ThermoPower Library Simulation

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Introduction

- Back in 2002, work started at Politecnico di Milano on the modelling of power plants using the Modelica language
- The tool we used back then was Dymola 5.3, using Modelica 2.0
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Proceedings
of the 3rd International Modelica Conference,
Linköping, November 3-4, 2003,
Peter Fritzson (editor)

Francesco Casella, Alberto Leva
Dipartimento di Elettronica e Informazione, Politecnico di Milano:
Modelica open library for power plant simulation: design and experimental validation
pp. 41-50

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- Modelica_Media was still under development, so the library used Hubertus Tummescheit's ThermoFluid library for water/steam properties
- The library evolved together with the Modelica language
  - Modelica.Media
  - Modelica 3.x
  - Stream connectors
  - Homotopy-based initialization
- In the meantime, OpenModelica has evolved
  - from an exotic Computer Science project with lots of limitations
  - to a full-fledged, fully Modelica 3.2r2 compliant tool
- We never thought of investing time to develop a *downgraded* version of ThermoPower to work with OpenModelica
- The tool needs to catch up, not the library!

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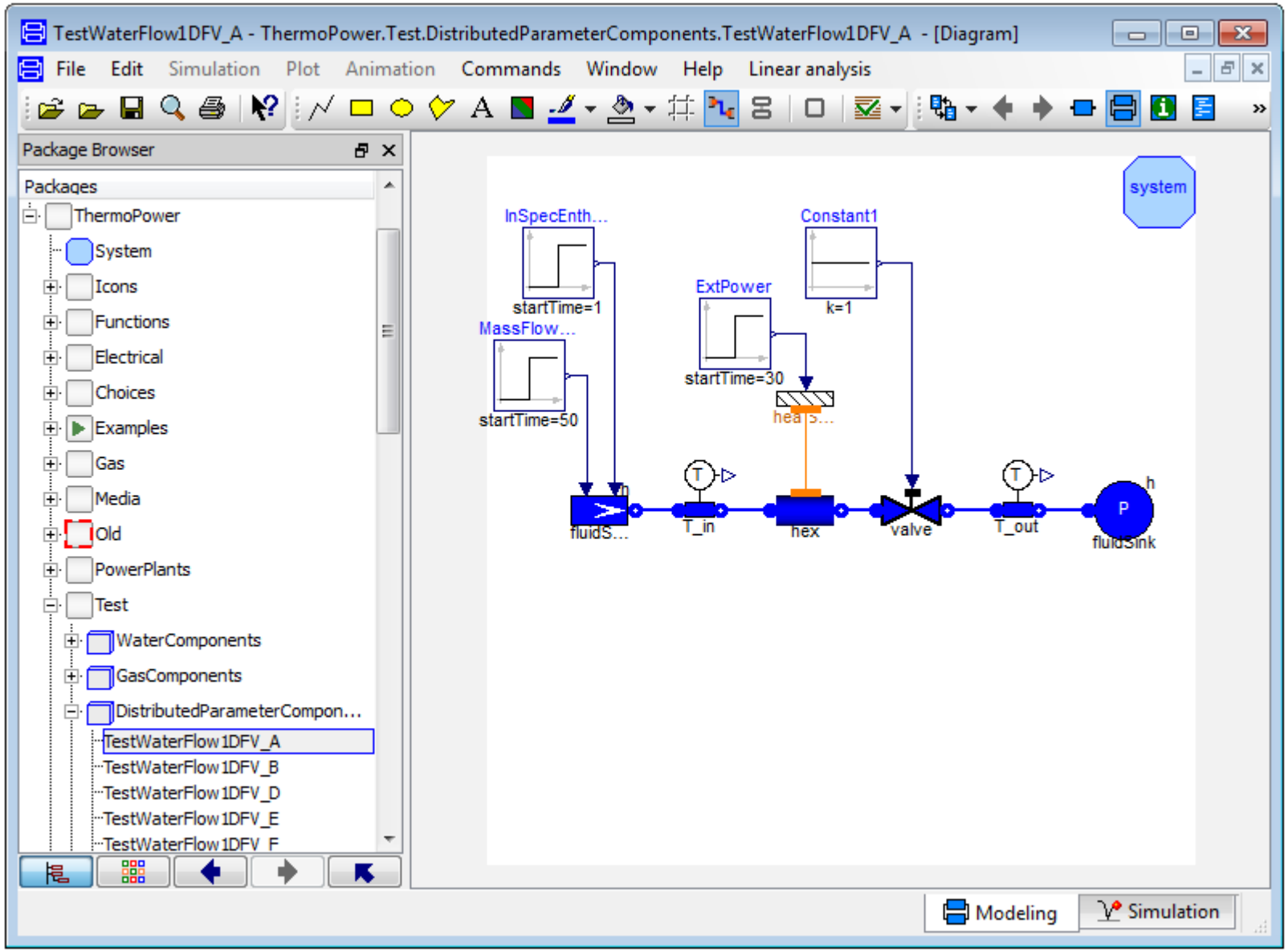
- The tool needs to catch up, not the library!

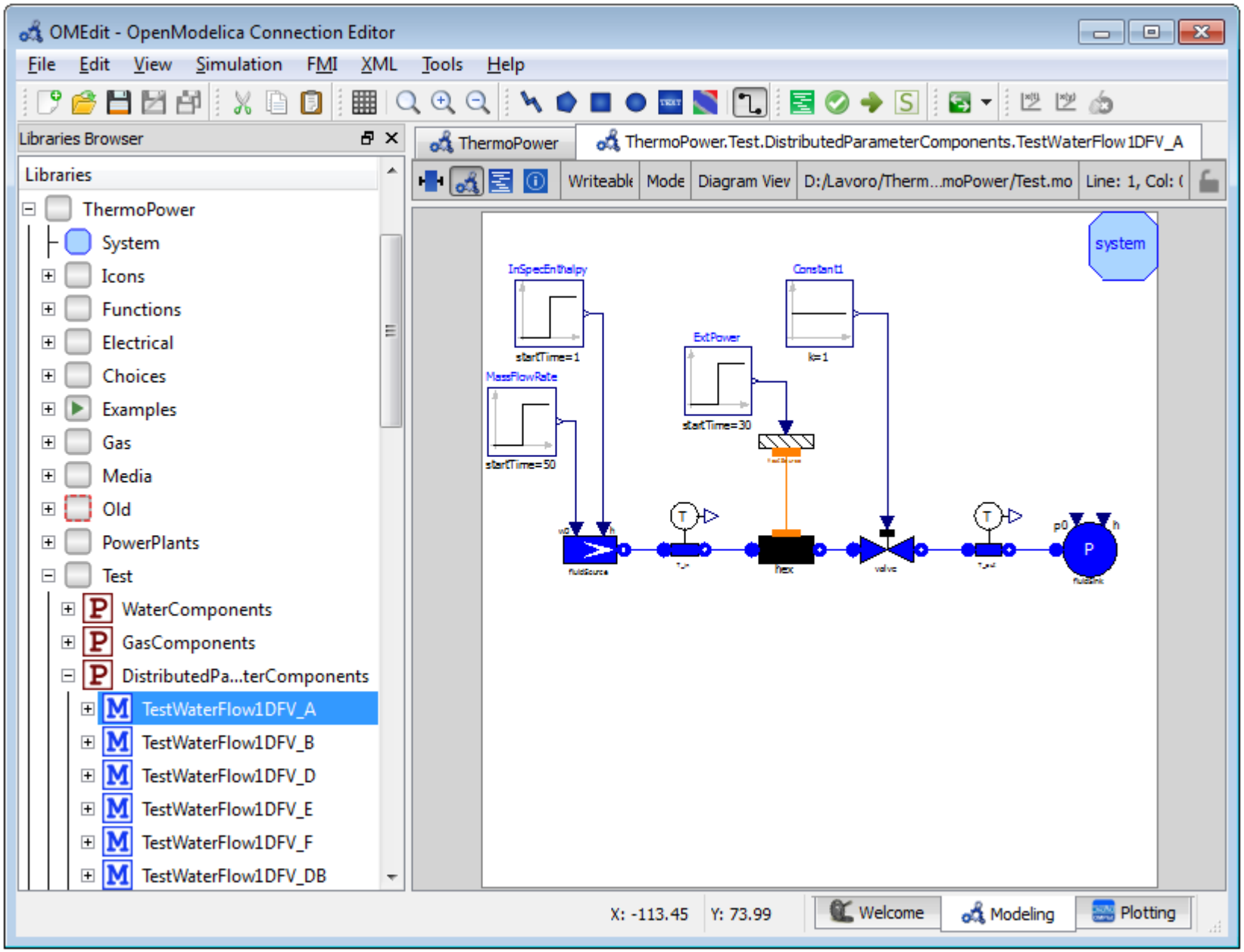
Has the moment finally arrived?

