openCPS

Data reconciliation with Modelica and OpenModelica

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Outlook

1. Industrial challenge in measurement quality
2. Introduction to data reconciliation
3. Data reconciliation with Modelica and OpenModelica implementation
4. Preliminary results
5. Conclusion and future work

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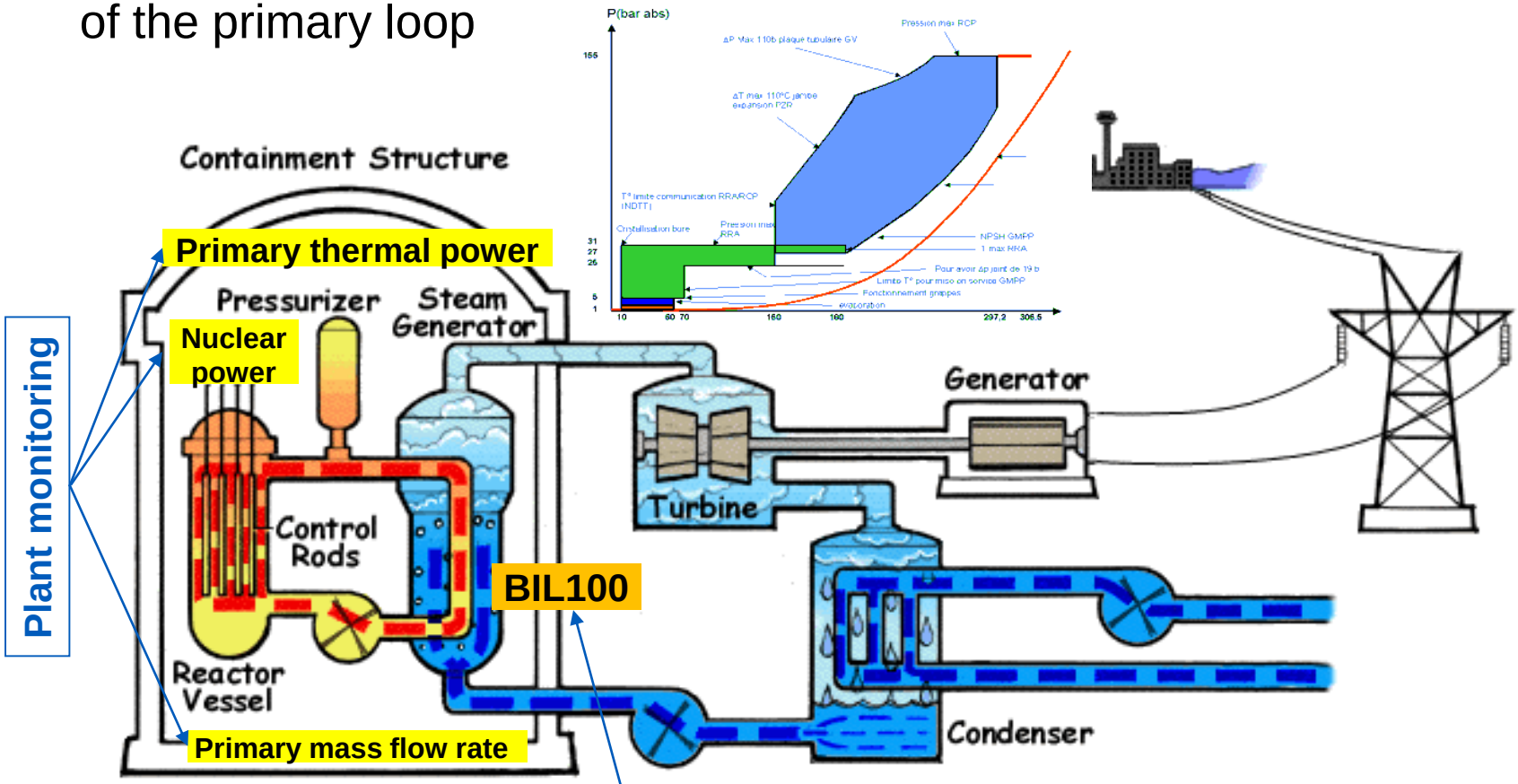
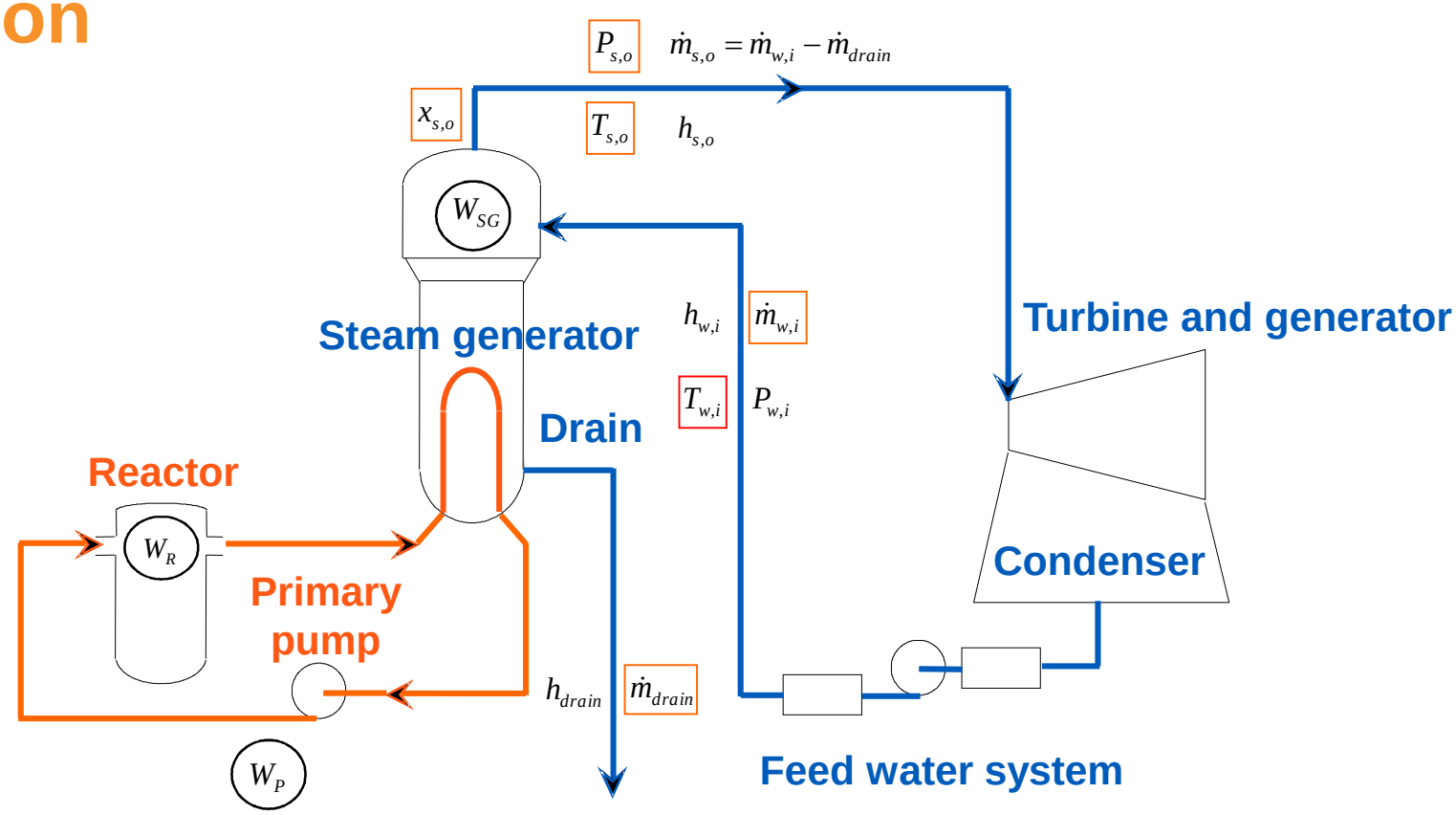
BIL100: assessing the thermal power of a nuclear power plant

