Modelica Library for Hybrid Simulation of Mass Flow in Process Plants

S. Fabricius and E. Badreddin

Modelica'2002, Munich, Germany

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

Overview

I. Background, motivation and solution approach
II. Fundamental relations for quasi-steady-state fluid flow
III. Modelica library implementation, selected component models
IV. Application examples
V. Conclusions
VI. Look into two other libraries currently developed

I.

Background and Motivation

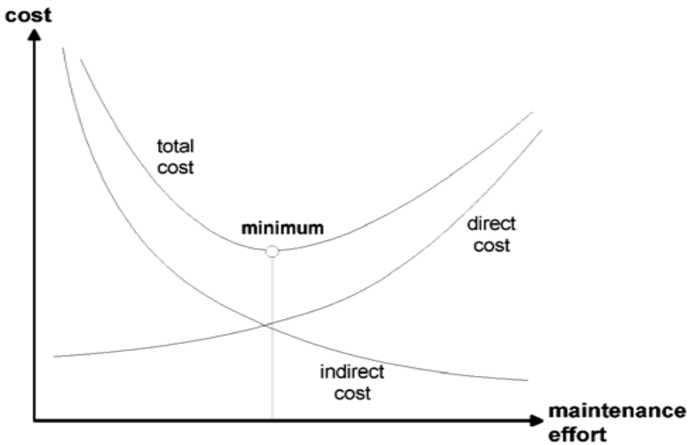
- Operation, control, maintenance of process plants: energy, cost-intensive

→ Reduction of unplanned down-time due to component failures

→ Definition of cost-efficient strategy for maintenance and monitoring

- Aspects:
  - Technical
  - Organizational
  - Economic
  - Safety

→ *multi-criteria optimization problem*



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

I. Solution Approach

- Extension of classical analysis concepts
  - Reliability data analysis
  - FTA, ETA, HAZOP...
  - Not sufficient, static characteristic
- Use of *dynamic plant models* for simulative investigation; account for:
  - Internal feedback loops
  - Non-linearities
- Main flow: Mass
  Modelica fluid flow library
  - System level focus, quasi-steady-state fluid flow
  - Ease-of-use, openness, flexibility, scalability

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

II. Fundamental Relations

- Mass balance for fluid storage (liquids, constant density)

$$\frac{dM}{dt} = \sum_i \dot{m}_i$$

- Constitutive relation between flow rate and pressure drop

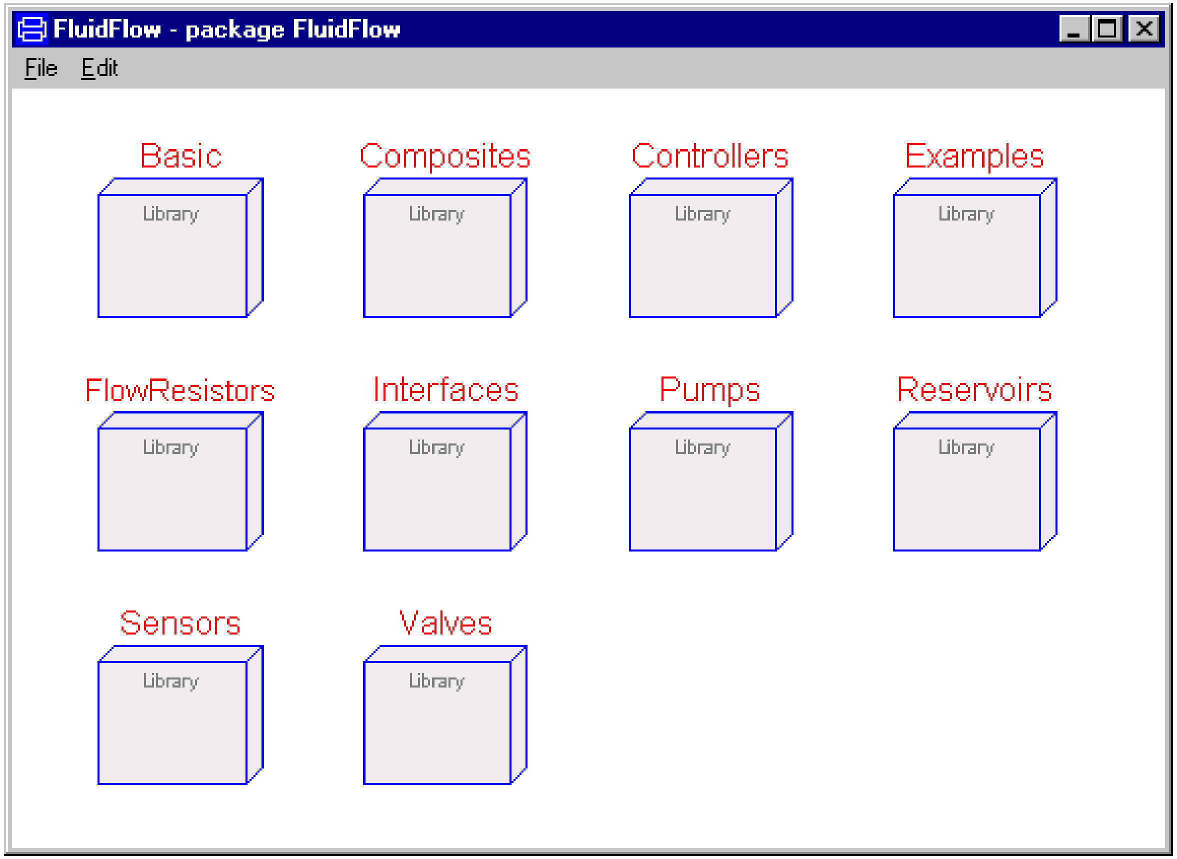
$$\Delta p = f\left(q\right)$$

- Mechanical energy along flow trajectories (Bernoulli extended with frictional terms)

$$\frac{p}{\rho} + \frac{v^2}{2} + gz + \sum \Delta p_{friction} + \sum \Delta p_{pump} = constant$$

