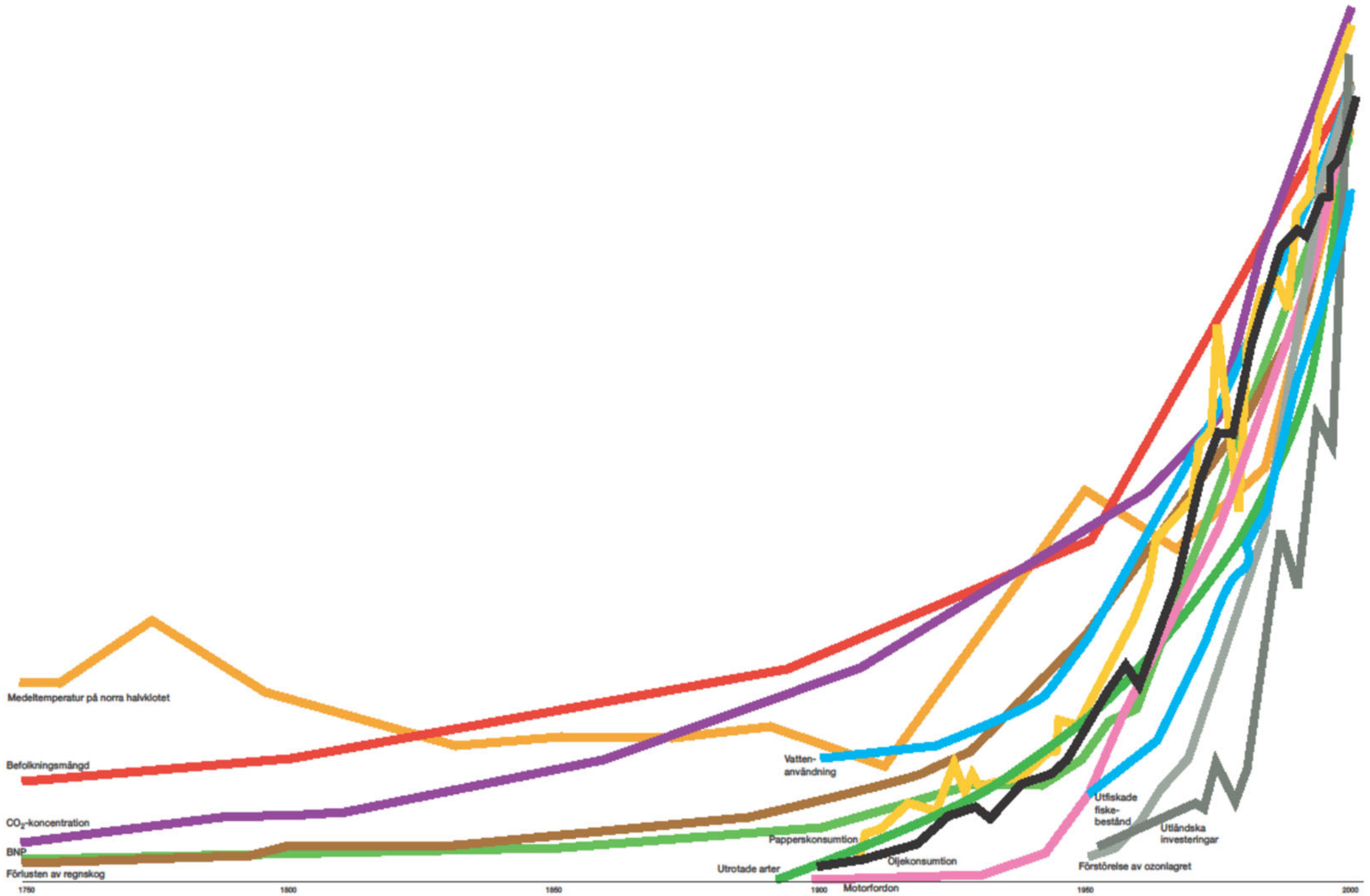
Example Emissions CO2e / person
- Earth can handle 2 ton/yr
- Flight Spain – 1 ton
- Flight Canaryisl – 2 ton
- Flight Thailand – 4 ton

References

New Scientist, 28 february 2009
IPCC, business as usual scenario
www.climate-lab-book.ac.uk
www.atmosfair.de

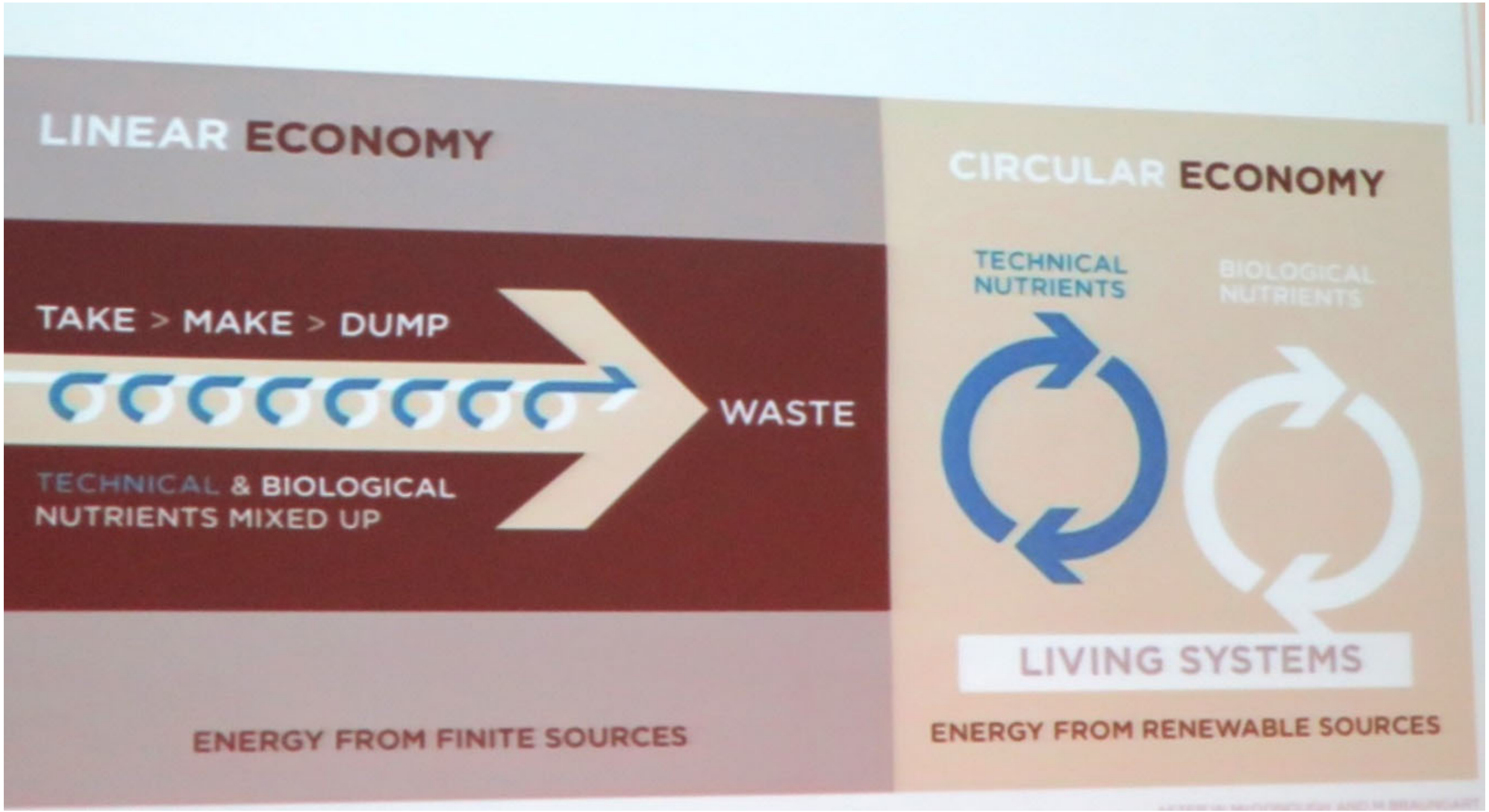
A Unique Point in History – Exponential Trends Approaches Planet Earth Boundaries

Year 1750-2000:



- Mean temperature north hemisphere,
- Population,
- CO_2-concentration,
- BNP,
- Loss av rain forest,
- Water usage
- Paper consumption,
- Exterminated species
- Oil consumtion,
- Motor vehicles
- Destroyed fish populations
- Destruction of ozon layer
- Foreign investments

Need Smart Systems to Support a Circular Economy for a Sustainable Society

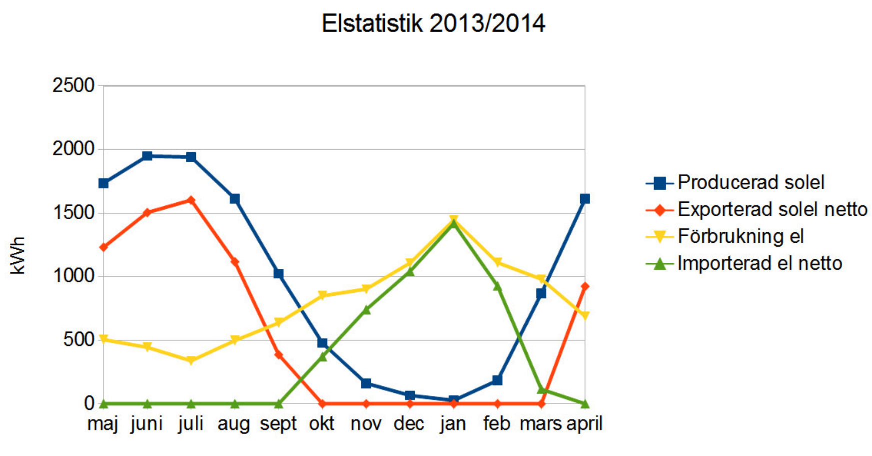


- **Circular** management of products, material, throughout the life-cycle
- Optimize manufacturing and usage over the **entire life cycle**

What Can You Do?
Need Global Sustainability Mass Movement

- Develop smart Cyber-Physical systems for reduced energy and material footprint
- Model-based circular economy for re-use of products and materials
- Promote sustainable lifestyle and technology
- Install electric solar PV panels
- Buy shares in cooperative wind power

20 sqm solar panels on garage roof, Nov 2012
Generated 2700 W at noon March 10, 2013



Expanded to 93 sqm, 12 kW, March 2013
House produced 11600 kwh, used 9500 kwh
Avoids 10 ton CO_2 emission per year

Example Electric Cars
Can be charged by electricity from own solar panels

Renault ZOE; 5 seat; Range:
22kw (2014) vs 41 kw battery (2017)

- Realistic Swedish drive cycle:
- Summer: 165 km, now 300 km
- Winter: 110 km, now 200 km

Cheap fast AC chargers (22kw, 43kw)

Tesla model S
range 480 km

DLR ROboMObil

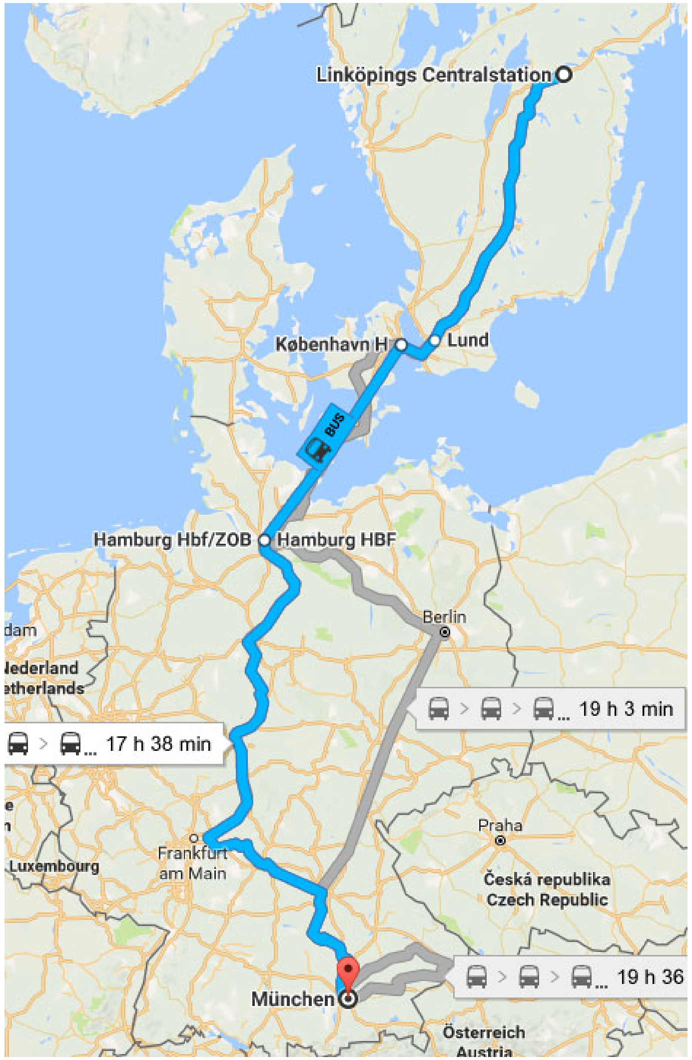
- experimental electric car
- Modelica models

What Can You Do?
More Train Travel – Less Air Travel

- Air travel by Swedish Citizens – about the same emissions as all personal car traffic in Sweden!
- By train from Linköping to Munich and back – saves almost 1 ton of CO2e emissions compared to flight
- Leave Linköping 07.00 in Munich 23.14

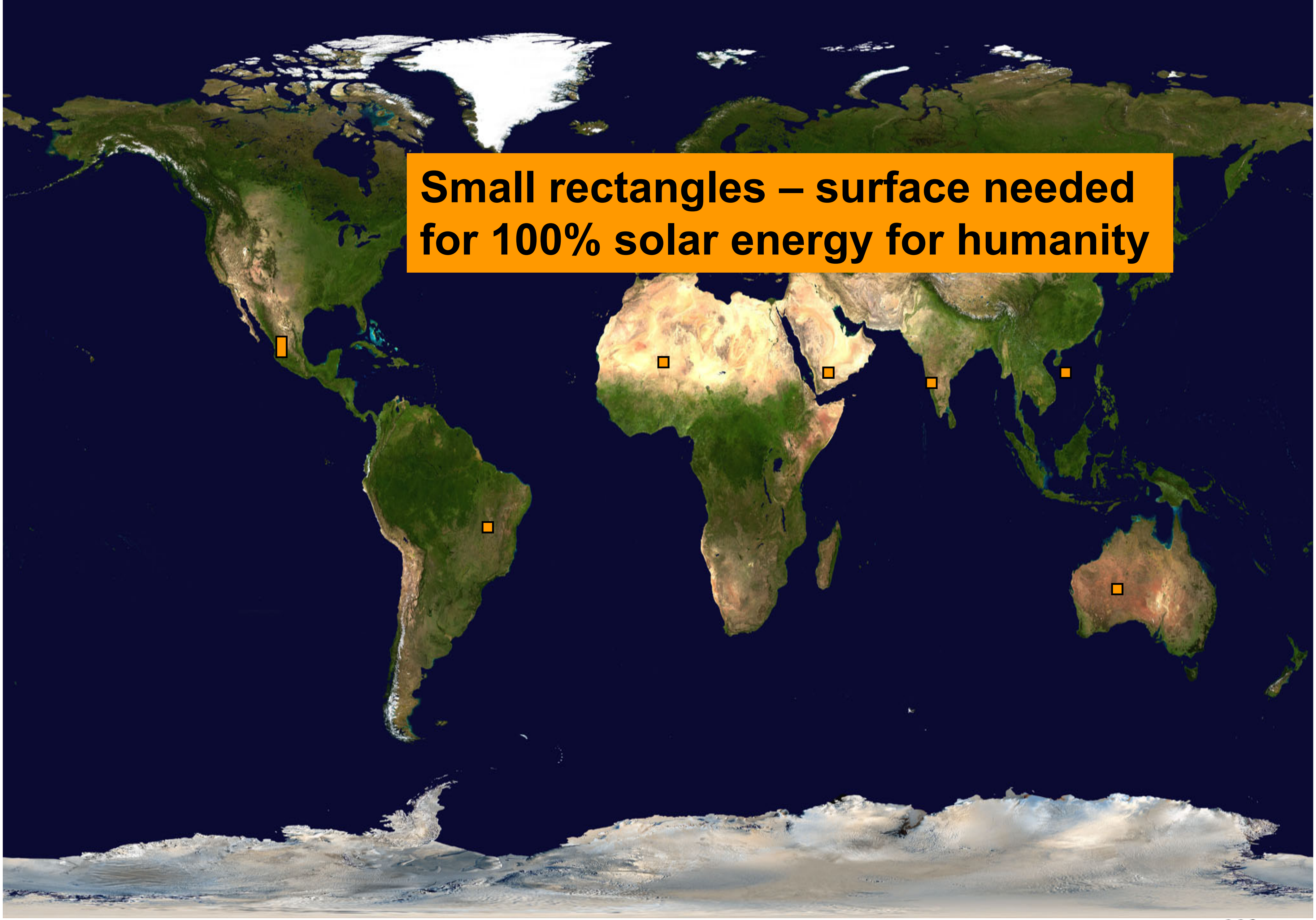
More Examples, PF travel 2016:

- Train Linköping-Paris, Dec 3-6, EU project meeting
- Train Linköping-Dresden, Dec 10-16, 1 week workshop



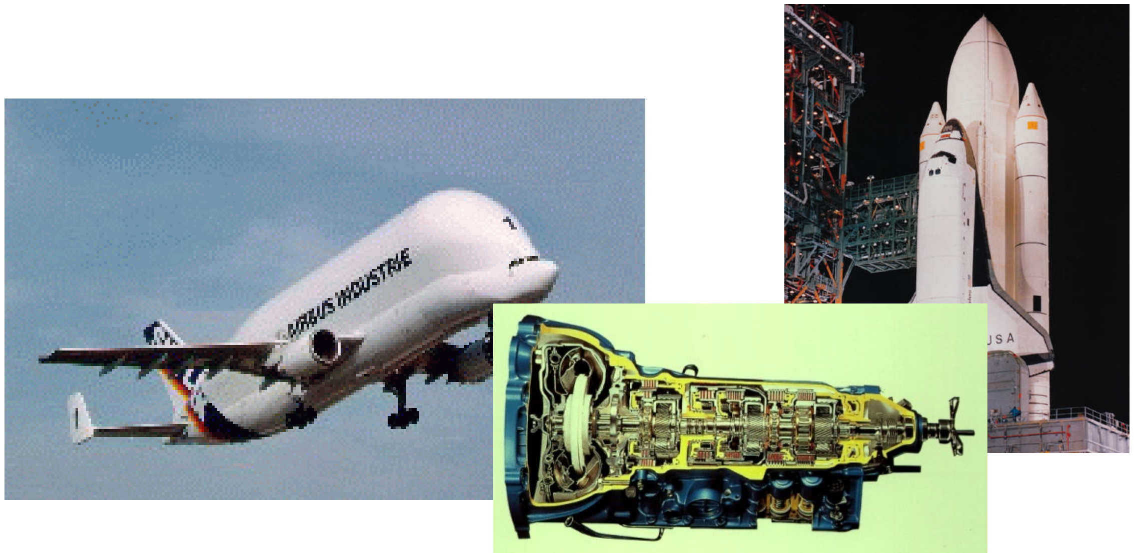
Train travel Linköping - Munich

MODELICA


Small rectangles – surface needed
for 100% solar energy for humanity

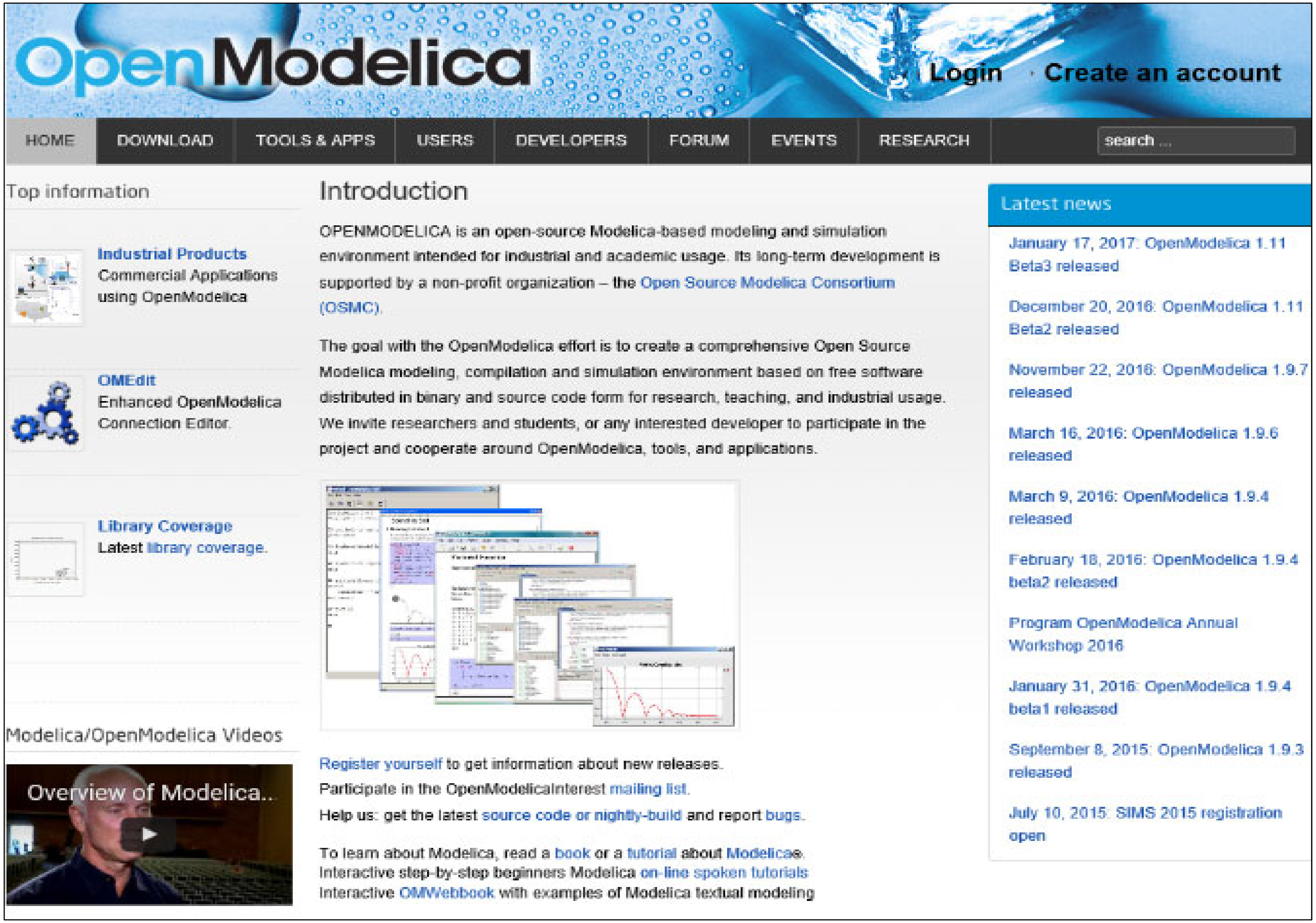
Part II

Introduction to the OpenModelica Environment



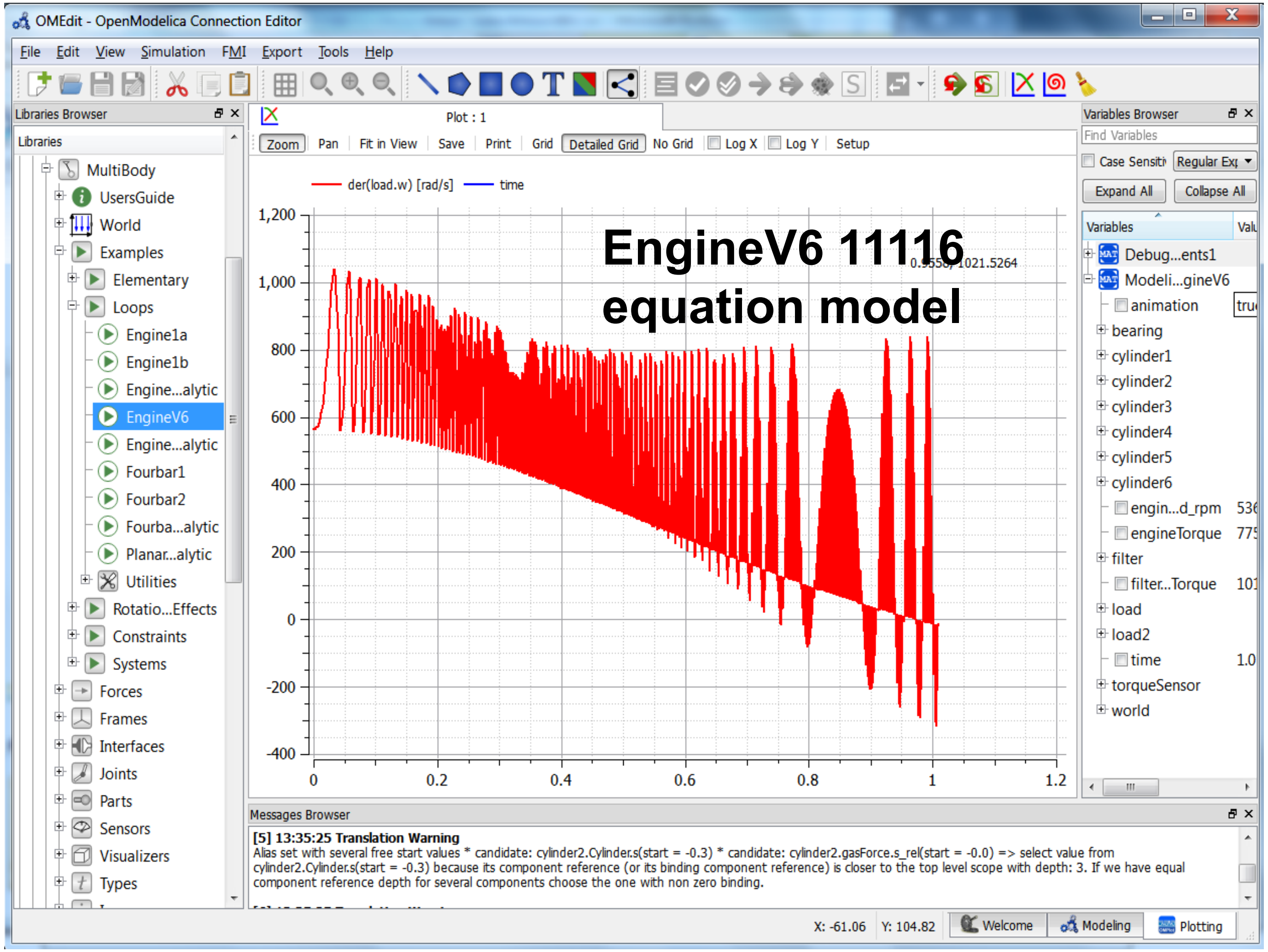
The OpenModelica Environment

www.openmodelica.org



OpenModelica – Free Open Source Tool
Developed by the Open Source Modelica Consortium (OSMC)

- Graphical editor
- Model compiler and simulator
- Debugger
- Performance analyzer
- Dynamic optimizer
- Symbolic modeling
- Parallelization
- Electronic Notebook and OMWebbook for teaching
- Spokentutorial for teaching

