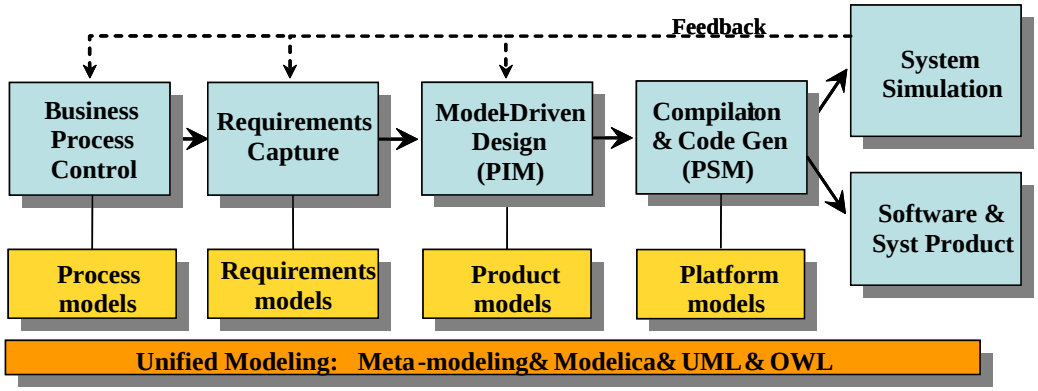
ITEA 2

INFORMATION TECHNOLOGY FOR EUROPEAN ADVANCEMENT



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5th OpenModelica Annual Workshop

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Handling of Uncertainties in OpenModelica: Data Reconciliation and Propagation of Uncertainties

audrey.jardin@edf.fr
daniel.bouskela@edf.fr

EDF

LINKÖPINGS UNIVERSITET

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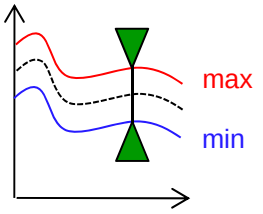
Rationale (1/2)

- Handling uncertainties… OK…
- But FOR WHICH industrial needs?

(1) Use models to estimate the uncertainties of quantities that are not directly measurable or accessible

e.g.: radioactive areas, problem of space requirements, …

(2) Use redundant information (model+ measurements)
- to reduce the uncertainty of the state estimation



- and detect sensor failures

e.g.: drift, calibration problem, …

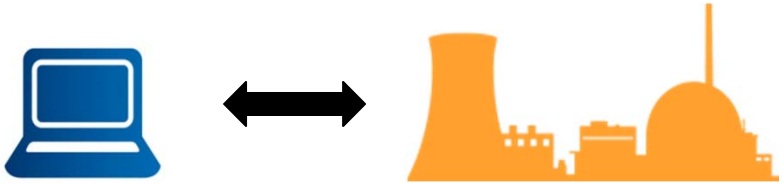
Rationale (2/2)

- WHY managing uncertainties in Modelica?

(1) To reuse existing models not necessarily written initially for uncertainties studies
(capitalization on modelling efforts)

(2) To have control over the equations used for handling uncertainties
(contrary to proprietary languages of some dedicated software)

Introducing uncertainties in Modelica models is an efficient way to reuse models initially conceived for virtual design for monitoring and predictive simulation of real systems



Outline

HOW to manage uncertainties in Modelica?

1. Implementation Strategy

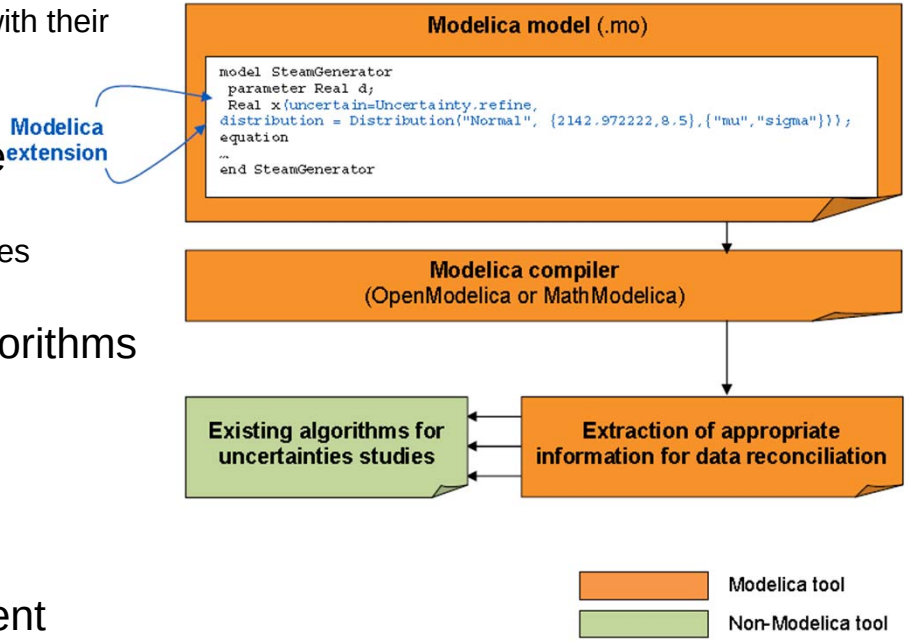
2. Application to Propagate Uncertainties through a Model
   - Principles of the Method
   - Prototype Architecture & Demo