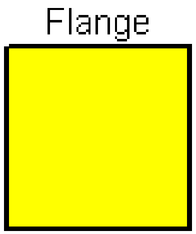
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

III. Library Structure



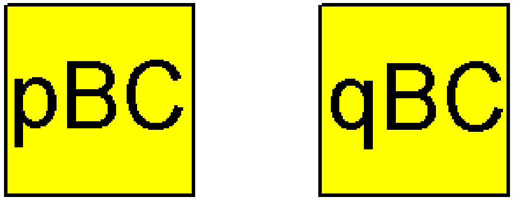
III. Connector, Boundary Conditions

- Flange




```
connector Flange
        SI.Pressure p;
  flow SI.VolumeFlowRate q;
end Flange
```

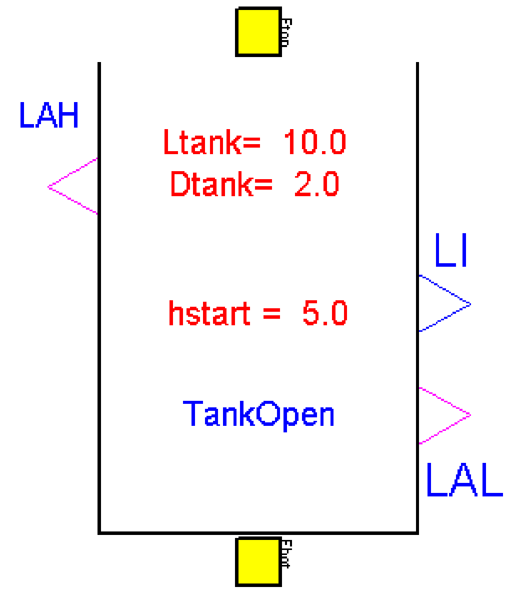
- Flow and pressure boundary conditions



III. Fluid Storage, Open Tank Example

- Open to atmosphere, two flanges (top, bottom) constant cross section *A*
- Tank level $$\frac{dh}{dt} = \frac{1}{A}\sum_i q_i$$
- Pressure distribution in the tank

$$p_{top} = p_\infty, \quad p_{bottom} = p_\infty + \rho g h$$



- Self contained, realistic in- and outflow pressure drops (reversible and irreversible)

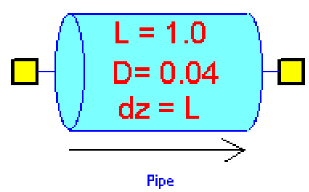
$$\Delta p_{fr,inlet} = \frac{\rho}{2} v^2_{inlet,pipe}, \quad \Delta p_{fr,outlet} = K_{con} \frac{\rho}{2} v^2_{inlet,pipe}$$

III. Flow Resistors, Bends, Pipes...

- Considered as purely resistive pressure drop $\Delta p = \zeta \frac{\rho}{2} v^2$ with $\zeta = f\left(\mathrm{Re}, geometry\right)$

- Bends (armatures…), constant factor *k* $\Delta p = k \cdot \frac{\rho}{2} v^2$

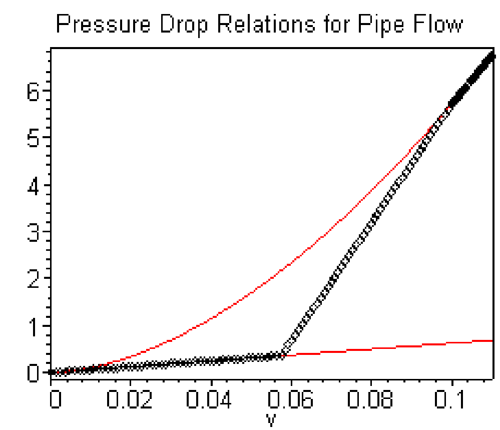
- Pipe $\Delta p = \lambda \frac{L}{D} \frac{\rho}{2} v^2$



Pipe friction factor
  - Laminar (Re<2300)
  - Turbulent (Re>4000)
  - Transient region

$$\lambda_{\mathrm{laminar}} = \frac{64}{\mathrm{Re}}$$

$$\lambda_{\mathrm{turbulent}} = 0.364 \cdot \mathrm{Re}^{-1/4}$$

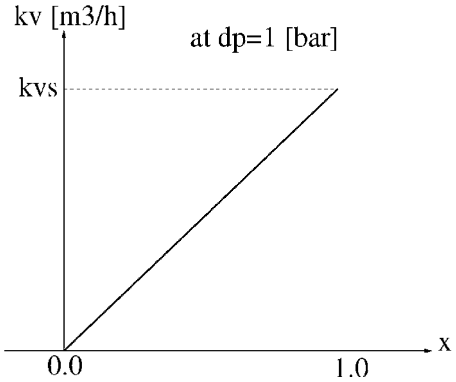


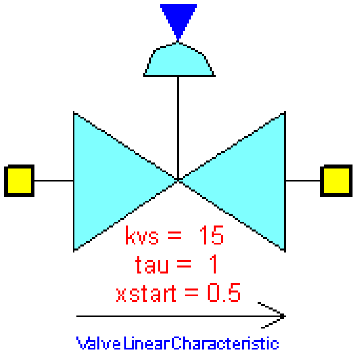
III. Valves

- Relation (fully open valve) $$q = k_{vs} \cdot \sqrt{\frac{|\Delta p|}{p_0}} \cdot sign(\Delta p)$$

- Valve characteristic
(x: valve travel)

