

## COMPARISON OPEN MODELICA - DYMOLA FOR POWER PLANT SIMULATION

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### ABSTRACT

In this paper a comparison is made between OpenModelica and Dymola for a simulation model of a power boiler. The similarities and differences are presented. Dymola has the advantage of having a more elaborate user interface and solver, but the OpenModelica user interface and solver has improved very much during last few years. The advantage of OpenModelica is that anyone can use the models without having to pay high license fees, something that is of significant interest when installations are made in industries. In many ways a combination of the two is advisable, where Dymola can be used for application developments and later OpenModelica can be used in the actual installations. It has been seen in this application for a CFB boiler that it is easy to use the same model in both environments without any modifications. Still, the solver for Open Modelica is not as powerful as for Dymola, which may be a problem for on-line applications for larger models, while no problem for small models.

### 1. INTRODUCTION AND LITERATURE REVIEW

Energy conversion system models are usually complex models which require a high structured programming language. Generally dynamic models are preferred in order to reach a deeper understanding of the process. Many studies have pointed out Modelica as a straightforward object oriented language developed for modeling of large physical systems (Fritzson, 2004), (Modelica Association, 2007). Dymola is an engineering simulation tool using Modelica language (Mattsson et al, 1998). OpenModelica is an alternative tool based on open source code. Both Dymola and OpenModelica include several Modelica libraries (MSL – the Modelica Standard Library) from Modelica Association in their distributions (Otter and Elmquist, 2001). There are also Modelica libraries for e.g. power plants (Casella and Leva, 2005) and other energy conversion systems (Salogni and Colonna, 2010). In Casella et al. (2007) a dynamic model of a biomass-fired-power-plant is presented. Jansson et al (2008), Järvensivu (2001), Hauge et al (2005), Mercangöz and Doyle (2006) and Dhak et al (2004) have shown how model based control can be implemented and Karlsson et al (2009) how models can be adapted to compensate for fouling. Sandberg et al. have modeled the actual fouling. Mälardalen University has developed their own Modelica models for pulp and paper industry and power plant applications, as well as for gasification. There is also commercial equation-based modeling and simulation software similar to Modelica used for process industry. This is named gPROMS and was developed by Imperial College in London under leadership of professor Costas Pantelides. Model structure is similar, but at least some years ago there were only two solvers available for gPROMS. These have a varying time step depending on how fast the dynamics of the process is. OpenModelica and Dymola have solvers for both varying time step and fixed time step. Dymola have additional functions compared to Open Modelica, but Open Modelica is adding new functions continually as well.

### 2. METHODOLOGY:

A semi-dynamic on-line application of the proposed simulation approach has been used in the simulation of a CFB boiler at Mälarenergi in Västerås as well as at Korsnäs pulp mill in Gävle in tests during 2010 - 2011. Here the connection between the DCS and the simulation model was established with Simulink. Modelica models were used after compilation allowing better control of the signal processing between simulation and the process database. The project at Mälarenergi was financed by Värmeforsk (and power companies) and the project at Korsnäs by KKS (and Korsnäs and ABB).

The CFB boiler model developed by Mälardalen University (MDH) includes the combustion section, the water/steam system and the exhaust gas train. The model is validated towards real plant data and is capable to successfully predict operation performance. A more detailed description of this model can be found in Sandberg et al. (2011).

During 2010 and 2011 the model was used on-line at Mälarenergi AB for diagnostic purposes. The plant is a combined heat and power plant (CHP). Boiler 5 has been modeled. This is a 180 MW<sub>th</sub> biomass fired CFB boiler.

