A HYDRAULIC SCILAB TOOLBOX FOR WATER DISTRIBUTION SYSTEMS

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Abstract: The purpose of this paper is to show the possibilities offered by Scilab/Xcos to model hydraulic time-dependent systems. In particular, we develop a new Xcos module combined with the use of Modelica language to show how water distribution systems can be modeled and studied. In this paper we construct a reduced library composed by few elements: reservoirs, pipes and nodes. The library can be easily extended to obtain a more complete toolbox. The developed library is tested on a simple well-known hydraulic circuit.

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1. Introduction

Studying water distribution systems (WDS) is very important for a correct supply of water. These studies can guarantee an adequate water pressure at each location of frequent use and can reduce the total costs of water distribution systems.

Studying of water distribution systems requires a simulation tool that can be based on the following (at least) elements that are the basic building blocks of any network:

1. Pipes;
2. Node or junctions;
3. Storage tanks and reservoirs.

Moreover, the developed library can be straightforward extended with other elements like pumps and valves that are typically found in a hydraulic network.

Solving the network problem consists of finding the flow of water in each pipe and pressure level at each node. The required input data are:

1. The network layout;
2. The governing equations which describe the physics of the system;
3. The consumer's demand;

Here, in this work, we consider only the numerical modeling of the hydraulic part. The library is developed in Scilab/Xcos with the use of Modelica features. For more real-case applications the interested reader can contact the Openeering team.

Typically, the WDS problem is often associated to a multiobjective optimization problem where we want to maximize the minimum of the pressure level at nodes and minimize the total cost of the entire network. For optimizing the network we need to couple the hydraulics simulator with an appropriate multiobjective optimization tool. In Scilab, this can be done in a unified language since the hydraulic part can be modeled in Xcos/Modelica while the optimization part can be done using the available multiobjective optimization toolbox.

The paper is organized as follows. First we presented the basic modeling strategy, then the constitutive laws of the network elements and finally we presented an application of the developed library to simulate a simple hydraulic circuit. Comparison results are done with respect to the Epanet [1] software.

2. The problem description

In this tutorial we analyze the distribution network shown in Figure 1. It consists of 8 pipes, 6 junction nodes at different levels and one reservoir.

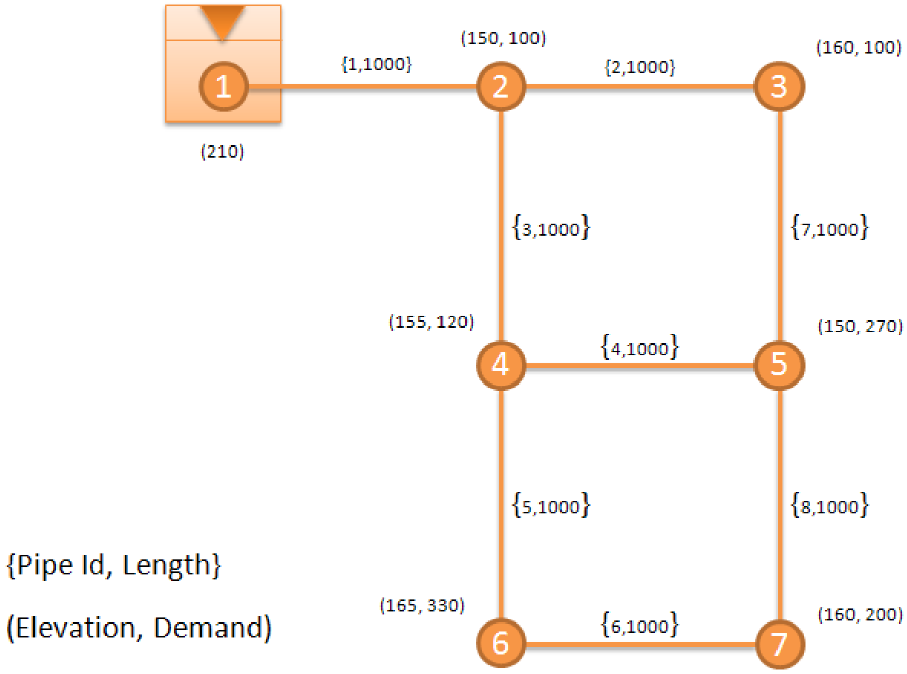


Figure 1: Network layout.