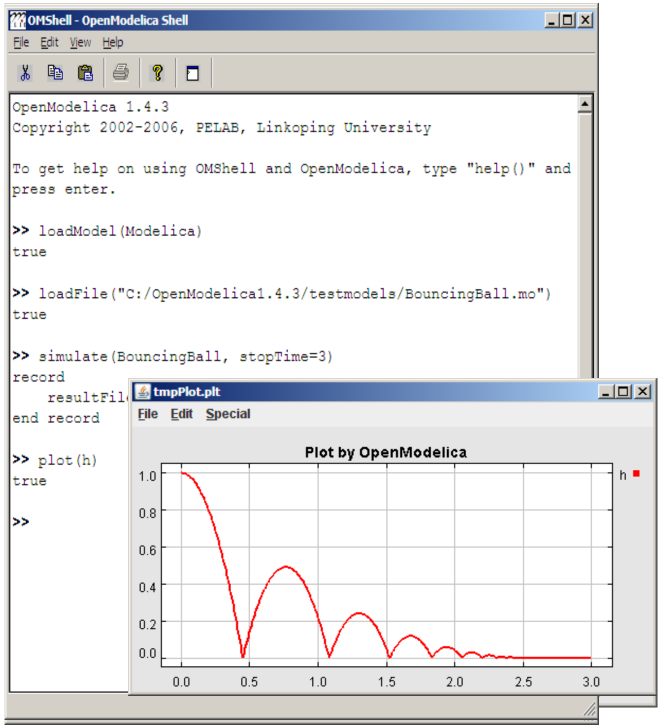


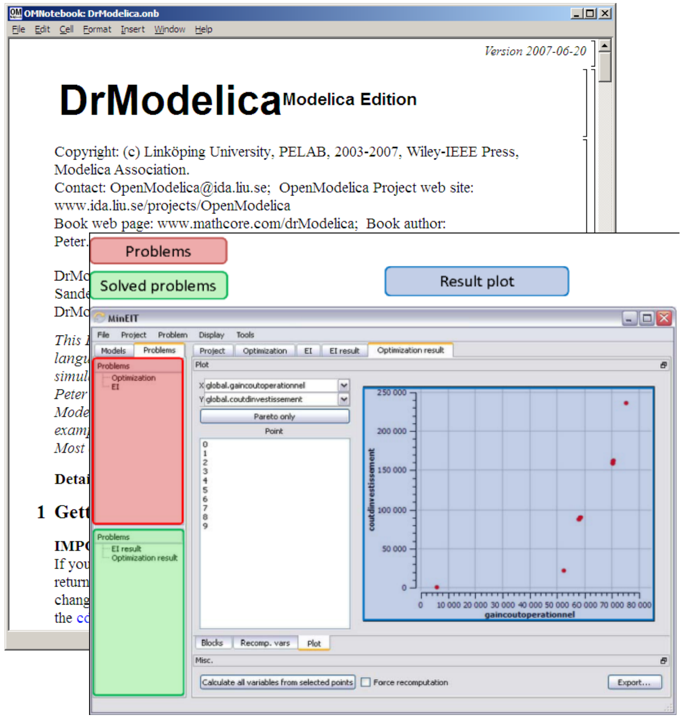
MODELICA

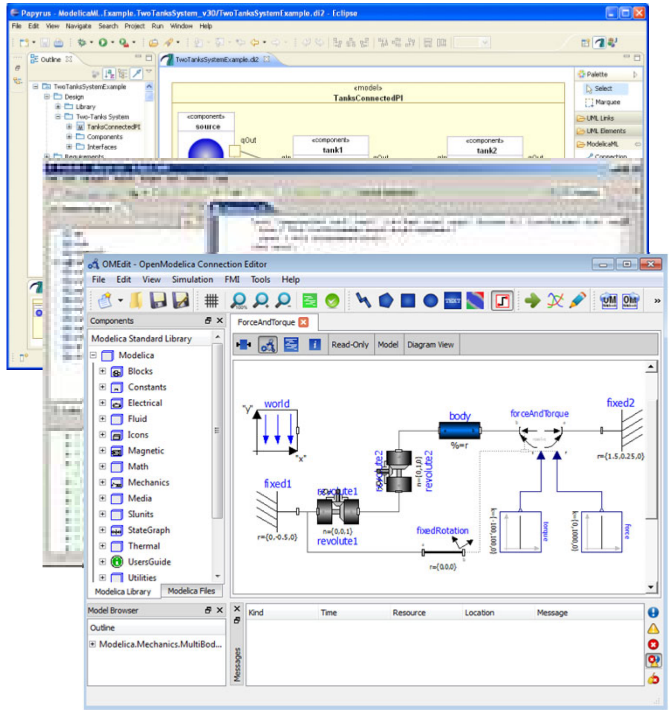
The OpenModelica Open Source Environment
www.openmodelica.org

- Advanced Interactive Modelica compiler (OMC)
  - Supports most of the Modelica Language
  - **Modelica** and **Python scripting**
- Basic environment for creating models
  - **OMShell** – an interactive command handler
  - **OMNotebook** – a literate programming notebook
  - **MDT** – an advanced textual environment in Eclipse

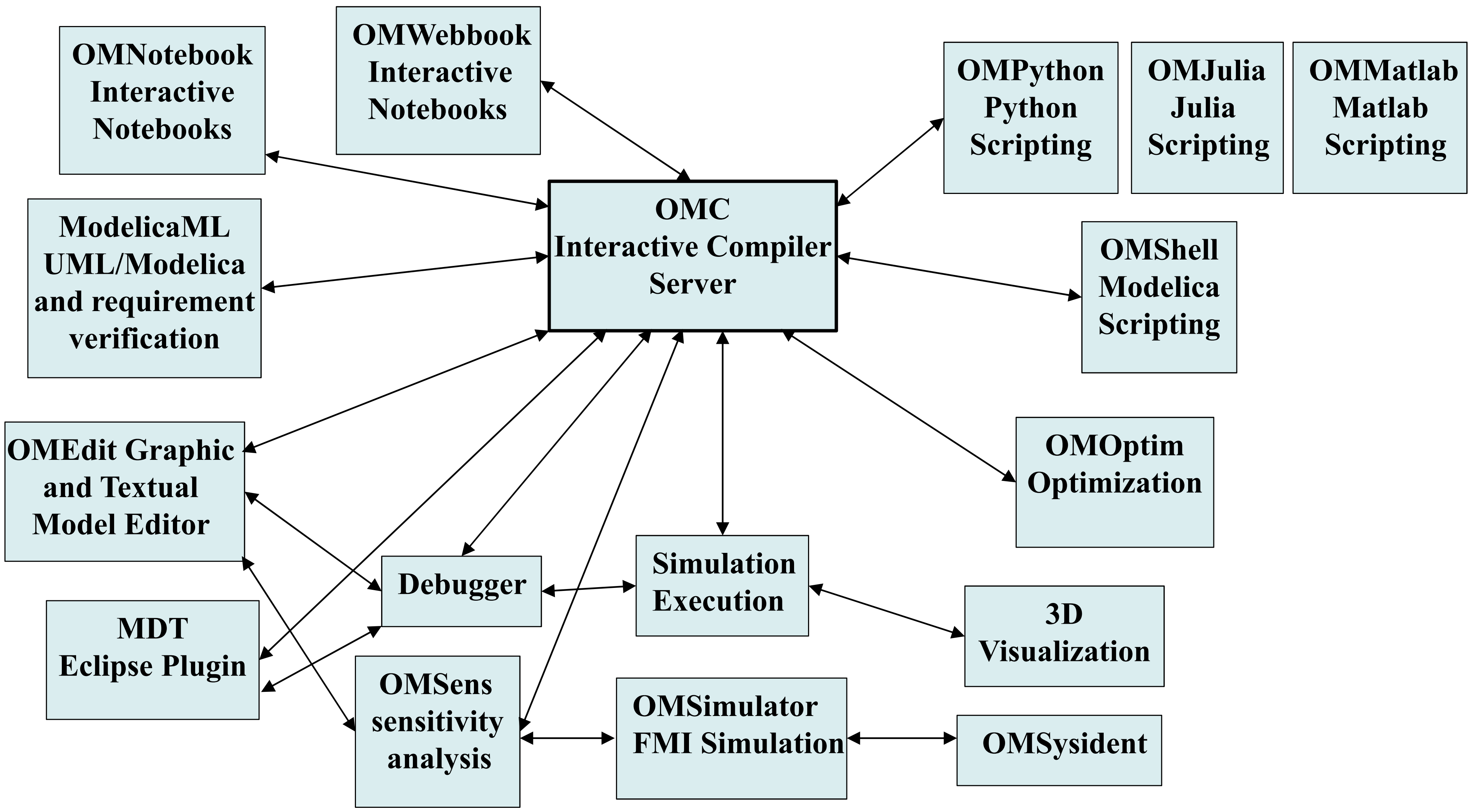
- **OMEdit** graphic Editor
- **OMDebugger** for equations
- **OMOptim** optimization tool
- **OM Dynamic optimizer** collocation
- **ModelicaML** UML Profile
- **MetaModelica** extension
- **ParModelica** extension
- new → **OMSimulator** – FMI/TLM simulator







The OpenModelica Tool Architecture



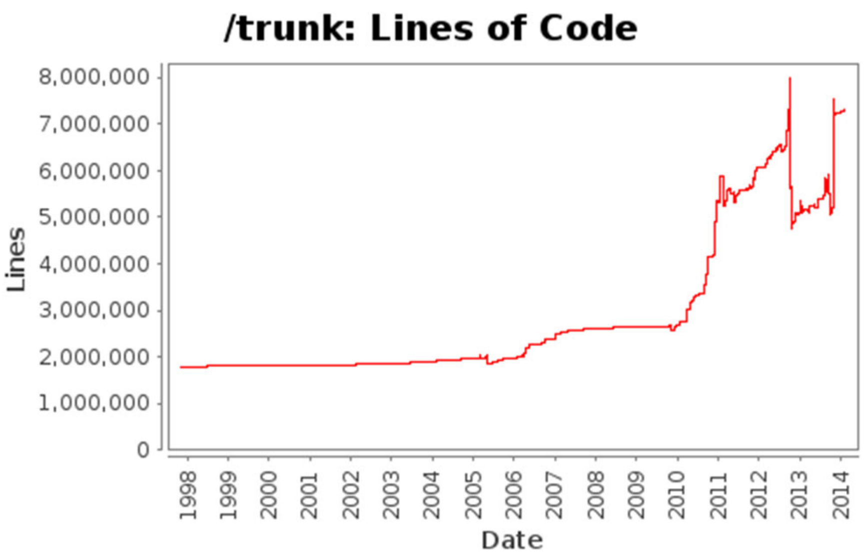
OSMC – International Consortium for Open Source Model-based Development Tools, 53 members Febr 2018

Founded Dec 4, 2007

Open-source community services

- **Website and Support Forum**
- **Version-controlled source base**
- **Bug database**
- **Development courses**
- **www.openmodelica.org**

Code Statistics



Industrial members

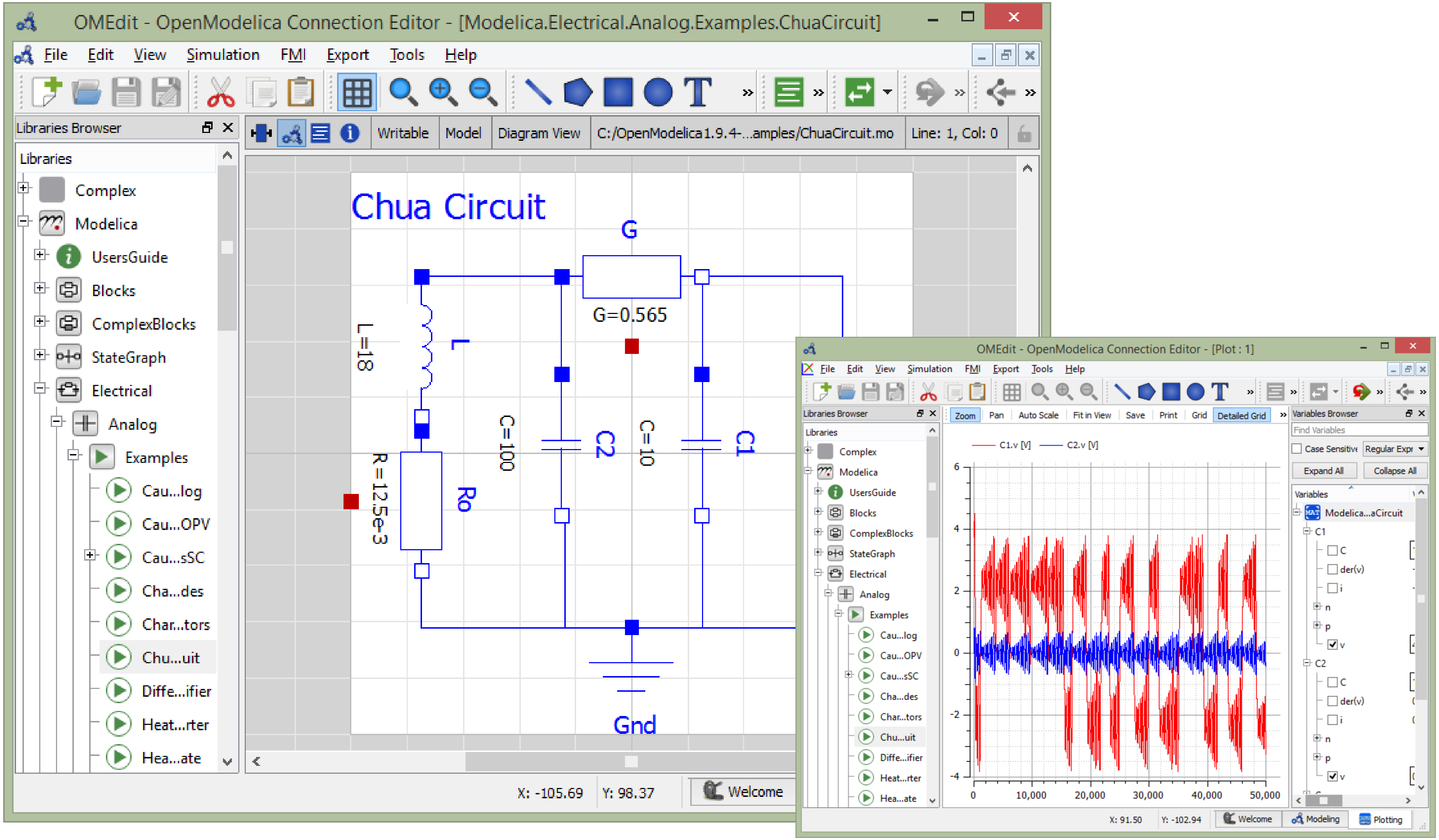
- **ABB AB, Sweden**
- **Berger IT-Cosmos, Germany**
- **Bosch Rexroth AG, Germany**
- **Brainheart Energy AB, Sweden**
- **CDAC Centre, Kerala, India**
- **Creative Connections, Prague**
- **DHI, Aarhus, Denmark**
- **Dynamica s.r.l., Cremona, Italy**
- **EDF, Paris, France**
- **Equa Simulation AB, Sweden**
- **Fraunhofer IWES, Bremerhaven**
- **INRIA, Rennes, France**
- **ISID Dentsu, Tokyo, Japan**
- **Maplesoft, Canada**
- **RTE France, Paris, France**
- **Saab AB, Linköping, Sweden**
- **Scilab Enterprises, France**
- **SKF, Göteborg, Sweden**
- **TLK Thermo, Germany**
- **Siemens Turbo, Sweden**
- **Sozhou Tongyuan, China**
- **Talent Swarm, Spain**
- **VTI, Linköping, Sweden**
- **VTT, Finland**
- **Wolfram MathCore, Sweden**

University members

- **FH Bielefeld, Bielefeld, Germany**
- **University of Bolivar, Colombia**
- **TU Braunschweig, Germany**
- **University of Calabria, Italy**
- **Univ California, Berkeley, USA**
- **Chalmers Univ, Control,Sweden**
- **Chalmers Univ, Machine, Sweden**
- **TU Darmstadt, Germany**
- **TU Delft, The Netherlands**
- **TU Dresden, Germany**
- **Université Laval, Canada**
- **Georgia Inst of Technology, USA**
- **Ghent University, Belgium**
- **Halmstad University, Sweden**
- **Heidelberg University, Germany**
- **TU Hamburg/Harburg Germany**
- **IIT Bombay, Mumbai, India**
- **KTH, Stockholm, Sweden**
- **Linköping University, Sweden**
- **Univ of Maryland, Syst Eng USA**
- **Univ of Maryland, CEEE, USA**
- **Politecnico di Milano, Italy**
- **Ecoles des Mines, CEP, France**
- **Mälardalen University, Sweden**
- **Univ Pisa, Italy**
- **Univ College SouthEast Norway**
- **Tsinghua Univ, Beijing, China**
- **Vanderbilt Univ, USA**

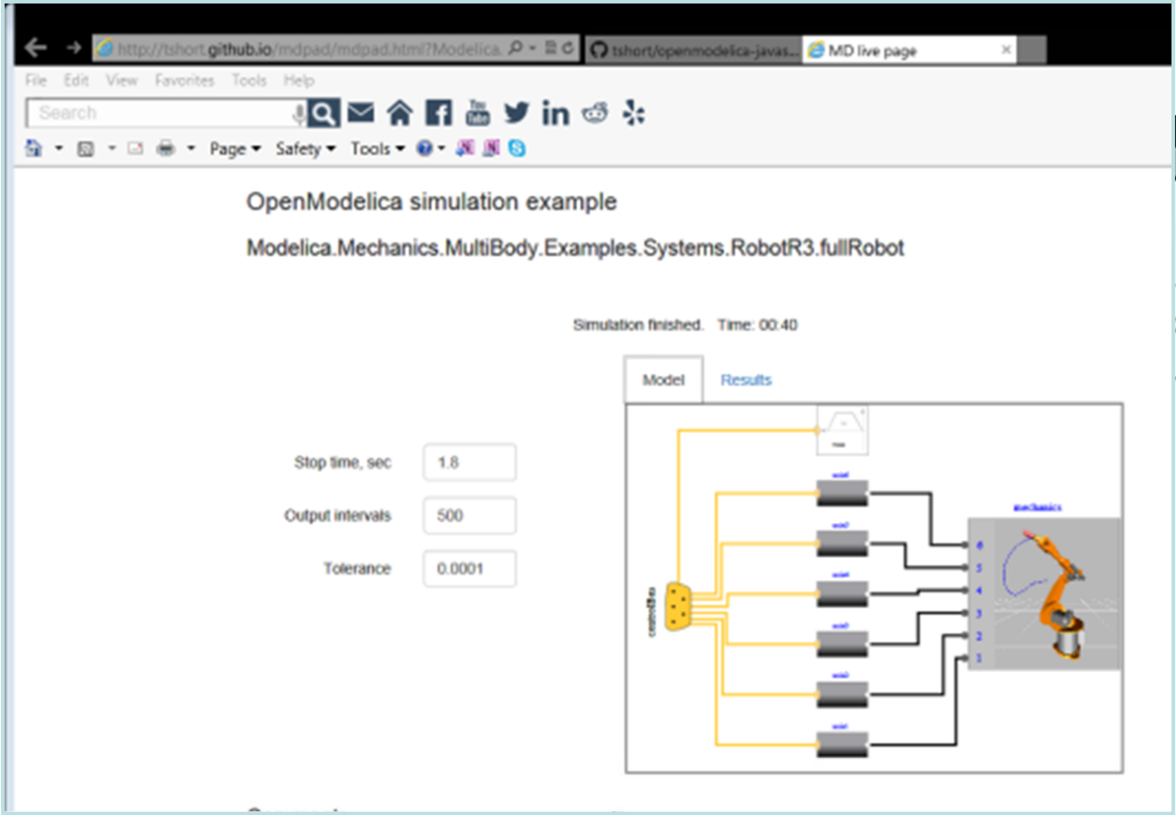
MODELICA

OpenModelica Graphical Editor and Plotting

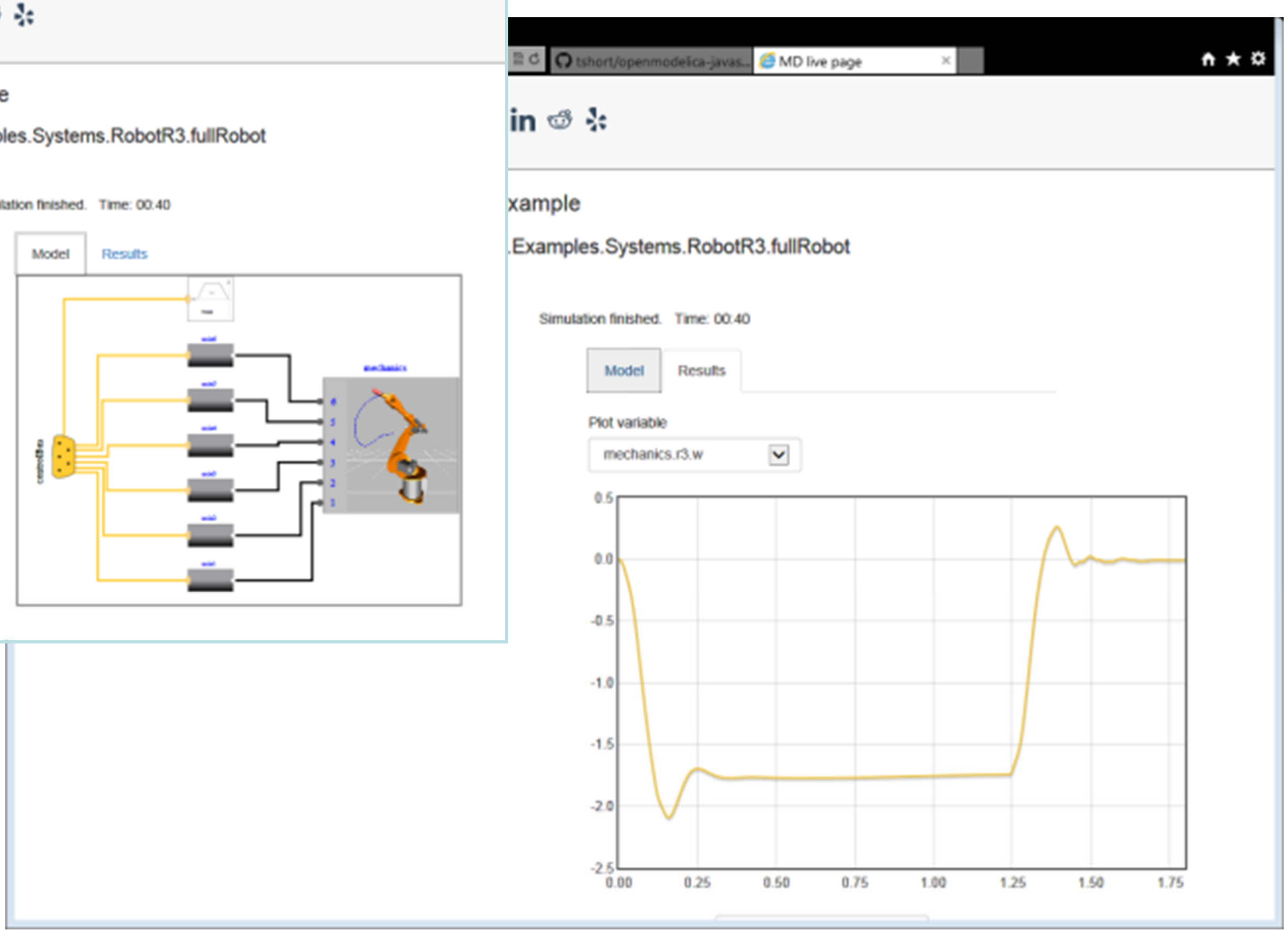


MODELICA

OpenModelica Simulation in Web Browser Client



MultiBody RobotR3.FullRobot



OpenModelica compiles to efficient Java Script code which is executed in web browser

Spoken-Tutorial step-by-step OpenModelica and Modelica Tutorial Using OMEdit. Link from www.openmodelica.org

OpenModelica

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Search Tutorials

To learn about Modelica, read a book or a tutorial about Modelica®.

Interactive step-by-step beginners Modelica on-line spoken tutorials

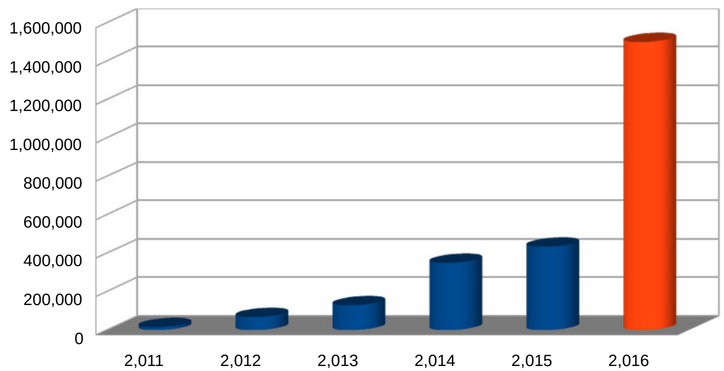
Interactive OMWebbook with examples of Modelica textual modeling

nglish (804) | Submit

Reset dropdowns

OpenModelica is an open source modelling and simulation environment intended for industrial and academic usage.It is an object oriented declarative multi domain modelling language for complex systems. This environment can be used to work for both steady state as well as dynamic systems. Attractive strategy when dealing with design and optimization problems. As all the equations are solved simultaneously it doesn't matter whether the unknown variable in an input or output variable. Read more

Number of students/teachers trained in their colleges/schools



About **12** results found.

Instruction Sheet

1. Introduction to OMEdit

Basic

Foss : *OpenModelica - English*

Outline: Introduction to OpenModelica Introduction to OMEdit Perspectives in OMEdit Browsers in OMEdit View icons in OMEdit Open a Class from Libraries Browser Checking for correctnes..

2. Examples through OMEdit

Basic

Foss : *OpenModelica - English*

Outline: Expand Modelica library Expand Electrical library Expand Analog library Open Rectifier Class Compare the values of IDC & Losses time vs Losses plot Expand Mechanics library ..