The Good News

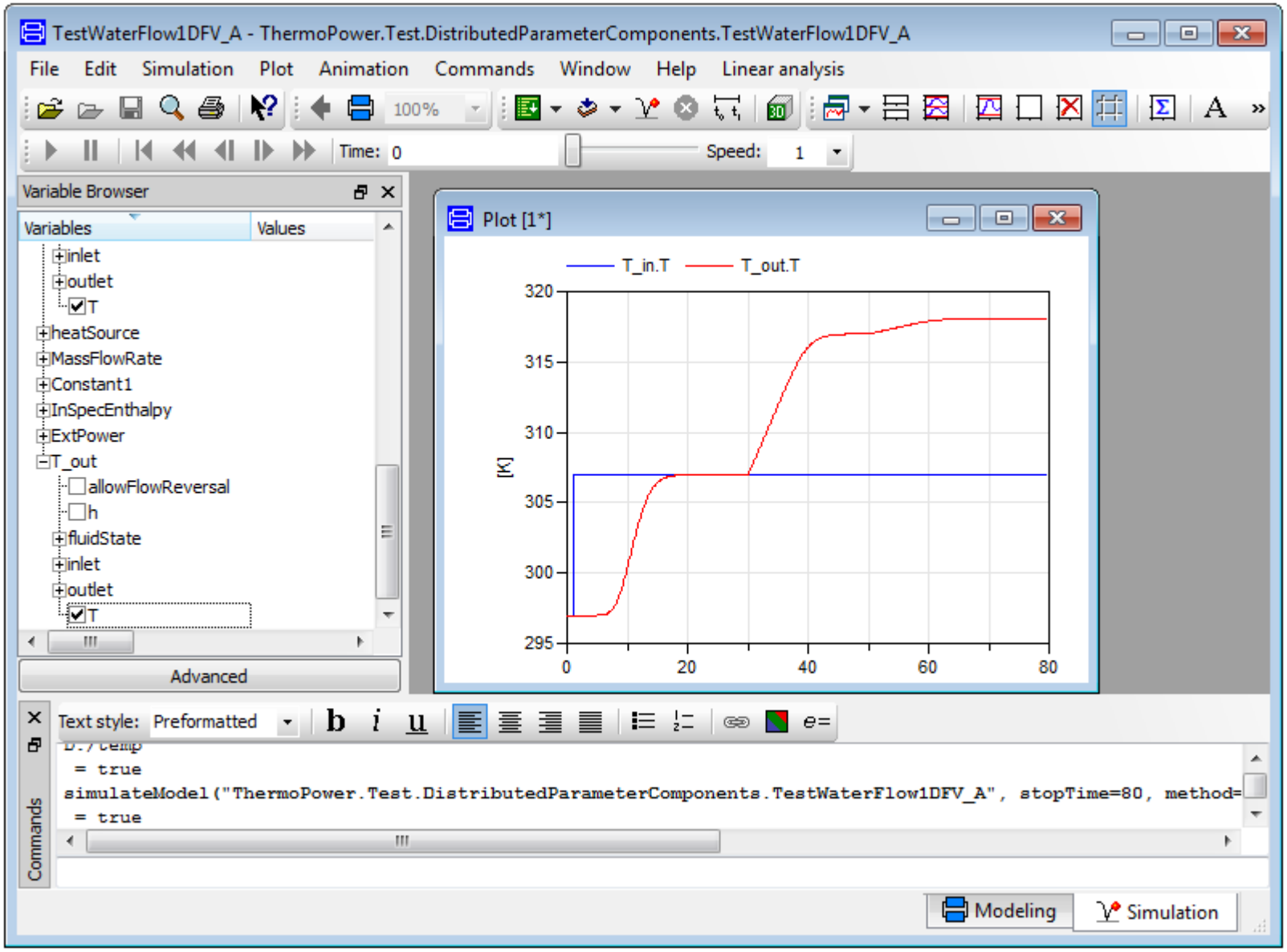
ThermoPower is handled by OMEdit



ThermoPower is handled by OMEdit (with some glitches...)



Models can be simulated, producing the right results



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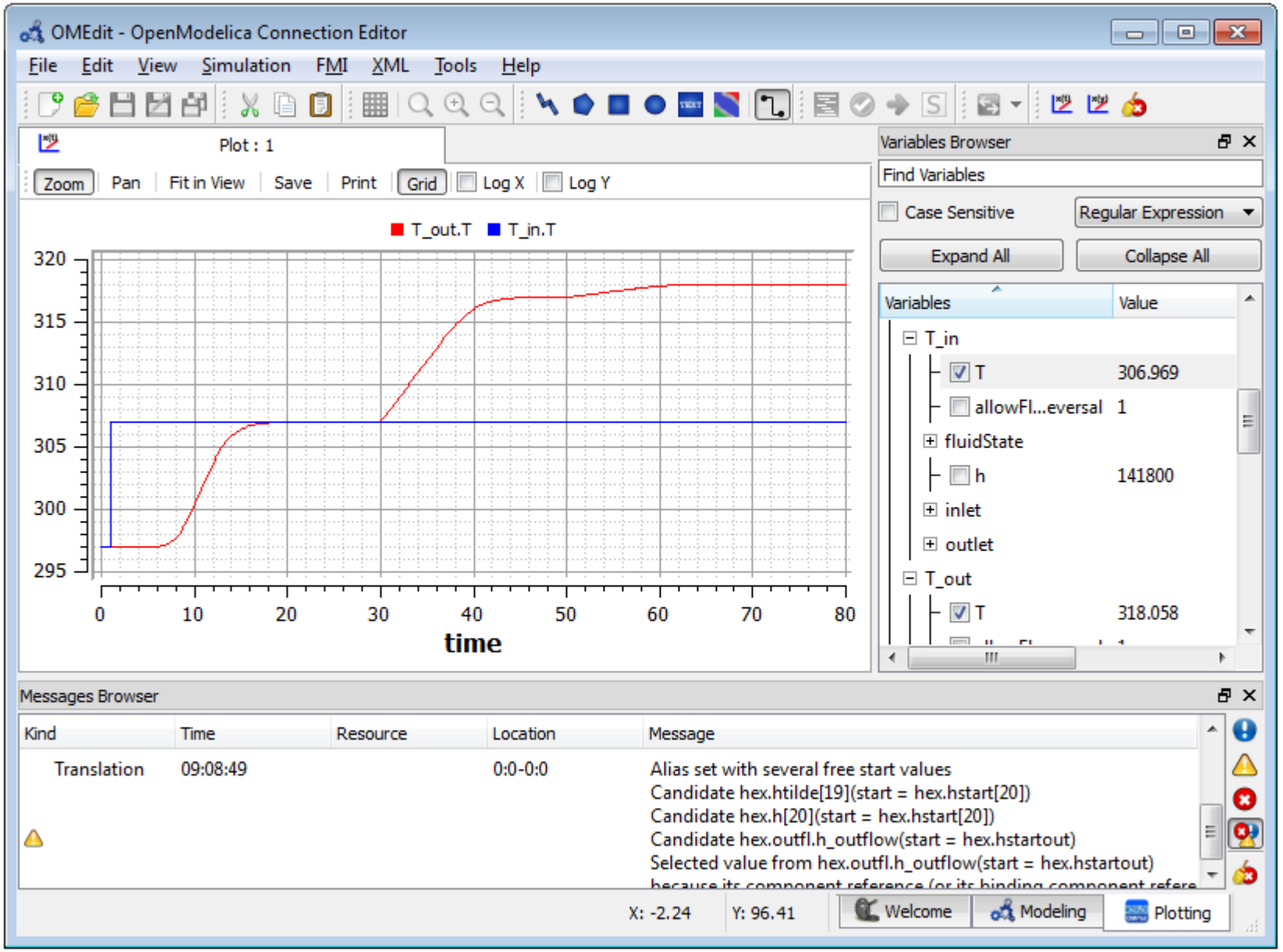
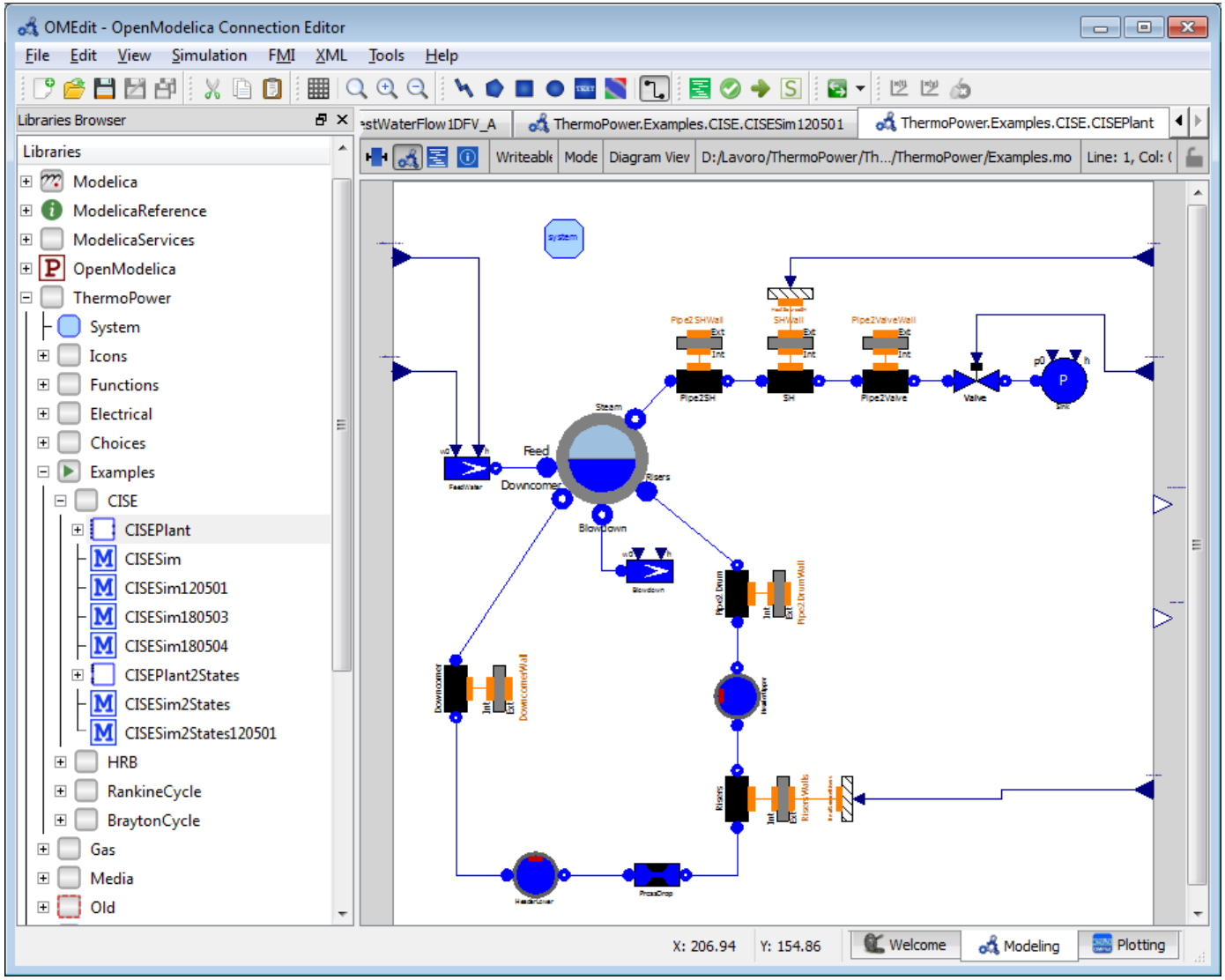