This model can be used as an example of water distribution systems where it is possible to detect negative value for the pressure. These negative values indicate situations where there is a deficit of pressure and this should be avoid in real situations. Finding the best combination of pipes can be easily done with our model if we couple it with an optimization algorithm. An example of this process is done in [2].

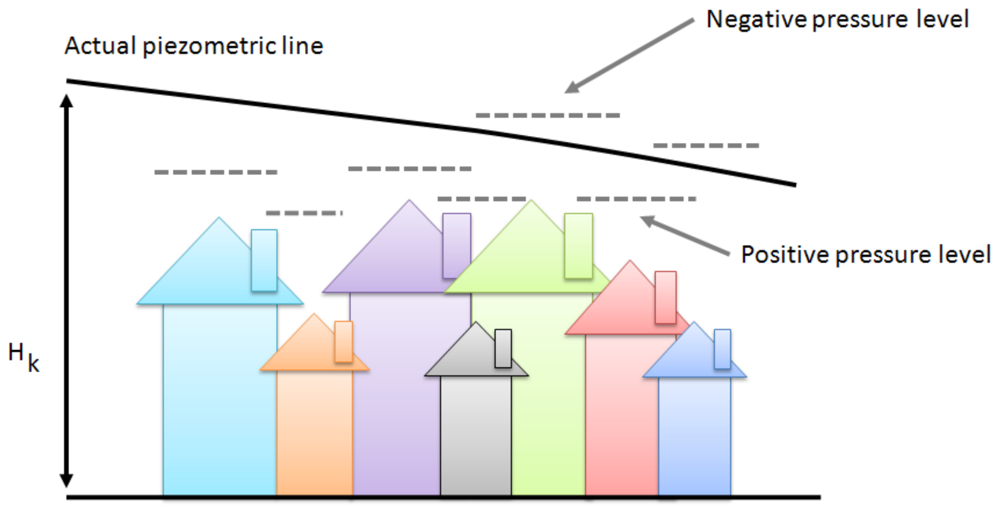


Figure 2: Actual piezometric line and pressure levels

The characteristics of the nodes are shown in Table 1 where we report elevation and customer's demand at each node.

Table 1: Nodes data

Node	Demand (m^3/h)	Elevation (ft)
1	---	210
2	100	150
3	100	160
4	120	155
5	270	150
6	330	165
7	200	160

Pipes properties are reported in Table 2.

Table 2: Pipes data

Pipe	Length (ft)	Diameter (in)
1	1000	18
2	1000	10
3	1000	16
4	1000	4
5	1000	16
6	1000	10
7	1000	10
8	1000	1

3. Library modeling

In this section we describe the basic library modeling approach. The Modelica developed package is named "WDS" (Water Distribution System) and it is contained in the file "WDS.mo". In this file we develop the library in the Modelica language 2.0 where the balance between equations and variables is not required for any local element.

A version of the file, using Modelica language 3.0, can be found in the file "WDS_new.mo" and it is described in Appendix A.

The implementation of the toolbox is done in Scilab/Xcos through the use Modelica features. The first step is to identify *through* and *across* system variables and the use of the "passive sign convention[1]" for all elements.

For our problem we choose:

- the ***volumetric flow rate*** q [GPM] as the through variable;
- the ***total head*** H [ft] as an across variable.
- the ***elevation*** z [ft] as an across variable.

Hence, our modeling is characterized by one through variable and two across variables.

This is implemented in the connector class named "***Pin***":

```
connector Pin "Inlet port"
         Real H "Total head [ft]";
         flow Real q "Volumetric flow [GPM]";
         Real z "Elevation [ft]";
end Pin;
```

The previous class implements the basic conservation laws for a two pins element:

```
Flux of the element  = Flux element at the input node
                     = - Flux element at the output node
```

and

```
Head drop            = Head at the input node
                       - Head at the output node
```

and

```
Delta Elevation      = Elevation at the input node
                       - Elevation at the output node
```

[1] In the "user convention" the through variable enters the positive terminal of a component (in Scilab is denoted by the black square).

4. Element constitutive laws and properties

In this section we summarize the constitutive laws and properties that have been used to develop the toolbox.