3. Application to Reconcile Data
   - Principles of the Method
   - Prototype Architecture & Demo

4. Conclusion & Prospects

Handling of Uncertainties in Modelica
1. Implementation Strategy

- HOW to manage uncertainties in Modelica?
  - Extend the Modelica language
    - To declare uncertain (random) variables with their distribution laws
    - To tag approximated model equations
  - Extract automatically the appropriate information from existing models
    - Extract the description of uncertain variables
    - Extract the set of constraints
  - Pass the information to standard algorithms to compute the uncertainties
    - Automatic coupling with OpenTURNS
    - VDI 2048 algorithm for data reconciliation



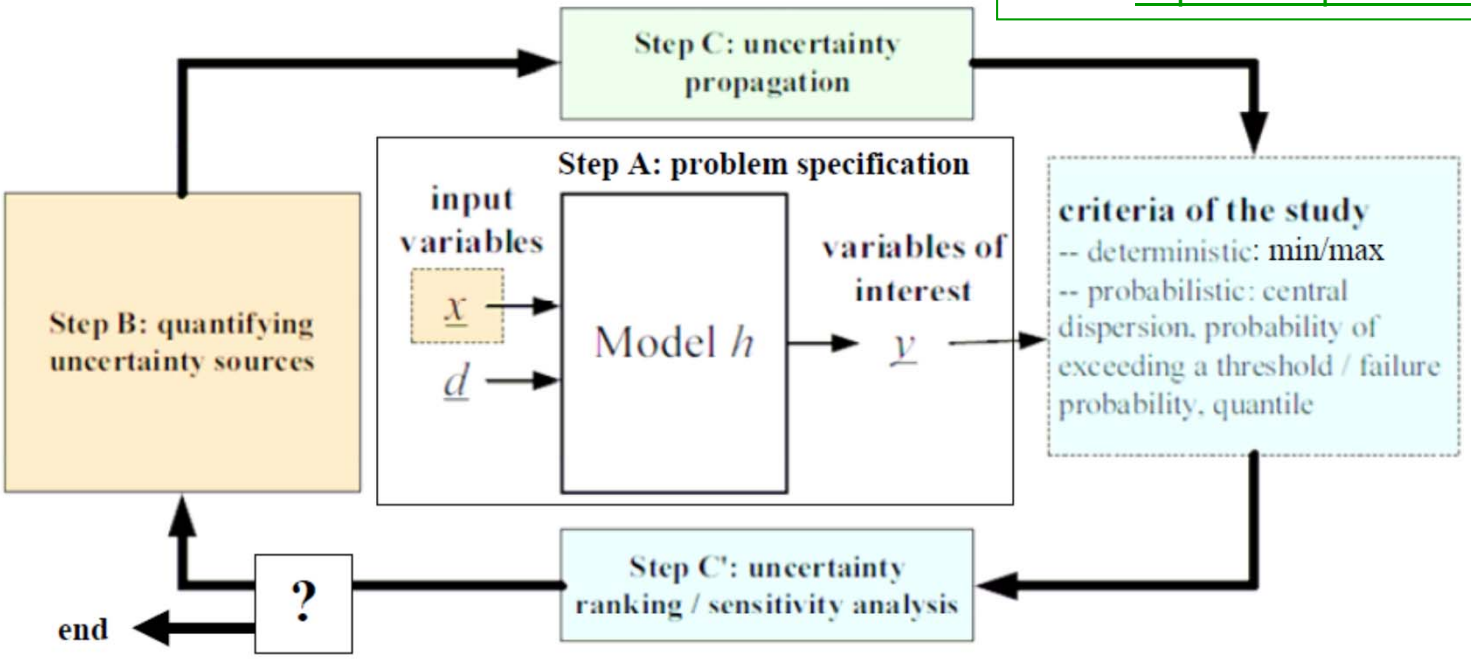
- Benefits
  - Obtention of an integrated environment
    - for both process modelling and uncertainty computations
    - open source
    - independent as much as possible from the chosen Modelica environment
  - Ease of knowledge transmission
    - information related to uncertainty is directly stored in the physical model