The components of the Modelica/Dymola model can be seen in Figure 1. The components are as follows: 1. Air flow to boiler, 2. Fuel flow and composition, 3. Boiler/reactor, 4. Ash flow, 5. Air flow to Intrex, 6. Intrex – fluid bed/G-valve where solids come down from cyclone and is heat exchanged towards steam, 7. Cyclone separator where larger particles are separated but also gas cooled, 8. The heat exchanger in the walls of the cyclone where gas is cooled towards steam, 9- 11. Steam heating, gas cooling heat exchangers, 12. Economizers where feed water is heated (and evaporated), 13. Air pre-heating, 14. Exhaust gas flow and composition, 15. Air flow to pre-heater, 16. Feed water flow, 17-18. Steam flow and temperature/pressure to turbine, 19. Electric power produced, 20-22. Feed water injection to heat exchangers. There are three mass inventories in the model: (i) gas in the boiler including the bed material, fuel etc.; (ii) bed material and gas in the so called Intrex, a bubbling bed below the cyclones where separated sand is fluidized and cooled in two super heaters before the sand is re-entering the CFB boiler; (iii) the steam system with water and steam.

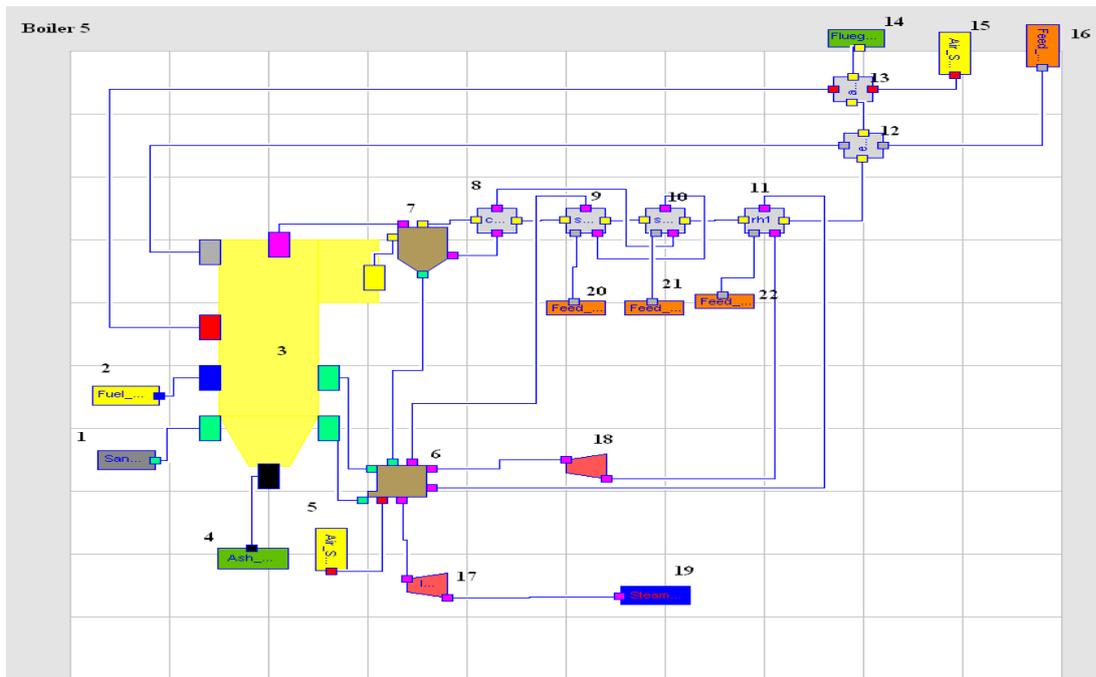


Figure 1. View of the CFB boiler in Dymola interface. Showing boiler 5 at Mälarenergi CHP plant.

Temperature, gas composition and flow rates are measured all the way through the boiler and exhaust gas train and in the steam system. These measurements are then compared to the values predicted from the simulation using the same input data. This includes fuel flow, fuel composition, air flow and feed water flow to the steam drum. Unfortunately the fuel composition has not been able to measure; if moisture content varies the impact will be significant. Measurement of moisture and higher heating value (HHV) of the fuel we want to include in the future research. Use of NIR (near infrared) measurement on-line is a tool we develop together with Bestwood. On-line measurement of moisture is already installed at Eskilstuna CHP, but the development of models for HHV is still ongoing at our lab in Västerås.