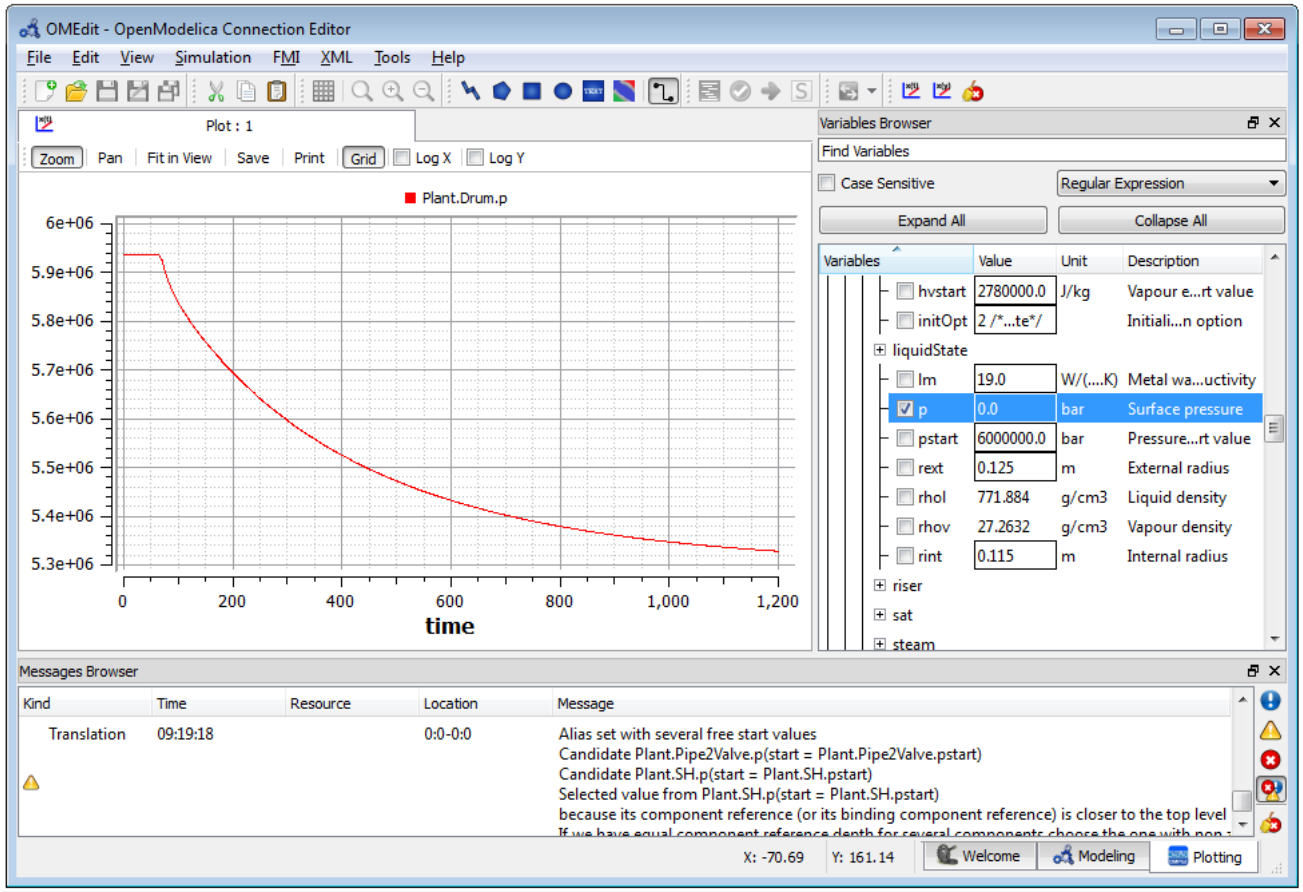
Non-trivial models are simulated correctly

- CISE plant model (see Modelica Conference 2003 paper)

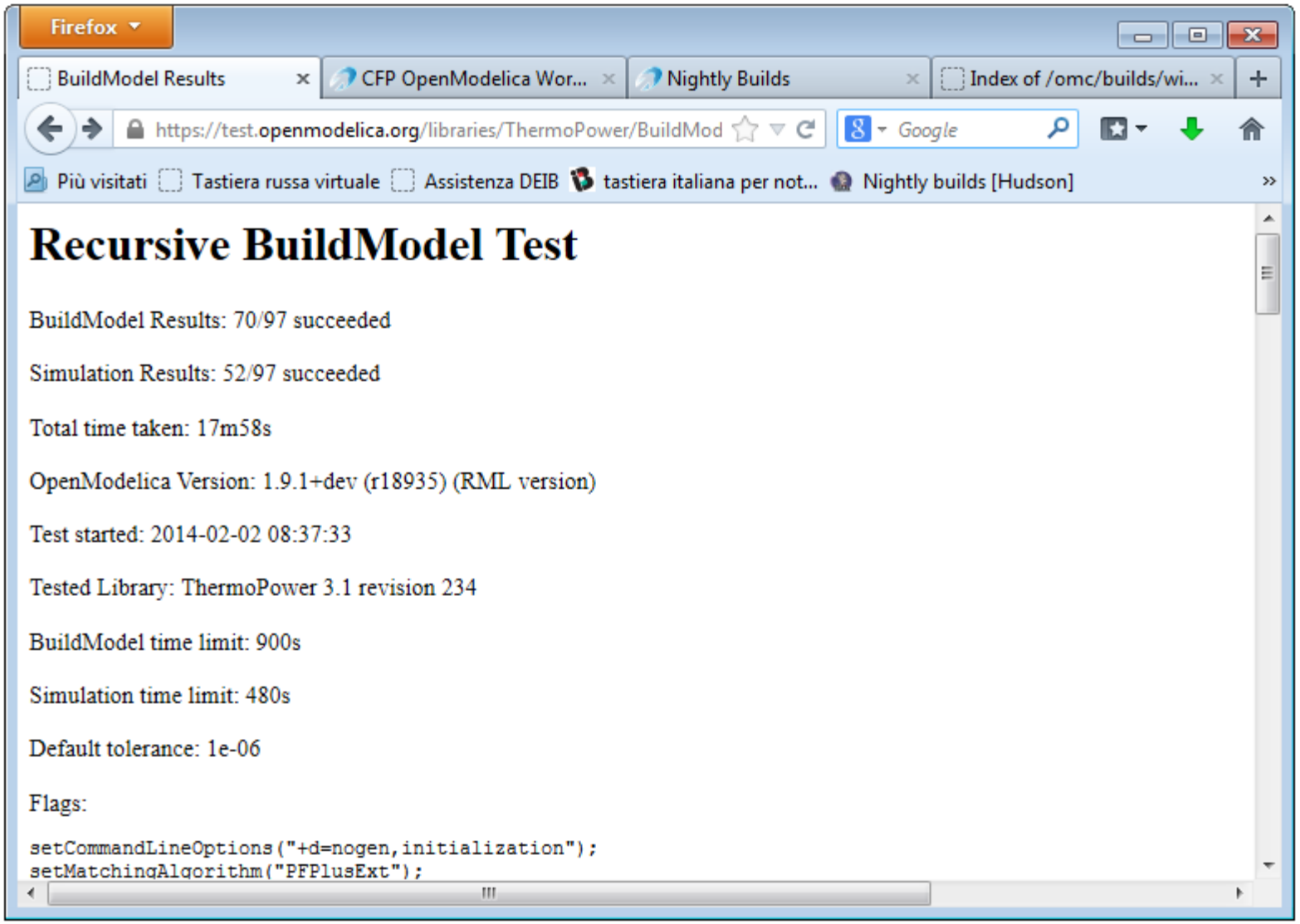


Non-trivial models are simulated correctly

- Model with about 40 states and 500 non-trivial algebraic variables compiled and simulated correctly
- Large initialization problem with 132 coupled nonlinear equations solved successfully