- BIL100: measurement of the thermal power of a NPP at 100% load
- Important for safety: measurement is used to calibrate safety parameters of the primary loop



BIL100: computed with one energy balance equation



Thermal power extracted by the k[th] steam generator from the primary circuit

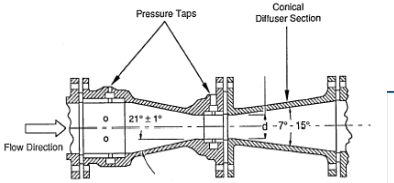
Thermal power provided to the primary circuit other than the reactor

$$W_{th,reactor} = \sum_{k=1}^{n_{loops}} \left[\dot{m}_{w,i}^{k} \cdot (h_{s,o}^{k} - h_{w,i}^{k}) - \dot{m}_{drain}^{k} \cdot (h_{s,o}^{k} - h_{drain}^{k}) \right] - W_{th,primary}$$

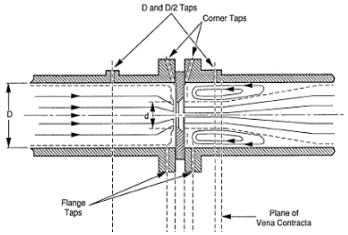
BIL100: quality of assessment is limited by uncertainties on the measurements

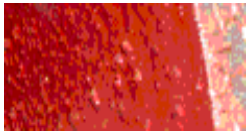
- Flow sensors are altered by deposits. May lead to under or over estimation of flow rates depending on the device.
  - ⇒ Measurement uncertainties are increased
  - ⇒ BIL100 uncertainty is increased
  - ⇒ May lead to operation issues (e.g. increase safety margins, lower production)

(ISO 5167)



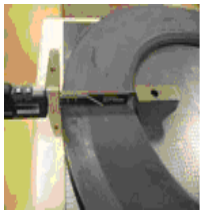
(ISO 5167)