The equations used are primarily stoichiometric calculations of how the biomass is converted through combustion, giving adiabatic temperature and cooling through heat transfer and through transport of material from the boiler combustion zone. The mass in the bed inventory as a function of time is given from:

$$\frac{\partial m_{\text{inventory}}}{\partial t} = \sum m_{i,\text{in}} - \sum m_{i,\text{out}} \quad (1)$$

where  $m_{i,\text{in}}$  is the mass input flow of each single component of the composition vector  $i = (\text{C}, \text{H}, \text{O}, \text{N}, \text{CO}_2, \text{H}_2\text{O}, \text{NO}_2, \text{ash})$  and  $m_{i,\text{out}}$  is the corresponding output flow. The change in concentration of each component is given by  $c_i$  in the bed inventory:

$$\partial c_i / \partial t = \left( \sum (c_i \cdot m_j)_{in} - \sum (c_i \cdot m_k)_{out} \right) / m_{inv.} \quad (2)$$

where j runs through all incoming flows and k all outgoing flows of the inventories. Except the bed inventory we also have one inventory for the Intrex and one for the steam system. The steam system has only water and steam components, while the Intrex has the same components as the bed. The temperature  $T_{inventory}$  in the inventory is calculated from the energy balance:

$$\partial T_{inventory} / \partial t = \left( \frac{\left( \left( \sum T_j \cdot cp_i \cdot c_i \cdot m_{j_{in}} \right) - \left( \sum T_j \cdot k \cdot cp_i \cdot c_i \cdot m_{k_{out}} \right) \right) + \left( \Delta H - U \cdot A \cdot (T_{inventory} - T_{outside}) \right)}{m_{inventory} \cdot \left( \sum c_i \cdot cp_i \right)} \right) \quad (3)$$

Here  $\Delta H$  (enthalpy) is the energy released during combustion and  $U$  is the overall heat transfer coefficient,  $A$  is the heat exchanger area and  $T_{outside}$  the temperature at the other side of the heat exchanger surface (steam temperature vs. exhaust gas temperature),  $cp_i$  is the heat capacity for each component  $i$ . The correlations describing the change in each single component is also included in the model. Carbon, C, in the biomass is combusted to  $CO_2$ , and the hydrogen is forming  $H_2O$ . Oxygen, O, in the fuel is used for the combustion aside of the oxygen in the air. N, in the fuel is assumed oxidized to  $NO_2$  partly, as a function of oxygen surplus and temperature. Separation of sand is performed in cyclones and cooling in heat exchangers with gas to gas, gas to steam or gas to water transfer. We have not included inventories in the heat exchangers as the residence time is very short.

The combustion/gasification processes are modeled as an extension of eq (2):

$$\partial c_i / \partial t = \left( \left( \sum (c_i \cdot m_j)_{in} - k \cdot [c_i]^a \right) - \sum (c_i \cdot m_k)_{out} \right) / m_{inv.} \quad (4)$$

where  $k$  is a reaction constant and  $a$  an exponent giving the non-linearity of the conversion. For components being removed  $c_i$  is decreasing while for those being created  $c_i$  is increasing

So far we have primarily been running the models as semi-steady state, but we want to include the full dynamics as this has a significant importance for both the diagnostics and the model based control, especially to meet varying moisture and HHV of the fuel.

### 3. MODEL VALIDATION AND RESULTS

The boiler simulation model has been verified towards process data. In Table 1 a comparison between measured and predicted data from the simulation for full load and partial load is presented. We have just included these situations for average load conditions to give a picture of how the model has been tuned towards process data. It should be noticed that the measurements in the boiler are not "the truth". In reality the temperature at different positions in the boiler varies a lot. We thus have tuned the model towards reasonable averages measured in the on-line positions at different positions in the boiler. The absolute value though may vary many hundred degrees between the wall and the center of the boiler at the same elevation, according to measurements we have made but not published yet.