The majority of test cases from the test suite now work



Summary of good news

- The ThermoPower library can be handled by OMEdit
  - with some glitches that will be discussed next
- Many models can be simulated, obtaining correct results
  - simple test cases
  - non-trivial examples
- Steady-state initialization works well even for non-trivial examples
  - new initialization solver with symbolic processing in place
  - homotopy transformations supported
  - *automatic elimination of redundant & consistent initial equations soon available*
- *Interactive debugger for equation-based models almost ready for use*
  - *still missing support for thorough debugging of solver failures for nonlinear equations solved by tearing*
  - *still missing support for initialization solver failures during homotopy transformations*

The Not-So-Good News

CPU time to compute Modelica.Media medium properties

- Results obtained by algebraic models, 10000 steps with Euler's algorithm
- Only pure simulation time reported
- Checked proportionality with number of steps (no one-time overhead)

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test1	0.85	0.15
WaterIF97Efficiency.Test2	2.05	0.15
WaterIF97Efficiency.Test3	0.82	0.15
WaterIF97Efficiency.Test4	5.46	1.47
WaterIF97Efficiency.Test5	0.42	0.15
WaterIF97Efficiency.Test6	4.25	1.41
IdealGasEfficiency.Test1	0.08	0.12
IdealGasEfficiency.Test2	0.06	0.13

WaterIF97Efficiency.Test1

```
model Test1 "Compute density of water via state record"
  package Water = Modelica.Media.Water.StandardWater;
  Water.ThermodynamicState state;
  Water.AbsolutePressure p;
  Water.Density rho;
  Water.SpecificEnthalpy h;
equation
  p = 1e5;
  h = 1e5 + time*1e5;
  state = Water.setState_ph(p,h);
  rho = Water.density(state);
  a
end Test1;
```

- IF97 properties computed via setState_ph() function
- most of the CPU time spent solving the equations of state when calling setState_ph()
- only density retrieved
- OMC almost 6X slower than Dymola

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test1	**0.85**	**0.15**

WaterIF97Efficiency.Test2

```
model Test2 "Compute multiple properties of water via state record"
  extends Test1;
  Water.Temperature T;
  Water.SpecificEntropy s;
  Water.DerDensityByPressure ddph;
  Water.DerDensityByEnthalpy ddhp;
equation
  T = Water.temperature(state);
  s = Water.specificEntropy(state);
  ddph = Water.density_derp_h(state);
  ddhp = Water.density_derh_p(state);
  a
end Test2;
```

- IF97 properties computed via setState_ph() function
- four more properties retrieved
- most of the CPU time should spent solving the equations of state when calling setState_ph()
- OMC almost 3X slower than previous case → unwanted repeated comp.
- probably something goes wrong with Inline/LateInline

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test1	0.85	0.15
WaterIF97Efficiency.Test2	**2.05**	**0.15**

WaterIF97Efficiency.Test3

```
model Test3 "Compute density of water via direct function call"
  package Water = Modelica.Media.Water.StandardWater;
  Water.AbsolutePressure p;
  Water.Density rho;
  Water.SpecificEnthalpy h;
equation
  p = 1e5;
  h = 1e5 + time*1e5;
  rho = Water.density(Water.setState_ph(p,h));
  a
end Test3;
```

- similar to Test1, no significant differences reported

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test1	0.85	0.15
WaterIF97Efficiency.Test3	**0.82**	**0.15**

WaterIF97Efficiency.Test4

```
model Test4
  "Compute multiple properties of water via direct function call"
  extends Test3;
  Water.Temperature T;
  Water.SpecificEntropy s;
  Water.DerDensityByPressure ddph;
  Water.DerDensityByEnthalpy ddhp;
equation
  T = Water.temperature(Water.setState_ph(p,h));
  s = Water.specificEntropy(Water.setState_ph(p,h));
  ddph = Water.density_derp_h(Water.setState_ph(p,h));
  ddhp = Water.density_derh_p(Water.setState_ph(p,h));
  a
end Test4;
```

- if Common Subexpression Elimination was applied correctly, same CPU time as Test 1
- Apparently CSE is applied by neither tool

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test3	0.82	0.15
WaterIF97Efficiency.Test4	**5.46**	**1.47**

WaterIF97Efficiency.Test5

```
model Test5 "Compute density of water via direct function call"
  package Water = Modelica.Media.Water.StandardWater;
  Water.AbsolutePressure p;
  Water.Density rho;
  Water.SpecificEnthalpy h;
equation
  p = 1e5;
  h = 1e5 + time*1e5;
  rho = Water.density_ph(p,h);
  a
end Test5;
```

- Test 5 should be perfectly equivalent to Test1
- For some reason, it works 2X fast as Test1 in OMC
- Still 3X slower than Dymola

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test1	0.85	0.15
WaterIF97Efficiency.Test5	**0.42**	**0.15**

WaterIF97Efficiency.Test6

```
model Test6
  "Compute multiple properties of water via direct function call"
  extends Test3;
  Water.Temperature T;
  Water.SpecificEntropy s;
  Water.DerDensityByPressure ddph;
  Water.DerDensityByEnthalpy ddhp;
equation
  T = Water.temperature_ph(p,h);
  s = Water.specificEntropy(Water.setState_ph(p,h));
  ddph = Water.density_derp_h(Water.setState_ph(p,h));
  ddhp = Water.density_derh_p(Water.setState_ph(p,h));
  
end Test6;
```

- Slight variation of Test4
- Surprisingly somewhat faster in OMC
- Same considerations apply as for Test4

Test Case	Sim. Time OMC	Sim. Time Dymola
WaterIF97Efficiency.Test1	0.85	0.15
WaterIF97Efficiency.Test4	5.46	1.47
WaterIF97Efficiency.Test6	**4.25**	**1.41**

IdealGasEfficiency.Test1 & Test2

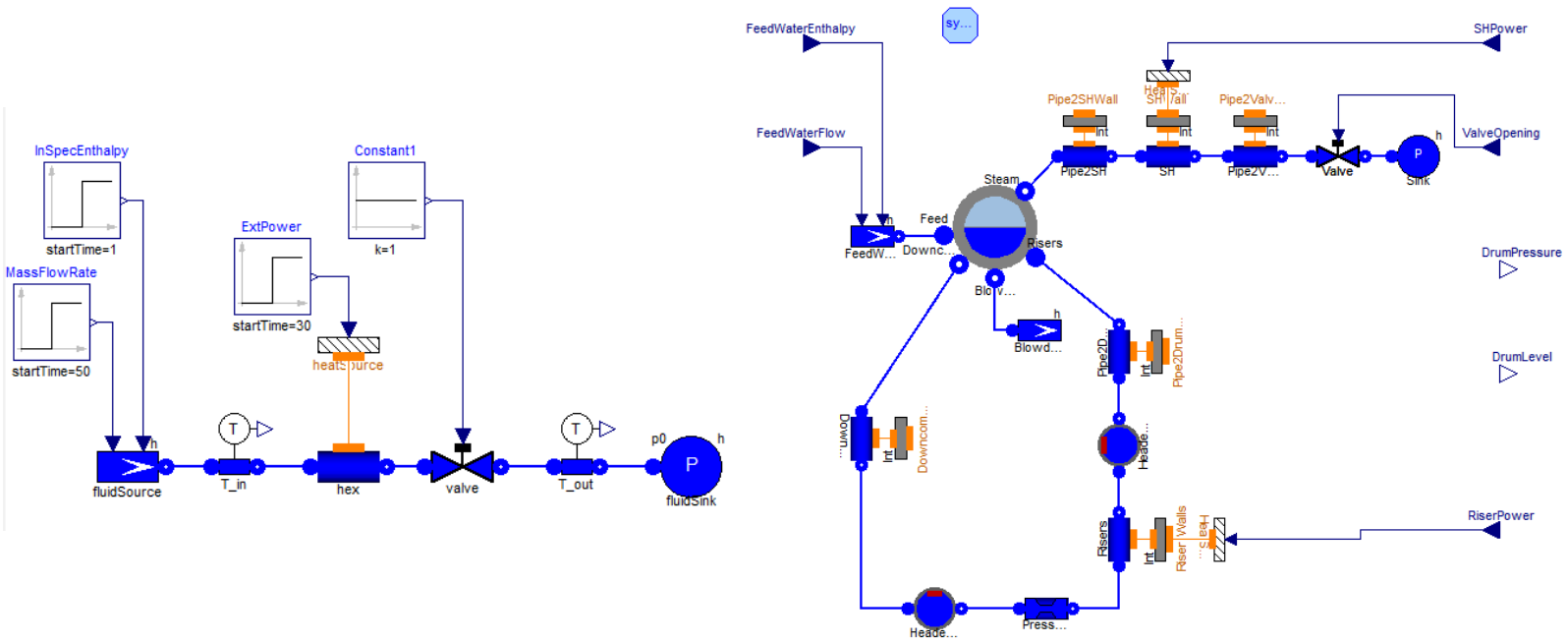
```
model Test1 "Compute properties of gas via state record"
  package Gas = Modelica.Media.IdealGases.MixtureGases.CombustionAir;
  Gas.ThermodynamicState state;
  Gas.AbsolutePressure p;
  Gas.Density rho;
  Gas.Temperature T;
  Gas.SpecificEnthalpy h;
  Gas.MassFraction X[Gas.nX] = Gas.reference_X;
equation
  p = 1e5;
  T = 300 + time*100;
  state = Gas.setState_pTX(p,T,X);
  rho = Gas.density(state);
  h = Gas.specificEnthalpy(state);
end Test1;
```

```
model Test2 "Compute density of gas via BaseProperties"
  package Gas = Modelica.Media.IdealGases.MixtureGases.CombustionAir;
  Gas.BaseProperties prop;
equation
  prop.p = 1e5;
  prop.T = 300 + time*100;
  prop.X = Gas.reference_X;
end Test2;
```