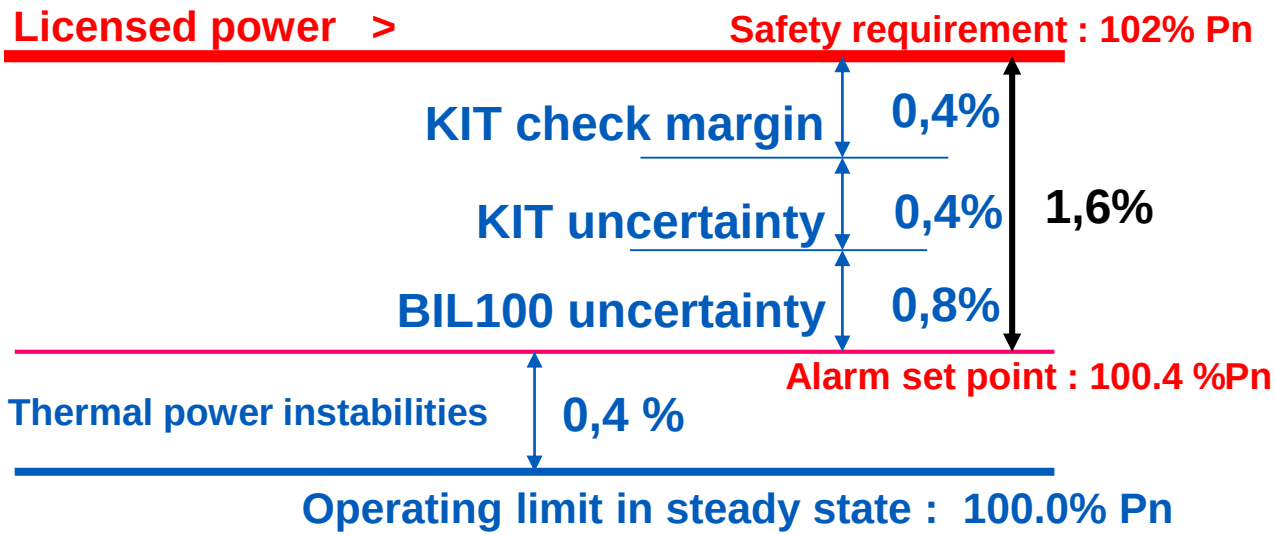


Venturi
± 1.5 %

Diaphragm
± 0.7%



BIL100: operational margins depend on the uncertainties



- Interest of data reconciliation:
  - Detect faulty sensors (make sure that uncertainties computation is correct).
  - Possibly, increase production by reducing measurement uncertainties (provided that the process is such that the data reconciliation hypotheses are correct).

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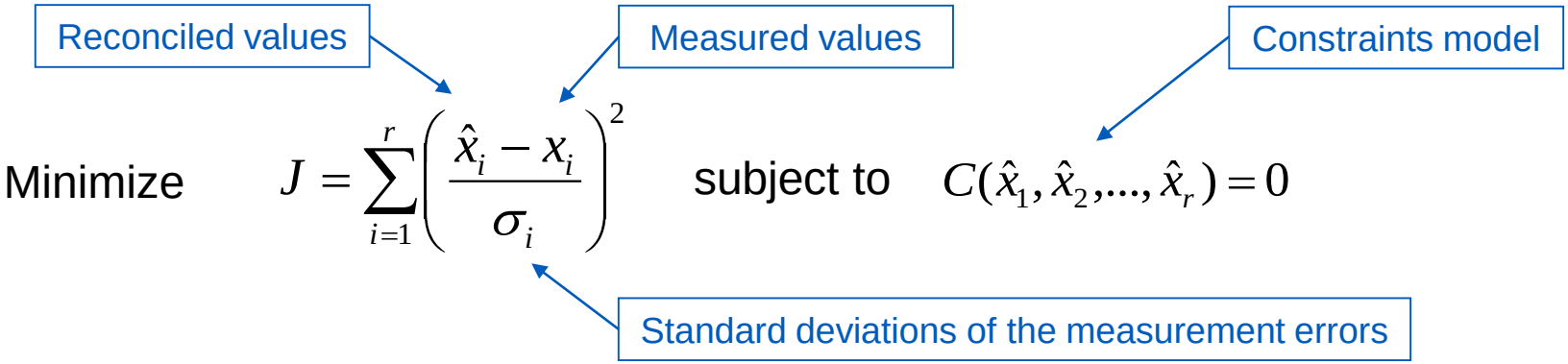
Data reconciliation: principle

- Data reconciliation aims at improving the accuracy of measurements by reducing the effect of random errors in the data.
- Data reconciliation uses a model to express the physical constraints on the variables of interest and adjusts their measured values such that the estimates satisfy the constraints: the variables are thus reconciled.
- Procedure is defined by VDI 2048 standard.



Minimum of function yields the reconciled values $\hat{x}_i$
and the covariance matrix on the reconciled values $S_{\hat{x}}$

Data reconciliation: hypotheses

- No uncertainties on the constraints (constraints model is perfect).
- The measured values of the variables of interest correspond to random variables whose distribution around the true values follows Gaussian distribution laws.
- To check the validity of this hypothesis, one must analyze the reconciled values obtained from a statistical point of view.
- This is done by performing a χ^2 test on the reconciled values.

$$J^* \leq \chi^2_{r,95\%}$$

- If the test fails, the Gaussian hypothesis is not verified and the initial values must be rejected.
- Individual tests can be performed to detect which measured values induce too large corrections (e.g. faulty sensors).