Table 1 Measured process data (DCS) compared to predictions made with the simulation data

<i>Part load (July 5, 2011) at 6.2 kg/s fuel, 30.1 kg/s air flow and 24 kg/s feed water flow</i>			
Variables	DCS	Prediction	Error%
Steam temperature after HPSH2 (°C)	434	439	1.0
Fluegas temperature after cyclone (°C)	550	566	2.9

Fluegas temperature before cyclone (°C)	551	576	4.6
Steam temperature after cyclone (°C)	366	353	-3.6
<i>Full load (September 2011) 16.5 kg/s fuel, 79.8 kg/s air, 48.8 kg/s feed water</i>			
Steam temperature after High Pressure Super Heater 2 (°C)	494	488	-1.2
Bed temperature (°C)	833	879	5.2
Fluegas temperature before cyclone (°C)	758	757	0
Steam temperature after cyclone (°C)	385	379	-1.5

As can be seen the absolute error varies between 0 and 5 %. With the proposed approach with a new methodology for adaptation of models to process data we will improve the accuracy significantly. This includes correlating the on-line measurements to manual measurements of the temperature profile at specified positions.

In figure 2 below we can see how the difference between different sensors in the boiler at the same elevation varies in time over five hours. As can be seen they change level simultaneously, but the absolute value varies with approximately 40 °C in this case.

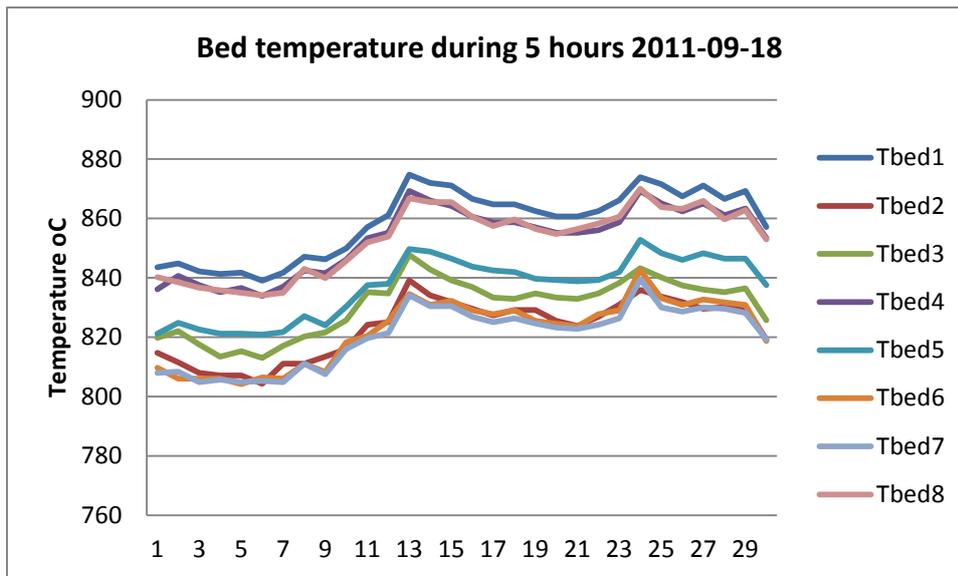


Figure 2. Bed temperature at the same elevation for eight meters.

For our purpose of using the model for diagnostics, decision support, maintenance on demand and model based control still it is the variations we want to measure and not primarily the absolute values of temperature etc. Then it is OK just to have reasonable data to fit the mass and energy balances.

#### 4. COMPARISON OF DYMOLA AND OPENMODELICA FROM A USER PERSPECTIVE

OpenModelica and Dymola, as well as gPROMS all are equation-based and object oriented and all have simultaneous solver approach. OpenModelica and Dymola as well as some other vendors support the Modelica model standard, whereas gPROMS has its own model format. You configure the complete simulation problem as a big equation system, which is solved simultaneously. In reality the equation system is split into smaller systems automatically, to get faster convergence, but it is a big difference compared to the earlier simulation systems with sequential solvers. With the simultaneous solver we can really correlate different sensor along the process to each other, which gives us the possibility to get better diagnostics.