Handling of Uncertainties in Modelica
2. Application to Propagate Uncertainties

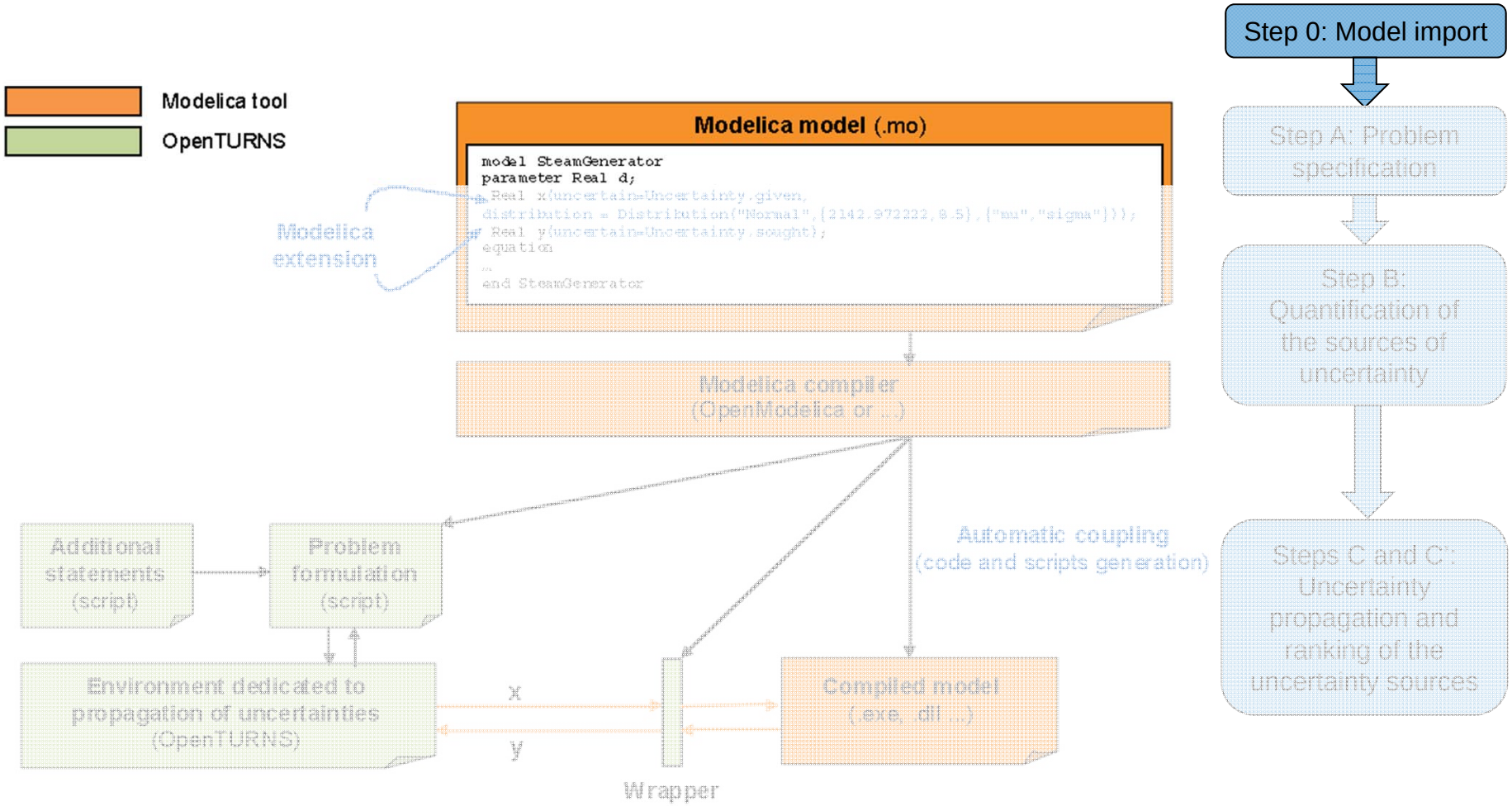
- Objective
  - Evaluate the uncertainties of variables of interest by propagating sources of uncertainty through a model