$$\left| \frac{\hat{x}_i - x_i}{s_{v_{i,i}}} \right| \leq \lambda_{95\%}$$

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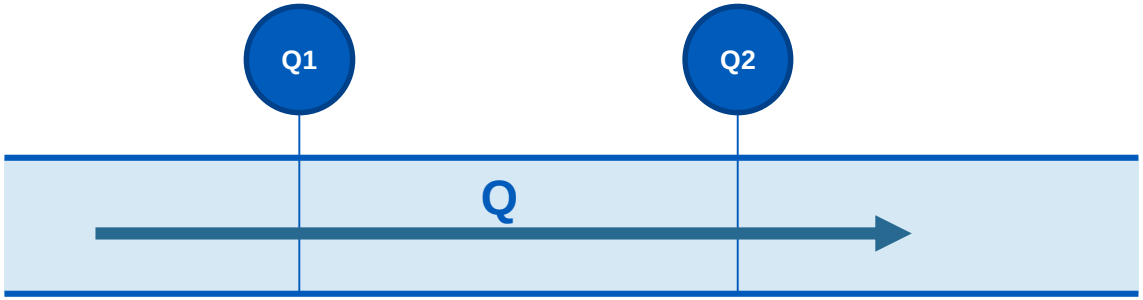
Objective: reuse Modelica models for data reconciliation

- Current situation: data reconciliation must be performed in dedicated tools (e.g. VALI).
- Drawback:
  - The model of the constraints must be specifically developed in the dedicated tool.
  - Validation of the model is difficult as it cannot be simulated: *the model constraints are underdetermined* hence they do not specify an initial value problem.
  - Model development is costly (several person*months for a medium size model).
- Solution: use existing Modelica models.

Problem: how to extract the constraint equations *C* from the Modelica model?



Minimize $J = \sum_{i=1}^{r} \left(\frac{\hat{x}_i - x_i}{\sigma_i} \right)^2$ subject to $C(\hat{x}_1, \hat{x}_2, ..., \hat{x}_r) = 0$

- Q1 and Q2 measure the mass flow rate Q through the pipe.
- Q1 and Q2 are the variables of interest subject to the model constraint Q1 = Q2.
- As the Modelica model is square, an additional equation must be provided to compute Q1 and Q2, in the form of a boundary condition, e.g. Q1 = p with p = 2 kg/s.

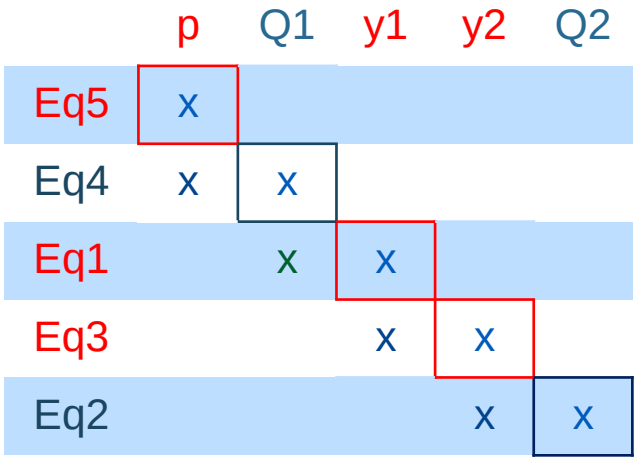
```
model Pipe
  Real p=2kg/s; // Eq5
  Real Q1, Q2;
  Real y1, y2;
equation
  Q1 = y1; // Eq1
  Q2 = y2; // Eq2
  y1 = y2; // Eq3
  Q1 = p;  // Eq4
end Pipe;
```

How to extract Q1 = Q2 from the Modelica model?

Solution: new automatic extraction algorithm

- A new extraction algorithm has been developed which removes unwanted equations from the Modelica model that unduly constrain variables of interest:
  - Boundary conditions: cannot be used because they correspond to assumptions on the environment of the system.
  - Equations flagged as approximated: cannot be used because the constraints model must be perfect.
- Algorithm:
  - Is based on classical BLT decomposition.
  - Produces two sets: set C of constraints and set S of intermediate equations