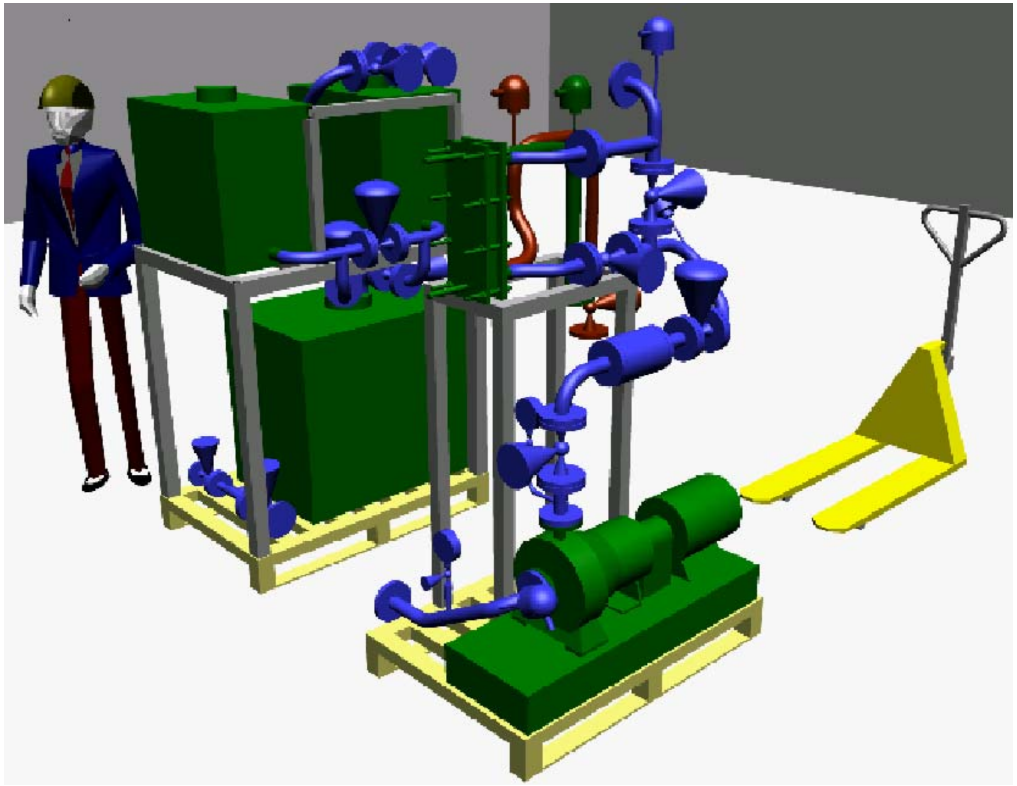
$$k_v = f(k_{vs}, x)$$



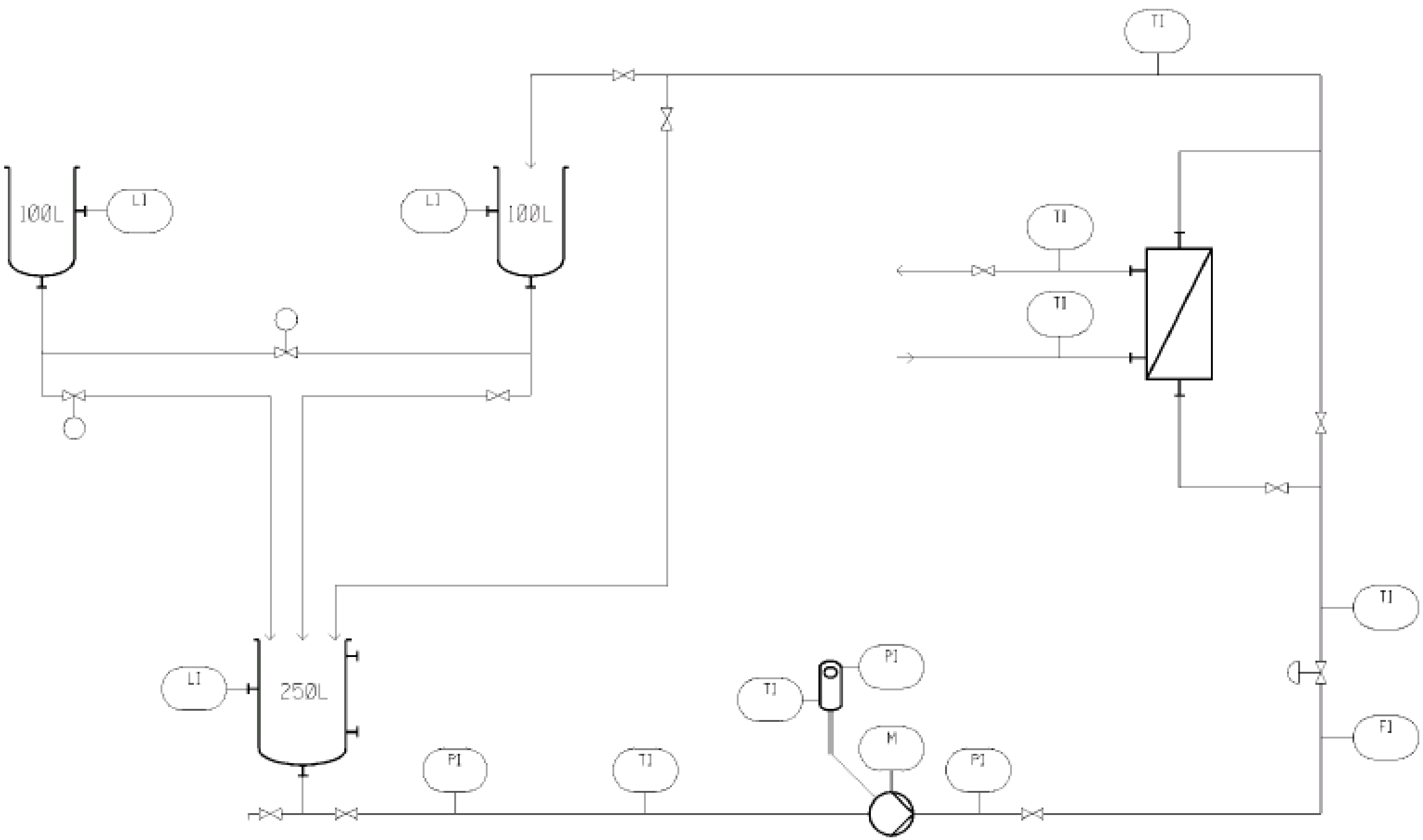


- With or without positioning dynamics
(e.g., servo-mechanism as first order exponential lag)