3. Developing an equation-based model

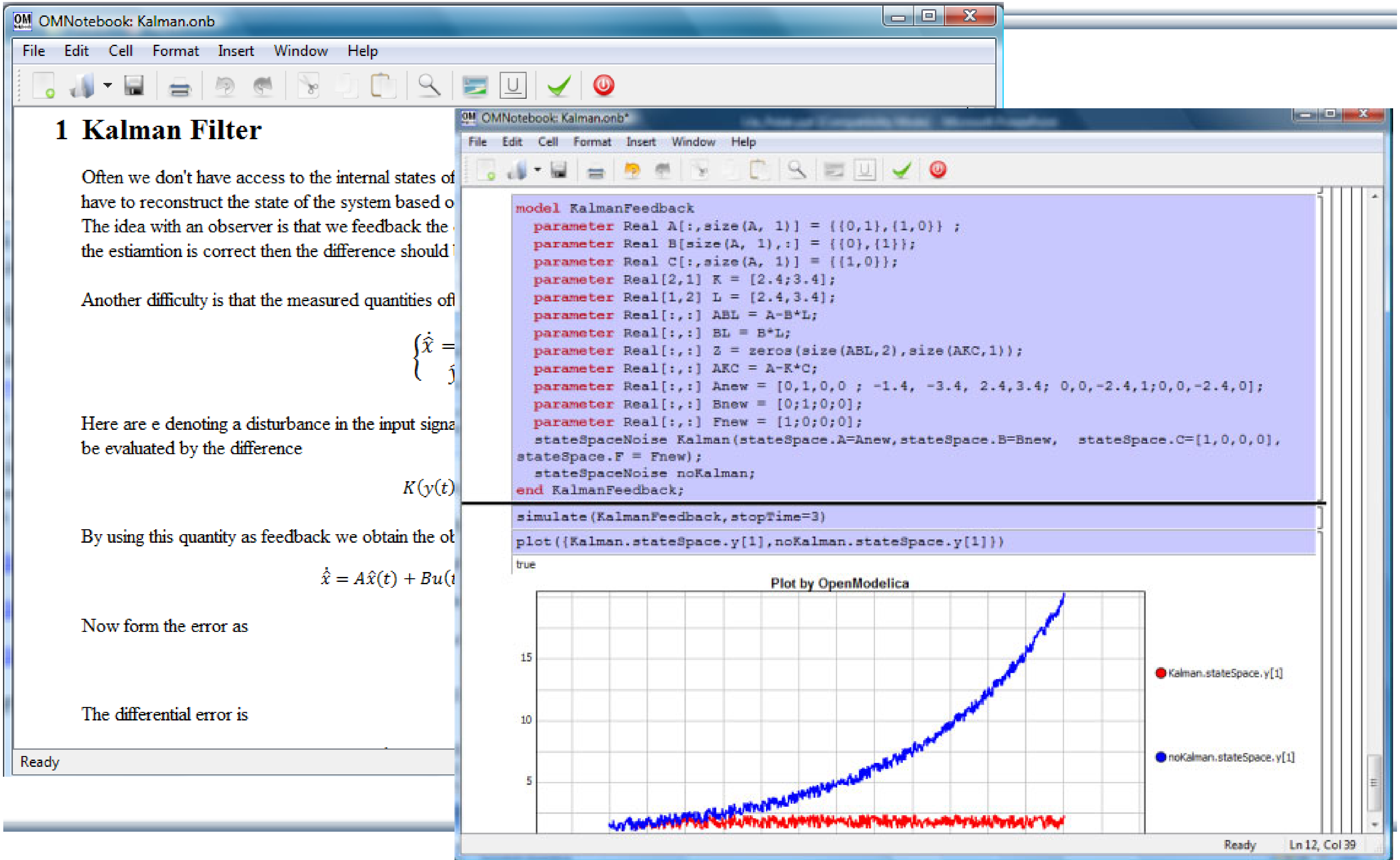
Basic

Foss : *OpenModelica - English*

Outline: Introduction to OMEdit Declaration of variables and equations Simulation of a model in

MODELICA

OMnotebook Interactive Electronic Notebook Here Used for Teaching Control Theory

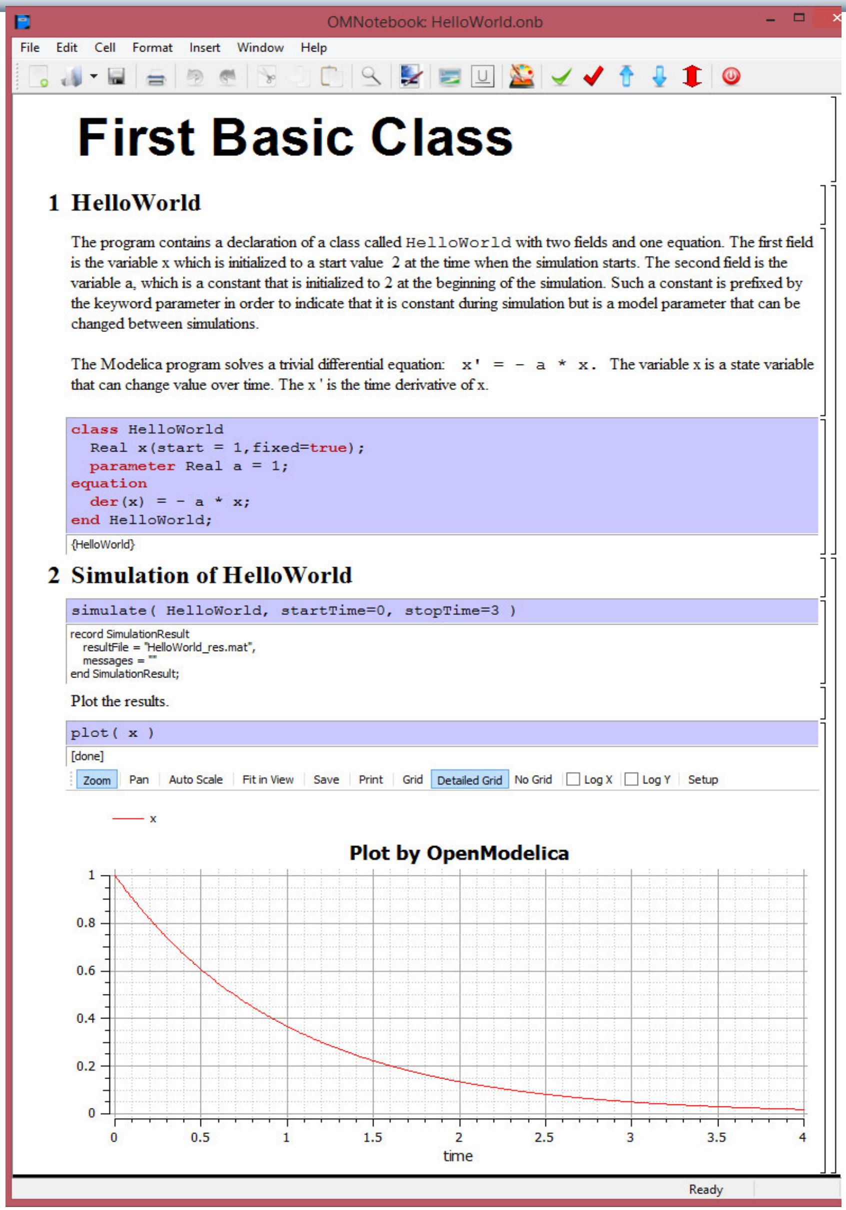


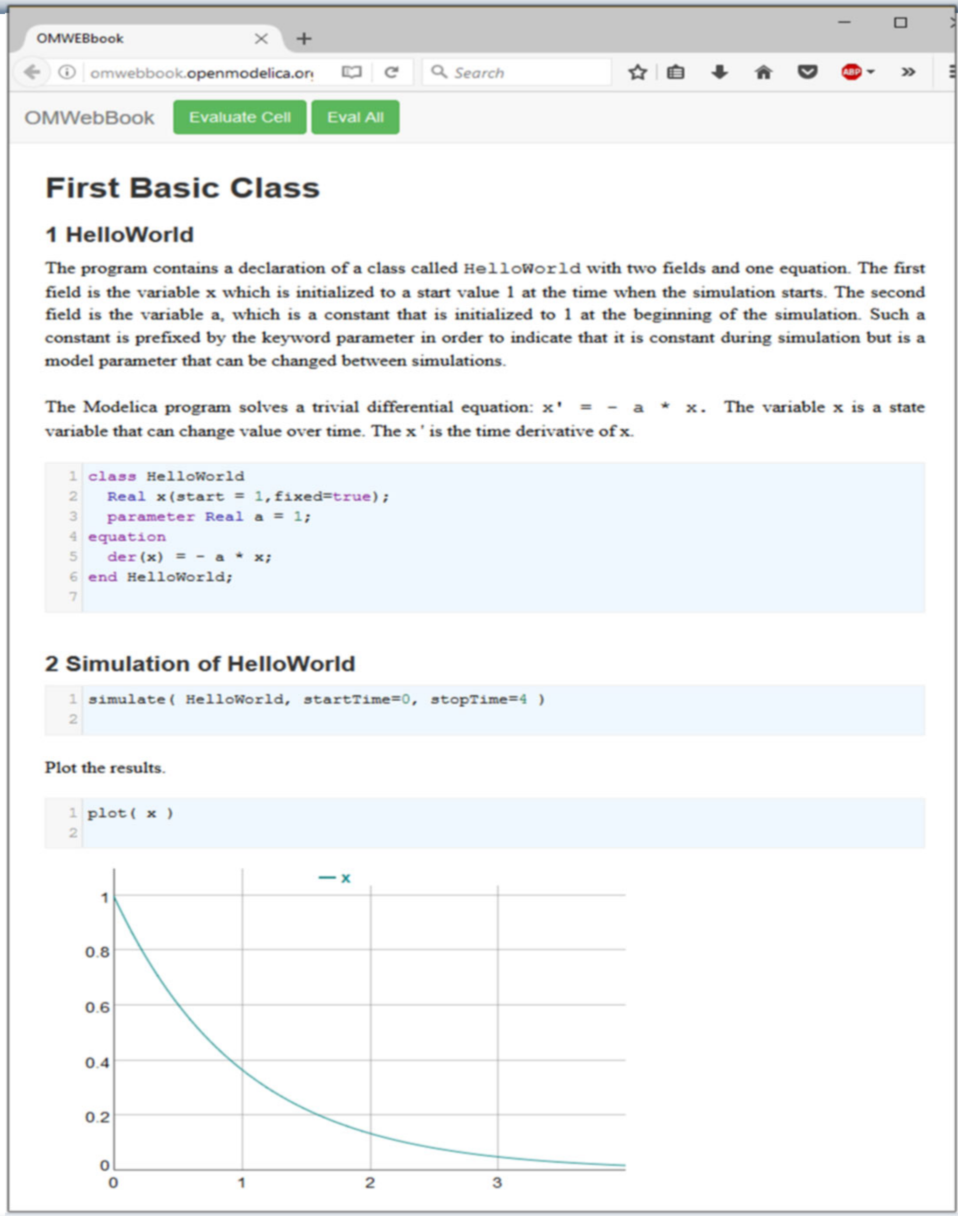
OM Web Notebook Generated from OMNotebook

Edit, Simulate, Plot Models on a Web Page

http://omwebbook.openmodelica.org/

OMNotebook

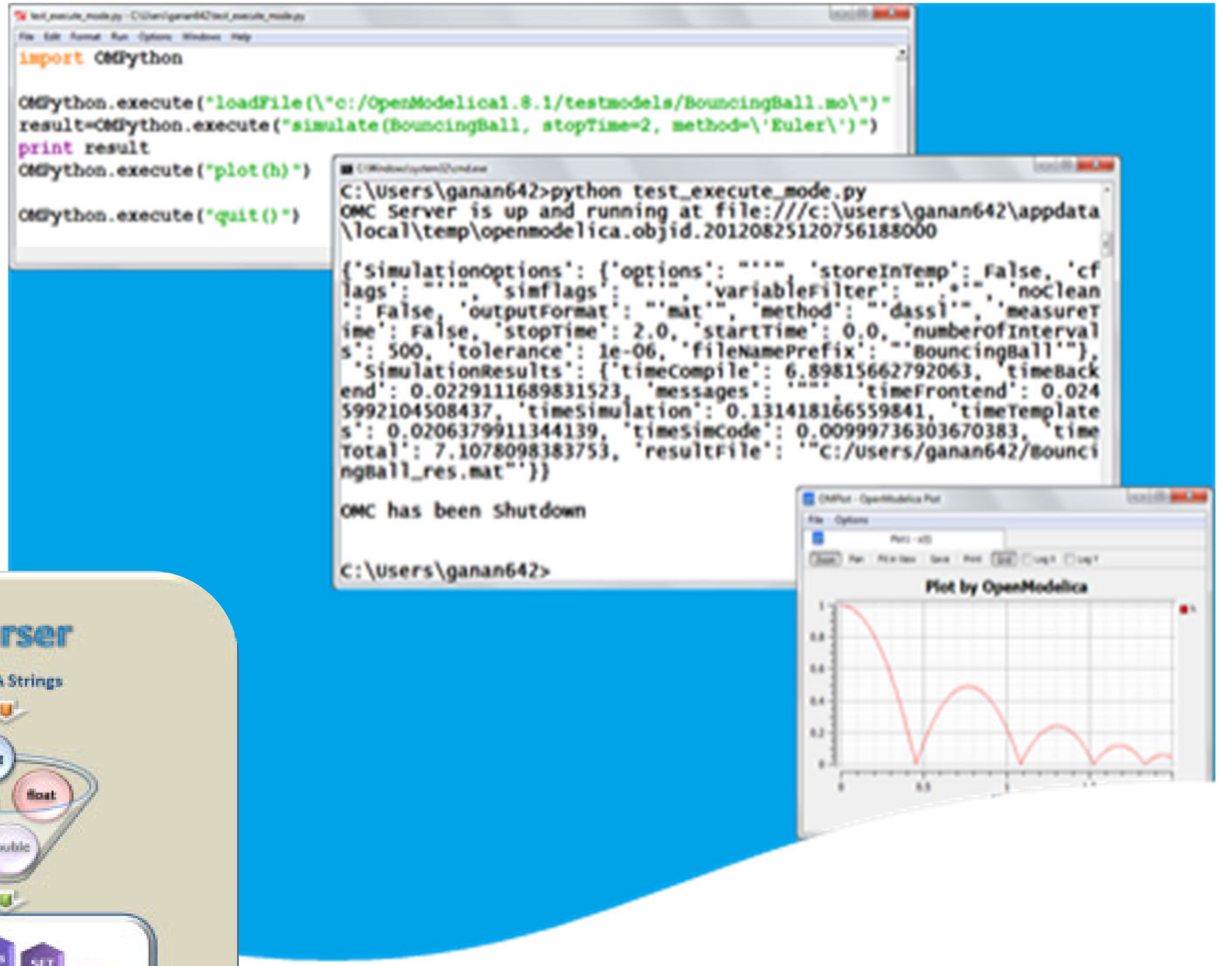


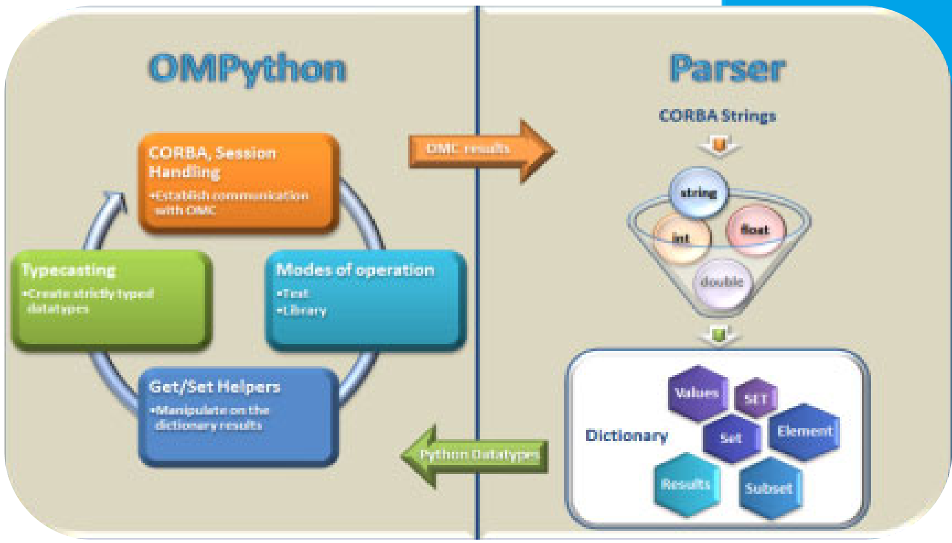


OMweb book

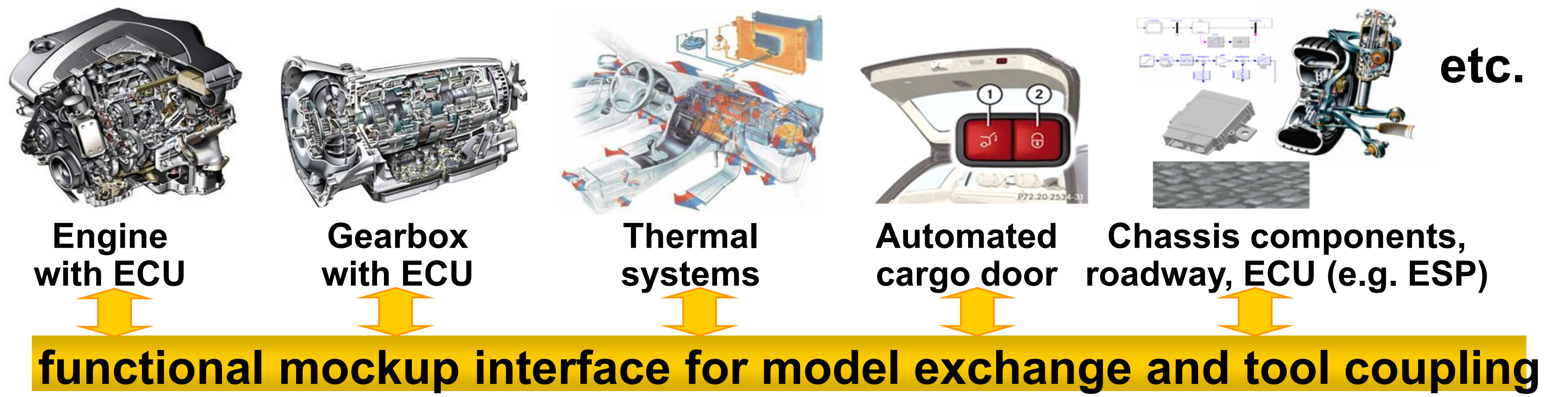
OMPython – Python Scripting with OpenModelica

- Interpretation of Modelica commands and expressions
- Interactive Session handling
- Library / Tool
- Optimized Parser results
- Helper functions
- Deployable, Extensible and Distributable





General Tool Interoperability & Model Exchange Functional Mock-up Interface (FMI)

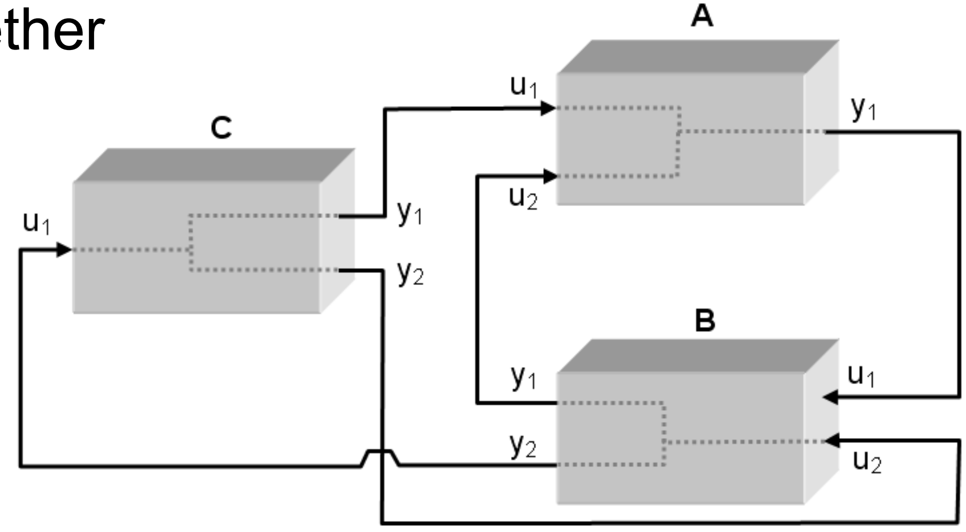


courtesy Daimler

- FMI development was started by ITEA2 MODELISAR project. FMI is a Modelica Association Project now
- **Version 1.0**
- FMI for Model Exchange (released Jan 26,2010)
- FMI for Co-Simulation (released Oct 12,2010)
- **Version 2.0**
- FMI for Model Exchange and Co-Simulation (released July 25,2014)
- **> 80 tools** supporting it (https://www.fmi-standard.org/tools)

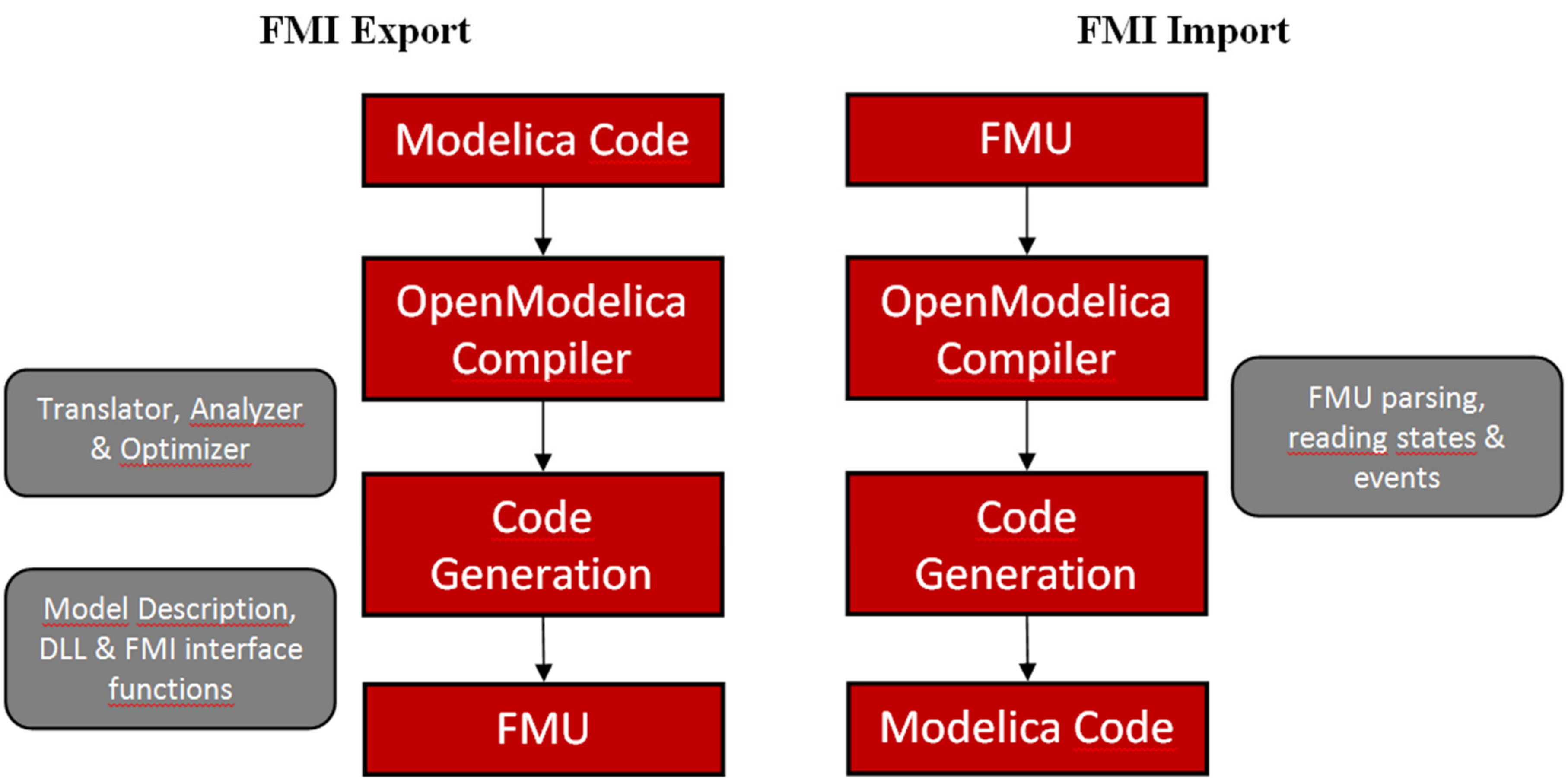
Functional Mockup Units

- Import and export of input/output blocks – **Functional Mock-Up Units – FMUs**, described by
  - differential-, algebraic-, discrete equations,
  - with time-, state, and step-events
- An **FMU** consists of **(compiled) C-code**, + interface description in **XML**
- An FMU can be large (e.g. 100 000 variables)
- An FMU can be used in an embedded system (small overhead)
- FMUs can be connected together

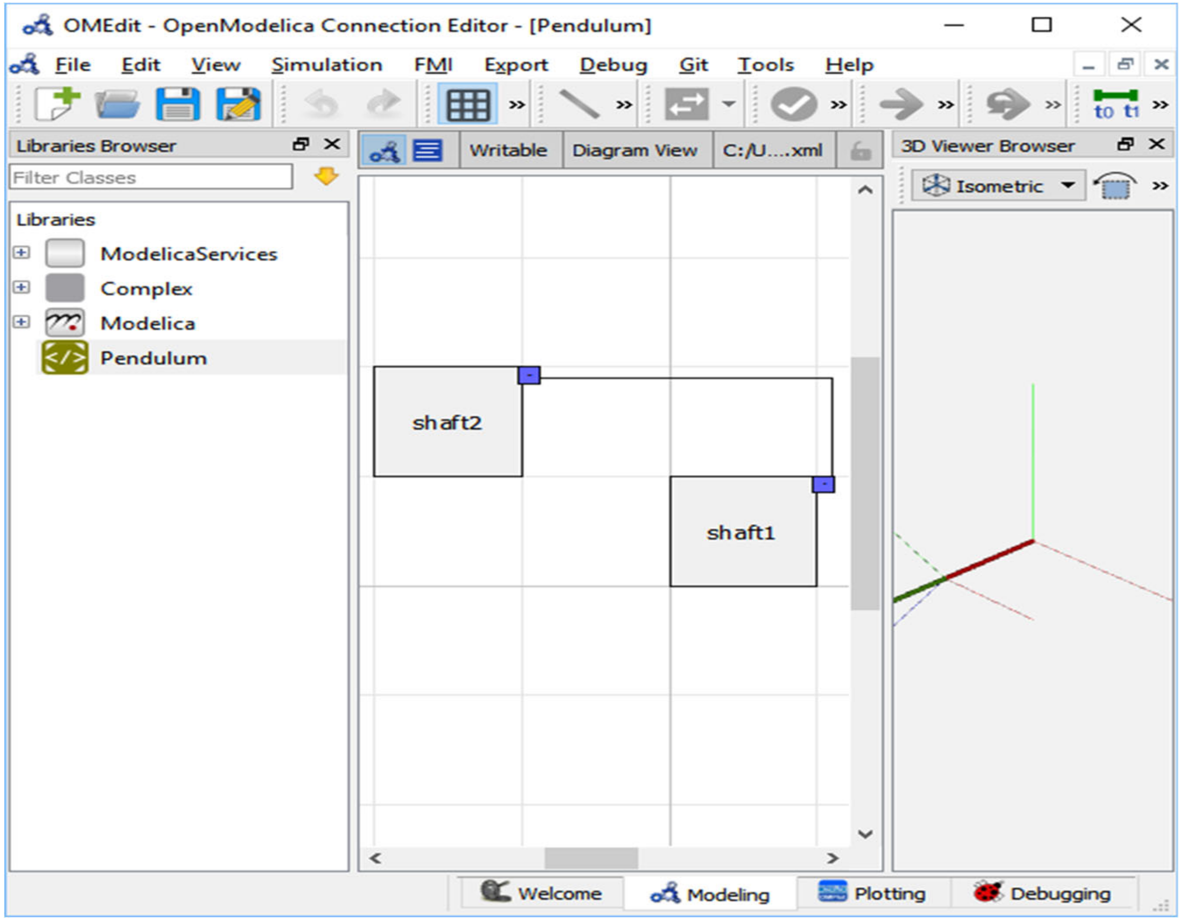


MODELICA

OpenModelica Functional Mockup Interface (FMI)

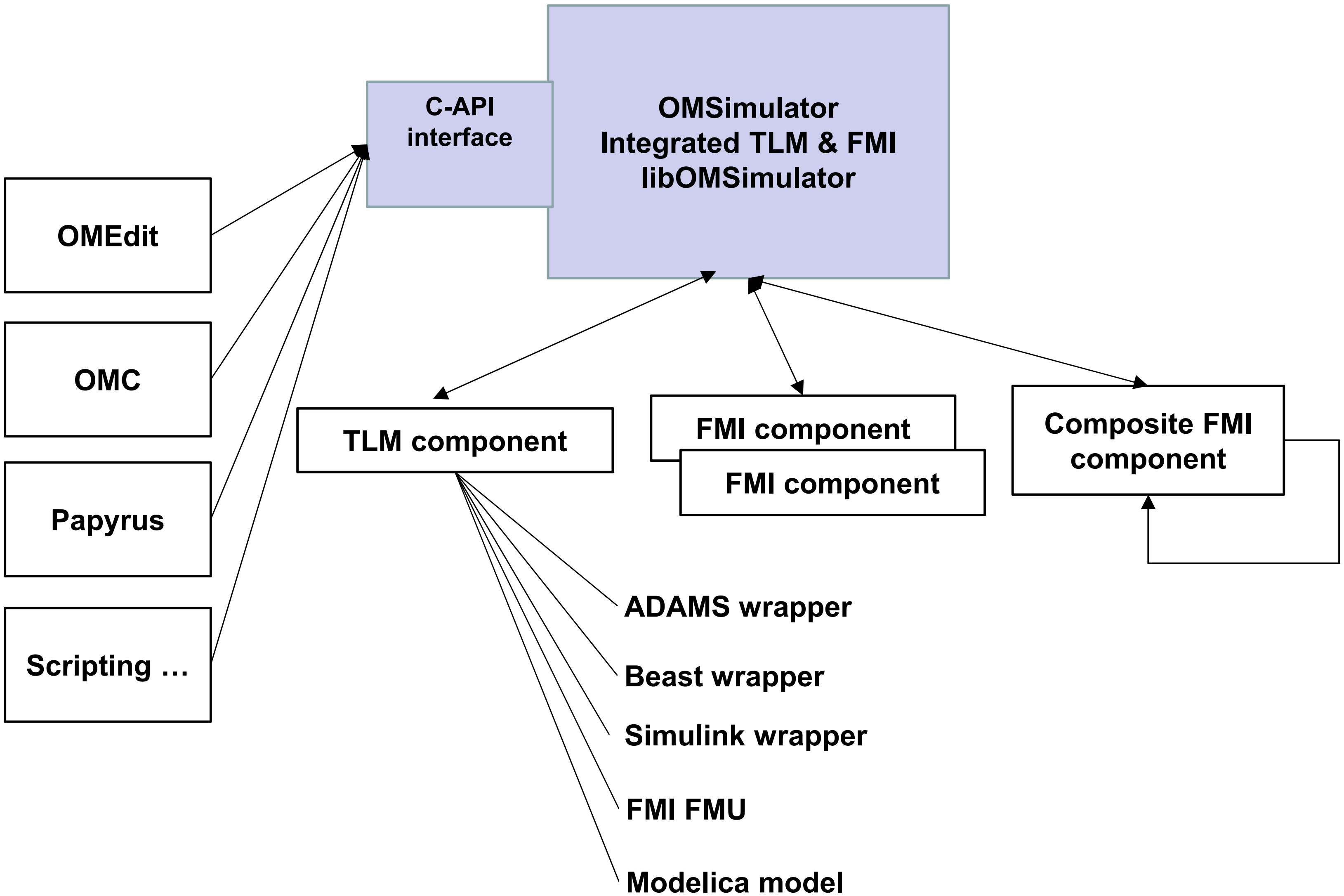


OMSimulator Composite Model Editor with 3D Viewer
Combine External (FMI) Models into New Models