- Ideal gas property computation
- setState_pTX() and equation-based BaseProperties tested
- OMC is 33% faster than Dymola
  (different accounting of overheads could be the cause)
- In steam power plant models, the bottleneck are the
  IF97 water/steam computations, not the ideal gas computations

Test Case	Sim. Time OMC	Sim. Time Dymola
IdealGasEfficiency.Test1	0.08	0.12
IdealGasEfficiency.Test2	0.06	0.13

CPU Time to Simulate Models



Test Case	Sim. Time OMC	Sim. Time Dymola
TestFlow1DFV_A	7.4	0.42
CISESim120501	74.9	2.4

TestFlow1DFV_A – DASSL – tol = 1e–6

Dymola

```
CPU-time for integration      : 0.424 seconds
CPU-time for one GRID interval: 0.848 milli-seconds
Number of result points       : 507
Number of GRID   points       : 501
Number of (successful) steps  : 332
Number of F-evaluations       : 1962
Number of H-evaluations       : 835
Number of Jacobian-evaluations: 66
Number of (model) time events : 3
Number of (U) time events     : 0
Number of state    events     : 0
Number of step     events     : 0
Minimum integration stepsize  : 1.21e-007
Maximum integration stepsize  : 2.88
Maximum integration order     : 5
```

OMC

```
LOG_STATS          | info    | timer
|                  | |       | |   0.00163591s [  0.0%] pre-initialization
|                  | |       | |     0.112609s [  1.5%] initialization
|                  | |       | |   0.00412725s [  0.1%] steps
|                  | |       | |    0.0271429s [  0.4%] creating output-file
|                  | |       | |   0.00924873s [  0.1%] event-handling
|                  | |       | |   0.00700192s [  0.1%] overhead
|                  | |       | |      7.43596s [ 97.9%] simulation
|                  | |       | |      7.59773s [100.0%] total
LOG_STATS          | info    | events
|                  | |       | |     3 state events
|                  | |       | |     0 time events
LOG_STATS          | info    | solver: DASSL
|                  | |       | |   344 steps taken
|                  | |       | |   460 calls of functionODE
|                  | |       | |    78 evaluations of jacobian
|                  | |       | |     3 error test failures
|                  | |       | |     0 convergence test failures
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|                  | |       | |     5 error test failures
|                  | |       | |     0 convergence test failures
```

CISESim120501 – DASSL – tol = 1e–6

```
CPU-time for integration      : 2.4 seconds
CPU-time for one GRID interval: 2.4 milli-seconds
Number of result points       : 1013
Number of GRID   points       : 1001
Number of (successful) steps  : 243
Number of F-evaluations       : 2294
Number of H-evaluations       : 1249
Number of Jacobian-evaluations: 94
Number of (model) time events : 6
Number of (U) time events     : 0
Number of state    events     : 0
Number of step     events     : 0
Minimum integration stepsize  : 0.0002
Maximum integration stepsize  : 52.4
Maximum integration order     : 5
```

Dymola

OMC

```
LOG_STATS          | info       | ### STATISTICS ###
LOG_STATS          | info       | timer
|            | |     | |   0.00213257s [  0.0%] pre-initialization
|            | |     | |      1.40867s [  1.8%] initialization
|            | |     | |    0.0254833s [  0.0%] steps
|            | |     | |     0.111198s [  0.1%] creating output-file
|            | |     | |    0.0591024s [  0.1%] event-handling
|            | |     | |    0.0296431s [  0.0%] overhead
|            | |     | |      74.946s [ 97.9%] simulation
|            | |     | |     76.5623s [100.0%] total
LOG_STATS          | info       | events
|            | |     | |     6 state events
|            | |     | |     0 time events
LOG_STATS          | info       | solver: DASSL
|            | |     | |   255 steps taken
|            | |     | |   316 calls of functionODE
|            | |     | |    88 evaluations of jacobian
|            | |     | |     1 error test failures
|            | |     | |     0 convergence test failures
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LOG_STATS          | info       | events
|                  | |          | |     6 state events
|                  | |          | |     0 time events
LOG_STATS          | info       | solver: DASSL
|                  | |          | |   255 steps taken
|                  | |          | |   316 calls of functionODE
|                  | |          | |    88 evaluations of jacobian
|                  | |          | |     1 error test failures
|                  | |          | |     0 convergence test failures
```

CISESim120501 – DASSL – tol = 1e–6

```
CPU-time for integration      : 2.4 seconds
CPU-time for one GRID interval: 2.4 milli-seconds
Number of result points       : 1013
Number of GRID   points       : 1001
Number of (successful) steps  : 243
Number of F-evaluations       : 2294
Number of H-evaluations       : 1249
Number of Jacobian-evaluations: 94
Number of (model) time events : 6
Number of (U) time events     : 0
Number of state    events     : 0
Number of step     events     : 0
Minimum integration stepsize  : 0.0002
Maximum integration stepsize  : 52.4
Maximum integration order     : 5
```

Dymola

OMC

```
LOG_STATS          | info       | ### STATISTICS ###
LOG_STATS          | info       | timer
|                  | |          | |   0.00213257s [  0.0%] pre-initialization
|                  | |          | |      1.40867s [  1.8%] initialization
|                  | |          | |    0.0254833s [  0.0%] steps
|                  | |          | |     0.111198s [  0.1%] creating output-file
|                  | |          | |    0.0591024s [  0.1%] event-handling
|                  | |          | |    0.0296431s [  0.0%] overhead
|                  | |          | |       74.946s [ 97.9%] simulation
|                  | |          | |      76.5823s [100.0%] total
LOG_STATS          | info       | events
|                  | |          | |     6 state events
|                  | |          | |     0 time events
LOG_STATS          | info       | solver: DASSL
|                  | |          | |   255 steps taken
|                  | |          | |   316 calls of functionODE
|                  | |          | |    88 evaluations of jacobian
|                  | |          | |     1 error test failures
|                  | |          | |     0 convergence test failures
```

Issues with code generation

- Some models still generate errors in the back-end stages:
  - Error: Internal error Transformation Module PFPlusExt index Reduction Method Pantelides failed!
  - Errors in the compilation of the C-code, due to incorrect C-code being generated
- Sometimes problem with models that work in Dymola and fail in OMC are due to subtle issues, e.g.:
  - semantics of parameter Real p(fixed = false) = 0
    - earlier versions of Dymola ignored the binding, but OMC did not
    - in this case Dymola was not complying to the specification
    - library and Dymola have been fixed a few months ago
  - semantics of parameter Real p(start = 2);
    - in this case, Modelica 3.3 suggests to add a binding equation p=2 and issue a warning
    - OMC didn't do that → underdetermined initialization system
    - error discovered and fixed on Feb 1st, 2014
  - other, still undiscovered problems...

Issues with OMEdit

Main issues with the OMEdit GUI

- OMEdit applies extensive reformatting to the code
  - whitespace and carriage returns
  - numerical literals (e.g. 1e6 → 1000000)

Not possible to co-develop with OMC & Dymola

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- Replaceable models are not handled by OMC
  - they are used for replaceable heat transfer models
  - they are used in many other places in the MSL