- Principles of the Method

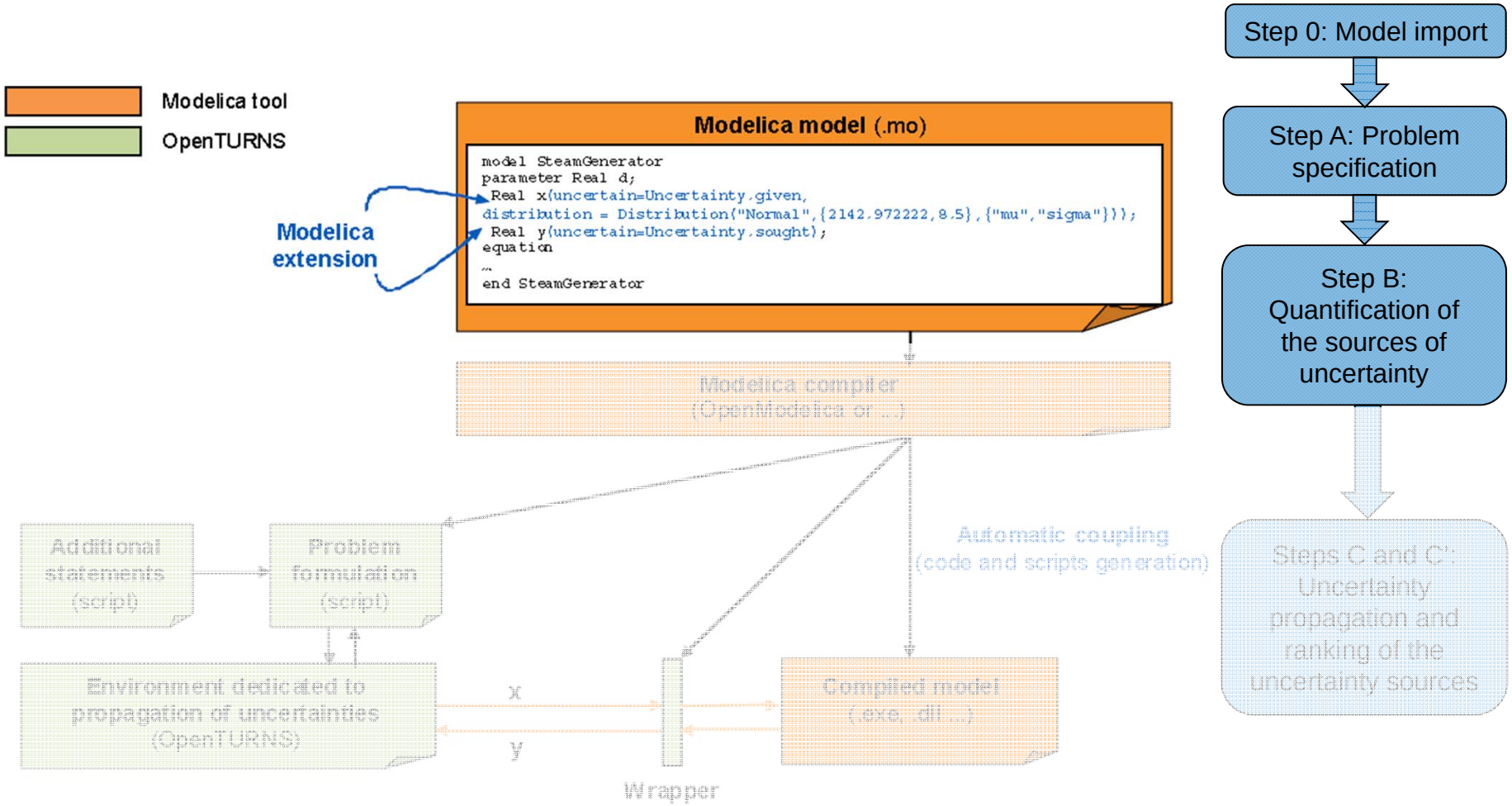
Open TURNS
≈ reference tool for propagation techniques
- open source
- developed by EDF, PhiMeca & EADS
- http://trac.openturns.org/