C = { Eq2 }
S = { Eq4, Eq1, Eq3 }

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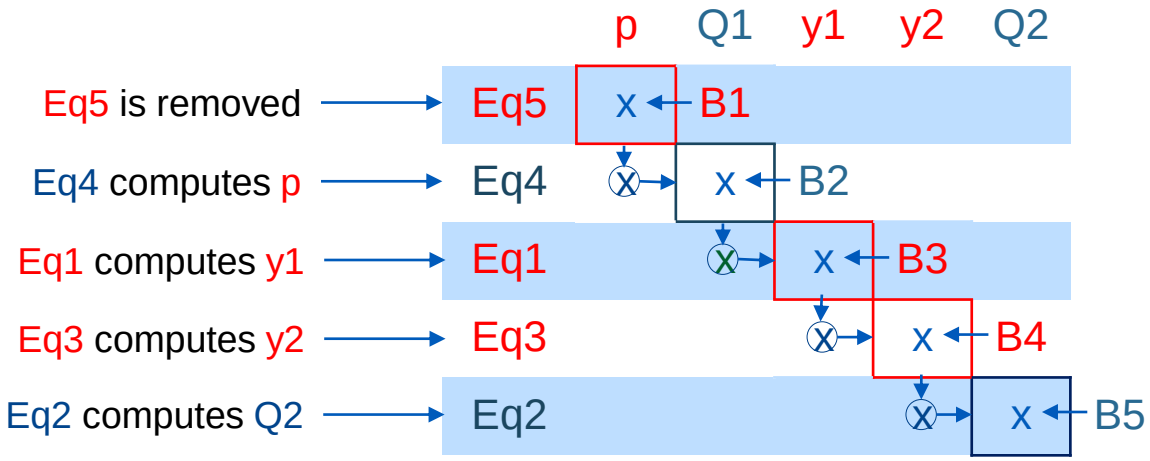
  Real y1, y2;
equation
  Q1 = y1; // Eq1
  Q2 = y2; // Eq2
  y1 = y2; // Eq3
  Q1 = p;  // Eq4
end Pipe;
```

Solution: new automatic extraction algorithm

- Principle of the extraction algorithm
  - Remove as few equations as possible from the BLT in order to ensure that all blocks in the BLT are underdetermined.