- **Composite model editor** with 3D visualization of connected mechanical model components which can be FMUs, Modelica models, etc., or co-simulated components
- **3D animation** possible
- Composite model saved as **XML**-file

OMSimulator – Integrated FMI and TLM-based Cosimulator/Simulator in OpenModelica



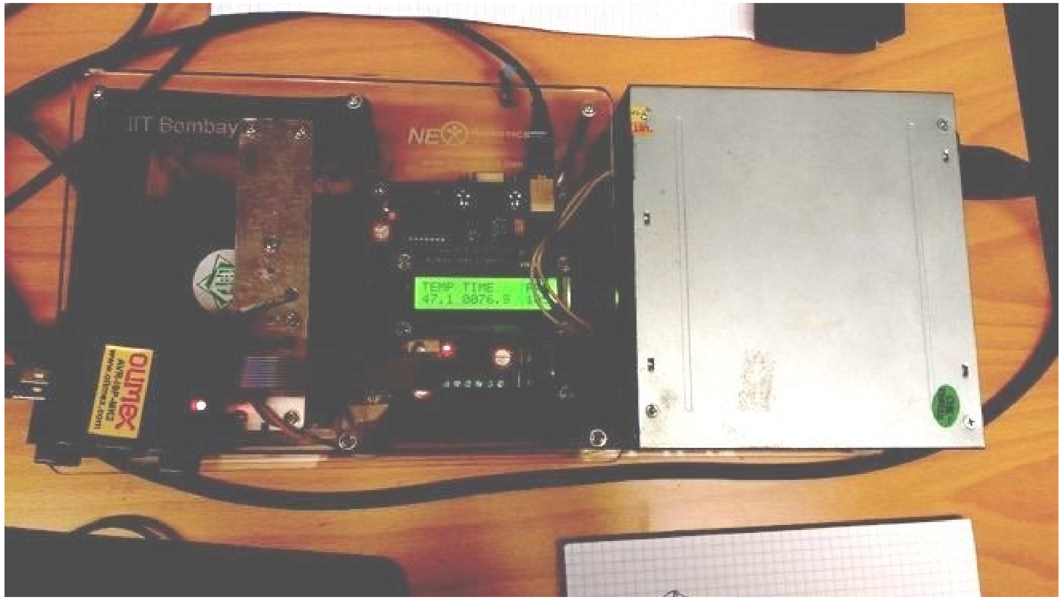
Embedded System Support in OpenModelica

- Code generation of real-time Controllers from Modelica models for small foot-print platforms

Use Case: SBHS (Single Board Heating System)

Single board heating system (IIT Bombay)

- Use for teaching basic control theory
- Usually controlled by serial port (set fan value, read temperature, etc)
- OpenModelica can generate code targeting the ATmega16 on the board (AVR-ISP programmer in the lower left). Program size is 4090 bytes including LCD driver and PID-controller (out of 16 kB flash memory available).



Movie Demo!

Example – Code Generation to SHBS

Code Generator Comparison, Full vs Simple

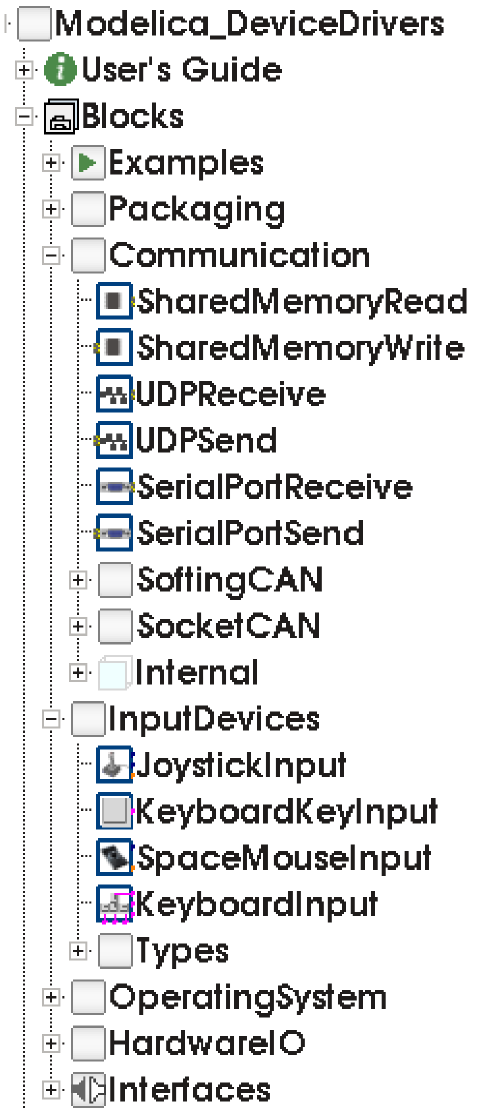
	Full Source-code FMU targeting 8-bit AVR proc	**Simple code generator targeting 8-bit AVR proc**
Hello World (0 equations)	43 kB flash memory 23 kB variables (RAM)	130 B flash memory 0 B variables (RAM)
SBHS Board (real-time PID controller, LCD, etc)	**68 kB** flash memory **25 kB** variables (RAM)	**4090 B** flash memory **151 B** variables (RAM)

The largest 8-bit AVR processor MCUs (Micro Controller Units) have 16 kB SRAM.

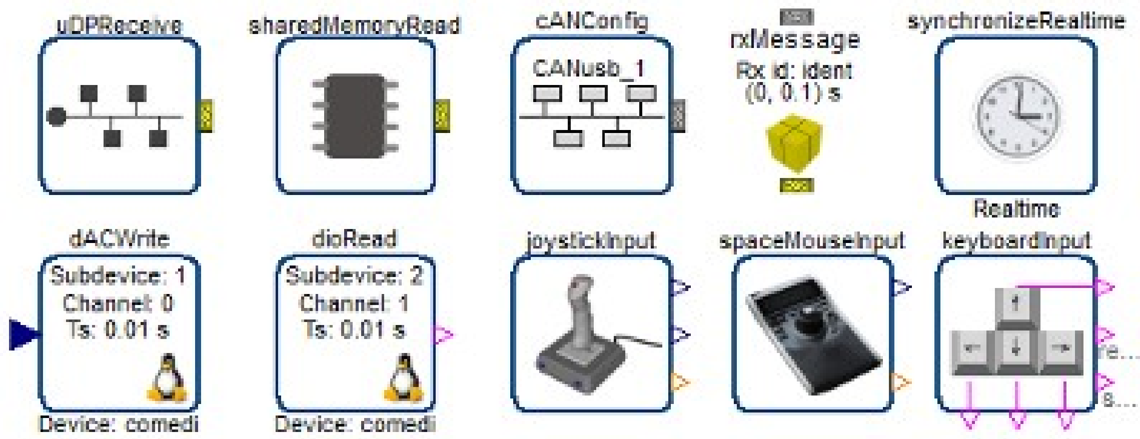
One of the more (ATmega328p; Arduino Uno) has 2 kB SRAM.

The ATmega16 we target has **1 kB SRAM available** (stack, heap, and global variabl

Communication & I/O Devices: Modelica_DeviceDrivers Library

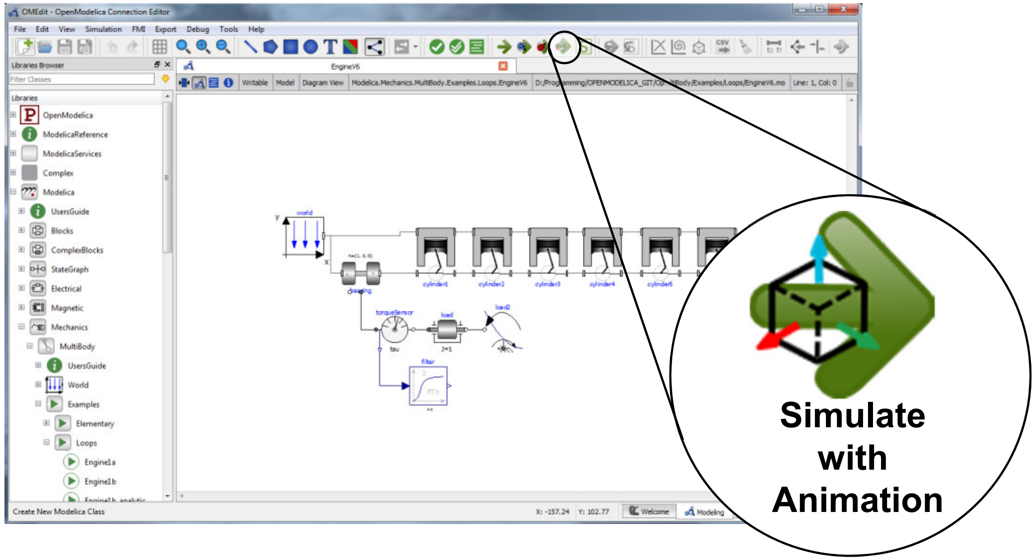


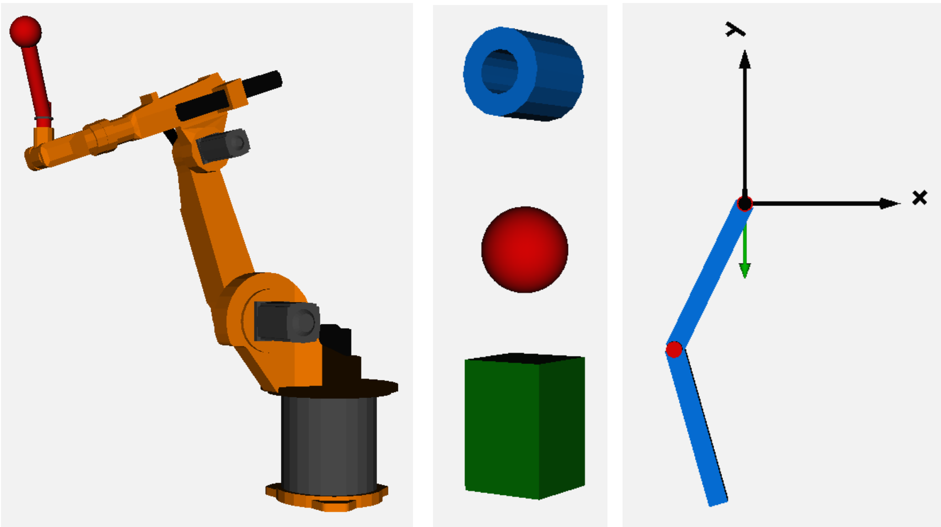
- **Free library** for interfacing hardware drivers
- **Cross-platform** (Windows and Linux)
- UDP, SharedMemory, CAN, Keyboard, Joystick/Gamepad
- DAQ cards for digital and analog IO (only Linux)
- Developed for **interactive real-time** simulations

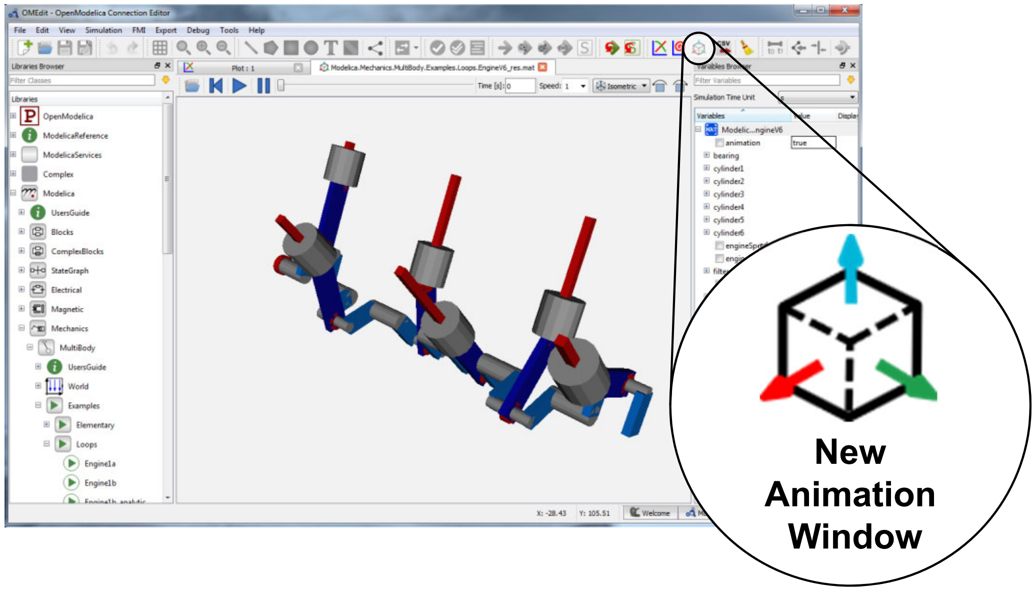


OMEdit 3D Visualization of Multi-Body Systems

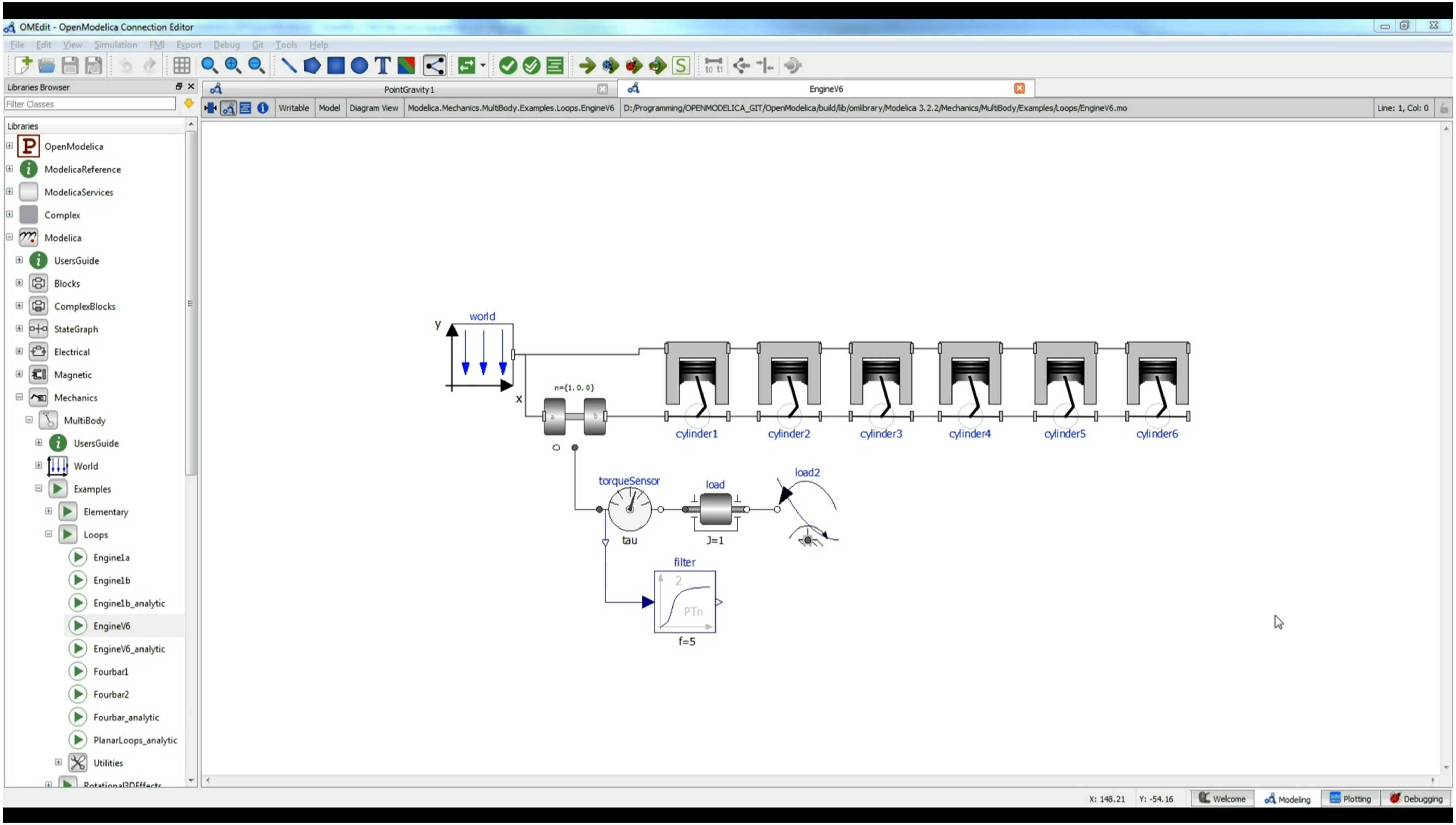
- Built-in feature of OMEdit to animate MSL-Multi-Body shapes
- Visualization of simulation results
- Animation of geometric primitives and CAD-Files



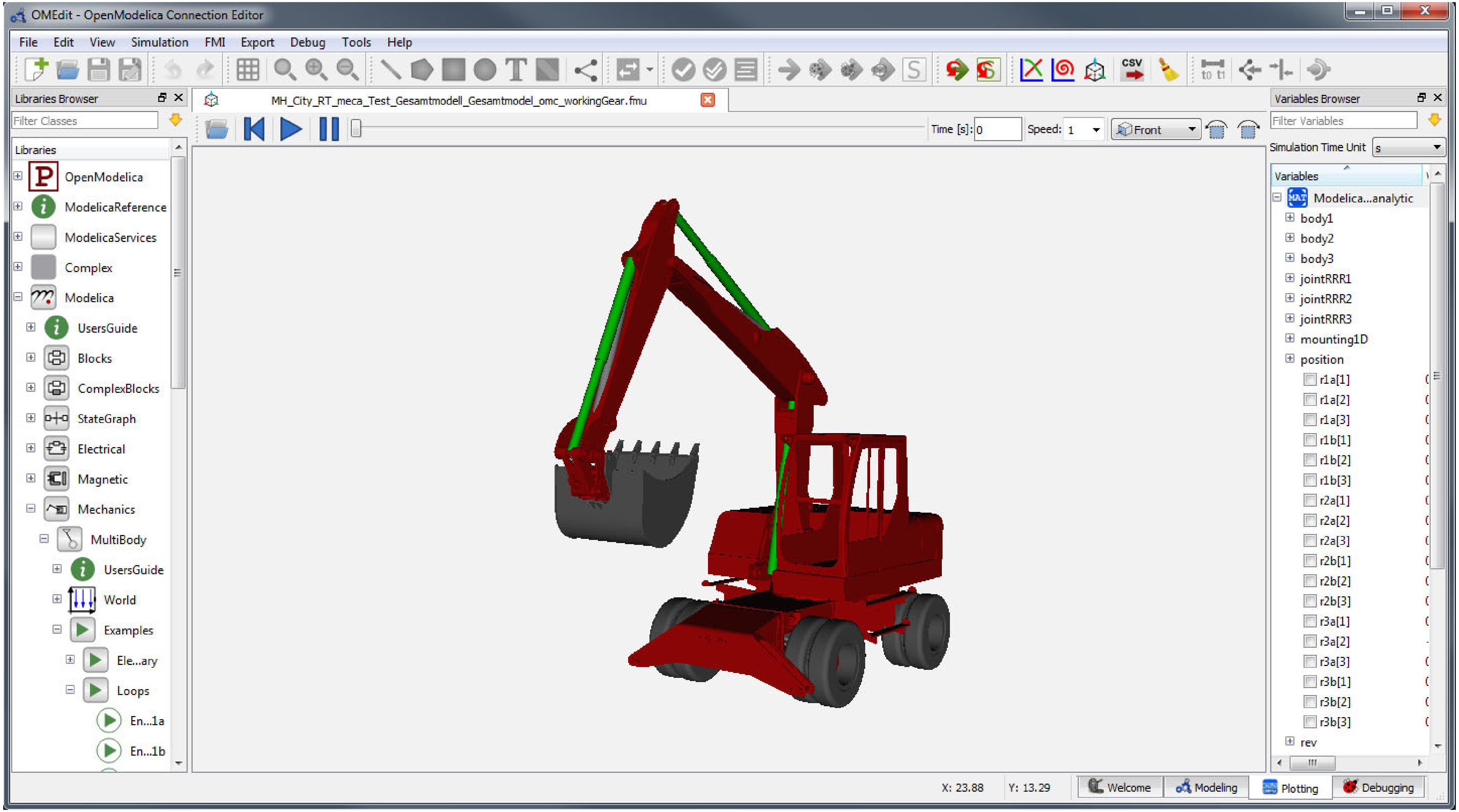




OpenModelica 3D Animation Demo

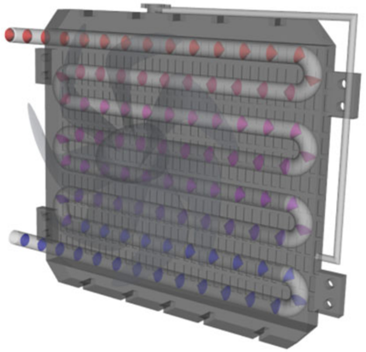


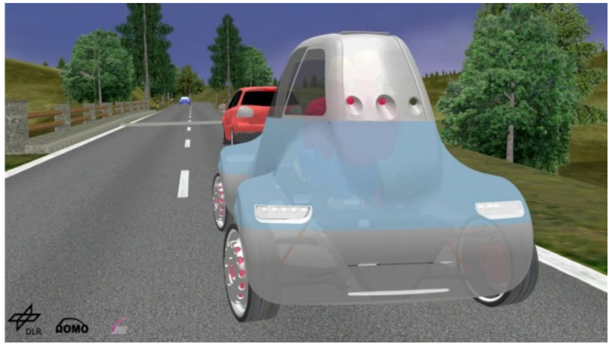
OpenModelica 3D Animation Demo – Excavator

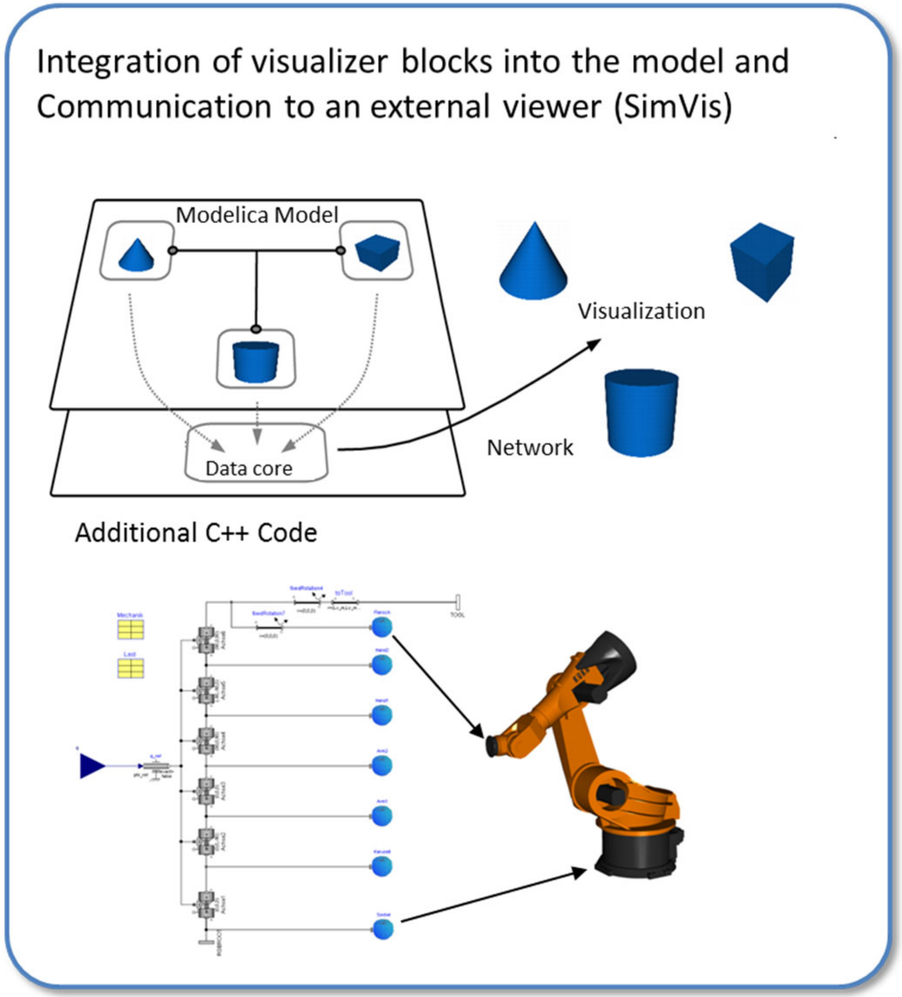


Visualization using Third-Party Libraries: DLR Visualization Library

- Advanced, model-integrated and vendor-unspecific visualization tool for Modelica models
- Offline, online and real-time animation
- Video-export function
- Commercial library, feature reduced free Community Edition exists







Courtesy of Dr. Tobias Bellmann (DLR)