A key task is then to formulate equations covering all modeling tasks, where the number of equations and variables must be the same for each sub-model. This can seem like a simple task- just do it. In reality still it is not self-evident what is a variable or a parameter and thus it may be complicated to know “where you are”. We have noticed that it is even stricter with this in OpenModelica than in Dymola. A major problem thus for the model developer is to both get the right number of variables and equations, as well as to know that it is actually the RIGHT equations we have formulated. Sometimes you can note that you really would need one extra equation, but it is definitely not clear which you can take away instead! A preliminary (not released) version of OpenModelica contains a debugging tool that is addressing many of these problems, explaining which equations give rise to selected computed variables, and providing on-line interactive stepping, breakpoints, browsing of variable values, etc. (Pop et al, 2012). See also OpenModelica on-line simulation (Asghar et al, 2011).

Because of the structure with simultaneous equation solver it is very difficult to do debugging. In principle you can work in a structured way so that you make a smaller system and then connect several smaller systems to one big one. This is in principle simple, but in practice not that easy. This is especially tricky when you want to use simulations on line, and start developing a steady state model with fixed values as input. When you then connect dynamic input signals it may be quite tricky to really get the simulator to work, as the number of variables and equations suddenly are incorrect. At MDH we have been using a link to process data bases making Modelica models as compiled objects into Simulink/Matlab. When you then debug the actual Modelica model and all is working, it may still be tough to get the compiled model to work when you make the linking to the on-line signals. It thus would be interesting in the future to have some kind of automatic function between on-line use and off-line use, where you just run with constants or simple general functions to generate input to the simulations.

Concerning the transfer between Dymola and OpenModelica we have noticed that the new version of OpenModelica actually can directly convert a Modelica Dymola model into one that can be simulated in OpenModelica and reverse. Still, where we see a warning in Dymola it may be a real fault in Open Modelica, as this has stricter definitions of what is accepted, more in accordance with the Modelica language standard. This is both good and bad, but is definitely a problem as you have even more difficulty to debug them in Dymola. A

recommendation thus would be to have less strict rules for this, so that you have a chance to compile and test-run your code, before you do changes in the code. In future versions of Open Modelica there will be a warning instead, to make it easier to debug.

Concerning accuracy we have not seen any difference between OM and Dymola, but sometimes the solutions have taken longer time with OM. As the solvers for OM are developed continuously we hope this will be less in the future, but it is of course a “moving target”.

An example of results from the on-line application of simulation towards measured process data is seen in the figure 3 below.