  - For each block in the BLT, insert into S one equation for each intermediate variable, then insert into C one equation for each variable of interest if available.

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equation
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end Pipe;
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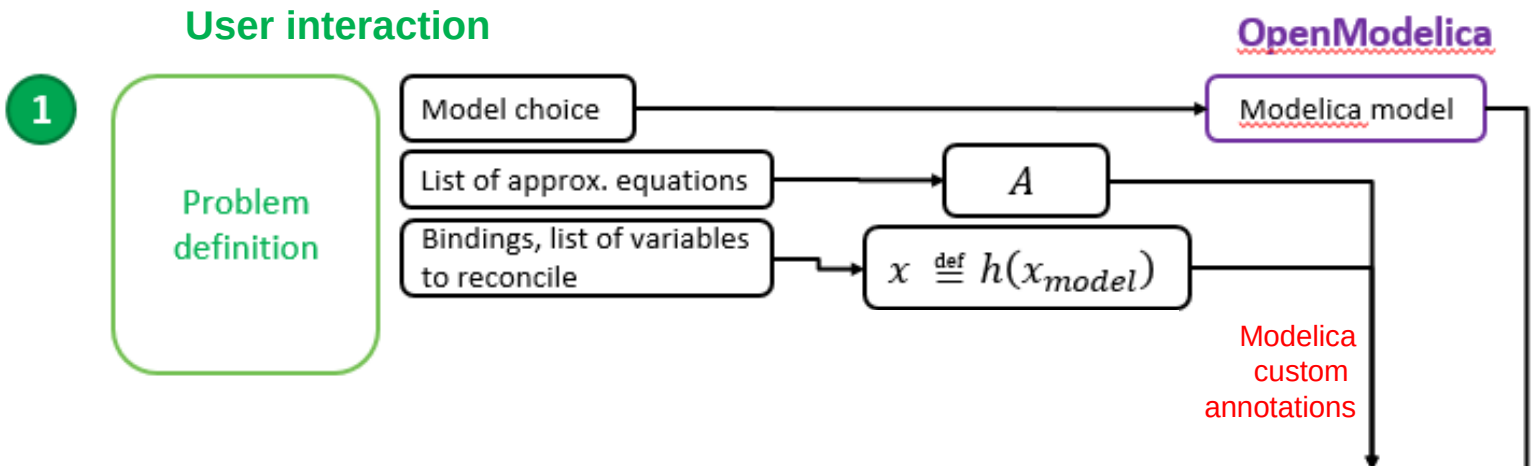
C = { Eq2 }
S = { Eq4, Eq1, Eq3 }

Implementation in OpenModelica



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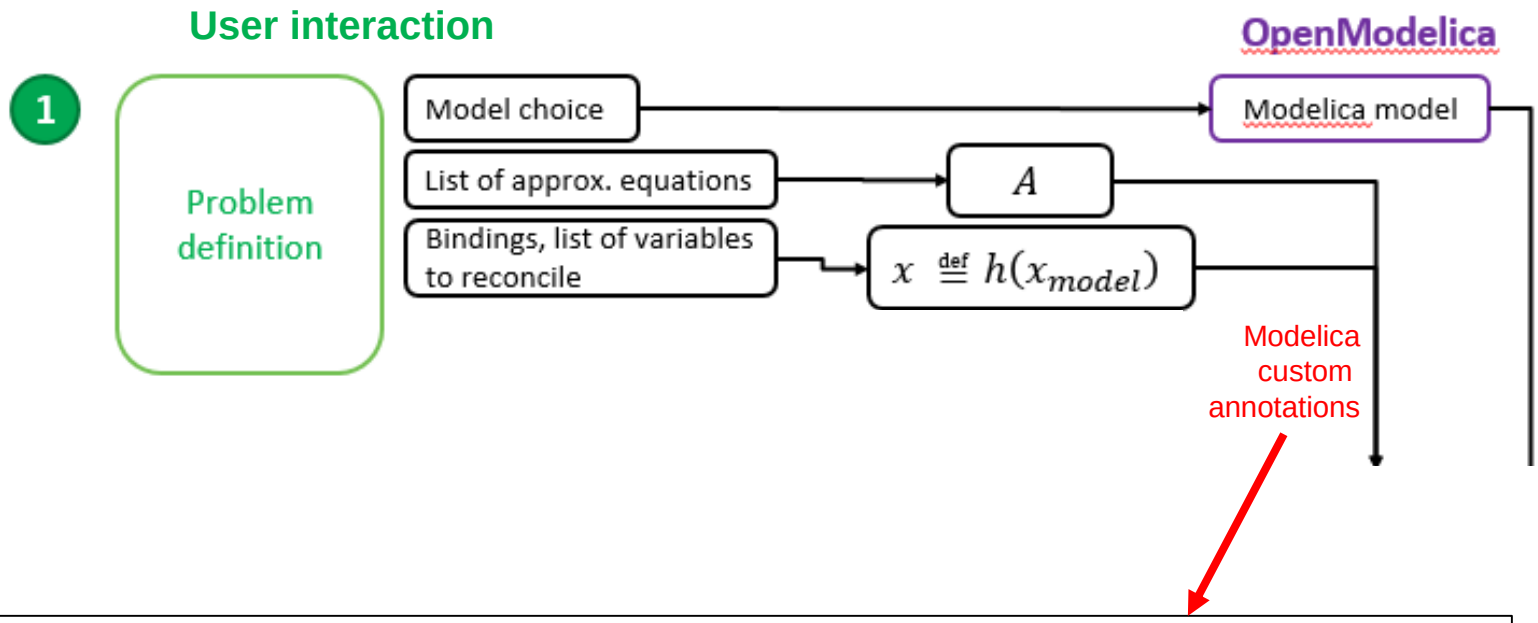
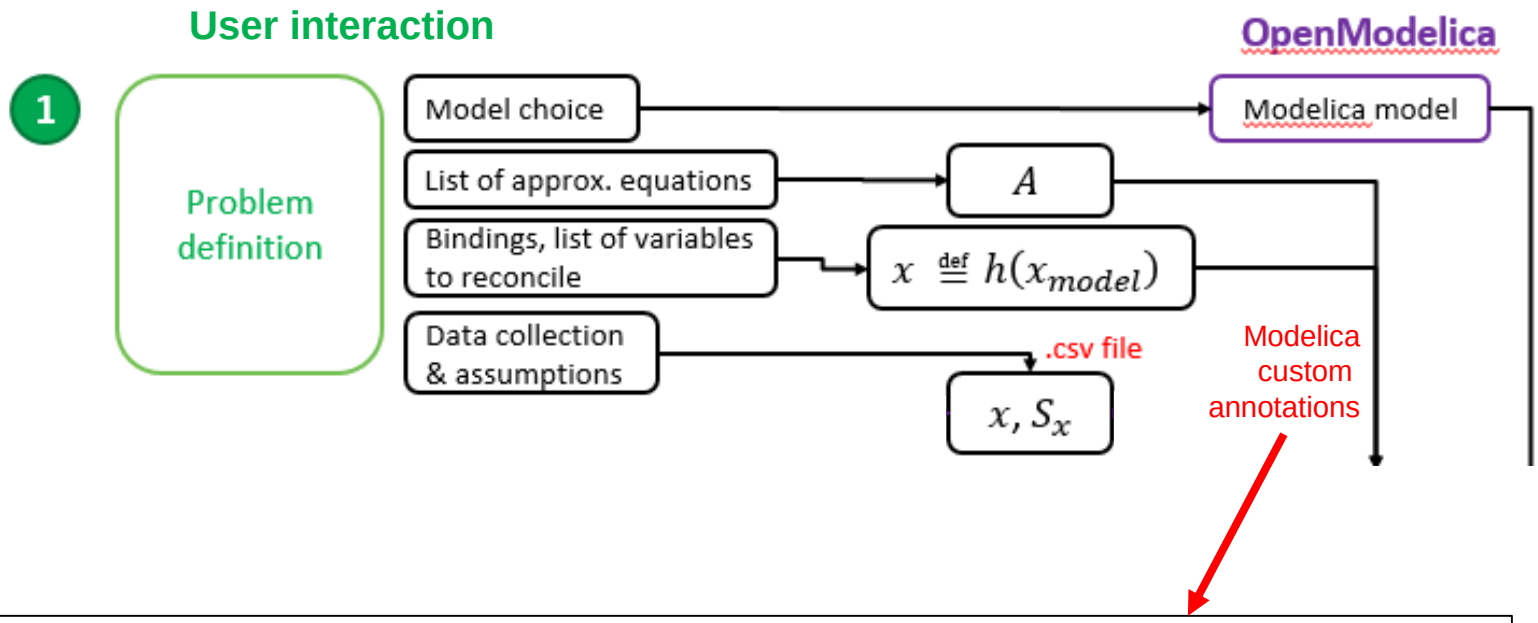