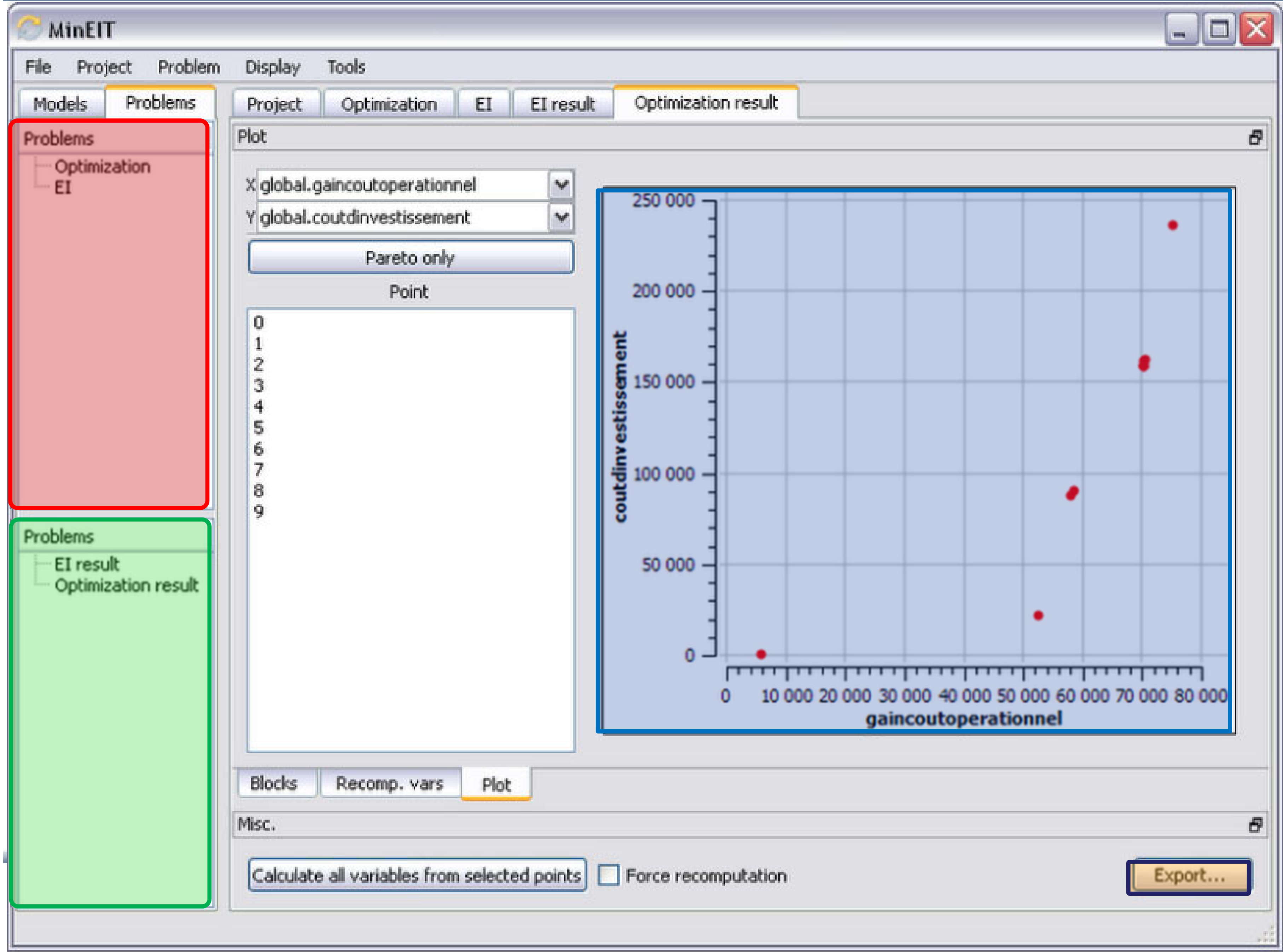
OMOptim – Parameter Sweep Design Optimization

Problems

Solved problems

Result plot

Export result data .csv



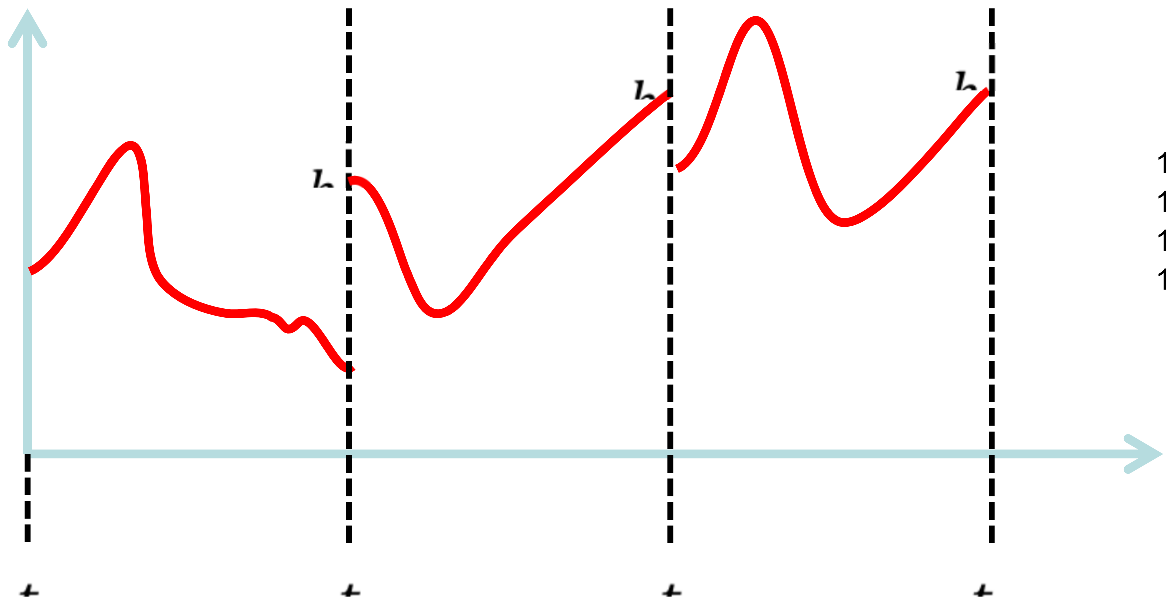
Here Pareto front optimiza-tion

Optimization of Dynamic Trajectories Using Multiple-Shooting and Collocation

- Minimize a goal function subject to model equation constraints, useful e.g. for NMPC
- Multiple Shooting/Collocation
  - Solve sub-problem in each sub-interval

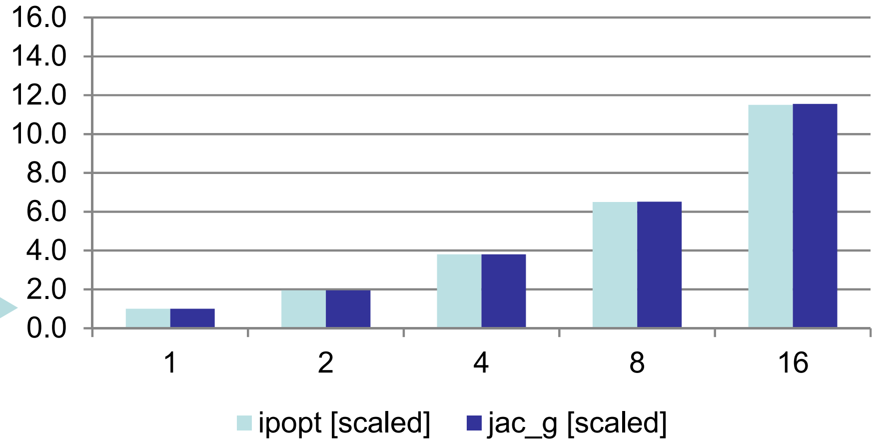
In OpenModelica 1.9.1 beta release Jan 2014.

$$x_i(t_{i+1}) = h_i + \int_{t_i}^{t_{i+1}} f(x_i(t), u(t), t)\, dt \approx F(t_i, t_{i+1}, h_i, u_i), \qquad x_i\,(t_i) = h_i$$

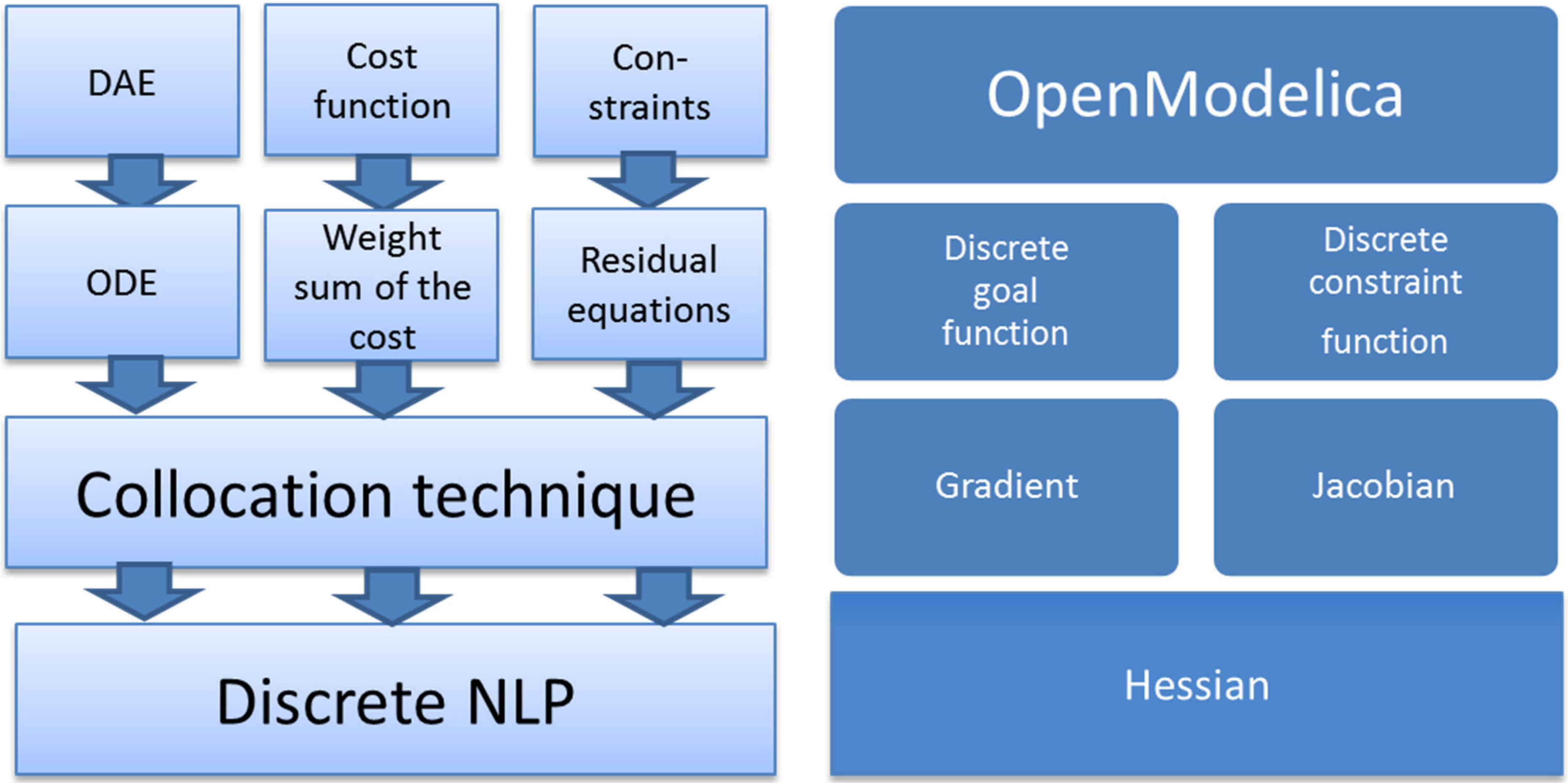


Example speedup, 16 cores:

MULTIPLE_COLLOCATION

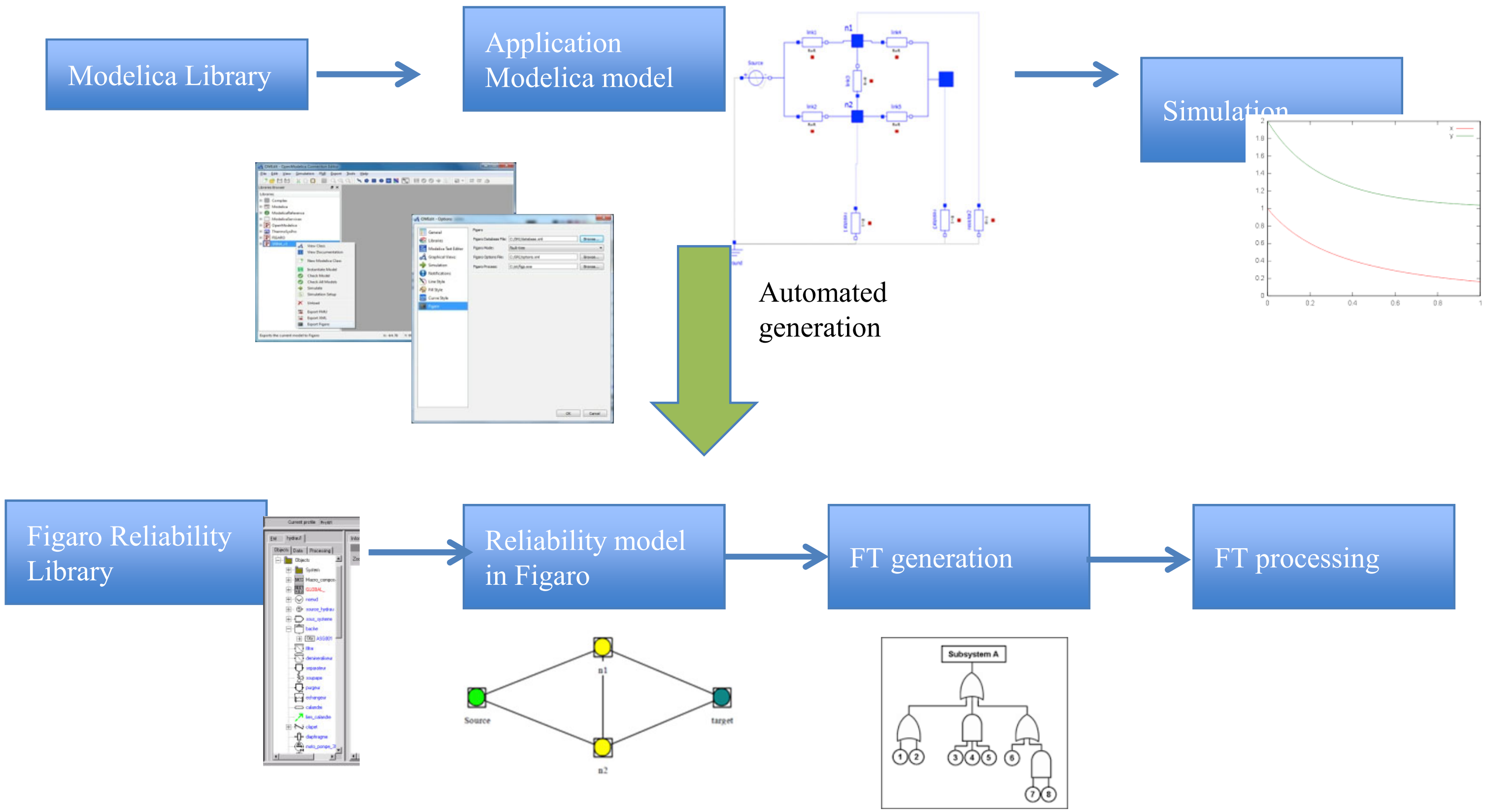


OpenModelica Dynamic Optimization Collocation



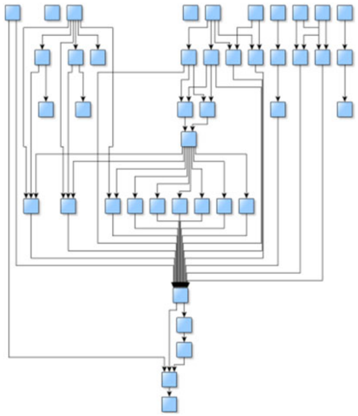
Failure Mode and Effects Analysis (FMEA) in OM

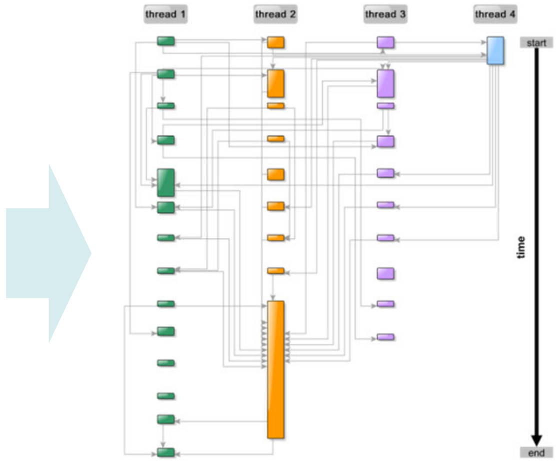
- Modelica models augmented with reliability properties can be used to generate reliability models in Figaro, which in turn can be used for static reliability analysis
- Prototype in OpenModelica integrated with Figaro tool

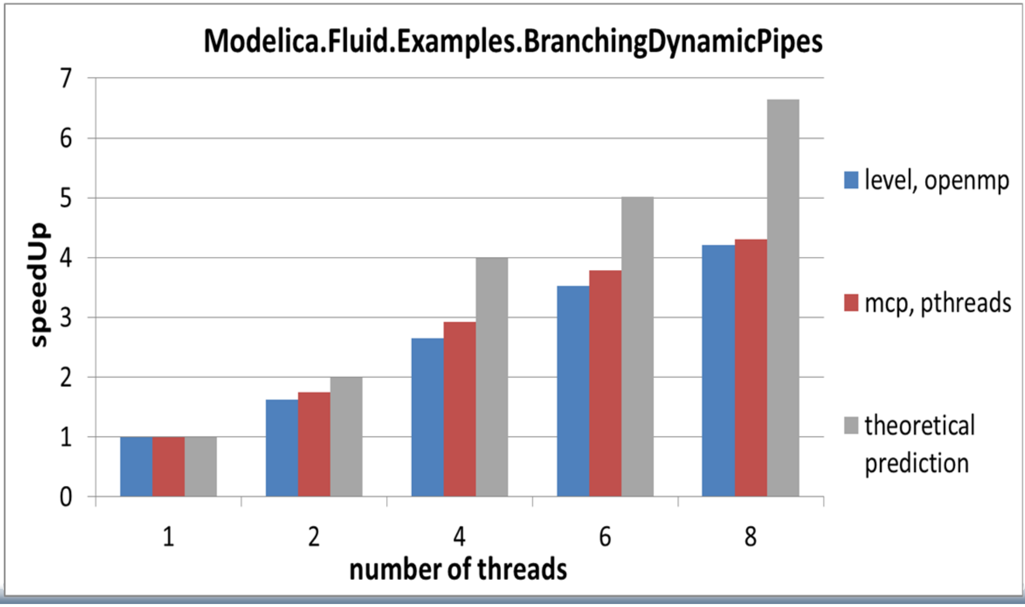


OpenModelica Model Parallelization Faster Simulation on Multi-Core

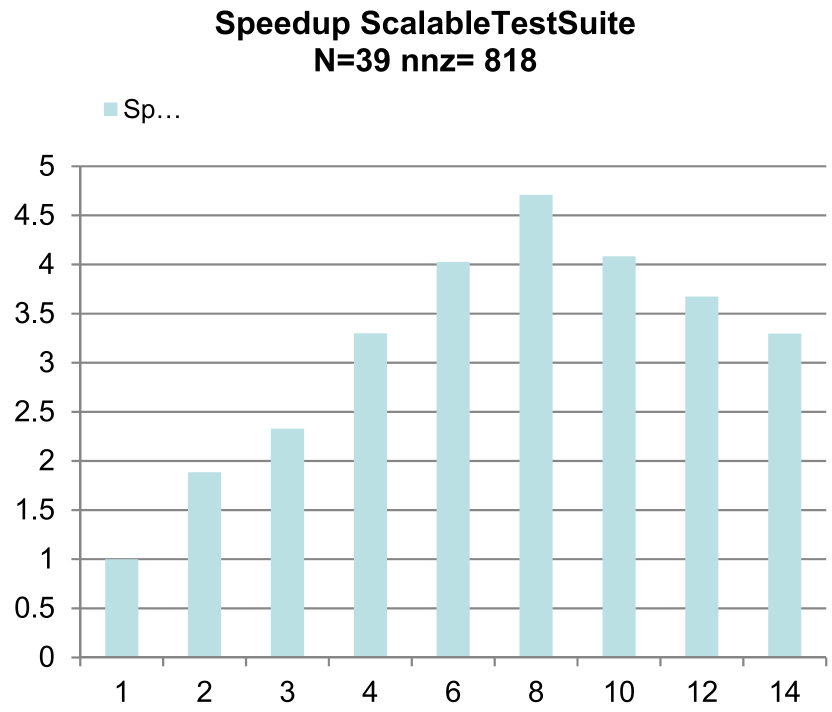
Automated parallelization of models







Parallelizing numeric Jacobian computations in simulation



number of threads

Speedup about 4 using 8 threads

MODELICA

Recent Large-scale ABB OpenModelica Application

Generate code for controlling 7.5 to 10% of German Power Production

ABB OPTIMAX PowerFit

- Real-time optimizing control of large-scale virtual power plant for system integration
- **Software including OpenModelica** now used in managing more than 2500 renewable plants, total up to 1.5 GW

High scalability supporting growth

- 2012: initial delivery (for 50 plants)
- 2013: SW extension (500 plants)
- 2014: HW+SW extension (> 2000)
- 2015: HW+SW extension, incl. OpenModelica generating optimizing controller code in FMI 2.0 form

Manage 7.5% - 10% of German Power

- 2015, Aug: OpenModelica Exports FMUs for real-time optimizing control (seconds) of about **5.000 MW (7.5%) of power in Germany**

Part III

Equation-Based Model Dynamic Debugging and Performance Analysis

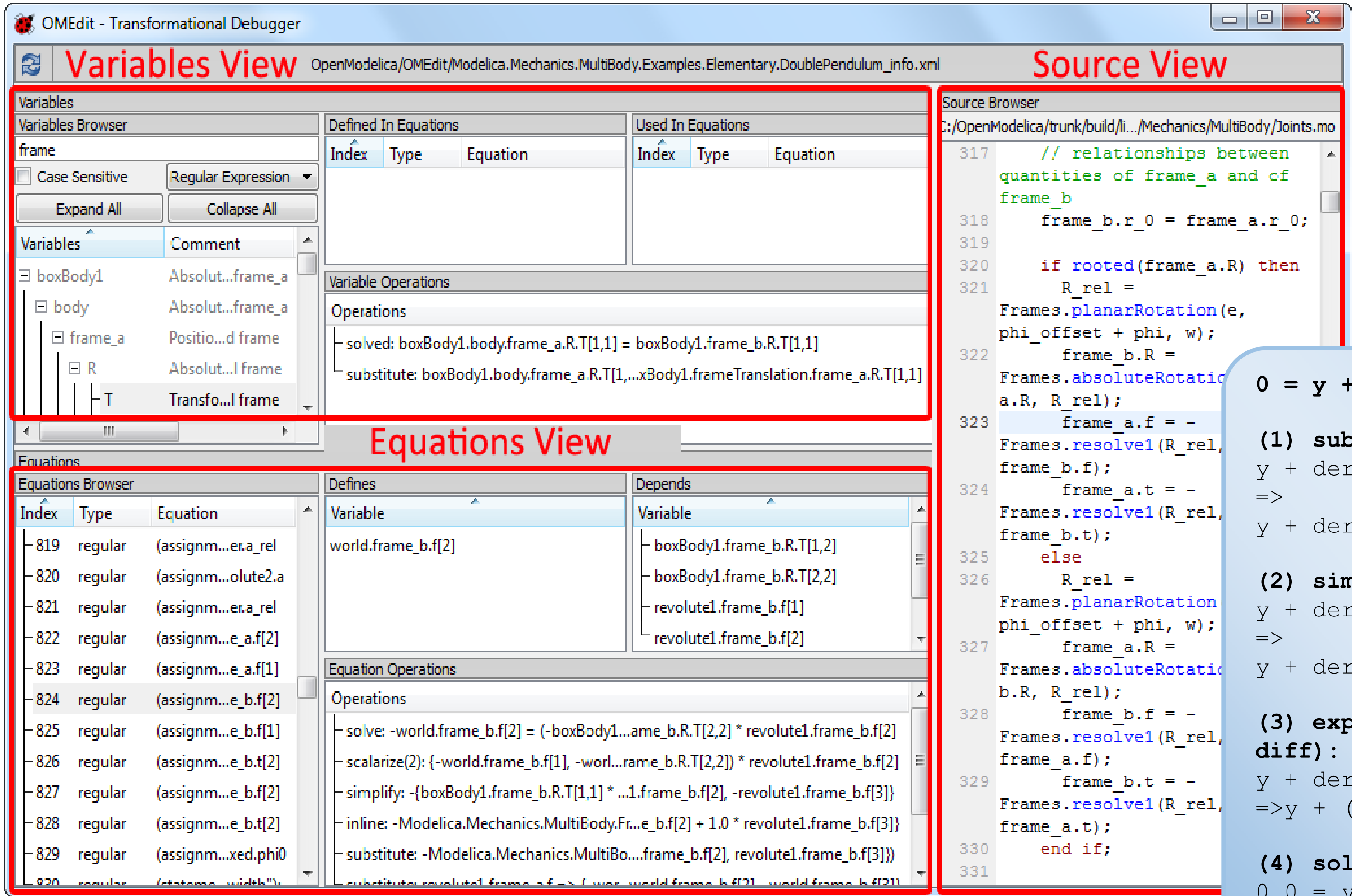
Need for Debugging Tools
Map Low vs High Abstraction Level

- A **major part** of the total **cost** of software projects is due to testing and debugging
- US-Study 2002:
  Software errors cost the US economy **annually~ 60 Billion $**

- **Problem: Large Gap in Abstraction Level** from **Equations** to **Executable Code**
- Example error message (hard to understand)

```
Error solving nonlinear system 132
    time = 0.002
    residual[0] = 0.288956
    x[0] = 1.105149
    residual[1] = 17.000400
    x[1] = 1.248448
    ...
```

OpenModelica Equation Model Debugger



Example of equation transformations on a model:

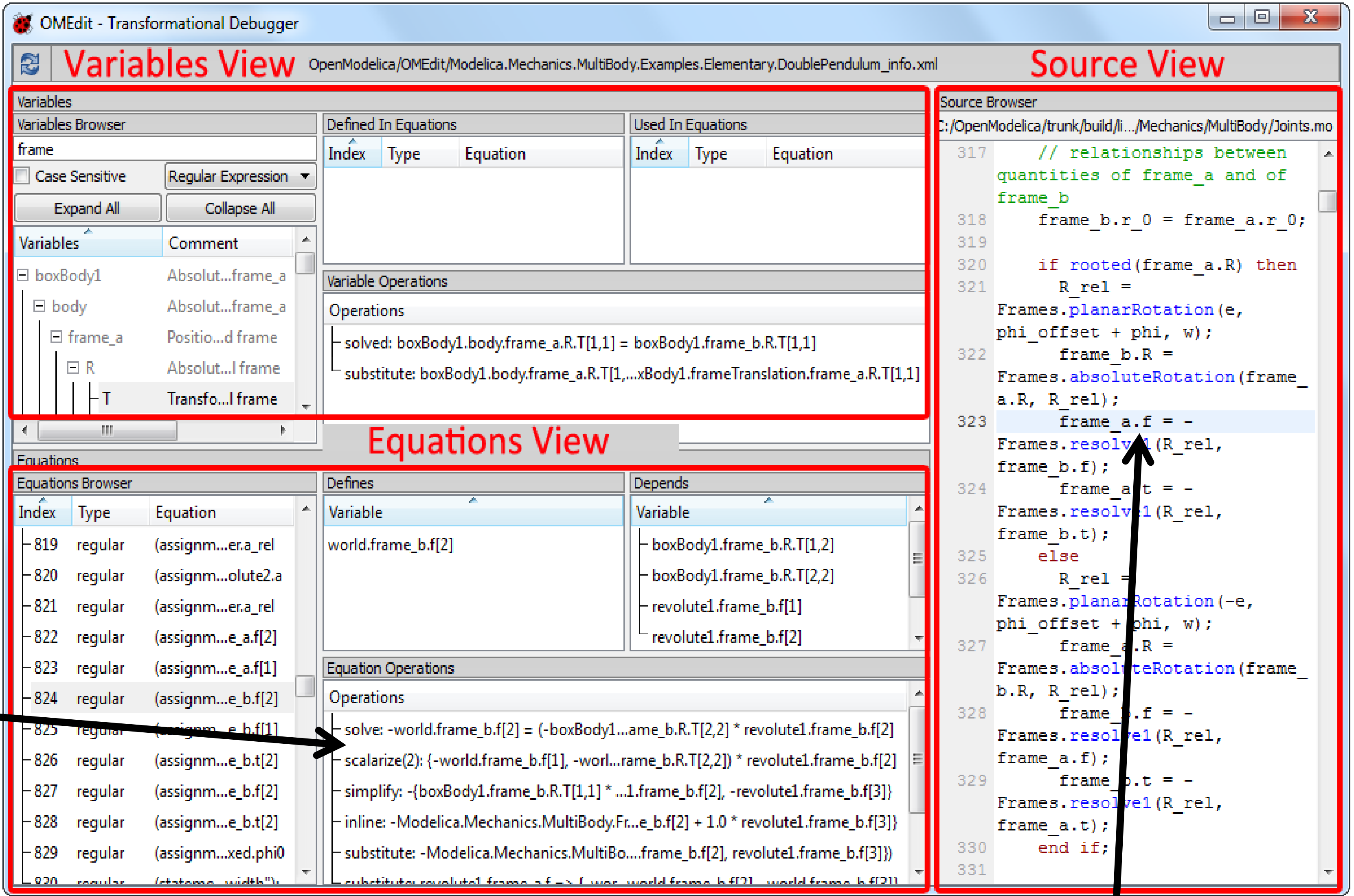
```
0 = y + der(x * time * z); z = 1.0;

(1) substitution:
y + der(x * (time * z))
=>
y + der(x * (time * 1.0))

(2) simplify:
y + der(x * (time * 1.0))
=>
y + der(x * time)

(3) expand derivative (symbolic
diff):
y + der(x * time)
=>y + (x + der(x) * time)

(4) solve:
0.0 = y + (x + der(x) * time)
=>
der(x) = ((-y) - x) / time
time <> 0
```