4.1. Some constants

Here we report some constants that are used in the development of the constitutive laws of the elements available in the library. Here we list the constants we use:

- pi is the π number;
- t_{min} is the minimum time used in the definition of the junction element;
- SG is the specific gravity or relative density that is the ratio between the substance density and the density of water at 4° [C];
- $p_{headconst}$ is the conversion pressure factor;
- k is the unit conversion factor used in the hydraulic pipe element;
- Q_{conv} is the conversion of 1 [ft^3/s] to 1 [US gallon per minute];
- Q_{min}.is the minimum value used in the modeling of the hydraulic resistance element.

The library constants are defined as follows:

```
package Constants "Simulation library constants"
        constant Real pi = 3.14159265358979323846 "pi";
        constant Real tmin = 1 "Minimum simulation time for linearization [s]";
        constant Real SG = 1 "Specific gravity";
        constant Real pheadconst = 2.3041475 "Unit conversion";
        constant Real k = 1.318 "Unit conversion";
        constant Real Qconv = 448.8312 "Unit conversion";
        constant Real Qmin = 1e-8 "Minimum flow [ft^3/s]";
end Constants;
```

4.2. Reservoir elements

The equations of a generic reservoir element fix the total head and the elevation given the user input specification Z_{val}, i.e.

- The total head equation: $H = Z_{val}$ [ft];
- The elevation equation: $z = Z_{val}$ [ft];

The Modelica implementation is done in the class “***Reservoir***”:

```
model Reservoir
        Pin Outlet;
        parameter Real Zval = 210. "Elevation [ft]";
equation
        Outlet.H = Zval "Total head";
        Outlet.z = Zval "Elevation";
end Reservoir;
```

4.3. Junction elements

A junction of a node is an element where it is possible to specify elevation Z_{val} and customer's demand Q_{val}.

The element is composed of the following two equations:

- The elevation equation that fixes the elevation $z = Z_{val}$ [ft];
- The flux equation that fixes the customer's demand $q = Q_{val}$ [GPM].

In our implementation the load (customer's demand) is modeled in a time dependent manner such that the customer's demand is reached after the time t_{min} . There is a transition zone in which the initial load is zero; this guarantees that at the initial time everything is in equilibrium.

The level pressure p is obtained from the equation (conversion from head feet to pressure in psi):

$$p = p_{headconst} \cdot SG \cdot \Delta H$$

where:

- p is the pressure level [psi];
- $p_{headconst} = \frac{1}{2.3041475} = 0.434$ is the conversion factor;
- SG is the specific gravity or relative density [-];
- $\Delta H = (H - Z)$ is the node head [ft]
- H is the node element total head [ft];
- Z is the node elevation [ft];

The Modelica implementation is done in the class "***Junction***":

```
model Junction
	Pin Inlet;
	parameter Real Zval = 150. "Elevation [ft]";
	parameter Real Qval = 100. "Base Demand [GPM]";
	Real Pressure "Pressure [psi]";
	Real Qflux "Current time base demand [GPM]";
protected
	constant Real tmin = WDS.Constants.tmin;
	constant Real SG = WDS.Constants.SG;
	constant Real pheadconst = WDS.Constants.pheadconst;
equation
	Qflux = if time<tmin then (Qval/tmin)*time else Qval "Current flux";
	Inlet.q = Qflux "Flux at the inlet";
	Inlet.z = Zval "Elevation";
	Pressure = (Inlet.H - Zval) * SG / pheadconst "Pressure head";
end Junction;
```

4.4. Hydraulic pipe

Hydraulic resistor in pipe is modeled using the Hazen-William friction loss equation:

$$V = k \cdot C \cdot R_h^{0.63} \cdot S^{0.54}$$

where:

- $Q = V \cdot A$ is the discharge [ft^3/s];
- $S = h_f/L$ is the energy slope [ft/ft];
- $R_h = D/4$ is the hydraulic radius [ft];
- V is the fluid velocity [ft/s];
- D is the hydraulic diameter [ft];
- L is the pipe length [ft];
- h_f is the energy head loss [ft];
- C is the H-W coefficient [-]
- k is the unit conversion factor.

This equation relates h_f and Q. As a note, a linear version of the equation is used if the flow is under a pre-fixed flow tolerance Q_{min}.