```
model Pipe1
    Real p;
    Real Q1(uncertain=Uncertainty.refine); // Annotation to tag a variable to reconcile
    Real Q2(uncertain=Uncertainty.refine);
equation
    p=2 annotation (__OpenModelica_ApproximatedEquation=true);
    // Declare equation as approximated => should not be considered for data reconciliation
    Q1 = Q2;
    Q1 = p;
end Pipe1;
```

Implementation in OpenModelica




```
model Pipe1
    Real p;
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    Real Q2(uncertain=Uncertainty.refine);
equation
    p=2 annotation (__OpenModelica_ApproximatedEquation=true);
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    Q1 = Q2;
    Q1 = p;
end Pipe1;
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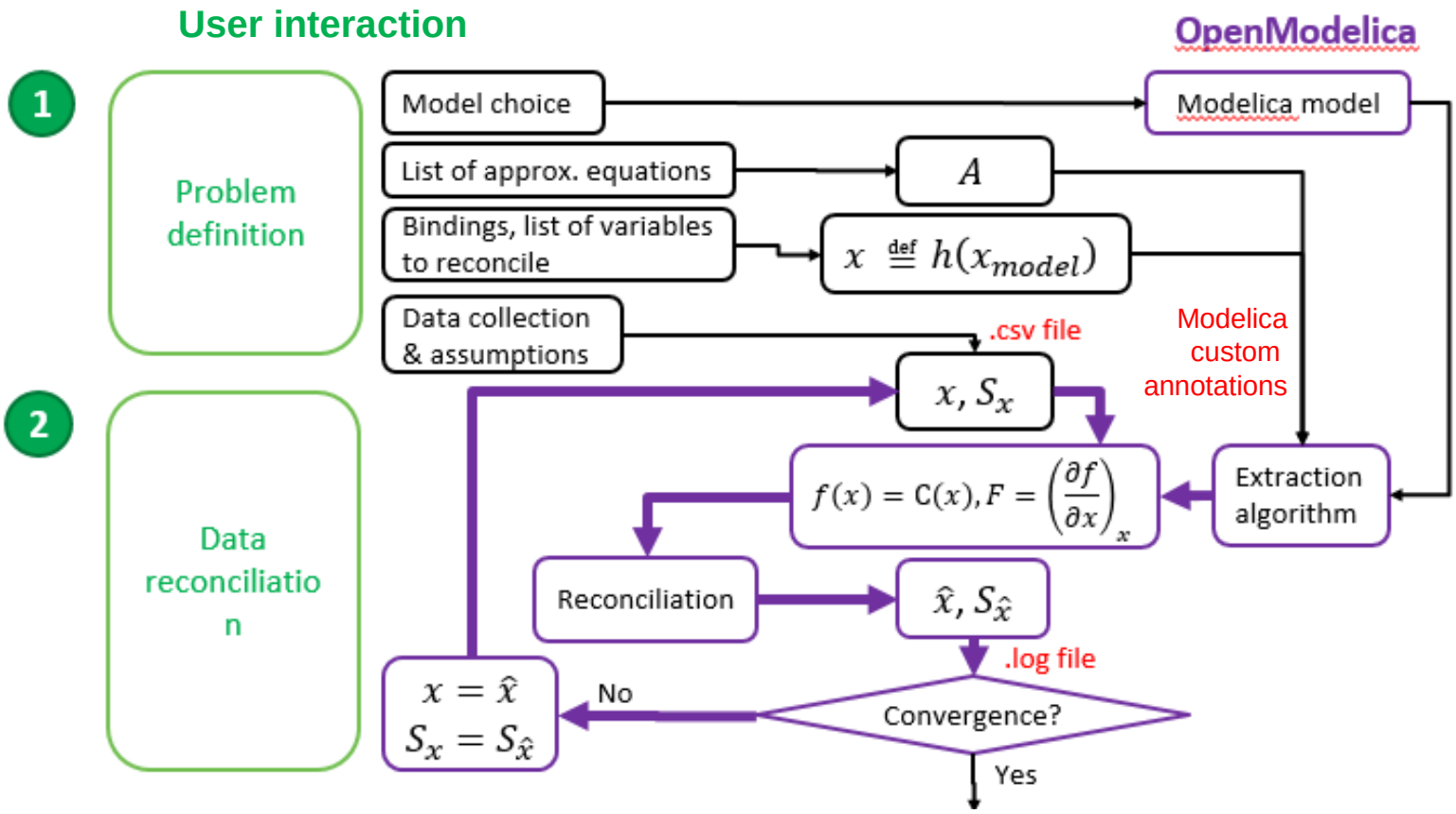
Implementation in OpenModelica