IV. Modeling Example: Laboratory Test-Bed

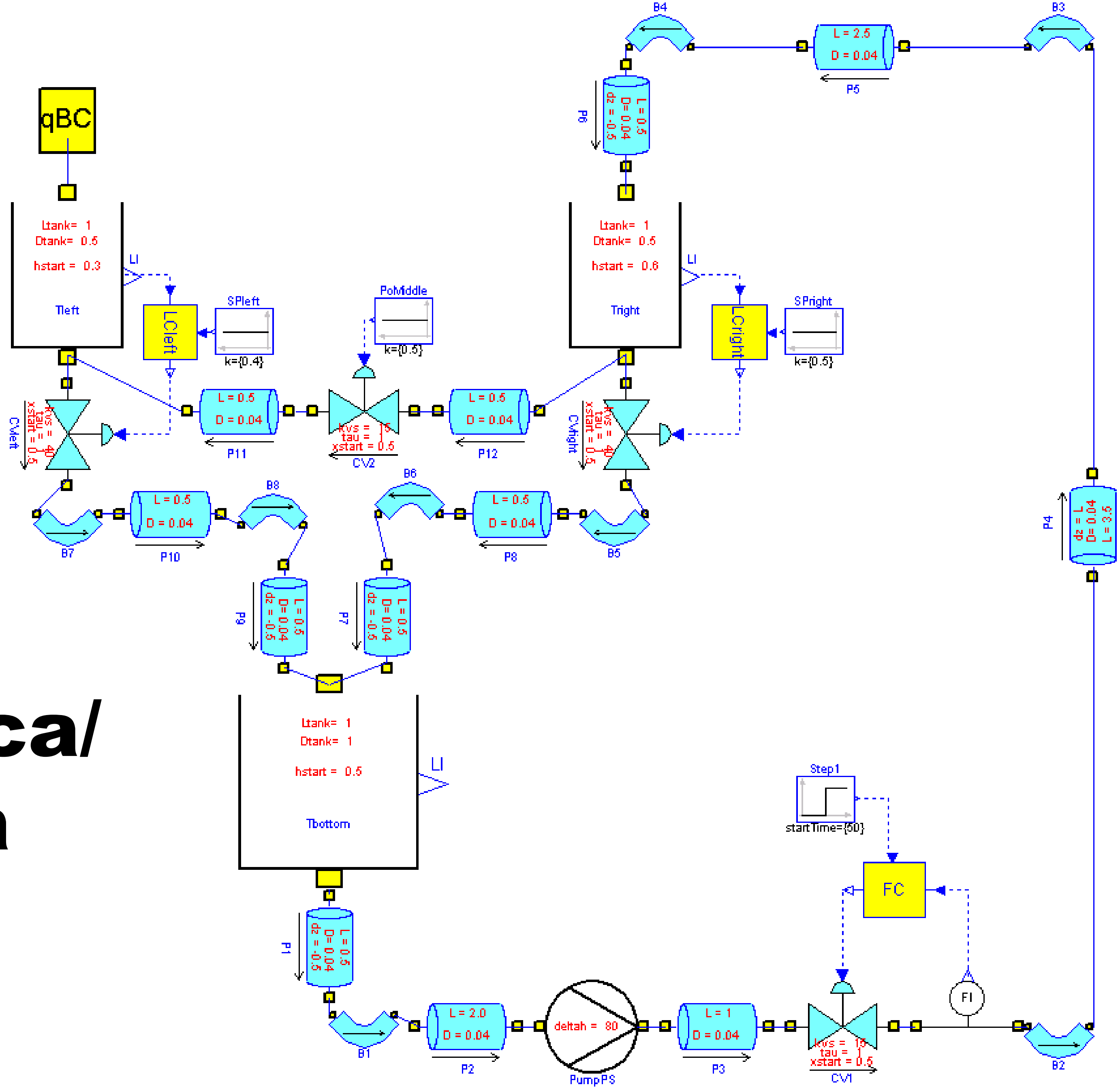


IV. Laboratory Test-Bed, PI-Scheme



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

IV.