The Modelica implementation is done in the class "***Pipe***":

```
model Pipe
         Pin Inlet;
         Pin Outlet;
         parameter Real Lval = 1000. "Pipe length [ft]";
         parameter Real Dval = 12. "Pipe diameter [in]";
         parameter Real Cval = 130. "Hazen-Williams coefficient [-]";
         Real q "Fluid through the element [GPM]";
         Real Dh "Hydraulic diameter [ft]";
         Real Rh "Hydraulic radius [ft]";
         Real A "Area [ft^2]";
         Real Qdisc "Discharge [ft^3/s]";
         Real v "Velocity [ft/s]";
         Real S "Energy slope [ft/ft]";
         Real hf "Energy loss [ft]";
         // - Linearize version due to numerical derivative problems
         Real vmin "Minimum velocity [ft/s]";
         Real Smin "Minimum energy slope [ft/ft]";
         Real hfmin "Minimum energy loss [ft]";
protected
         constant Real pi = WDS.Constants.pi;
         constant Real k = WDS.Constants.k;
         constant Real Qconv = WDS.Constants.Qconv;
         constant Real Qmin = WDS.Constants.Qmin;
equation
         Inlet.q = q "Flux inlet";
         Outlet.q = -q "Flux outlet";

         Dh = Dval / 12. "Hydraulic diameter [ft]";
```

```
          Rh = Dh / 4. "Hydraulic radius [ft]";
          A = pi * Dh^2 / 4. "Area [ft^2]";
          Qdisc = q / Qconv "Discharge [ft^3/s]";
          v = abs(Qdisc) / A "Velocity [ft^3/s]";
          S = (v/(k*Cval*Rh^0.63))^(1./0.54) "Energy slope [ft/ft]";
          hf = sign(Qdisc) * S * Lval "Energy loss [ft]";

          // Evaluate linearize version
          vmin = Qmin / A;
          Smin = (vmin/(k*Cval*Rh^0.63))^(1./0.54);
          hfmin = Smin * Lval;

          // Inlet.H - Outlet.H = hf "Pressure head"; // Not a good choice in
numerical analysis
          Inlet.H - Outlet.H = if abs(Qdisc) < Qmin then hfmin*(Qdisc/Qmin) else
hf "Pressure head";
end Pipe;
```

5. Example

The Xcos scheme of the problem is reported in Figure 3. See the Appendix B for the element specifications.

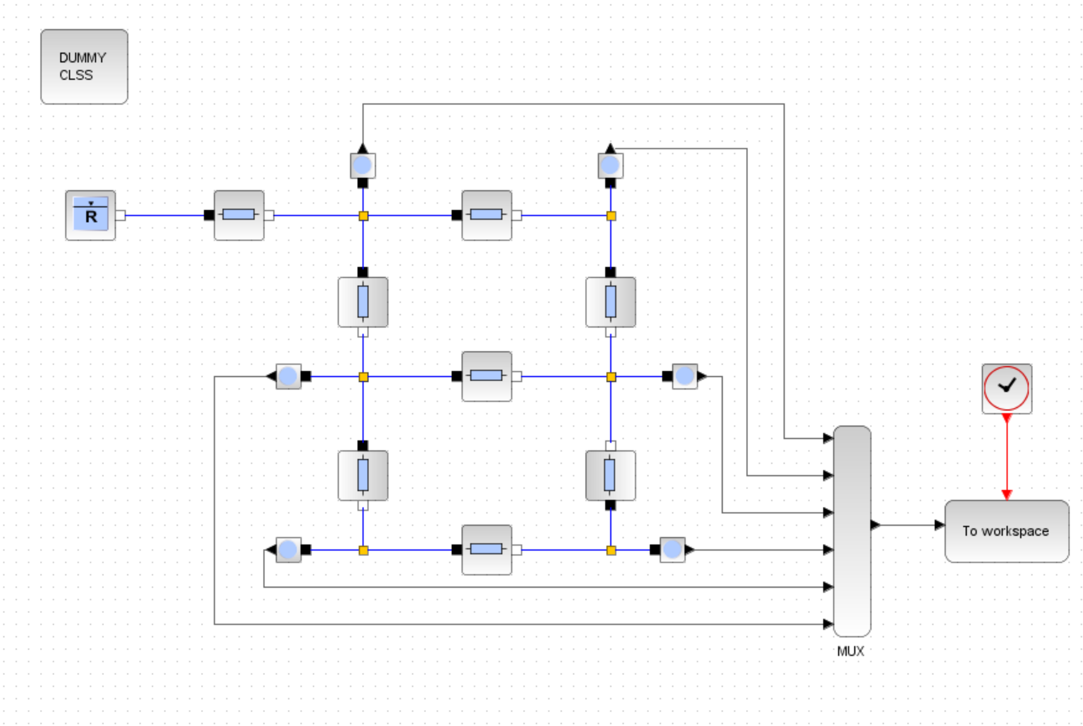


Figure 3: The simulation network.