Not possible to build heat exchanger models using OMEdit's GUI

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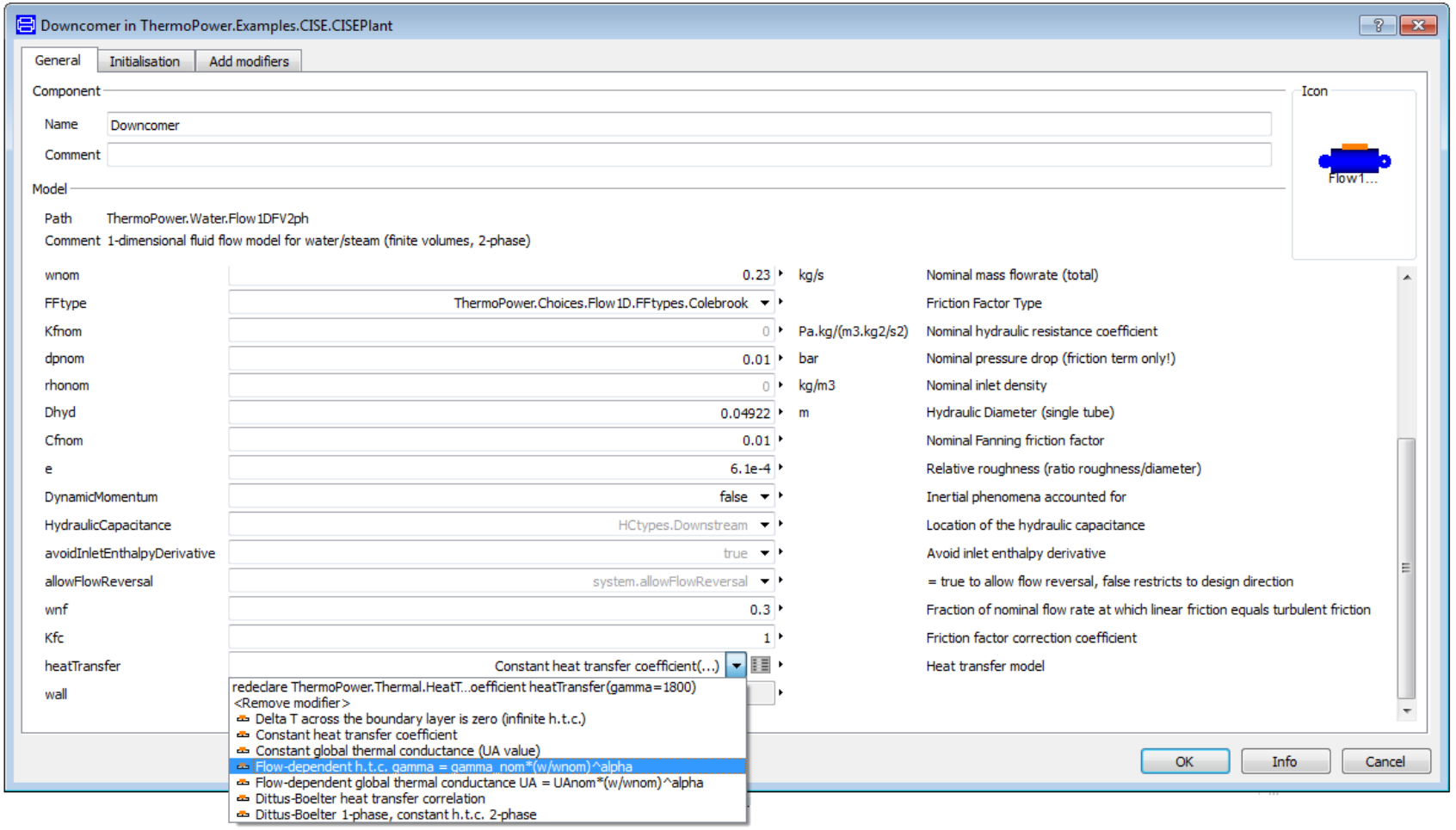
Not possible to build heat exchanger models using OMEdit's GUI

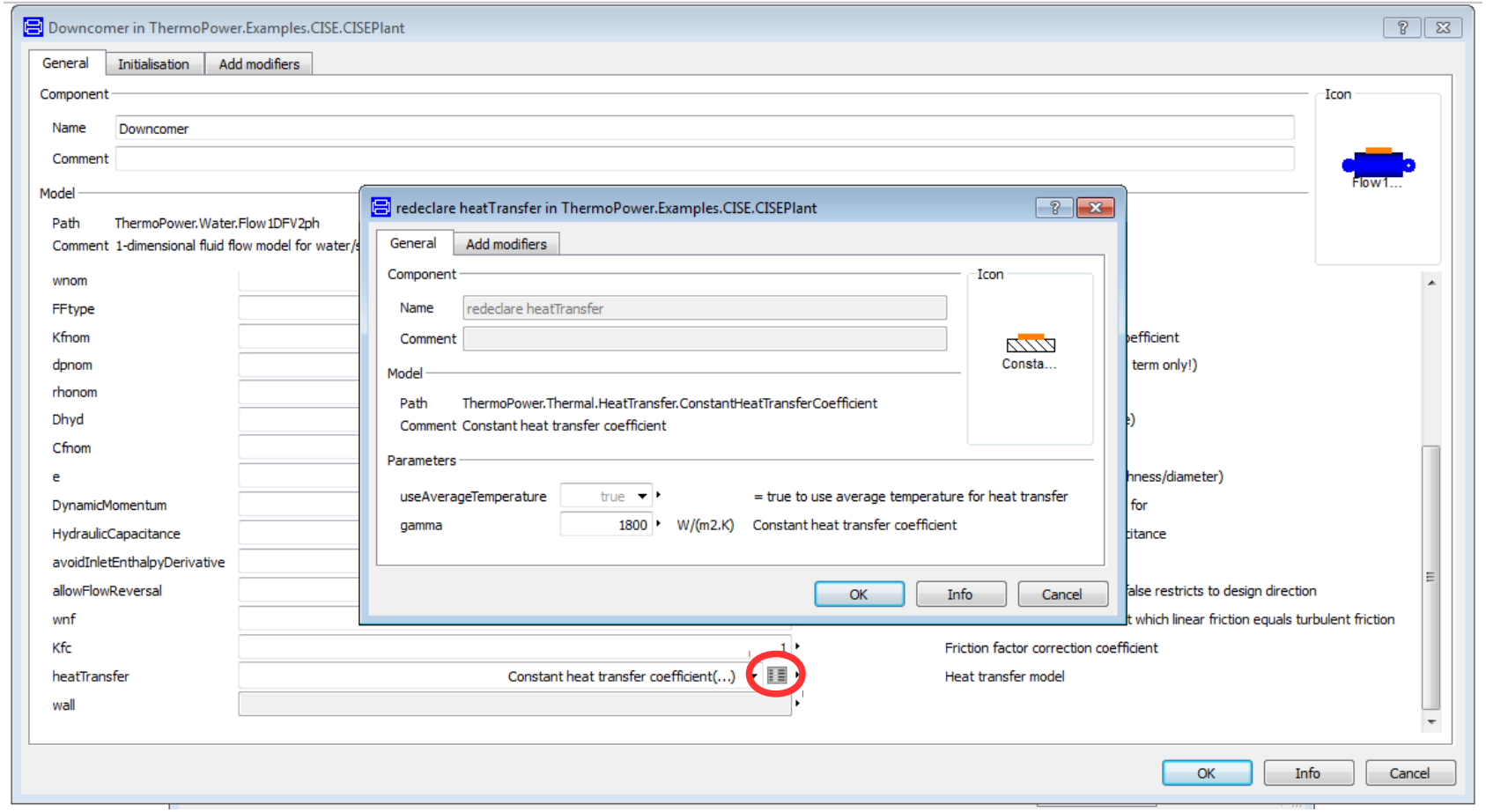
- It is not possible to apply or edit modifiers in hierarchically structured models using OMEdit's GUI
  - modifiers can only be applied in the textual mode
  - this requires to know the names of modified sub-components and parameters, which is inconvenient