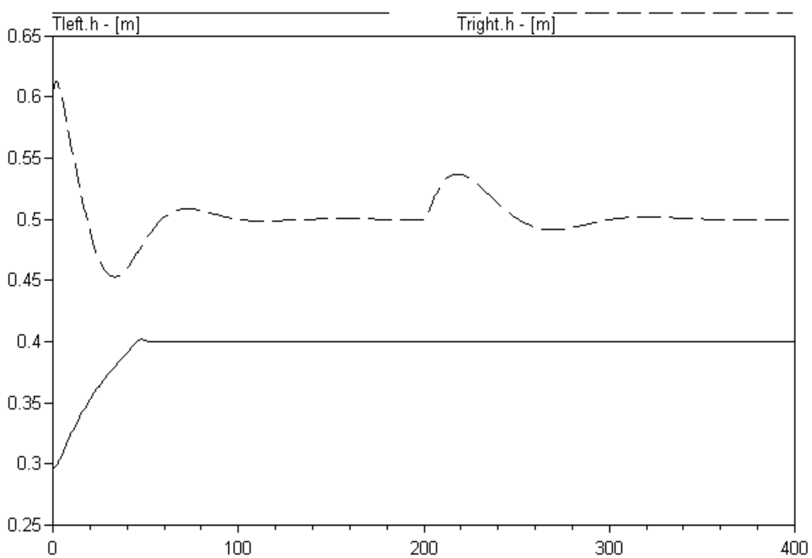
Modelica/ Dymola Model

S. Fabricius

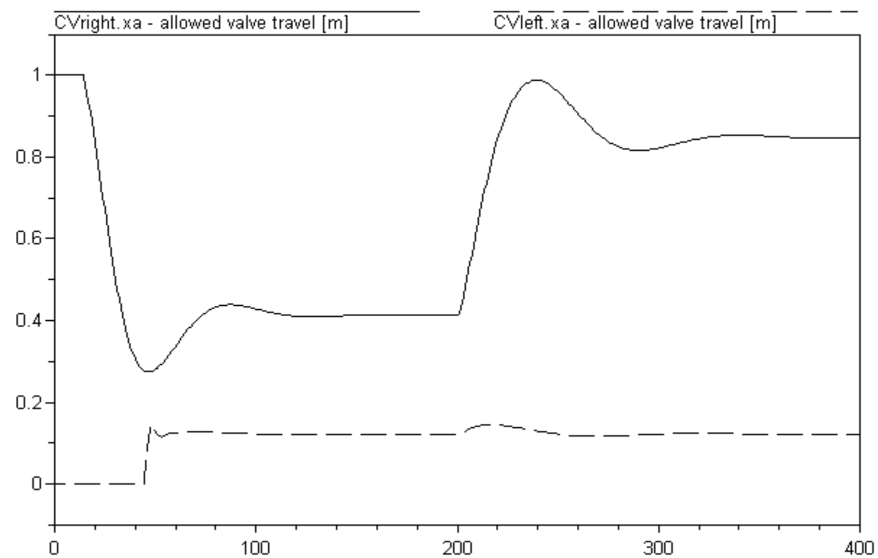
IV. Laboratory Test-Bed, Level Control Simulations

- Step (at *t*=200s) on the flow reference (set-point of the flow controller in the main pump line)

$$q_{ref} = 1.75 \quad \text{to} \quad 2.75 \quad [\text{ltr/s}]$$



Upper tank levels



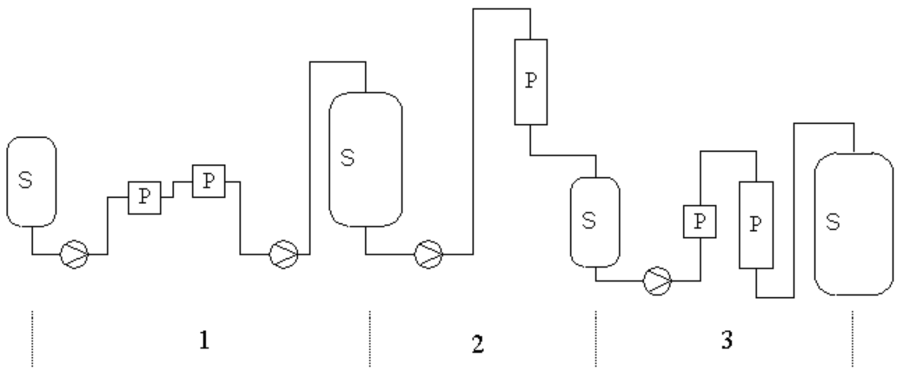
Level control valve positions

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

IV.
Process Plants

- Plant structure, segmentation
  - Flow sections (different maximum throughput capacities)
  - Vessels, intermediate buffer tanks