In Figure 4 we plot the pressure level in each node.

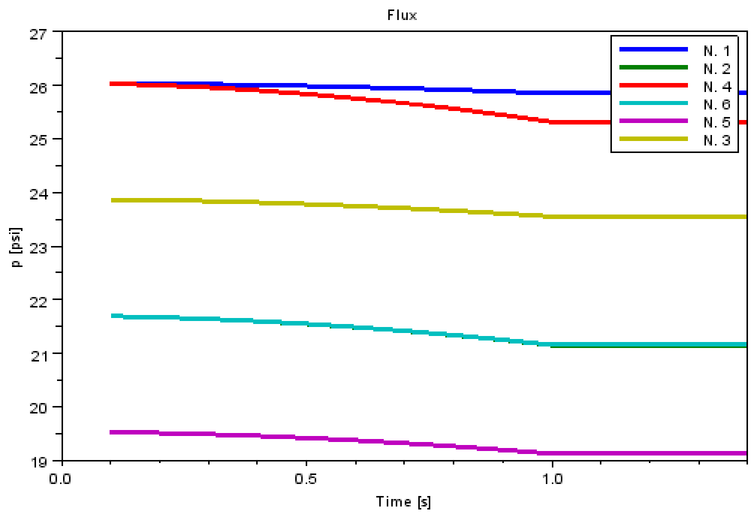


Figure 4: Simulation results

The results are compared with those obtained using Epanet [1], see Appendix D and E. From the tables reported in the Appendixes the results are very close.

6. Conclusion

Here, we have developed a Scilab/Xcos toolbox for hydraulic simulation. The toolbox will be extended in the future by providing further elements. For more real-case applications the interested reader can contact the Openeering team.

7. References

[1] Epanet software and user manual, http://www.epa.gov/nrmrl/wswrd/dw/epanet.html.

[2] Matteo Nicolini: A Two-Level Evolutionary Approach to Multi-criterion Optimization of Water Supply Systems. Evolutionary Multi-Criterion Optimization, Third International Conference, EMO 2005, Guanajuato, Mexico, March 9-11, 2005, Proceedings: 736-751

Appendix A – Library in new Modelica style

The connector

```
connector Pin "Inlet port"
         Real H "Total head [ft]";
         flow Real q "Volumetric flow [GPM]";
         Real z "Elevation [ft]";
end Pin;
```

is not a valid connector since the number of flow variables and the number of non-flow variables do not correspond. In new Modelica style it is required that the number of flow variables in a connector is equal to the number of non-causal, non-flow variables (variables without prefix flow, input, output, stream, parameter and constant) in order to guarantee that the model has balanced equations.

Here, we propose a simple solution by introducing a support flow variable (dummy). The definition of the new connector becomes:

```
connector Pin "Inlet port"
         Real H "Total head [ft]";
         flow Real q "Volumetric flow [GPM]";
         Real z "Elevation [ft]";
         flow Real dummy;
end Pin;
```

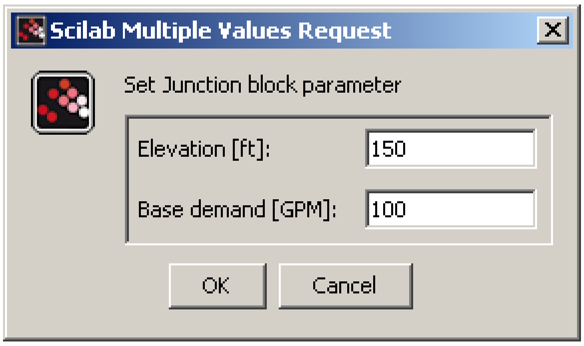
Then, it is only necessary to modify the element “Pipe” by introducing the following equations:

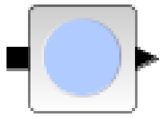
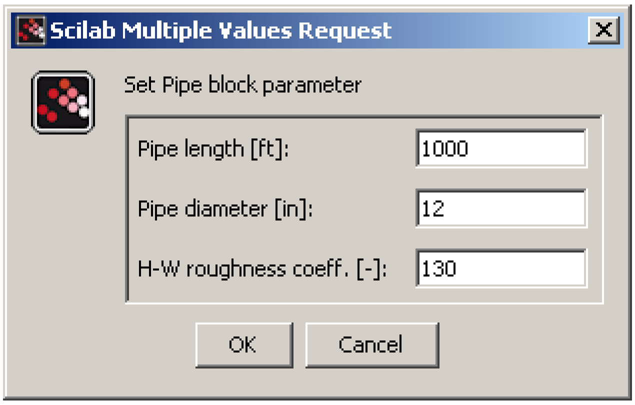
```
// dummy part
         Inlet.dummy = 0 "Flux inlet";
         Outlet.dummy = 0 "Flux outlet";
```

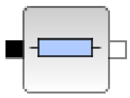
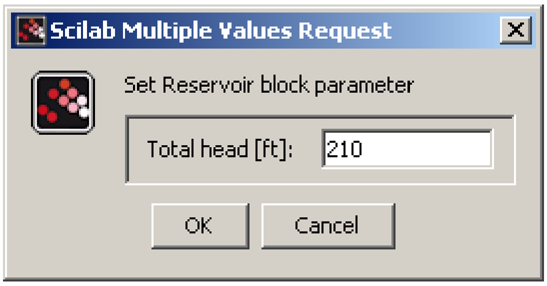
A more correct approach should be based on stream and input/output connectors but this is beyond the scope of this tutorial.

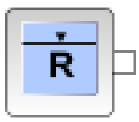
Appendix B – Library description

In the following table we report all the developed elements of our water distribution system (WDS) library.

<table>
<tr><th>Element</th><th>Required parameters</th><th>Xcos element</th></tr>
<tr><td>Junction</td><td>


</td><td>

</td></tr>
<tr><td>Pipe</td><td>


</td><td>

</td></tr>
<tr><td>Reservoir</td><td>


</td><td>


</td></tr>
</table>

Appendix C – Software installation and testing

The “hydraulic system toolbox” is available to registered users only. For downloading the library visit:

http://www.openeering.com/registered_users_area

Registration is free and automatic.

To load the library into the Xcos environment type

```
--> exec loader.sce
```

from the main directory. The new set of palette is loaded in your Xcos system.