MODELICA

Integrated Static-Dynamic OpenModelica Equation Model Debugger

Efficient handling of **Large** Equation Systems

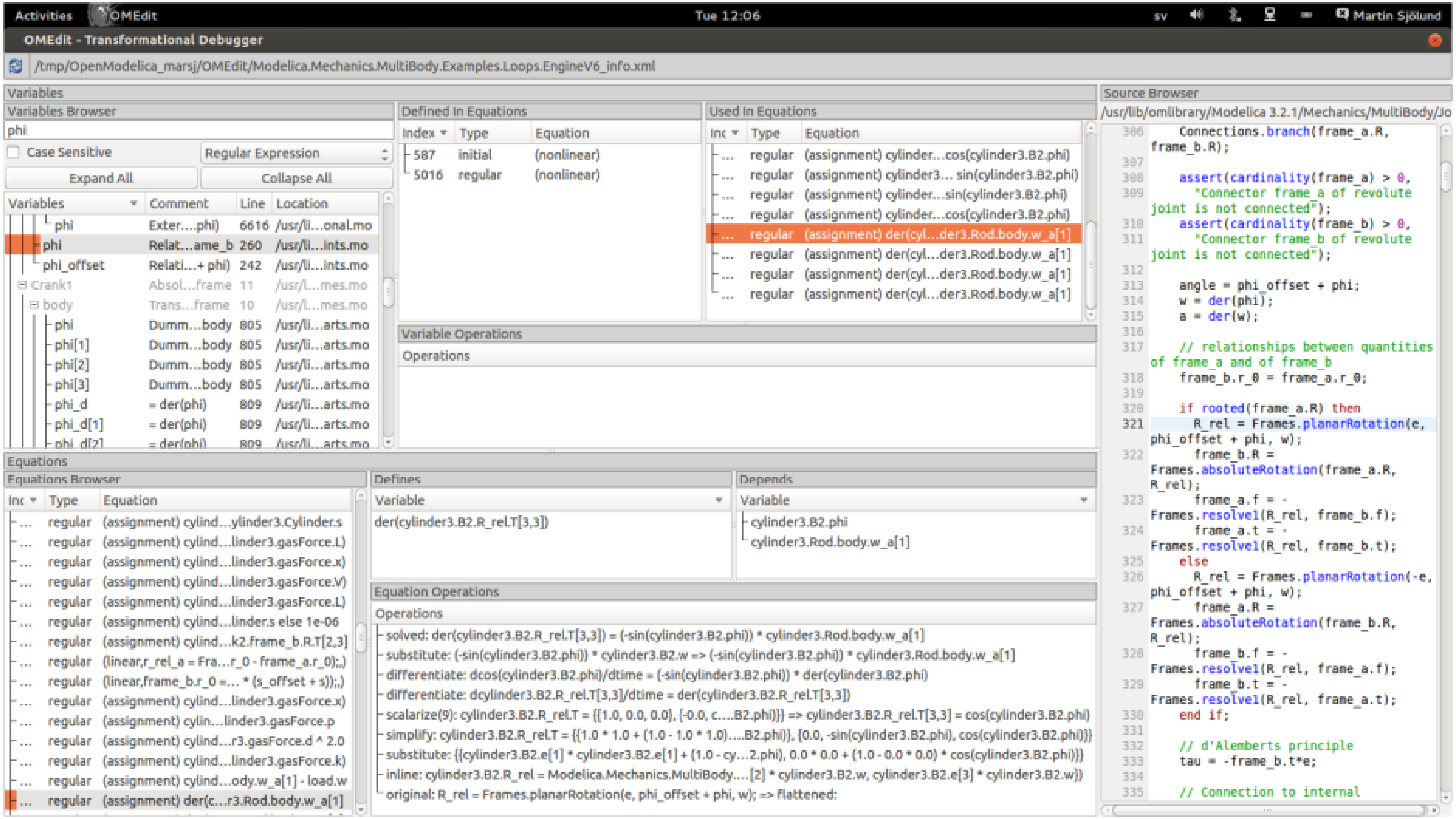
Showing equation transformations of a model:



Mapping dynamic run-time error to source model position

MODELICA

Transformations Browser – EngineV6 Overview (11 116 equations in model)



Performance Profiling

(Here: Profiling all equations in MSL 3.2.1 DoublePendulum)

- Measuring performance of equation blocks to find bottlenecks
  - Useful as input before model simplification for real-time platforms
- Integrated with the debugger so it is possible to show what the slow equations compute
- Suitable for real-time profiling (less information), or a complete view of all equation blocks and function calls

Equations Browser

Index	Type	Equation	Executi	Max time	Time	Fraction
+ 876	regular	linear, size 2	4602	0.000501	0.0134	75.7%
836	regular	(assignment) ...evolute2.phi)	1534	2.57e-05	0.000377	2.12%
840	regular	(assignment) ...mper.phi_rel)	1534	1.38e-05	0.000237	1.33%
837	regular	(assignment) ...evolute2.phi)	1534	8.38e-06	0.000235	1.32%
841	regular	(assignment) ...mper.phi_rel)	1534	8.48e-06	0.000192	1.08%
849	regular	(assignment) ...mper.phi_rel)	1534	8.04e-06	0.000146	0.824%

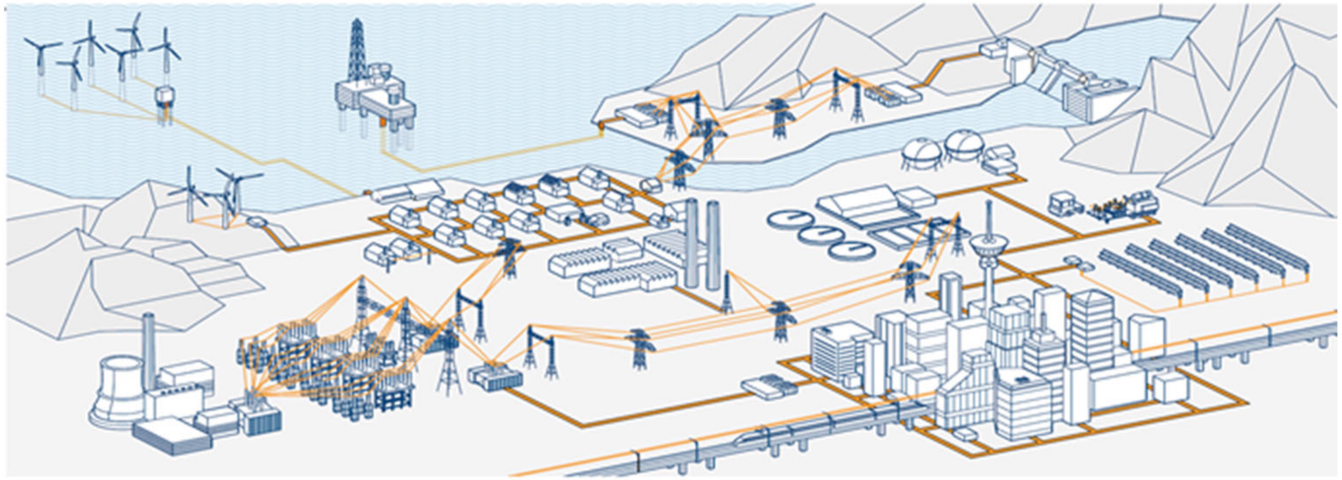
Defines

Variable
damper.a_rel
revolute2.frame_b.f[2]

MODELICA

ABB Commercial Application Use of Debugger

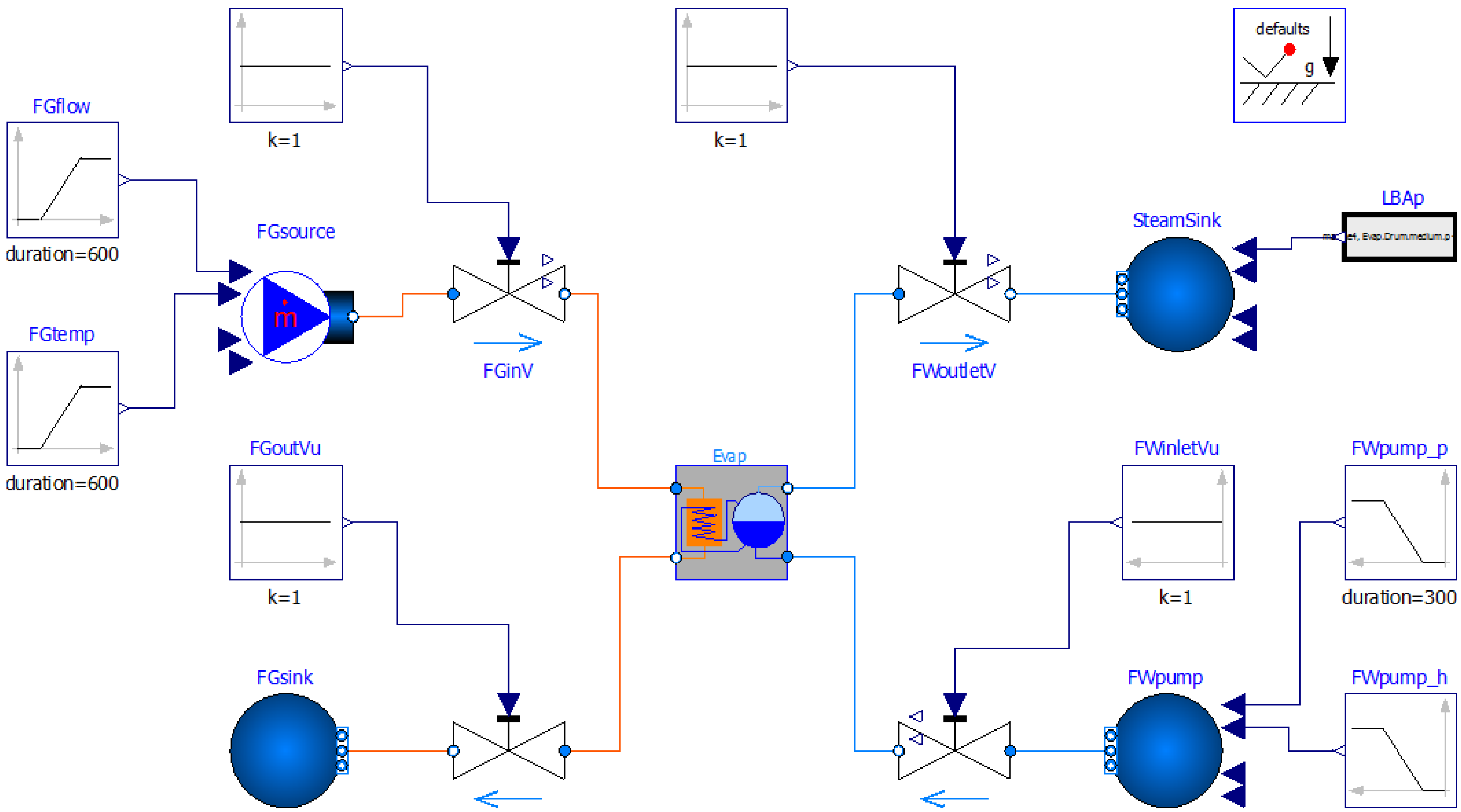
- ABB OPTIMAX® provides advanced model based control products for power generation and water utilities.



- ABB: “OpenModelica provides outstanding debugging features that help to save a lot of time during model development.”

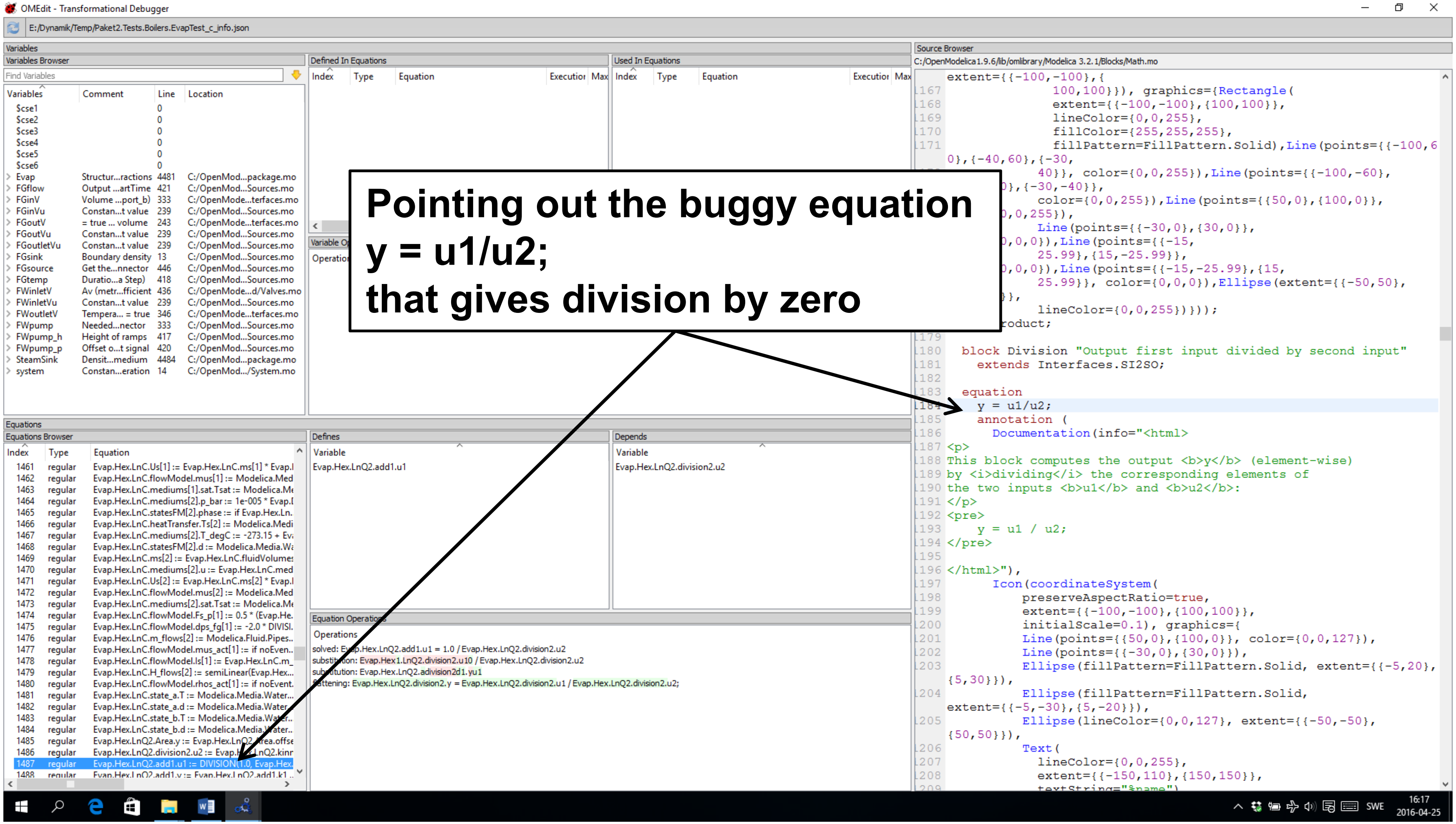
Equation Model Debugging on Siemens Model

(used on Siemens Evaporator test model, 1100 equations)



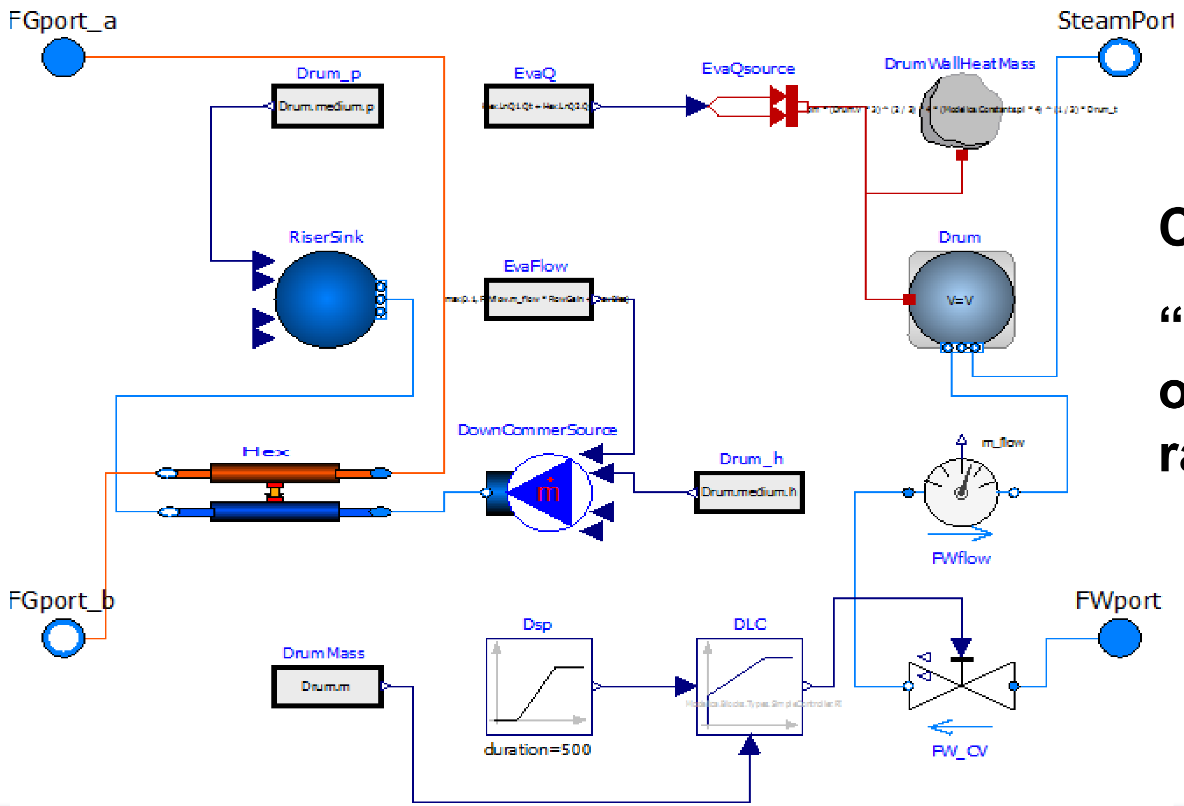
Equation Model Debugger on Siemens Model

(Siemens Evaporator test model, 1100 equations)



Performance Profiling for faster Simulation
(Here: Profiling equations of Siemens Drum boiler model with evaporator

- Measuring **performance** of equation blocks to find bottlenecks
  - Useful as input before model simplification for real-time applications
- Integrated with the debugger to **point out the slow equations**
- Suitable **for real-time profiling** (collect less information), or a complete view of all equation blocks and function calls



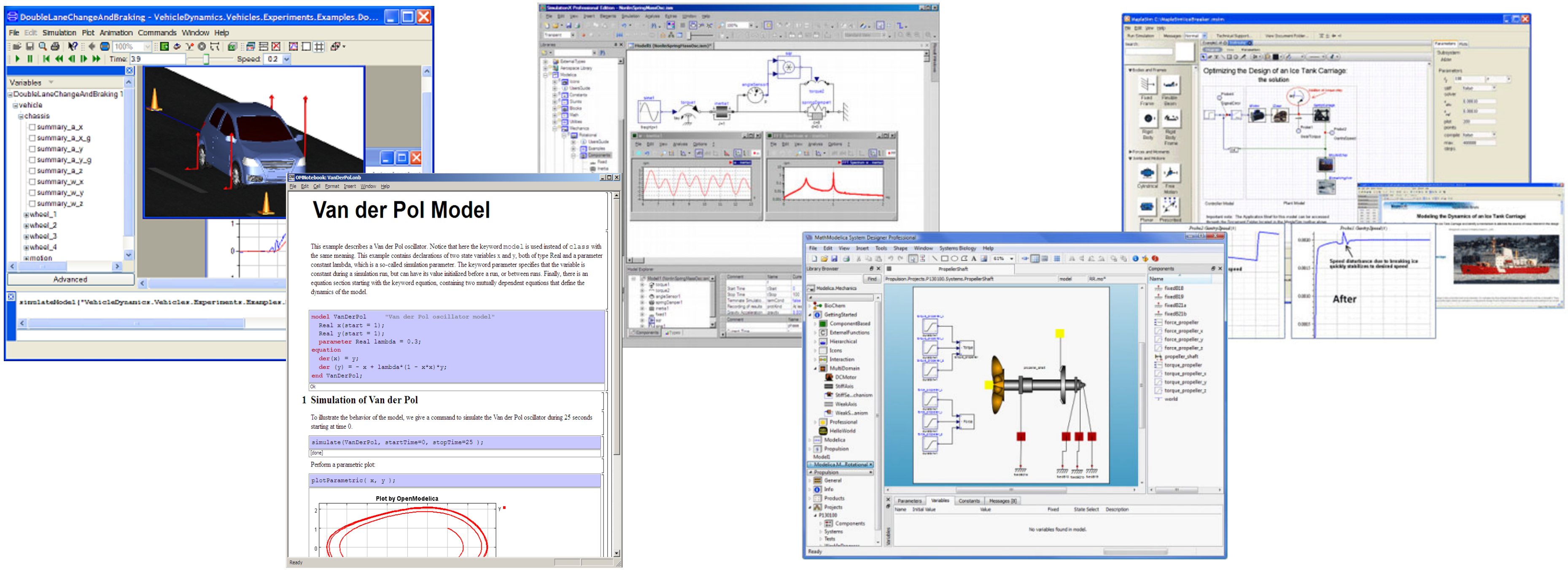
Conclusion from the evaluation:

"…the profiler makes the process of performance optimization radically shorter."

Part IV

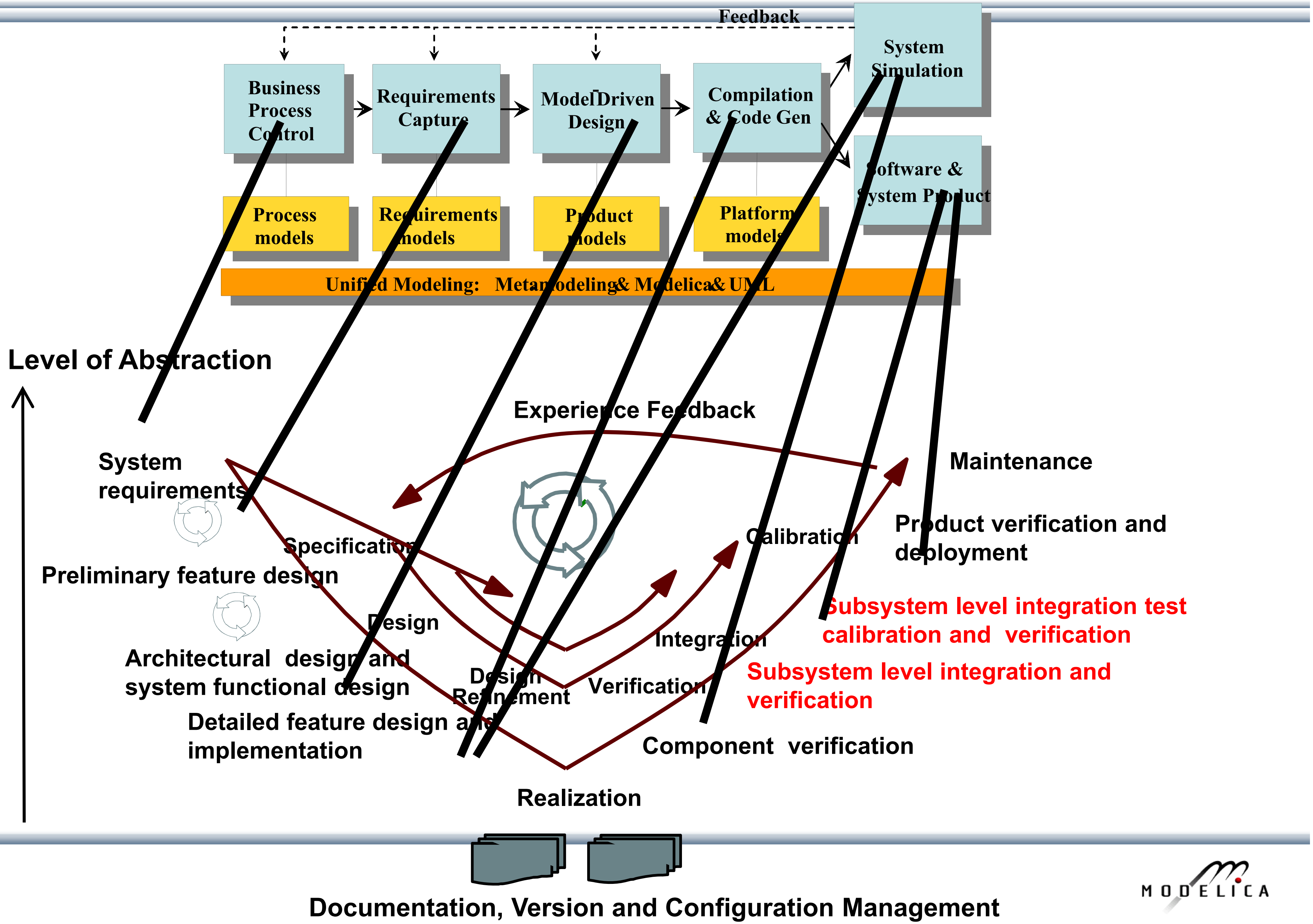
Dynamic Verification/Testing of Requirements vs Usage Scenario Models