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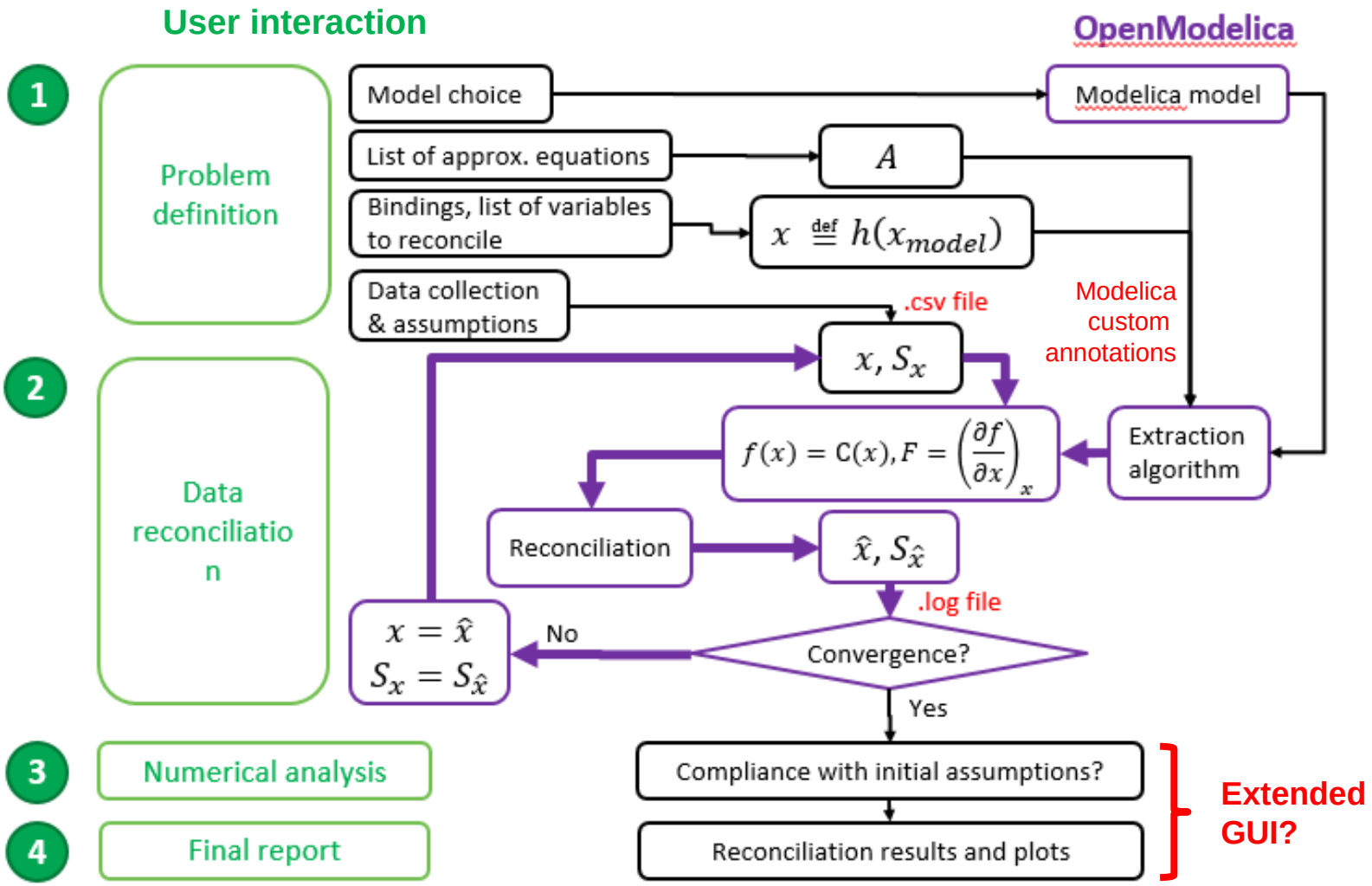

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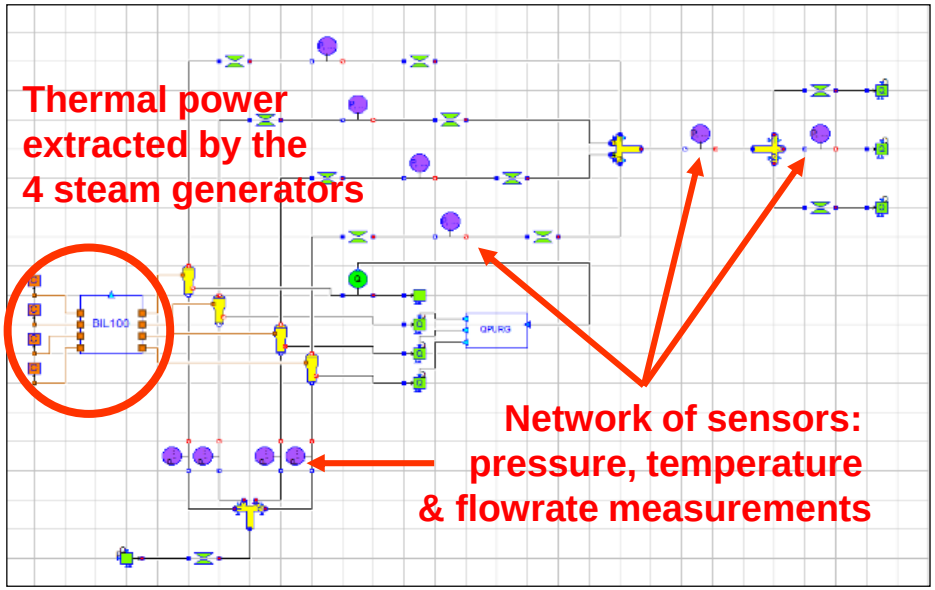
Preliminary results

- The main features of the tool chain have been implemented by LIU in OpenModelica: equation extraction + reconciliation procedure.
- Extraction has been successfully tested on small examples.
- Further experimentation is ongoing to:
  - Ensure good convergence of the reconciliation procedure in case of model nonlinearities.
  - Scale-up to use-cases of industrial-size such as the BIL100.
  - Diagnose ill-posed problems with appropriate error messages.



Partial model of power plant secondary loop

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Conclusion and future work

- Data reconciliation is a promising technique for power plant monitoring that takes into account sensors uncertainties and drifts.
- Use of data reconciliation is limited today because specific tools are needed that require to develop on-purpose models.
- Modelica is a way to democratize the use of data reconciliation for power plant monitoring provided that existing models developed for other purposes can be reused.
- This objective has been achieved thanks to the implementation made in OpenModelica that extracts automatically from the Modelica models the equations to be used by data reconciliation.
- This is still ongoing work.
- Still to be completed: complementary tests, a user-friendly GUI.

Thank you for your attention