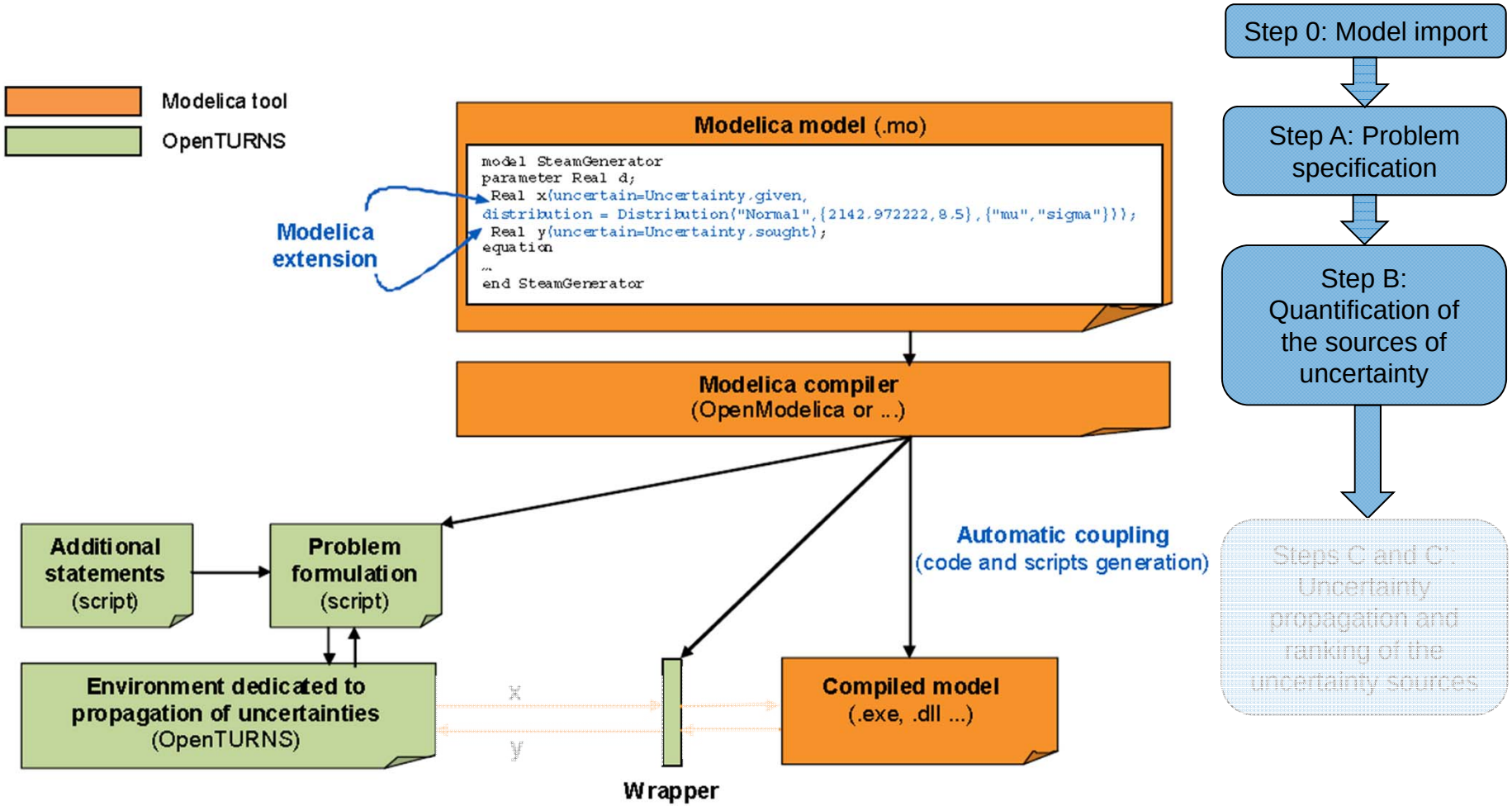
Handling of Uncertainties in Modelica
2. Application to Propagate Uncertainties