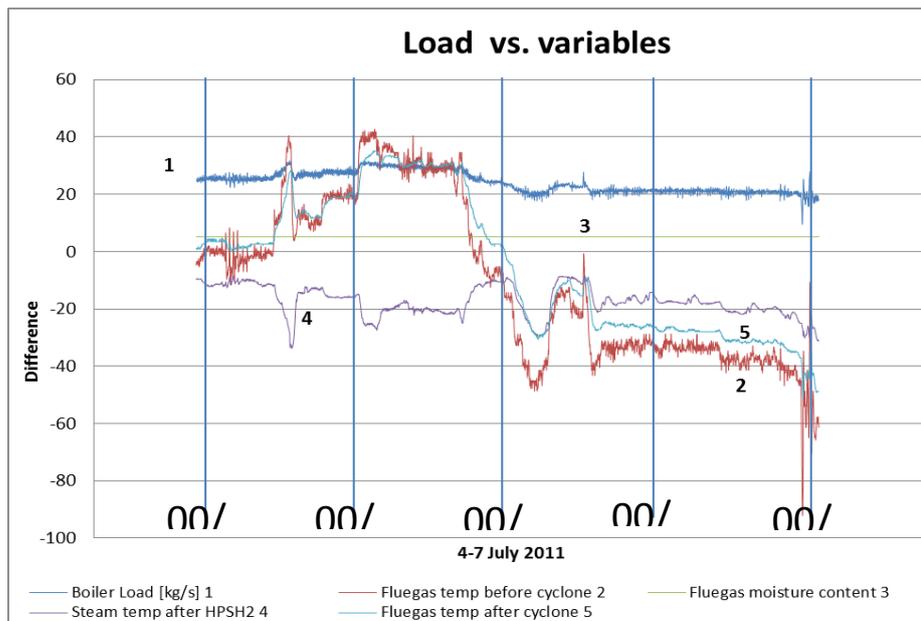


Figure 3. Difference between simulated and measured data for five variables in boiler 5 July 4-7 2011.

Here we can see that the load (curve 1) was going down after approximately July 5. We can see that the temperature predicted by the model first goes up in the flue gas compared to the measured temperature before the cyclone as well as after the cyclone, but as the load is lowered this swings to the opposite. The flue gas moisture signal (3) is constant all the time, and the variations are so small that it can be questioned if the sensor is giving correct values. The steam temperature in the corresponding heat exchanger High Pressure Super Heater 2 (HPSH2 , curve 4) is moving in the opposite direction during the first two days, but is following the same direction during the last two days. It is not obvious what the reason is, but may be related to fouling of the heat exchangers during the first two days with a reduced heat transfer rate as a result, while the heat transfer is better during the last two days. Still, this is not verified. The difference in fluegas temperature after cyclone (5) is first increasing, but later decreasing again. We believe it is due to temporarily combustion in the cyclone, which should not take place under normal conditions.

We also have sent the differences to a Bayesian Net, where different faults can be seen visually. An example of this is seen in the figure 4 below.

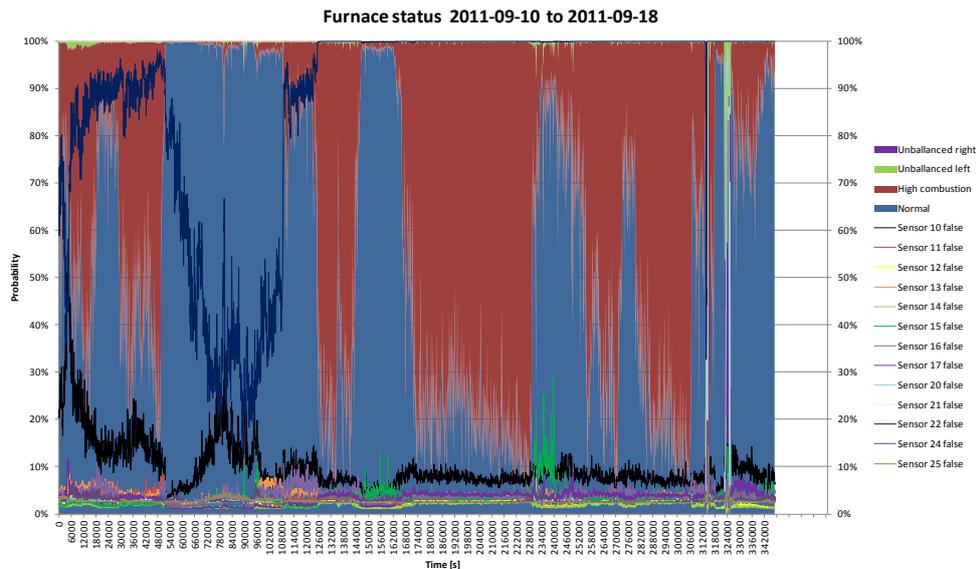


Figure 4. Bayesian Net of differences between simulated and measured data from Boiler 5 during the period September 10 to September 18, 2011,

Figure 4 indicates problems with high combustion, feeding problems of fuel on right (violet) and left (green) side, and also deviation between predicted and measured values for temperature meters in the bed above the feed at the left respectively right side of the bed. Variables to the right: Unbalance right, unbalanced left, high combustion, 6 temperature sensors in the bed, 7 temperature sensors above the bed.