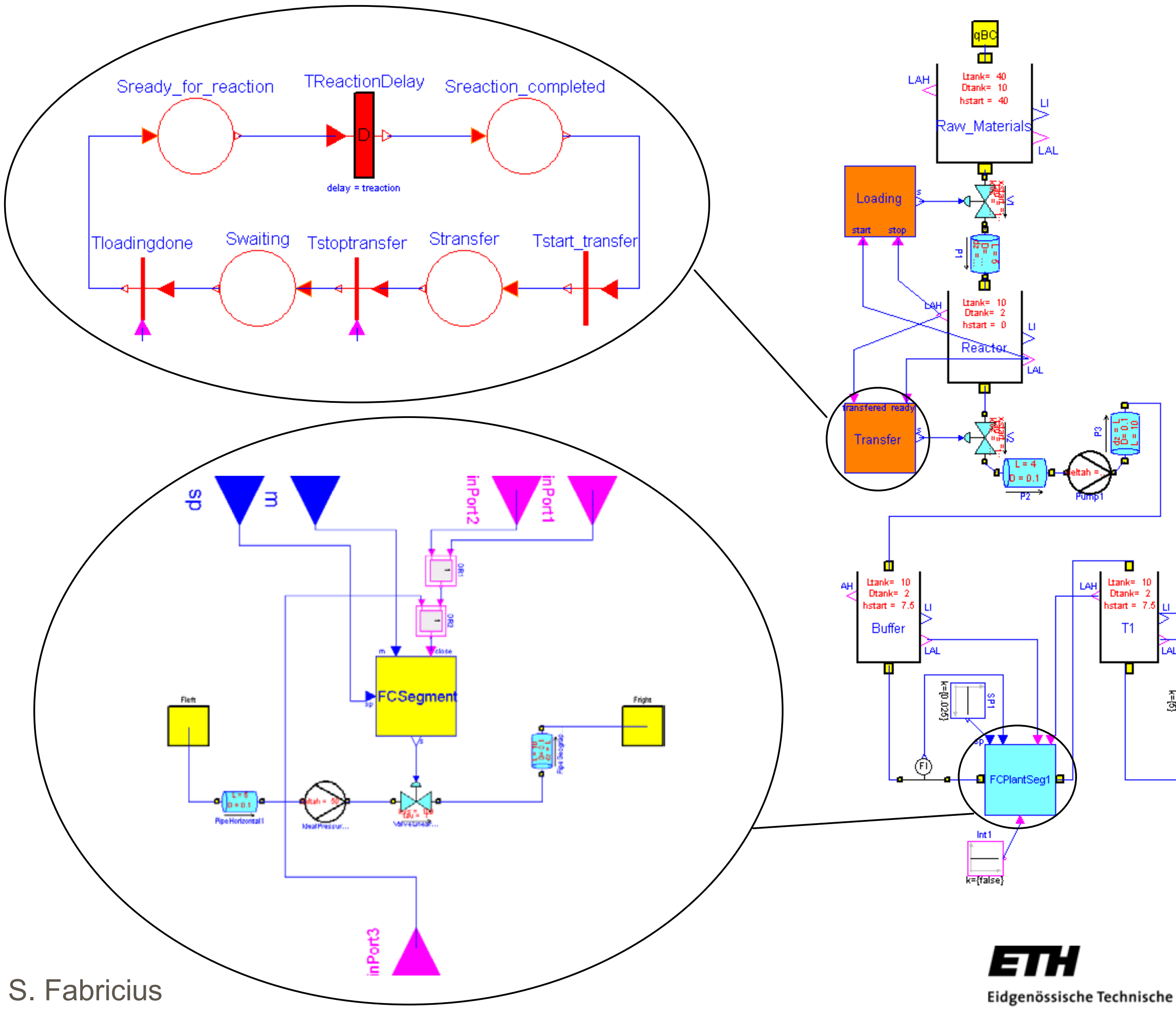
  → flow de-coupling



- Maintenance strategy definition
  - Account for mass flow dynamic effects
  - Component failure consequence (flow interruption propagation)
- Plant model, batch/continuous part

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

IV. Simple Process Plant Structure



- Plant topology (educts, reactor, buffer, tank1/2, product storage)
- Control (hierarchical)
- Flow interruptions

S. Fabricius

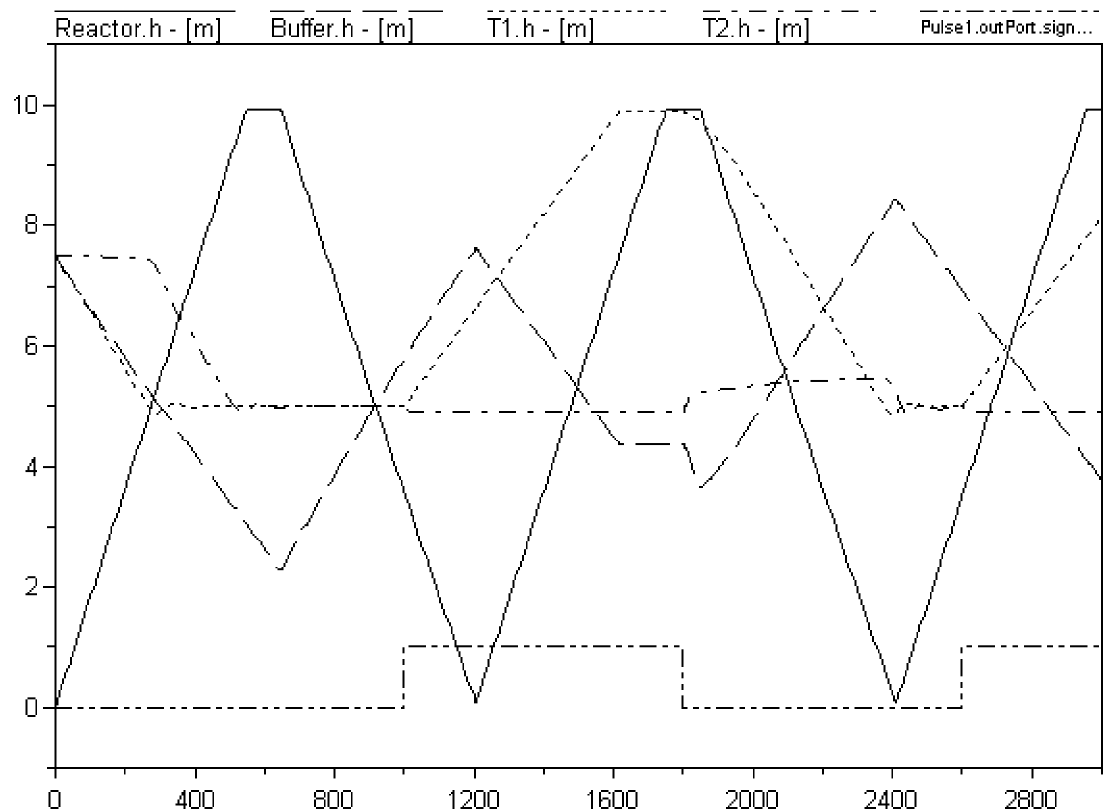
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis INSTITUTE FOR ENERGY TECHNOLOGY

proaut

IV.
Process Plant Simulation

Flow interruption in the continuous part, of interest:
  - Level behavior
  - Flow interruption propagation
- Sensitivity to flow interruptions
  - Control strategy
  - Segment throughput capacities (bottle-neck location)
  - Tank sizes



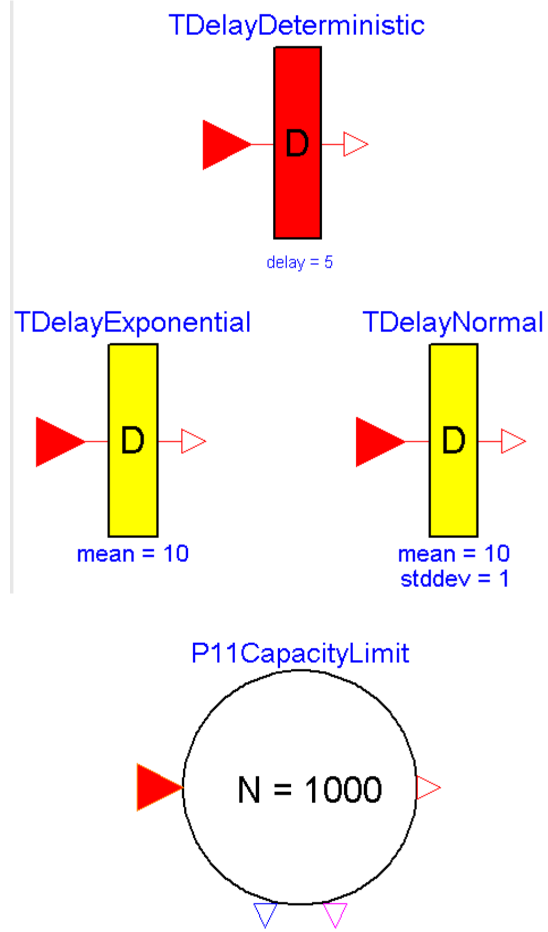
ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

V. Conclusions and Outlook

- Library allows to efficiently generate models of possibly large and complex mass flow networks (with their inherently non-linear behavior)
- Topology in the model remains similar to the real plant, intuitive
- Future:
  - Extend into thermal domain (e.g., heat exchange, combine with *Thermofluid* library?)
  - Bandwidth of characteristic times (different modes for normal operation to faulty behavior)
  - Online, real-time execution of models for fault monitoring
  - Initial value calculation, lower sensitivity to choice of starting values, Dymola next release?