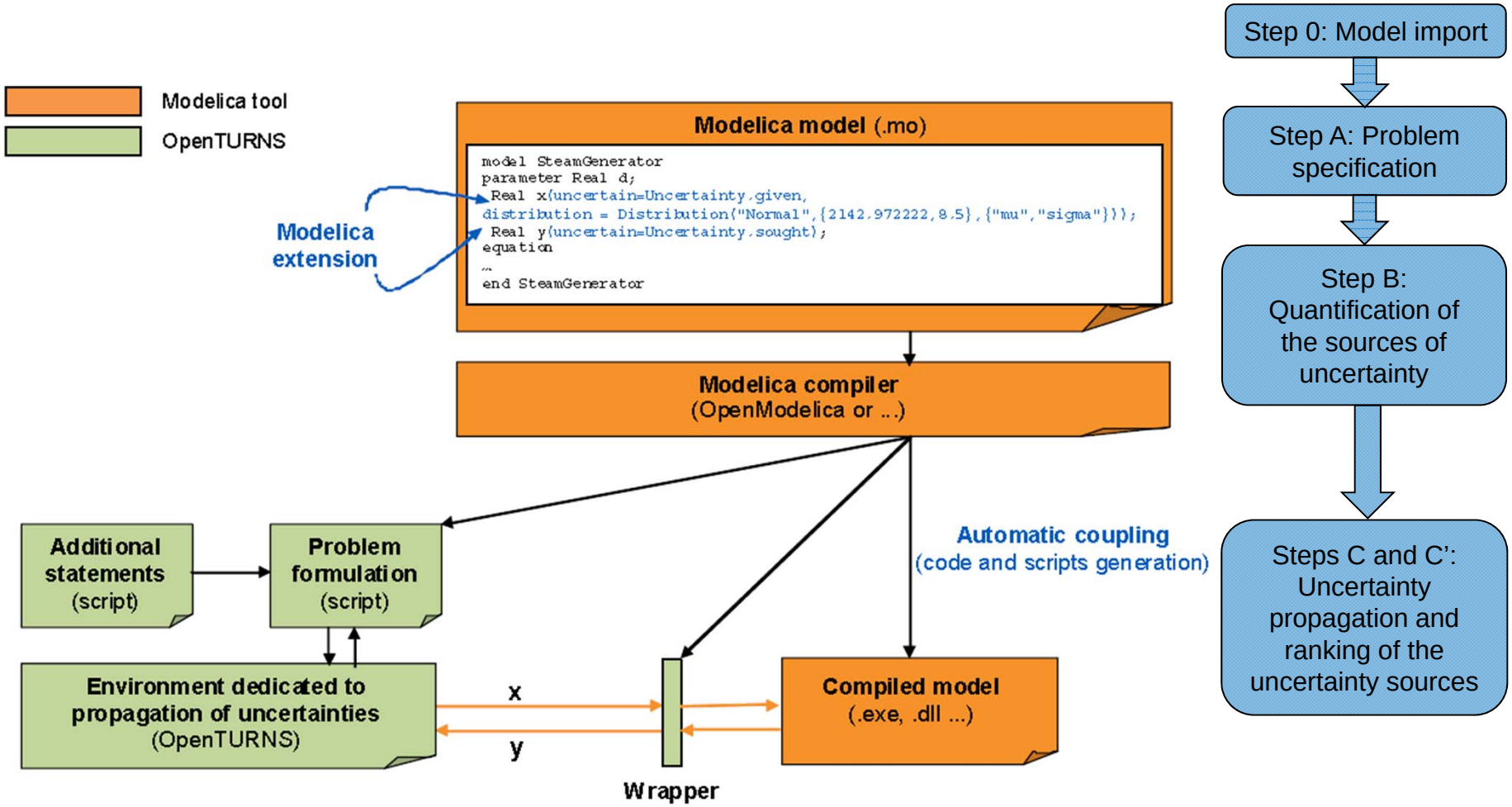
Handling of Uncertainties in Modelica
2. Application to Propagate Uncertainties