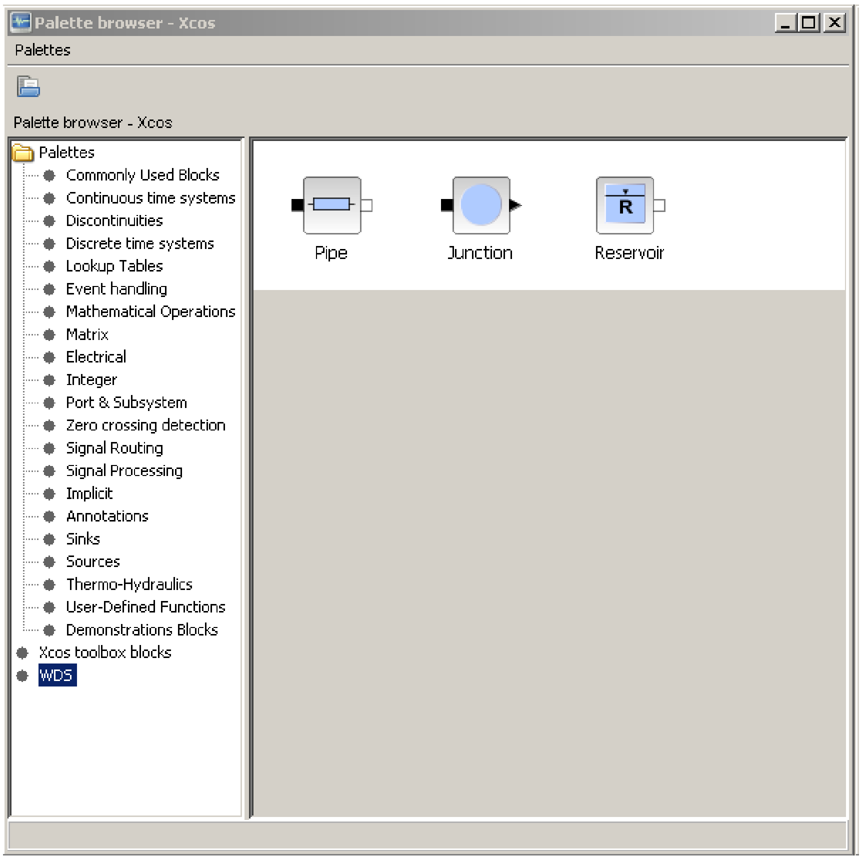


Figure 5: The Aeraulic library in Xcos

Open the Xcos model file " `Example_HydraulicNet.xcos`" and run it. Remember that to run an Xcos model with Modelica blocks, a C compiler should be installed in your system. Check if a compiler is available in your system with the Scilab command "`haveacompiler()`".

Then analysis of the data is done using the function "`Example_ProcessData.sce`", the plot can be generated using the function "`Example_PlotData.sce`".

The directory “other” contains the Epanet example and the Modelica libraries used to produce this article.

Appendix D – Epanet results

In the following we report the results obtained using Epanet software [1].

```
Page 1                                             03/05/2012 15.17.54
**********************************************************************
*                             E P A N E T                            *
*                     Hydraulic and Water Quality                    *
*                     Analysis for Pipe Networks                     *
*                             Version 2.0                            *
**********************************************************************


Input File: Example_HydraulicNet.net




Link - Node Table:
----------------------------------------------------------------------
Link              Start             End                Length  Diameter
ID                Node              Node                   ft        in
----------------------------------------------------------------------
1                 1                 2                    1000        18
2                 2                 3                    1000        10
3                 2                 4                    1000        16
4                 4                 5                    1000         4
5                 4                 6                    1000        16
6                 6                 7                    1000        10
7                 3                 5                    1000        10
8                 7                 5                    1000         1


Node Results:
----------------------------------------------------------------------
Node                    Demand      Head  Pressure   Quality
ID                         GPM        ft       psi
----------------------------------------------------------------------
2                       100.00    209.57     25.81      0.00
3                       100.00    208.74     21.12      0.00
4                       120.00    209.26     23.51      0.00
5                       270.00    208.32     25.27      0.00
6                       330.00    209.06     19.09      0.00
7                       200.00    208.75     21.12      0.00
1                     -1120.00    210.00      0.00      0.00 Reservoir
```

```
Link Results:
----------------------------------------------------------------------
Link                  Flow  VelocityUnit Headloss    Status
ID                     GPM        fps     ft/Kft
----------------------------------------------------------------------
1                  1120.00       1.41       0.43       Open
2                   336.88       1.38       0.82       Open
3                   683.12       1.09       0.31       Open
4                    32.56       0.83       0.94       Open
5                   530.56       0.85       0.19       Open
6                   200.56       0.82       0.31       Open
7                   236.88       0.97       0.43       Open
8                     0.56       0.23       0.43       Open
```

Appendix E – Simulation results

Here, we report the simulation results obtained using our modeling approach.

Link ID	Start node	End node	Length	Diam.	H-Z Const.
1	1	2	1000	18	130
2	2	3	1000	10	130
3	2	4	1000	16	130
4	4	5	1000	4	130
5	4	6	1000	16	130
6	6	7	1000	10	130
7	3	5	1000	10	130
8	7	5	1000	1	130

Link	Flow	Velocity	Headloss
1	1120.00000	1.41209	0.43422
2	336.87830	1.37614	0.82184
3	683.12160	1.09005	0.30847
4	32.56250	0.83136	0.94130
5	530.55910	0.84661	0.19317
6	200.55920	0.81928	0.31455
7	236.87840	0.96764	0.42811
8	0.55916	0.22842	0.43364

NODE	Demand	Head	pressure
1	-1120.00000	210.00000	0.00000
2	100.00000	209.56578	25.85155
3	100.00000	208.74394	21.15487
4	120.00000	209.25731	23.54767
5	270.00000	208.31601	25.30915
6	330.00000	209.06414	19.12383
7	200.00000	208.74965	21.15735