VI. A. Petri Net (PN) Library Extensions

- Basis: Modelica Standard library
- Extensions
  - Random firing delays on transitions $\rightarrow$ timed, stochastic PN
  - Places capable of holding more than one token, capacity limits
- Support:
  - $\rightarrow$ DE simulation
  - $\rightarrow$ Hybrid models

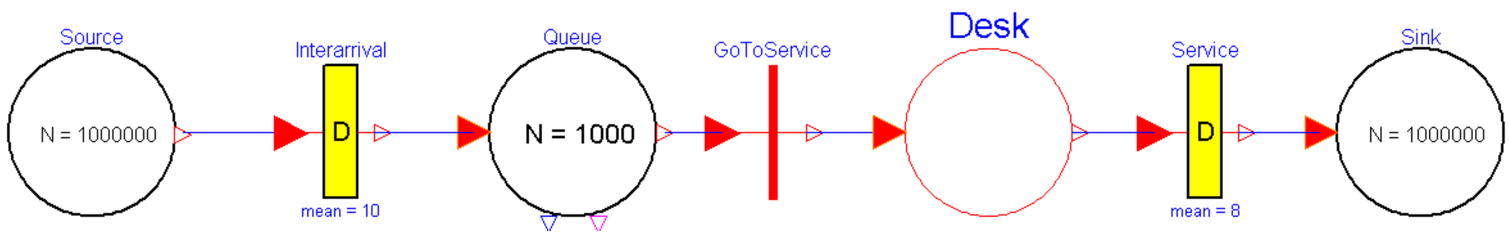


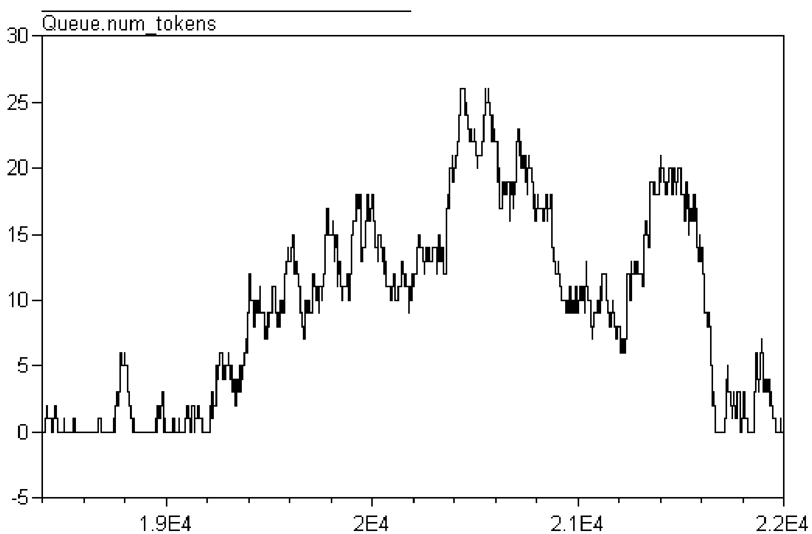
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
proaut

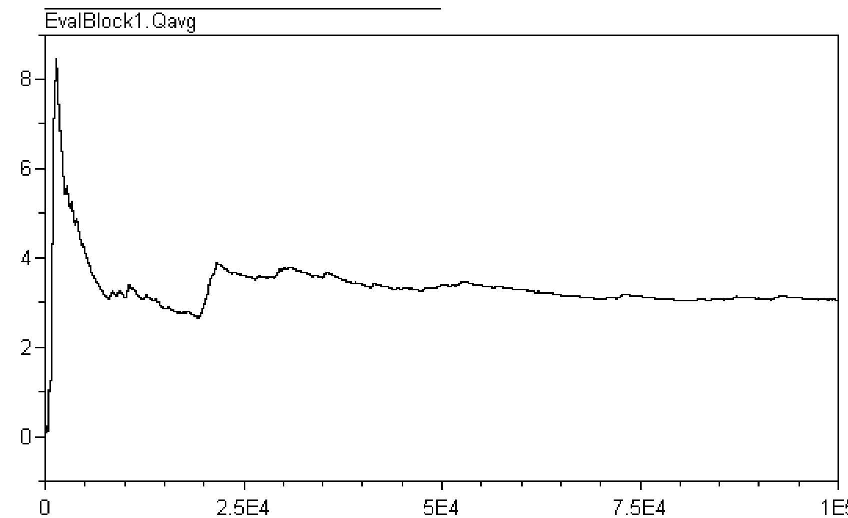
VI.