Handling of Uncertainties in Modelica
2. Application to Propagate Uncertainties



Handling of Uncertainties in Modelica
2. Application to Propagate Uncertainties

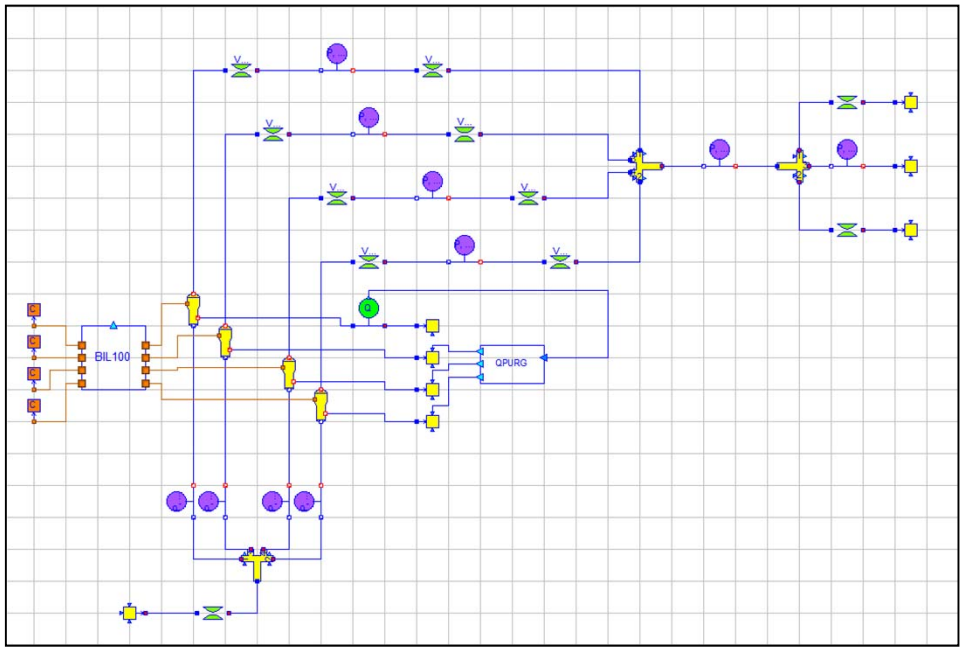


Handling of Uncertainties in Modelica
2. Application to Propagate Uncertainties

- Demo on which model?

  A **partial** model of the secondary loop of a nuclear power plant
  → 4-Steam Generator Unit

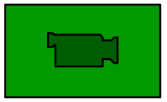
- For what? To assess the thermal power of the plant and its related uncertainty



$$W^i_{th,SG} = Q^i_{EE} \cdot \left(H^i_{SV} - H^i_{EE}\right) - Q^i_P \cdot \left(H^i_{SV} - H^i_P\right)$$

Demo scenario for OpenTURNS

The uncertainty of the thermal power is estimated by propagating the sensors measurements uncertainties through the Modelica model



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Handling of Uncertainties in Modelica
3. Application to Reconcile Data

- Objective
  - Improve the prediction of a model and validate measurements

- Principles of Data Reconciliation
  - Use of redundant information to correct measured values and better estimate the real behavior of the process

VDI 2048 ≈ standard for applying data reconciliation to energy systems

Contradictory measurements with uncertainties

Flows, Pressures,… $\Rightarrow x, \sigma_x$

$Q_1 = 5 \pm 1 \quad Q_2 = 5 \pm 1 \quad Q_3 = 12 \pm 2$

Physical knowledge

Mass balances, Sensors redundancies,… $\Rightarrow f(\bar{x}) = 0$

$\hat{Q}_1 + \hat{Q}_2 - \hat{Q}_3 = 0$

Data reconciliation

$$\min_{x_i} \left(\sum_i \left(\frac{\hat{x}_i - x_i}{\sigma_i} \right)^2 \right) \text{ with } f(\hat{x}) = 0$$

Optimization problem under constraints

Solving

Linearization

$$f(\hat{x}) \approx f(x) + \left(\frac{\partial f(x)}{\partial x} \right) \cdot \nu$$

→ Analytical solution

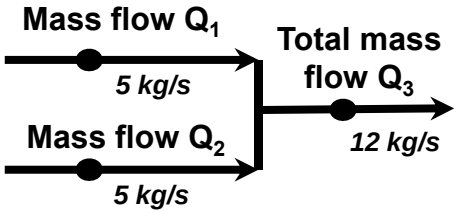
Reconciled values

- closer to the true values
- coherent with physical laws
- reduced uncertainties