## 5. DISCUSSION AND CONCLUSIONS

From the tests we have performed at Mälarenergy AB with on-line simulation combined with process data measurements we can conclude that a number of different type of faults have been possible to determine. The combination with BN, Bayesian Nets, is a feasible approach as experiences of different kind can be combined to generate a good decision support for process operators. Still, it will take time to make the system automatically adaptive with new experiences, although the goal will be to reach this. It is principally possible to develop a model in e.g. Dymola and then convert it into an Open Modelica model just by opening it in this environment, or the reverse. This is advantageous as it then is possible to make use of the advantages in the two platforms. This is very positive for the users of Modelica language. It is thus possible to use new functions developed in one of the platforms also for models developed in the other.

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## REFERENCES

- Asghar A., Tariq S., Torabzadeh-Tari M., Fritzson P., Pop A., Sjölund M., Vasaiely P., and Schamai W. An Open Source Modelica Graphic Editor Integrated with Electronic Notebooks and Interactive Simulation. In Proceedings of the 8th International Modelica Conference (Modelica'2011), Dresden, Germany, March.20-22, 2011.
- Avelin A, Jansson J, Dotzauer E., Dahlquist E.: (2009). Use of combined Physical and Statistical Models for On-line Applications in the Pulp and Paper Industry. *Mathematical and Computer Modeling of Dynamical Systems: Methods, Tools and Applications in Engineering and Related Sciences*, 1744-5051, 15-5, 425–434.

- Casella, F. and Leva, A. (2005). Object-Oriented Modelling & Simulation of Power Plants with Modelica. Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference. Seville, Spain, December 12-15, 2005.
- Casella, F., van Putten, H. and Colonna, P. (2007). Dynamic simulation of a biomass-fired steam power plant: a comparison between causal and a-causal modular modelling. Proceedings of the IMECE '07, International Mechanical Engineering Congress and Exhibition, No. IMECE2007-41091, ASME, Seattle, WA, 2007.
- Casella, F. and Colonna P. (2012). Dynamic modeling of IGCC. Applied Thermal Engineering, 35, 91-111.
- Chen S-C, Berggren J. and Zehnpfund A.: Multivariable CD control applications, ipw 10/2008, 6p.
- Chen S-C: Two dimensional web property variation modeling and control. US Patent 5,893,055. Apr 6, 1999.
- Ciarapica, F.E., Giacchetta, G. (2006). Managing the condition-based maintenance of a combined-cycle power plant: An approach using soft computing techniques. Journal of Loss Prevention in the Process Industries, 19, 316-325.
- Dahlquist E., Widarsson B. and Tomás-Aparicio E.: Demand-based maintenance and operators support based on process models. Project report P08-815. ISSN 1653-1248. Dec 2011.
- Dhak Janice, Dahlquist Erik, Holmström Kenneth, Ruiz Jean CTP, Grenoble, France, Belle Juergen, Goedsche Frank,.: Developing a generic method for paper mill optimization, Control Systems, Quebec city, Canada, June 14-17, 2004
- Donoso-Bravo A., Mailier J., Martin C., Rodriguez J., Aceves-Lara C.A. and Vande Wouwer A. (2011) Model selection, identification and validation in anaerobic digestion: A review. Water research, 45, 347-5364.
- Fritzson, P. Principles of Object Oriented Modeling and Simulation with Modelica 2.1, 940 pages, ISBN 0-471-471631, Wiley-IEEE Press. January 2004.
- Modelica Association. (2007). Modelica – A unified Object-Oriented Language for Physical Systems Modeling, Language Specification Version 3.0, www.modelica.org.
- Hauge, T. A., Slora, R. & Lie, B. (2005). "Application and roll-out of infinite horizon MPC employing a nonlinear mechanistic model to paper machines". Journal of Process Control 15(2), 201-213
- Jansson J., Grobler F. and Dahlquist E.: Modelbased control and optimization of continuous digester. TAPPSA Journal, July 2008, p 26- 33
- Javed, F., Arshad, N., Wallin, F., Vassileva, I., Dahlquist, E., 2010. Engineering Optimization Models at Runtime for Dynamically Adaptive Systems. 2010 15th IEEE International Conference on Engineering of Complex Computer Systems (ICECCS), art. no. 5628607, pp. 253 – 254, 22-26 March, 2010, Oxford, UK, ISBN 978-1-4244-6638-2
- Järvensivu M., Saari K. and Jämsä-Jounela S.-L., Intelligent control system of an industrial lime kiln process, Control Engineering Practice, Vol. 9, 589-606. 2001.
- Karlsson, Christer P.; Avelin, Anders; and Dahlquist, Erik (2009) "New Methods for Adaptation to Degeneration in Process Models for Process Industries," Chemical Product and Process Modeling: Vol. 4 : Iss. 1, Article 25. DOI: 10.2202/1934-2659.1127. Available at: <http://www.bepress.com/cppm/vol4/iss1/25>
- Lübken M., Wichern M., Schlattmann M., Gronauer A. and Horn H. (2007). Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops. Water Research, 41, 4085-4096.
- Mattsson, S.E., Elmqvist, H. and Otter, M. (1998). Physical system modeling with Modelica. Control Engineering Practice, 6 (4), 501-510.