**Wladimir Schamai, Lena Buffoni, Peter Fritzson
and contributions from MODRIO partners**

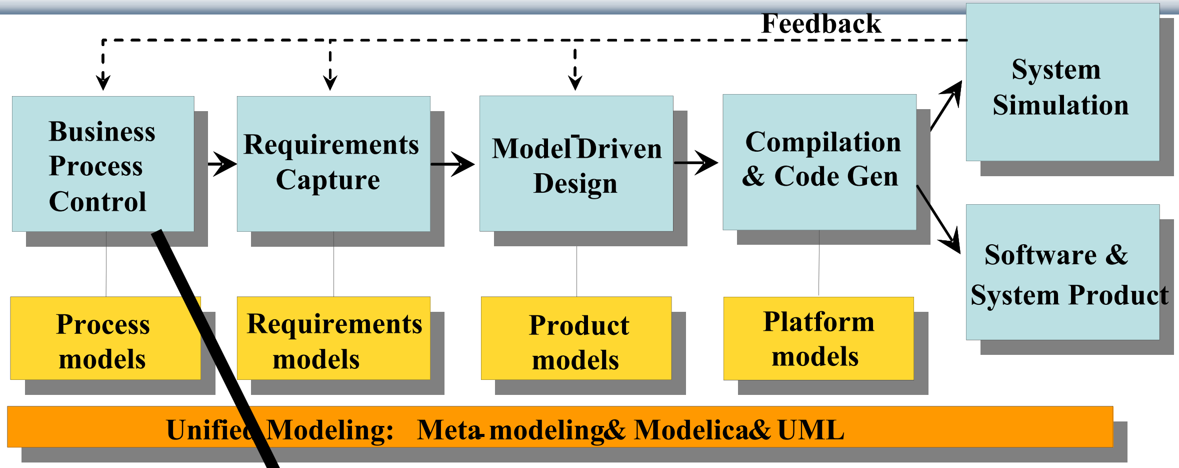


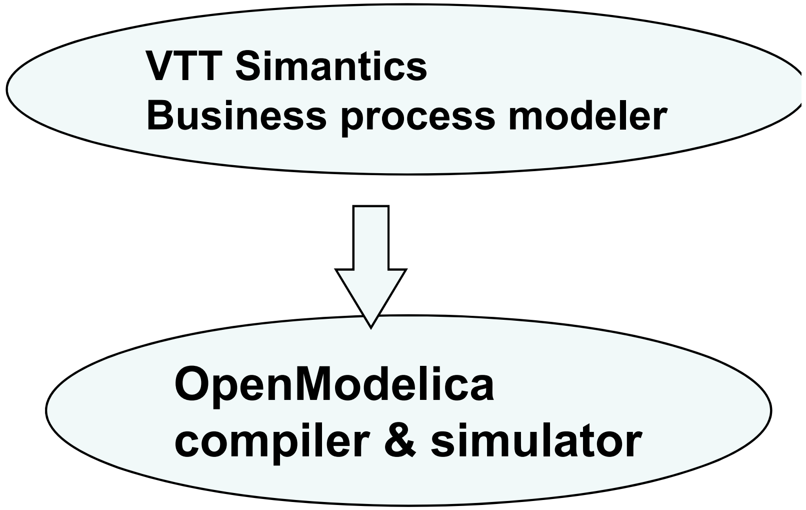
MODELICA

OpenModelica and Papyrus Based Model-Based Development Environment to Cover Product-Design V



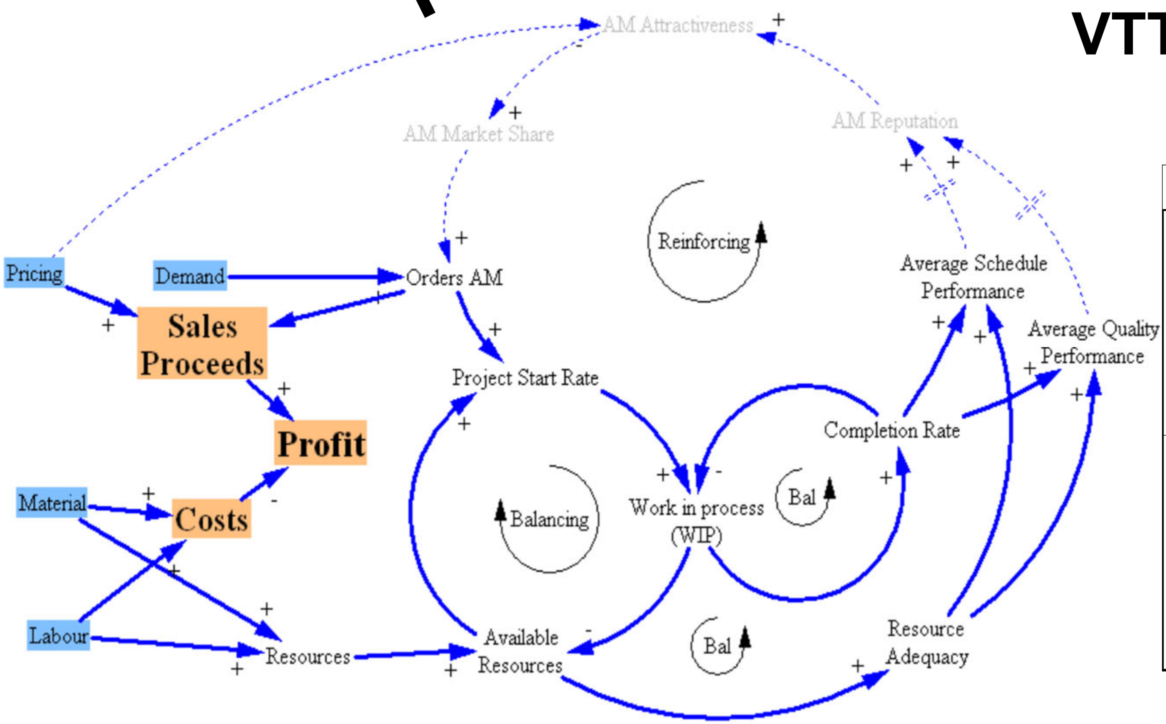
Business Process Control and Modeling



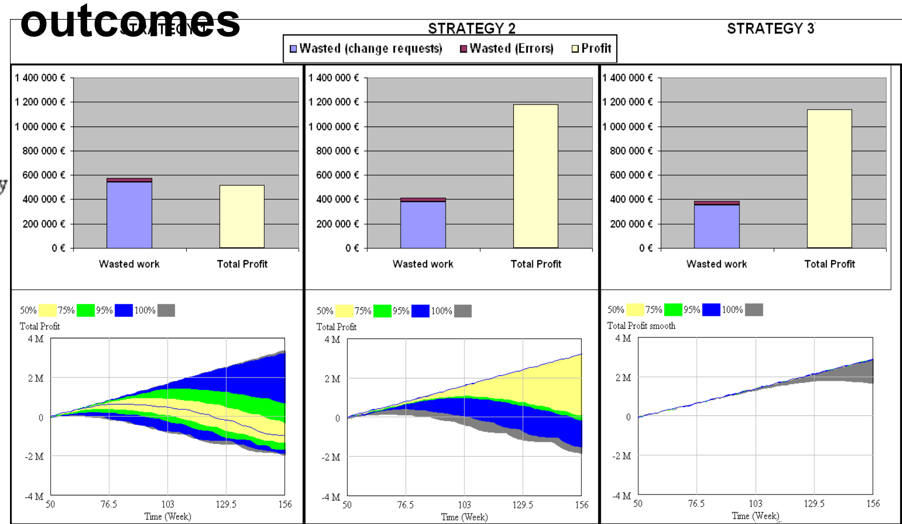


OpenModelica based simulation

Metso Business model & simulation
VTT Simantics Graphic Modeling Too

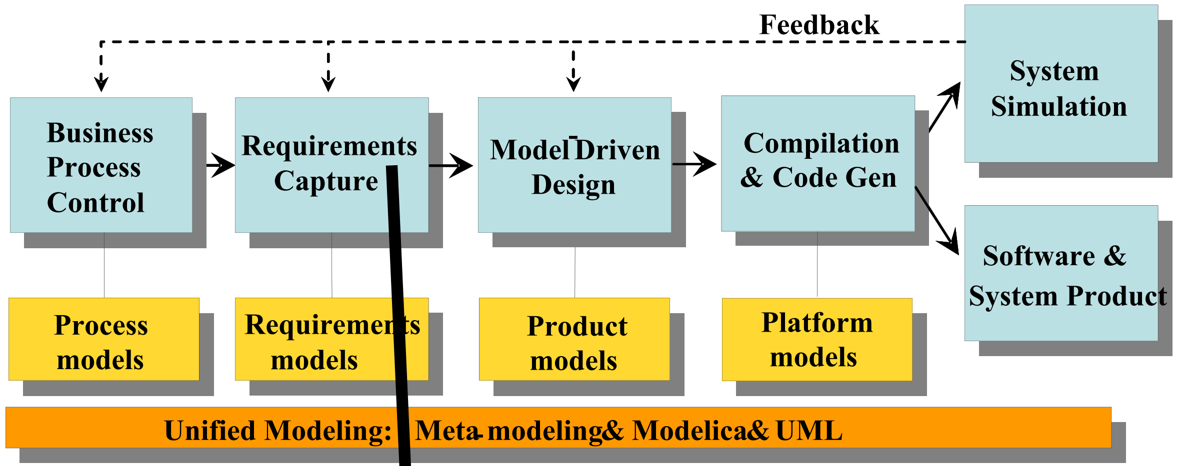


Simulation of 3 strategies with outcomes



MODELICA

Requirement Capture



vVDR (virtual Verification of Designs against Requirements)

in ModelicaML UML/Modelica Profile, part of OpenModelica

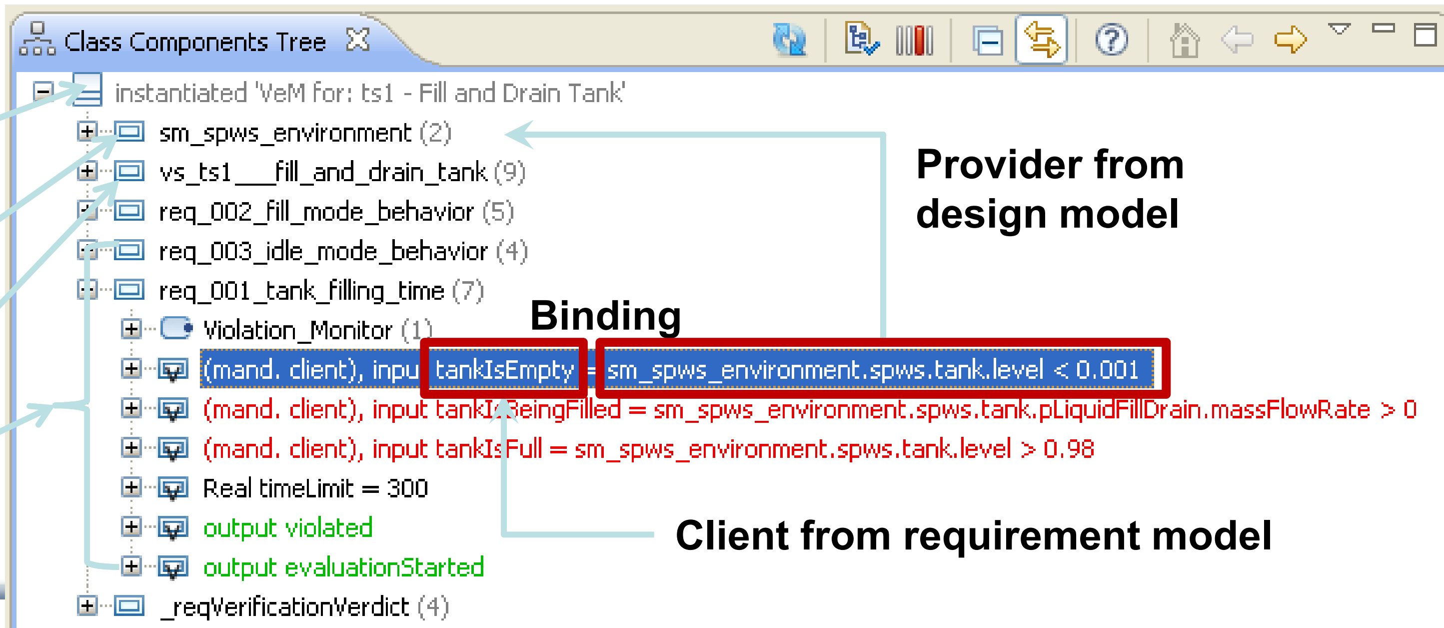
OpenModelica based simulation

Verification Model

Design Model

Scenario Model

Requirement Models

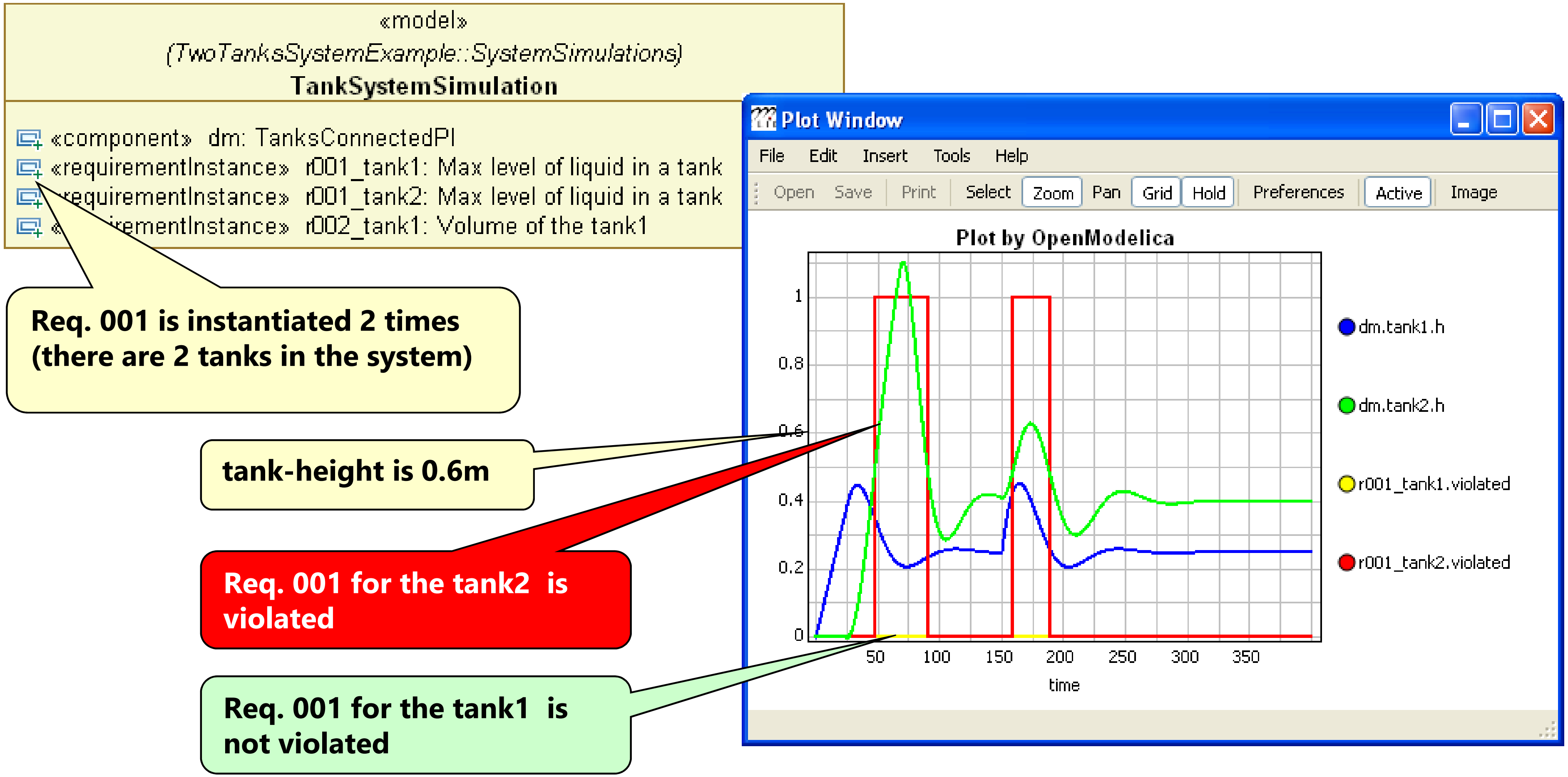


OpenModelica – ModelicaML UML Profile

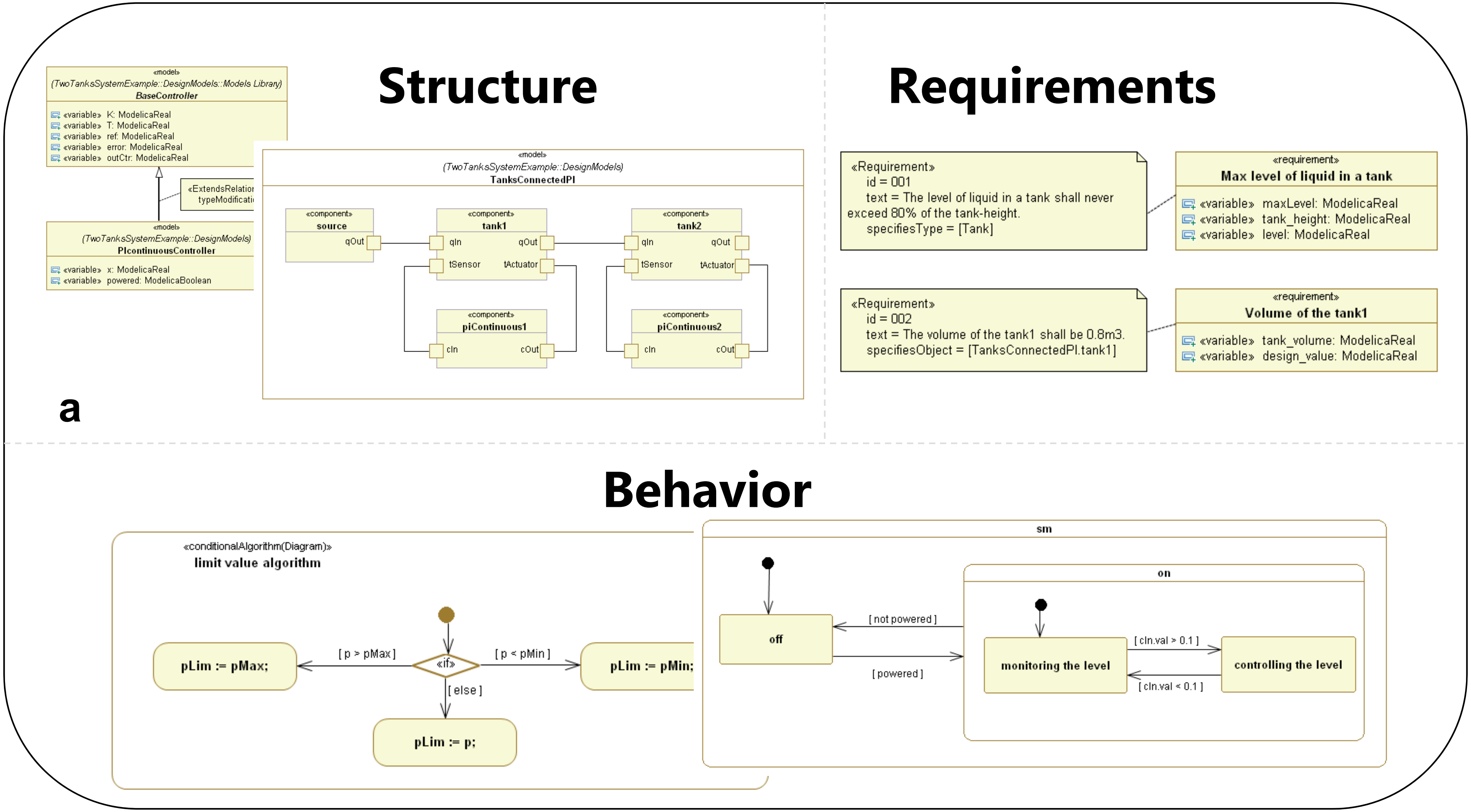
Based on Open-Source Papyrus UML and OpenModelica

- ModelicaML is a UML Profile for SW/HW modeling
  - Applicable to "pure" UML or to other UML profiles, e.g. SysML
- Standardized Mapping UML/SysML to Modelica
  - Defines transformation/mapping for **executable** models
  - Being **standardized** by OMG
- ModelicaML
  - Defines graphical concrete syntax (graphical notation for diagram) for representing Modelica constructs integrated with UML
  - Includes graphical formalisms (e.g. State Machines, Activities, Requirements)
    - Which do not yet exist in Modelica language (extension work ongoing)
    - Which are translated into executable Modelica code
  - Is defined towards generation of executable Modelica code
  - Current implementation based on the Papyrus UML tool + OpenModelica

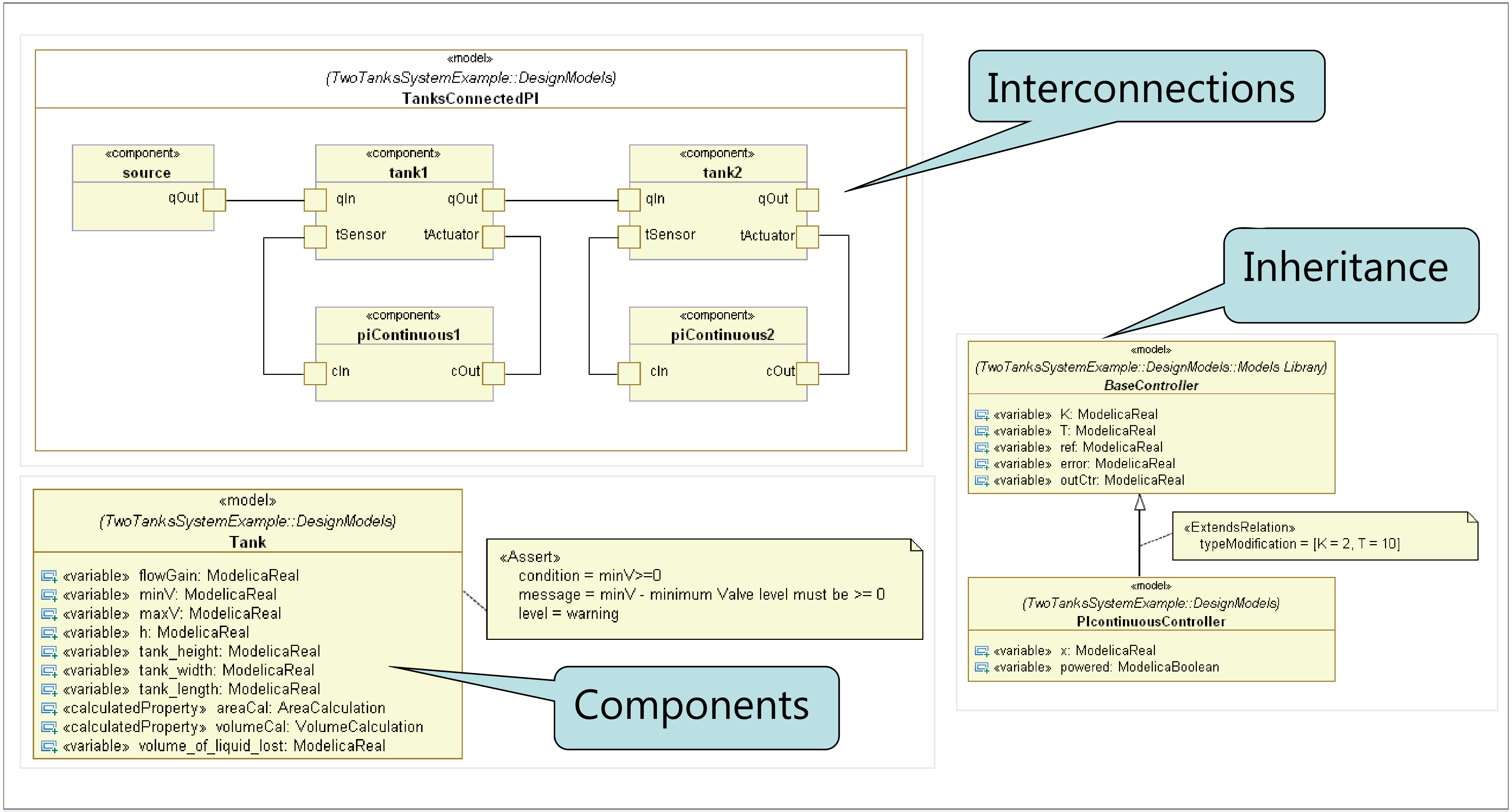
Example: Simulation and Requirements Evaluation



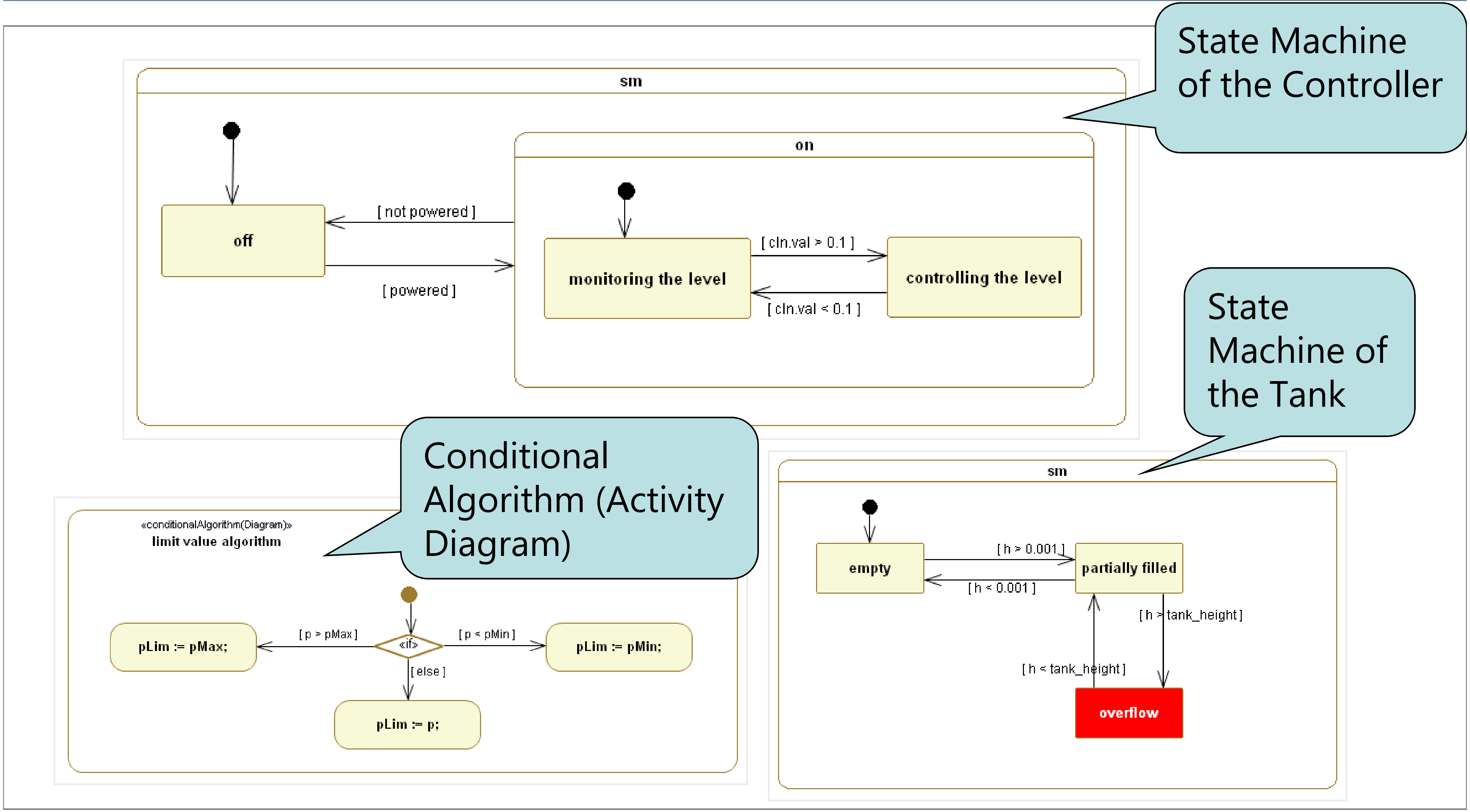
ModelicaML: Graphical Notation



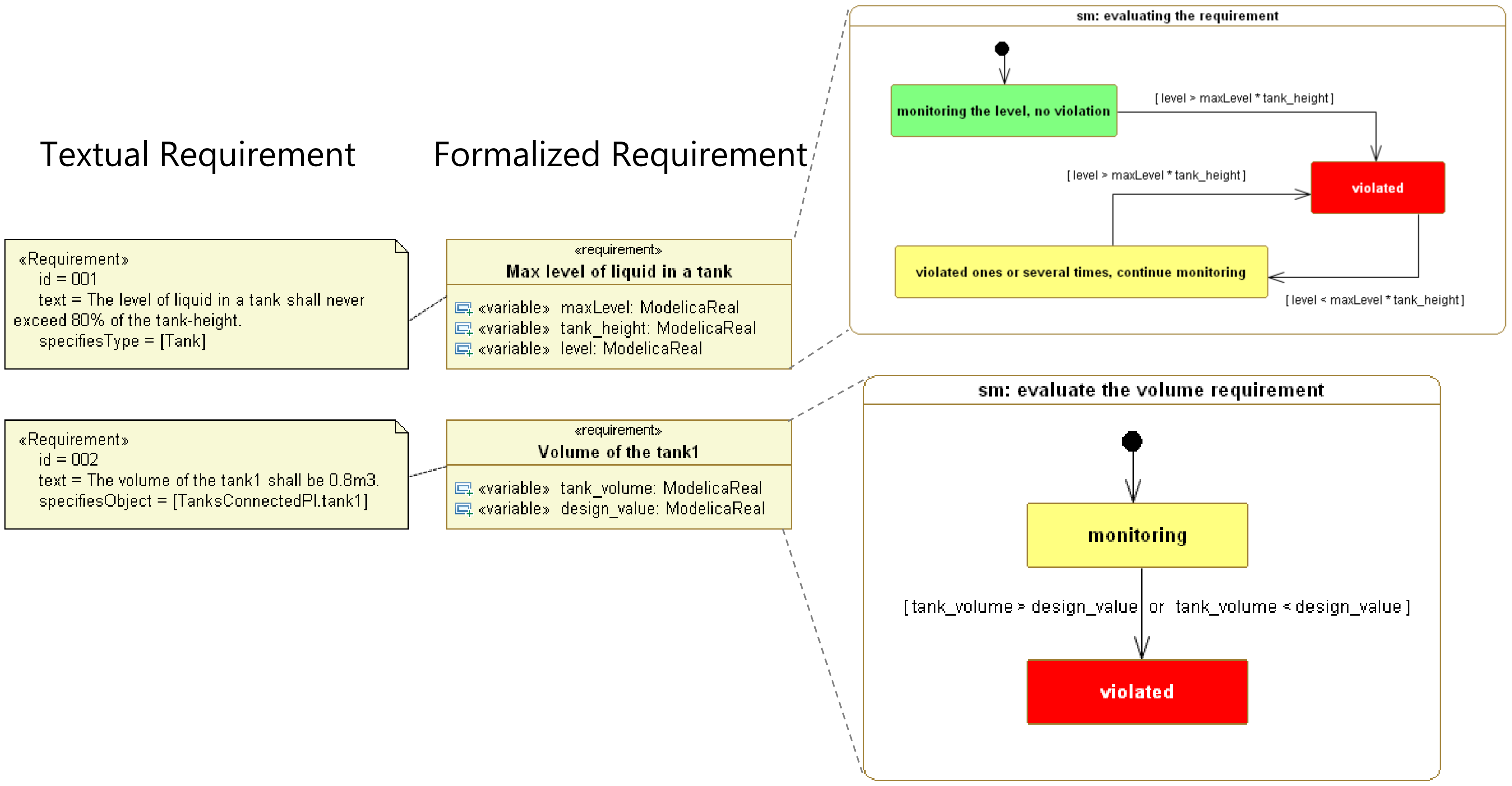
Example: Representation of System Structure