Example PN Model

- m/m/1 queuing system, average queue length



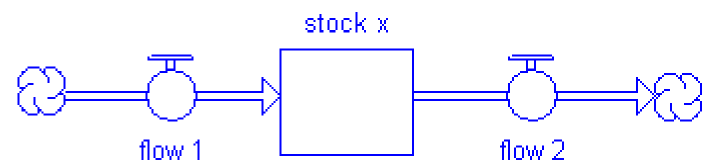


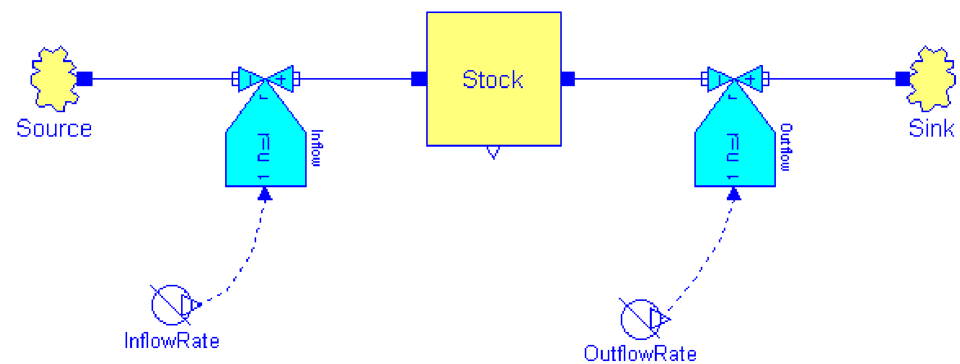


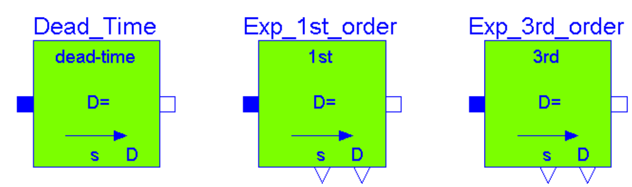
VI.

B. System Dynamics Library

- Originator: J. Forrester „Industrial Dynamics“
  - Level, rate equations
  - Information-feedback
- Tools: iThink (Stella), Vensim Powersim, Professional Dynamo
  - Application areas
    - Social systems, business
    - Ecology, environmental
    - Biology
- Modelica library
  - → Open, flexible, extendible
  - → Combine with powerful features of available Modelica libraries
  - → Multi-domain, multi-formalism
  - → Hybrid models
  - → Integrate socio-technical aspects

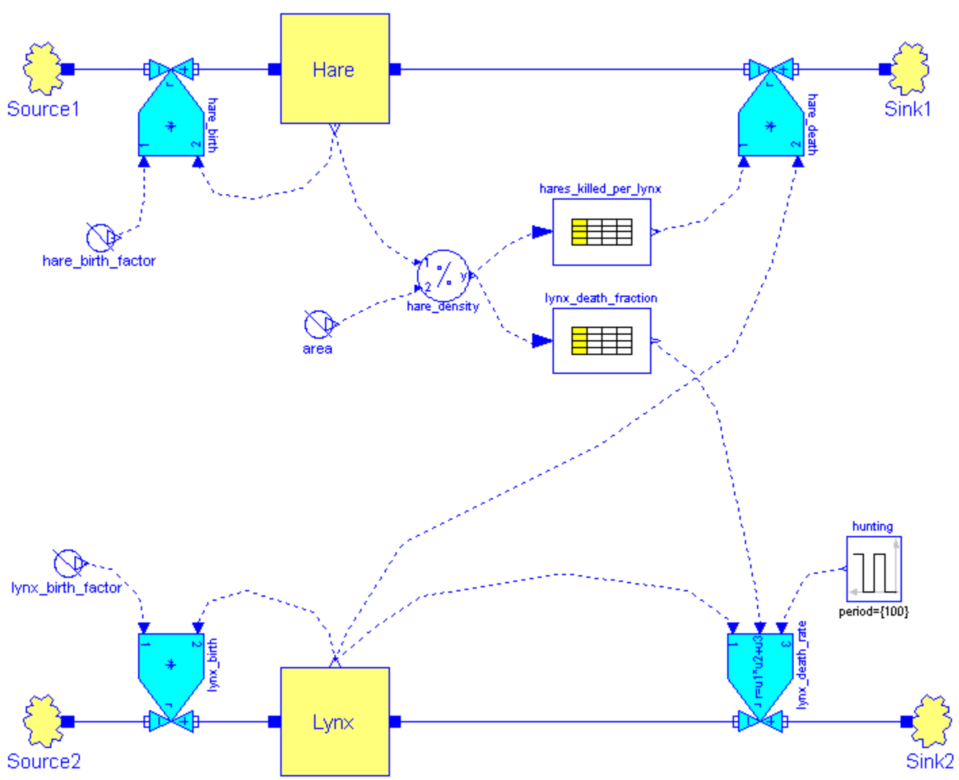


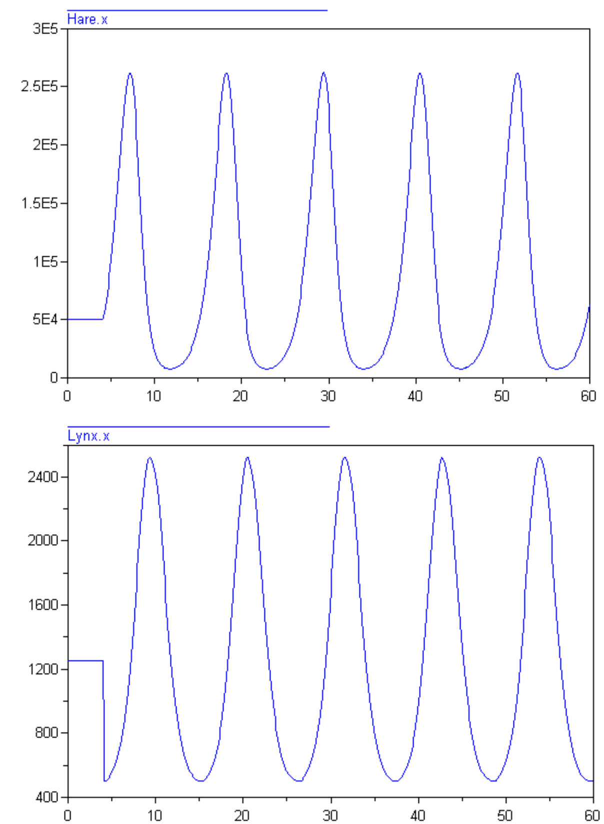




VI. Example System Dynamics Model

Prey-predator model, one time predator hunt, population development





S. Fabricius