Mercangöz Mehmet, Doyle Francis J., University of California, Santa Barbara, USA Plantwide optimization of a pulp mill process, Control Systems 2006 ,Tampere, Finland, June 6-8, 2006

Otter, M. and Elmquist, H. (2001). Modelica – Language, Library, Tools, Workshop and EU-Project RealSim.

Pop, A, Sjölund M , Asghar A, Fritzson P, Casella F. Static and Dynamic Debugging of Modelica Models. In Proceedings of the 8th International Modelica Conference (Modelica'2012), Munich, Germany, Sept.3-5, 2012.

Sandberg J., Bel Fdhila R., Dahlquist E. and Avelin A. (2011). Dynamic simulation of fouling in a circulating fluidized biomass fired boiler. Applied Energy, 88, 1813–1824.

Salogni, A. and Colonna, P. (2010). Modeling of solid oxide fuel cells for dynamic simulations of integrated systems. Applied Thermal Engineering, 30, 464-477.

Thorin E., Johan Lindmark; Erik Dahlquist; Eva Nordlander; Eva Nordlander; Jan Kastensson, Niklas Leksell. Performance Optimization of the Växtkraft Biogas Production Plant. Applied Energy. Accepted paper 6 March, 2012.

Vassileva, I., Wallin, F., Dahlquist, E.: Analytical comparison between electricity consumption and behavioral characteristics of Swedish households in rented apartments . Applied Energy 90 (1), pp. 182-188,2012.

Vassileva I. and Dahlquist E.: Economical savings through lowering energy consumption in rented apartments. a case study in Västerås area. Journal of numerical and applied mathematics, vol 1(90), 2008, pp 234-245

Venkatasubramanian V, Rengaswamy R, Yin K, Kavuri S N. (2003a). A review of process fault detection and diagnosis Part I: Quantitative model-based methods. Computers and Chemical Engineering, 27, 293-311.

Venkatasubramanian V, Rengaswamy R, Yin K, Kavuri S N. (2003b). A review of process fault detection and diagnosis: Part II: Qualitative models and search strategies. Computers and Chemical Engineering 27, 313-326.

Venkatasubramanian V, Rengaswamy R, Yin K, Kavuri S N. (2003c). A review of process fault detection and diagnosis: Part III: Process history based methods. Computers and Chemical Engineering, 27, 327-346.

Widarsson, B. and Dotzauer, E. (2008). Bayesian Networks-based early-warning for leakage in recovery boilers. Applied Thermal Engineering, 28-7, 750-764.

Widén J, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård and E. Wäckelgård (2009) Constructing load profiles for household electricity and hot water from time-use data – modeling approach and validation. Energy and Buildings. Energy and Buildings 41: 753–768