Example: Representation of System Behavior

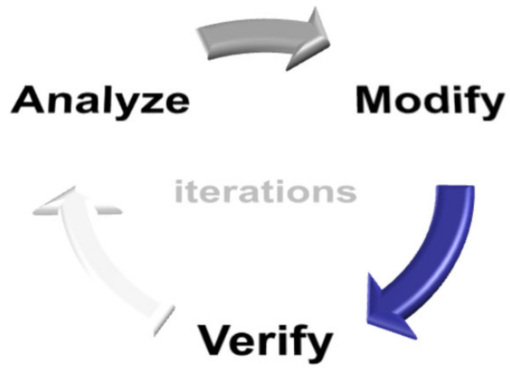


Example: Representation of System Requirements



vVDR Method –
virtual Verification of Designs vs Requirements

Actor	Task	Created Artifact
	Formalize Requirements	RMM Requirement Monitor Models
	Formalize Designs	DAM Designs Alternative Models
	Formalize Scenarios	SM Scenario Models
AUTOMATED	Create Verification Models *	VM Verification Models
AUTOMATED	Execute and Create Report	Reports
	Analyze Results	



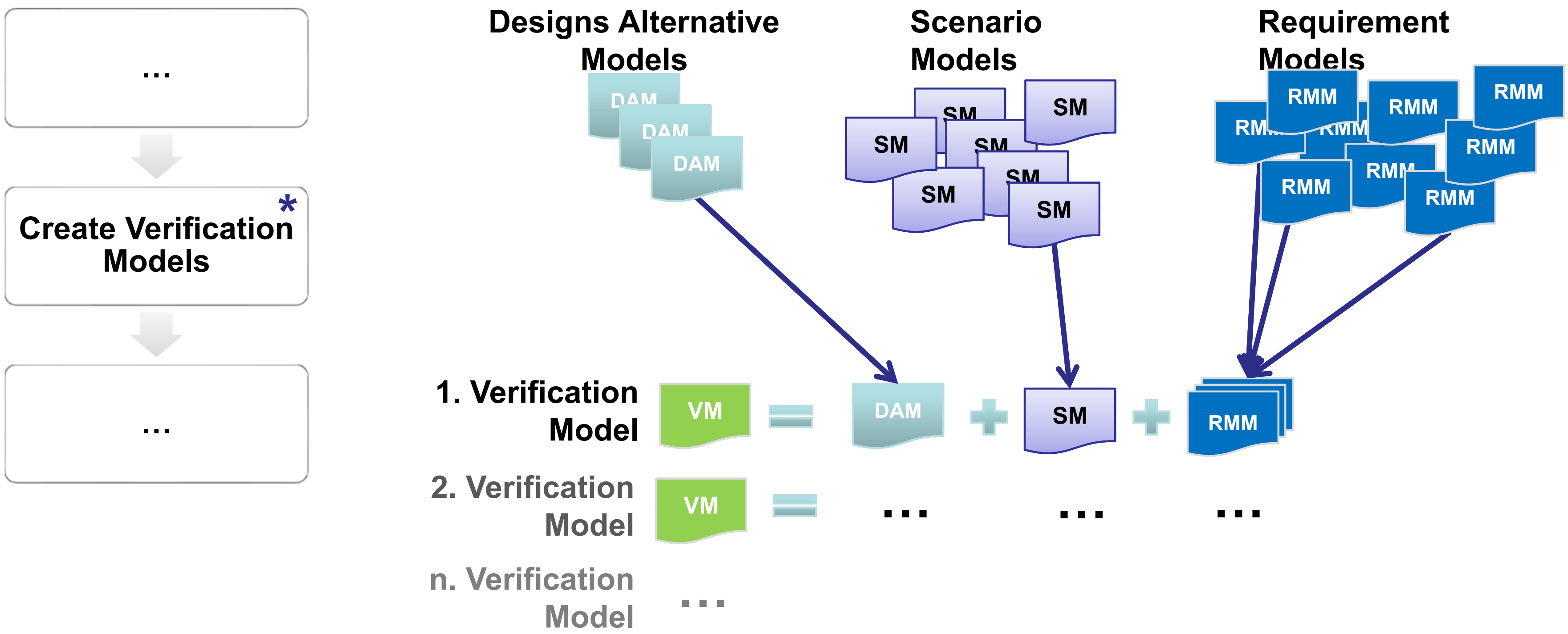
Goal: Enable on-demand verification of designs against requirements using automated model composition at any time during development.

MODELICA

Challenge

We want to verify **different design alternatives** against **sets of requirements** using **different scenarios**. Questions:

1) How to **find valid combinations** of **design alternatives**, **scenarios** and **requirements** in order to enable an automated composition of verification models?
2) Having found a valid combination: How to **bind all components correctly**?



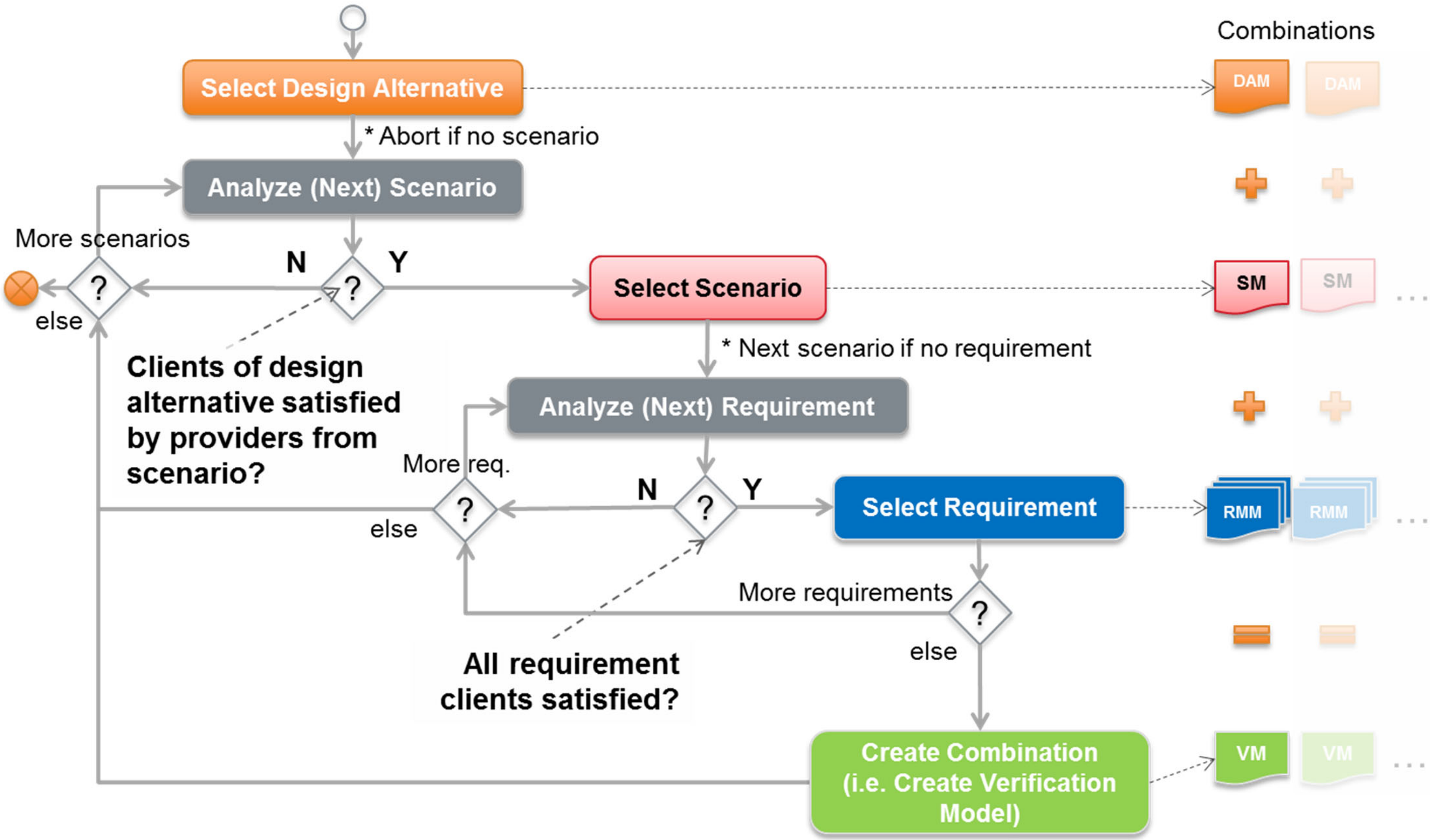
Composing Verification Models

main idea

- Collect all **scenarios**, **requirements**, import **mediators**
- Generate/compose *verification models* automatically:
  - Select the **system model** to be verified
  - Find all **scenarios** that can stimulate the selected system model (i.e., for each mandatory client check whether the binding expression can be inferred)
  - Find **requirements** that are implemented in the selected system model (i.e., **check** whether for **each requirement** for all mandatory clients binding expressions can be inferred)
- Present the list of scenarios and requirements to the user
  - The user can select only a subset or scenarios or requirements he/she wishes to consider

Generating/Composing Verification Models

algorithm



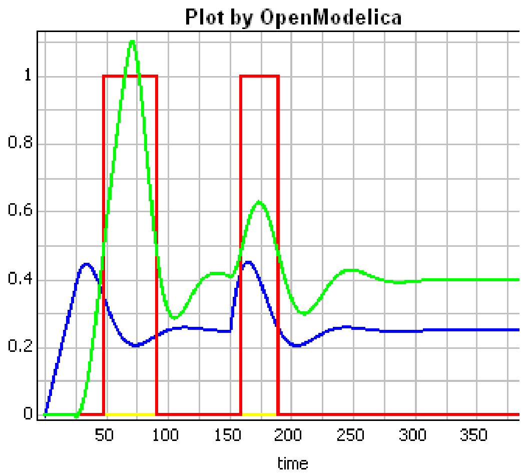
MODELICA

Simulation and Report Generation in ModelicaML

Verification models are simulated.

The generated **Verification Report** is a prepared summary of:

- Configuration, bindings
- Violations of requirements
- etc.



Verification models number (3), executed (3), passed (0), failed (3)

Failed VeM for: s1-Fill and Drain Tank (Plot)
Failed VeM for: s2-Fill tank (Plot)
Failed VeM for: s3-Drain tank (Plot)

Failed **VeM for: s1-Fill and Drain Tank** (**Plot**)
(ModelicaMLModel::GenVeMs for: SPWS Environment_1::VeM for: s1-Fill and Drain Tank)

Settings: startTime = 0, **stopTime** = **1500**, tolerance = default, intervals = 0, outputFormat = plt

verdict allRequirementsEvaluated : yes
verdict someRequirementsViolated : yes

Model to be verified: SPWS Environment
(ModelicaMLModel::Design::SPWS Environment)

Verification Scenario: s1-Fill and Drain Tank
(ModelicaMLModel::Verification Scenarios::s1-Fill and Drain Tank)

madantory client: vs_s1_fill_and_drain_tank.tankHeight (changed its value)
Type : = ModelicaReal
Variability : = continuous
Binding code : = sm_spws_environment.spws.tank.height

Violated Requirement: Drain mode behavior (ID 004)
(ModelicaMLModel::Requirements::Drain mode behavior)
Text: When the system is drained only the fill/drain valve should be open, all other valves should be closed.

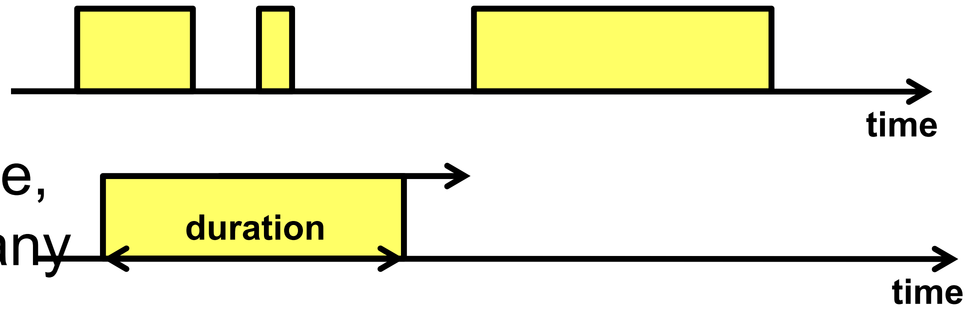
verdict evaluated : yes
verdict violated : yes

madantory client: req_004_drain_mode_behavior.fillDrainValveIsOpen (changed its value)
Type : = ModelicaBoolean
Variability : = continuous
Binding code : = sm_spws_environment.spws.fillDrainValve.isFullyOpen

madantory client: req_004_drain_mode_behavior.otherValvesAreClosed (changed its value)
Type : = ModelicaBoolean
Variability : = continuous
Binding code : = if sm_spws_environment.spws.overFlowValve.isFullyClosed and sm_spws_environment.spws.supplyVavle.isFullyClosed then true else false

Continuous and Discrete Time Locators for Time-related Requirements

- A Continuous Time Locator(CTL) specifies one or more time intervals
  - Time intervals have a duration
  - They usually have a position in time, but a sliding time window defines any time period of a given duration



- A Discrete Time Locator (DTL) defines one or more positions in time and has no duration
  - An event is associated with a DTL that specifies when the event occurred
  - The difference between events and DTLs is that a DTL is not an object
  - That position may be relative to the initialisation of the system or to another DTL

Time Locators Expressed in Modelica

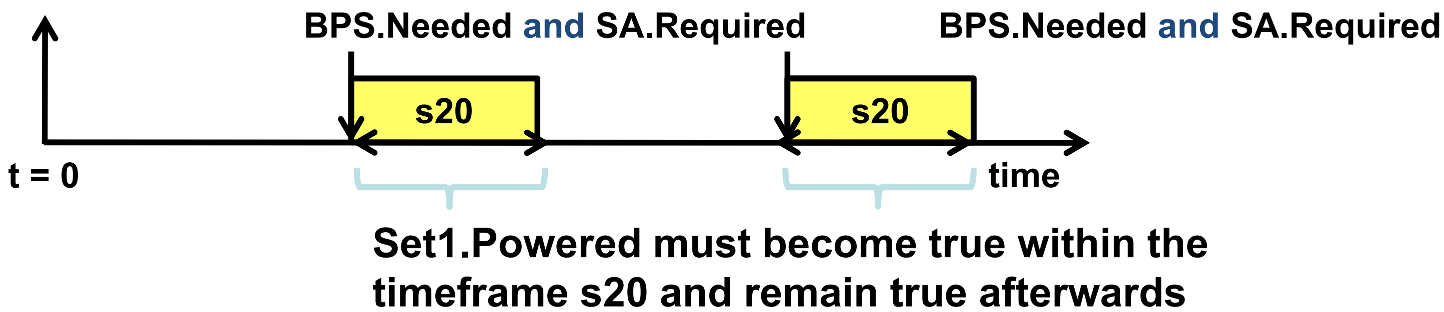
Special FORML-L syntax	Standard Modelica syntax
duringAny duration	**duringAny**(duration)
after event	**after**(event)
after event1 ***untilNext*** event2	**afterUntil**(event1, event2)
after event ***for*** duration	**afterFor**(event, duration)
after event ***within*** duration	**afterWithin**(event, duration)
until event	**until**(event)
every duration1 ***for*** duration2	**everyFor**(duration1, duration2)
when condition ***changes***	Maps to Modelica **if**

From Text to Simulated Requirement – Modelica Extended with new Operators

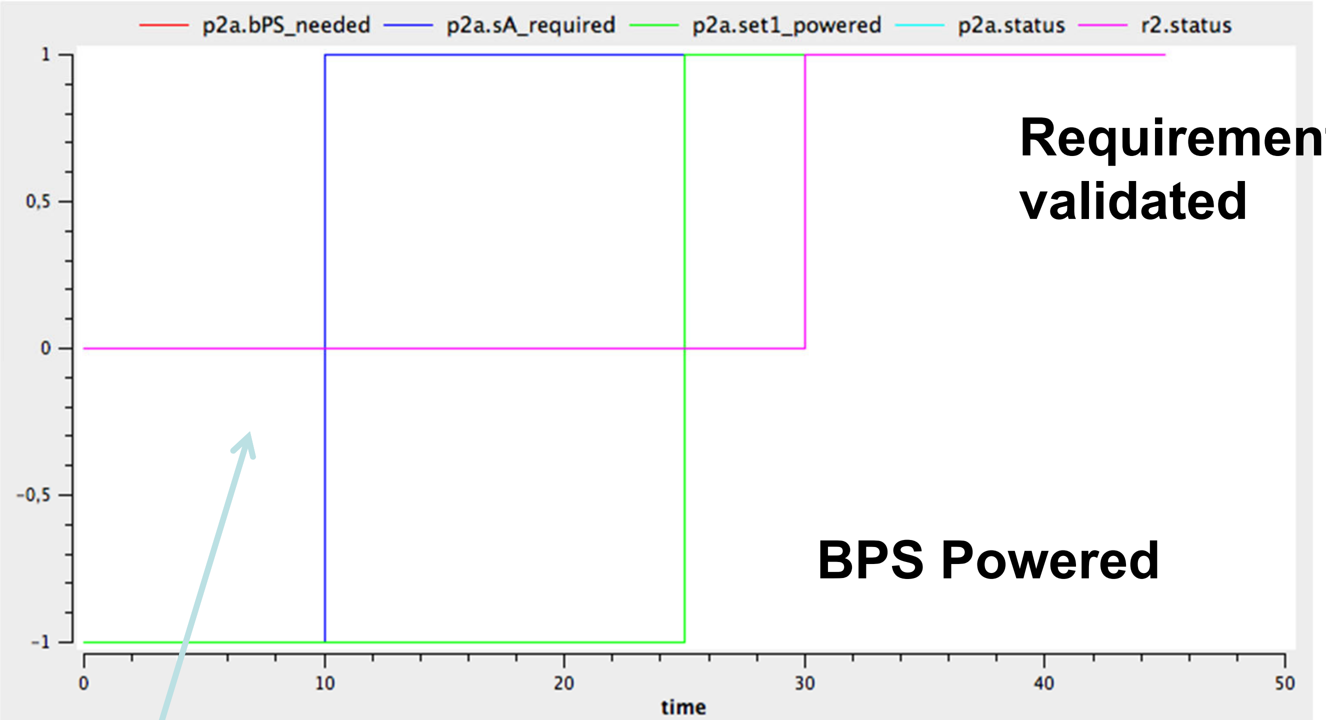
From a text requirement expressing a condition:

A - In the absence of any Backup Power Supply (BPS) component failure or in the presence of a single sensor failure, when the BPS is not under maintenance, in case of loss of MPS, and if safety injection is required, Set1 must be powered within 20 s

```
model P2a   extends Condition;
   input ConditionStatus bPSNeeded, sARequired, set1Powered;
equation
   status = if afterWithin (bPSNeeded == notViolated and
                                          sARequired == notViolated, 20) then
              if set1Powered == notViolated then
                     notViolated else violated else undefined;
 end P2a;
```



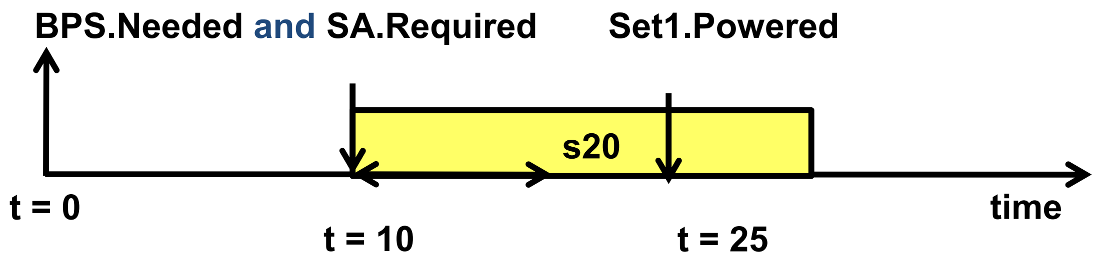
From Text to Simulated Requirement – Requirement not Violated – OpenModelica Simulation



3-valued logic prototype:
1 – true
0 – false
-1 – undefined

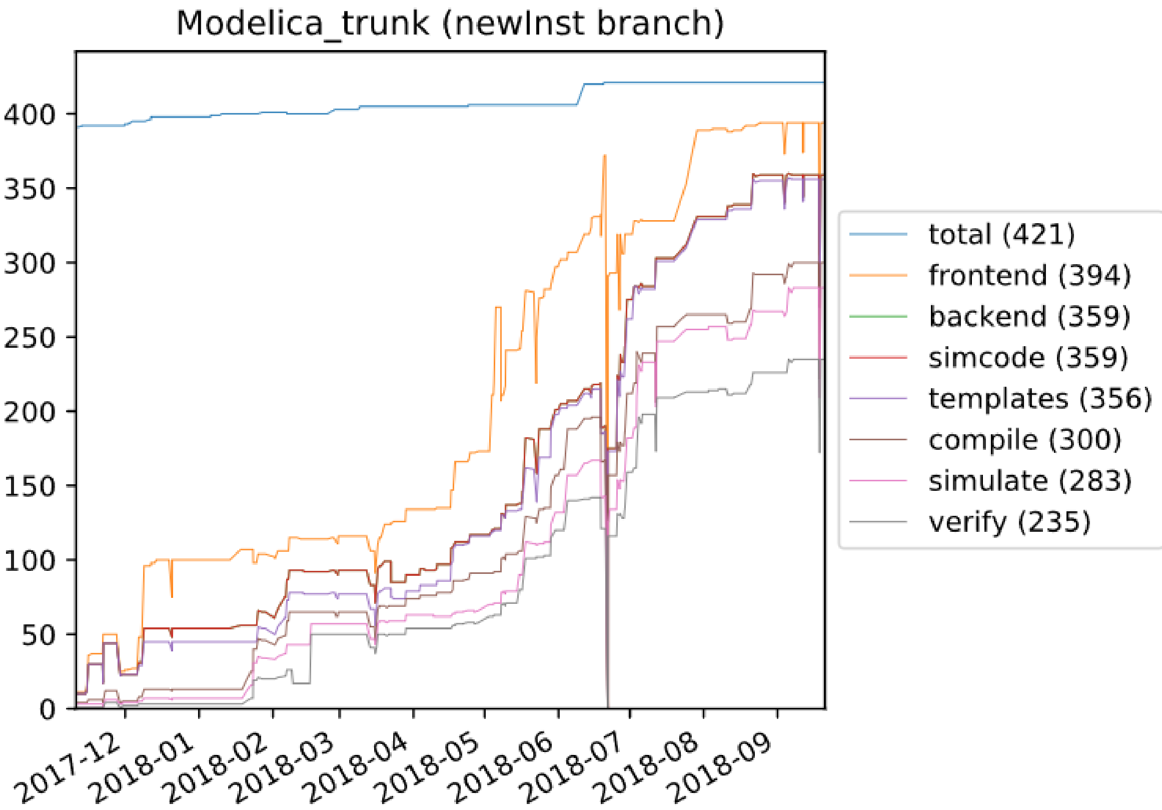
Within 20s

Requirement undefined outside the specified time window



Outlook:
New OpenModelica Frontend for Large-Scale models

- Soon: New OMC Compiler frontend for fast compilation and large-scale models
- Been under development the past 2-3 years
- Now (sept 24) simulates 67% of MSL models, coverage increases about 6% per month
- About 10-200 times faster than the old frontend, depending on model



OpenModelica DAEMode for Large-Scale models

- Goal – to handle hundreds of thousands to millions of equations
- Introduced sparse solvers in the solution chain:
  - KLU for linear algebraic equations,
  - Kinsol for nonlinear algebraic equations, and
  - IDA for causalized differential equations.
- Largest system so far: electro-mechanical power system model with about 600.000 differential-algebraic equations
- Under development for even larger systems

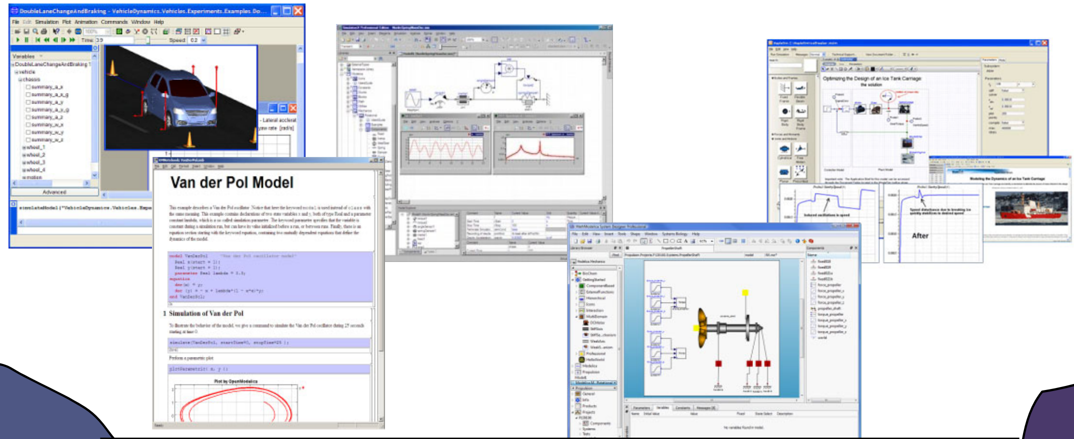
Summary and Questions

Multi-Domain Modeling

Visual Acausal Component Modeling

www.modelica.org – **Language, Standard Library**

www.openmodelica.org – **Open Source Tool**



Typed Declarative Textual Language

Thanks for listening!

Hybrid Modeling