Not possible to handle complex, structured models

Replaceable models

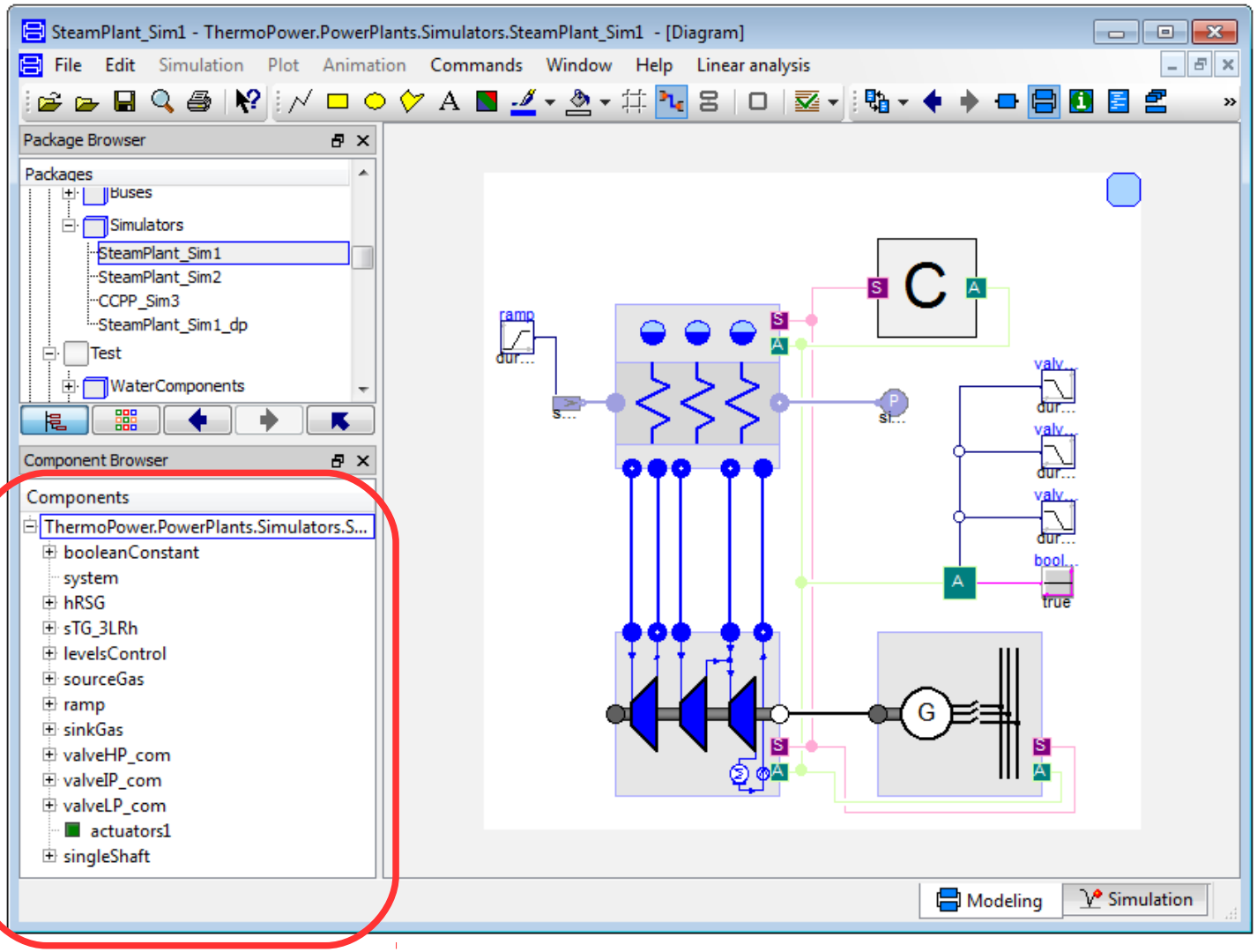


Replaceable models



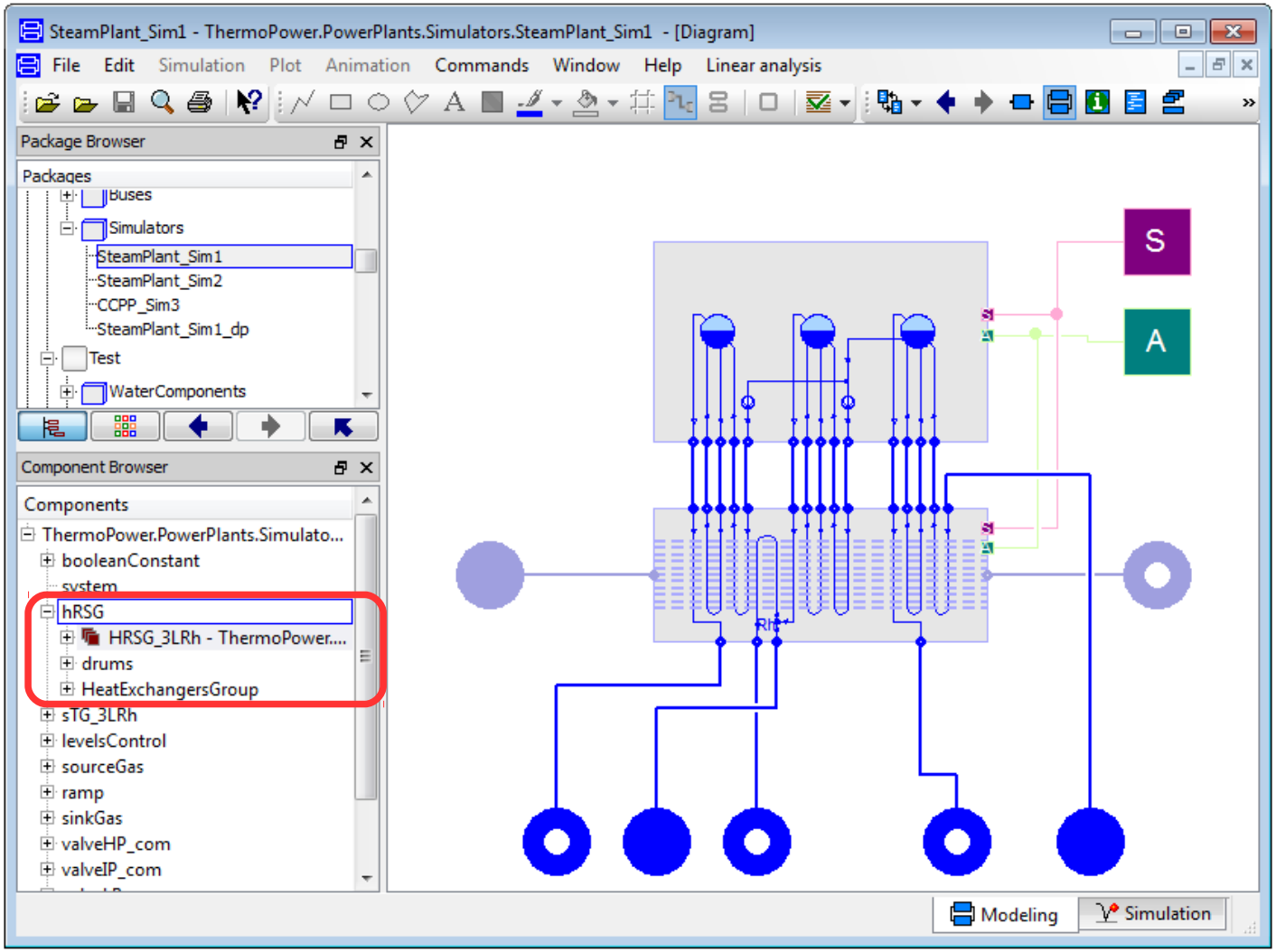
Editing parameters in hierarchically structured models

- ThermoPower.PowerPlants.Simulators.SteamPlant_Sim1



Editing parameters in hierarchically structured models

- ThermoPower.PowerPlants.Simulators.SteamPlant_Sim1



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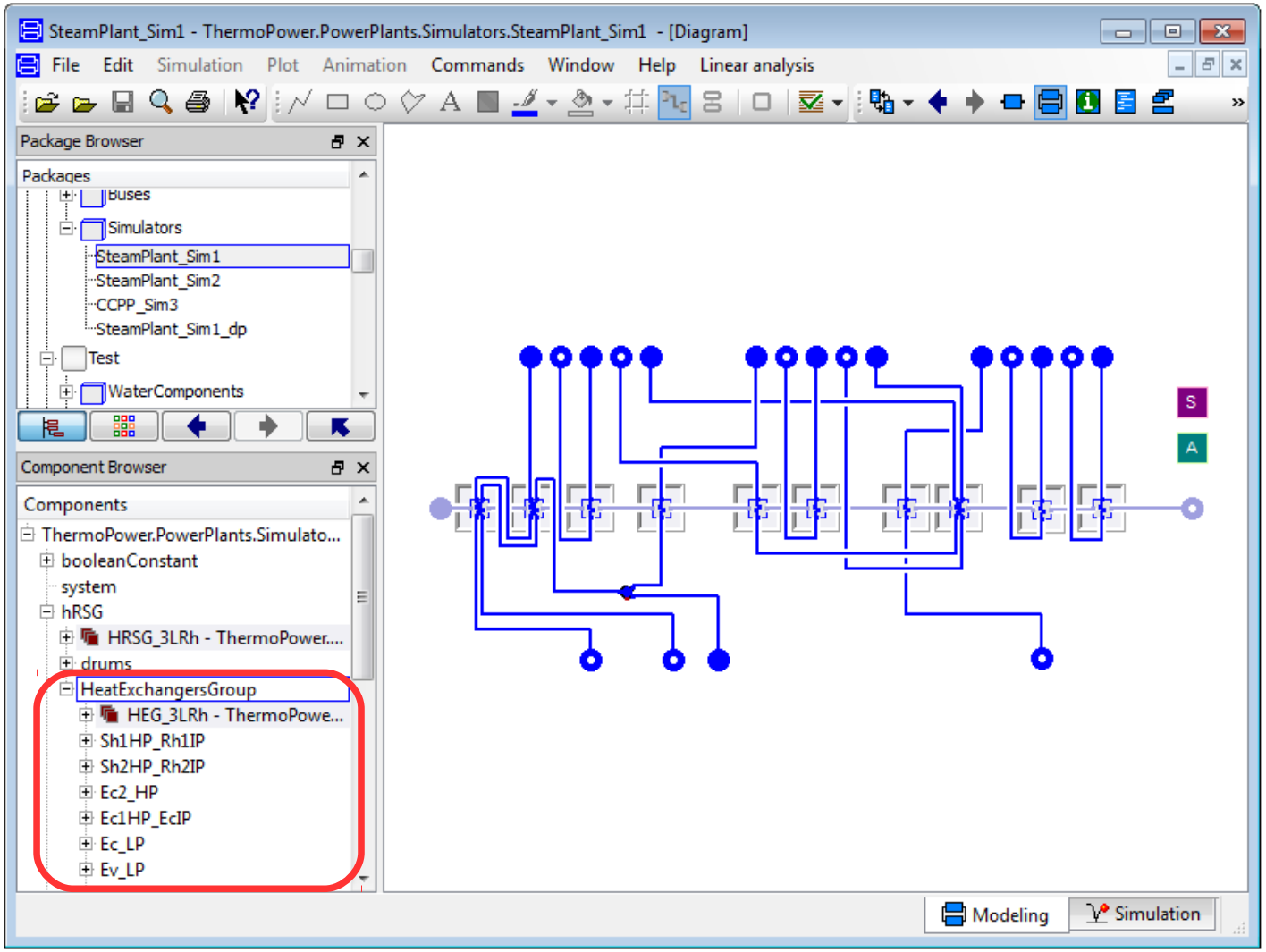

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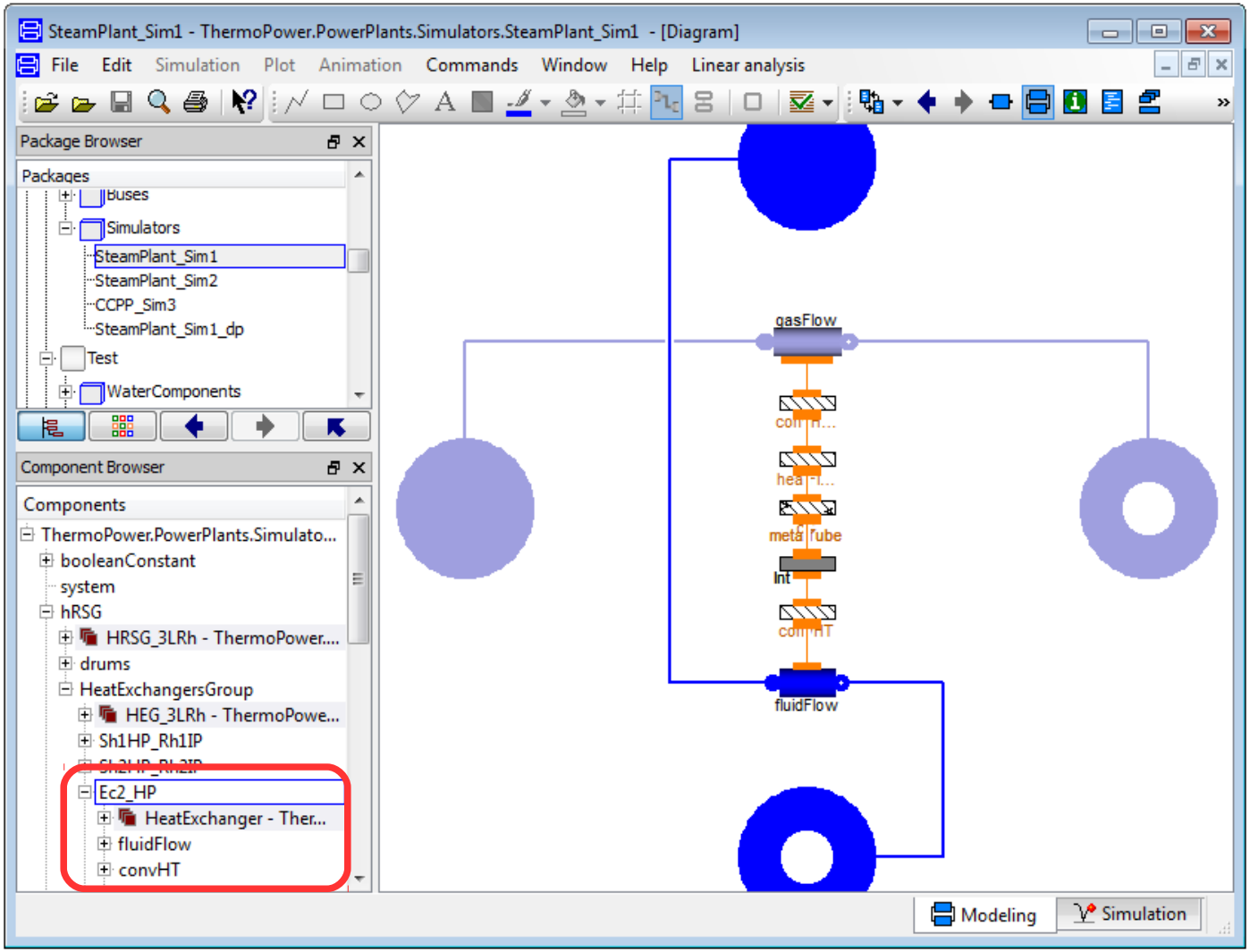

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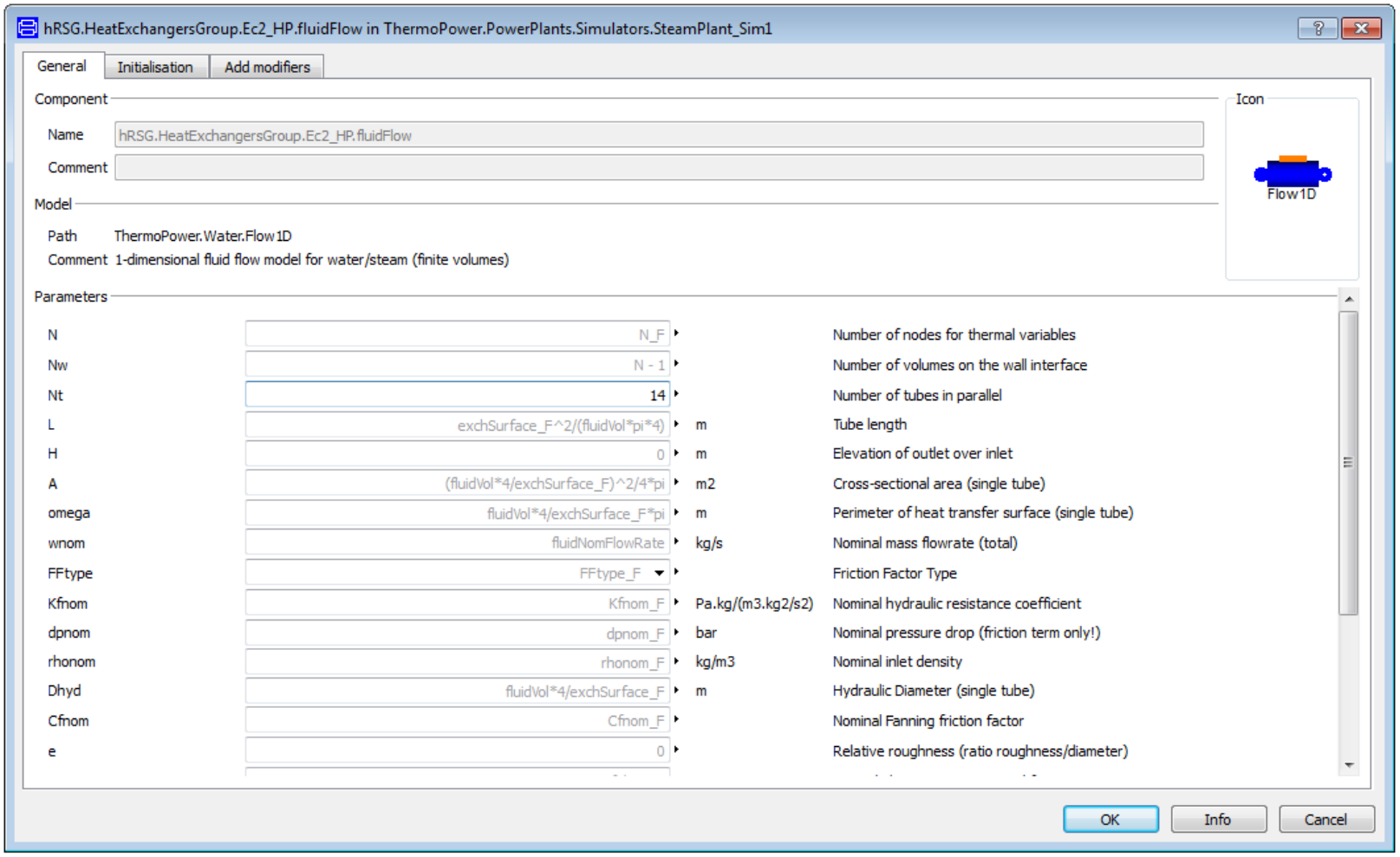

Editing parameters in hierarchically structured models

- This corresponds to applying the following modifier in the textual view

```
HRSG.Examples.HRSG_3LRh hRSG(
  HeatExchangersGroup(Ec2_HP(fluidFlow(Nt=14))))
```

- Possibly mixed up with other pre-existing modifiers
- This feature doesn't need to be implemented in the same way as Dymola,
- But it is **essential** that OMEdit has way to edit the parameters of hierarchically structured models by using the GUI

Exploiting parallelism

- The CISESim120501 model is compiled to executable simulation code
  - by Dymola/Visual Studio in 7 seconds
  - by OMEdit/OMC/gcc in 30 seconds
- It is probably possible to reduce the compilation time gap (currently 4X) by exploiting parallel compilation of the various C source files (is it already done by default?)
- OMEdit should automatically retrieve from the OS the number of parallel threads it can run, and use all of them by default
- Earlier work by Sjolund and Casella regarding the parallelization of the solution of the DAEs into ODEs should also become part of the mainstream implementation of OMEdit
- Also the parallel computation of Jacobians should be investigated, and become part of the mainstream implementation of OMEdit

Conclusions

- After 10 years from the start of the development of ThermoPower, the (open source!) library can now be used in the (open source) OpenModelica environment
- Many models can already be simulated, and produce the correct results
- Steady-state initialization is working nicely on fairly complex models
- Compilation time is still about 4X slower than Dymola
- Simulation time for models involving water/steam properties is still about 10X slower than Dymola
- The OMEdit GUI should be improved regarding replaceable models and parameter editing in hierarchically structured models
- Parallel thread execution should be used more aggressively
- The declarative debugger (once polished up) will be a boon

- We might expect OMC to be a viable alternative to Dymola for the simulation of ThermoPower-based models by the end of 2014!

Thank you for you kind attention!