$\Rightarrow \hat{x}, \sigma_{\hat{x}}$

$\hat{Q}_1 = 5.33 \pm 0.91 \quad \hat{Q}_2 = 5.33 \pm 0.91$

$\hat{Q}_3 = 10.67 \pm 1.15$



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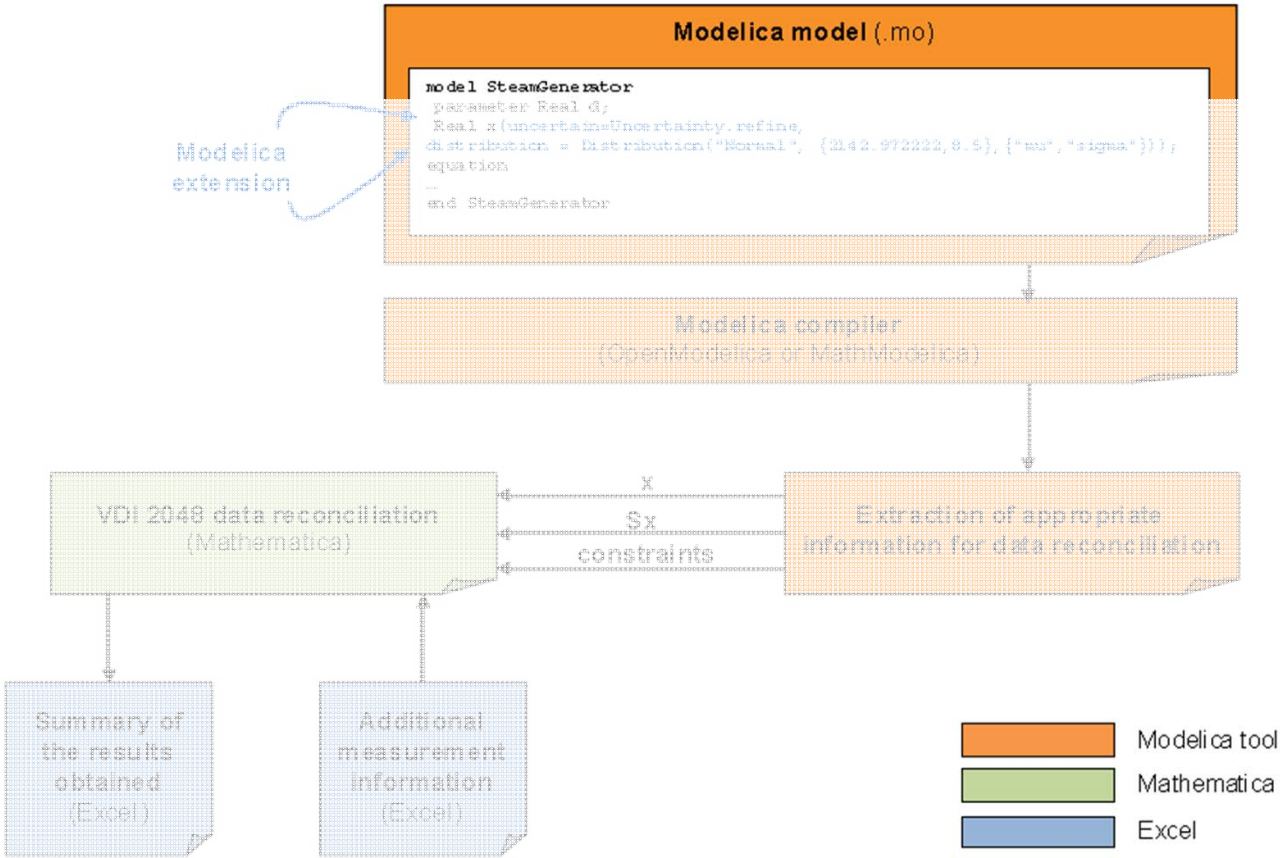
Handling of Uncertainties in Modelica
3. Application to Reconcile Data

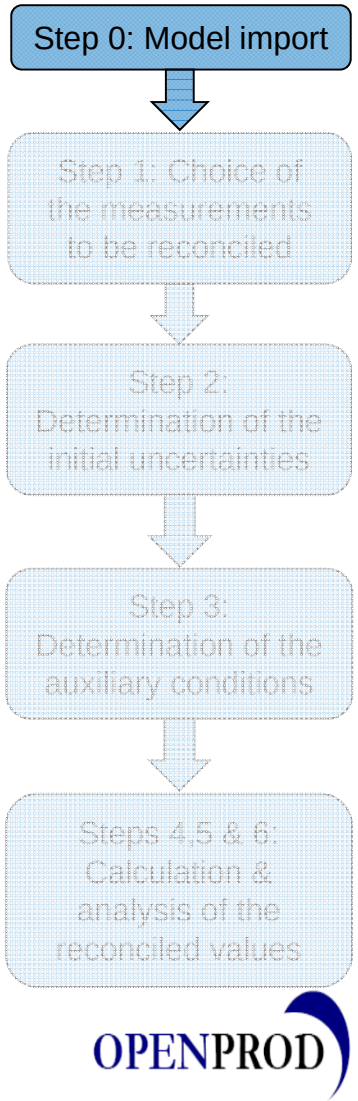
- Challenge
  - Extract from the existing simulation model only the equations that will constitute the auxiliary conditions of the reconciliation problem
  - These constraints are the equations that:
    - Relate variables to be reconciled with each other
    - Are assumed as exact (unless correcting the measurements superficially)
  - By definition, they form a non-square system

- Principles of the Extraction
  1. Eliminate as much as possible intermediate variables
  2. Remove equations flagged as approximated and under-constrained systems of equations w.r.t. intermediate variables
  3. If possible, remove unrelated variables and their associated equations
  4. If possible, remove output variables and their associated equations
  5. Extract the set S for solving the remaining variables from the known variables (i.e. the variables that are reconciled)
  6. Extract the set C of auxiliary conditions

Paves the way towards the reuse of models for other purpose than simulation

Handling of Uncertainties in Modelica
3. Application to Reconcile Data





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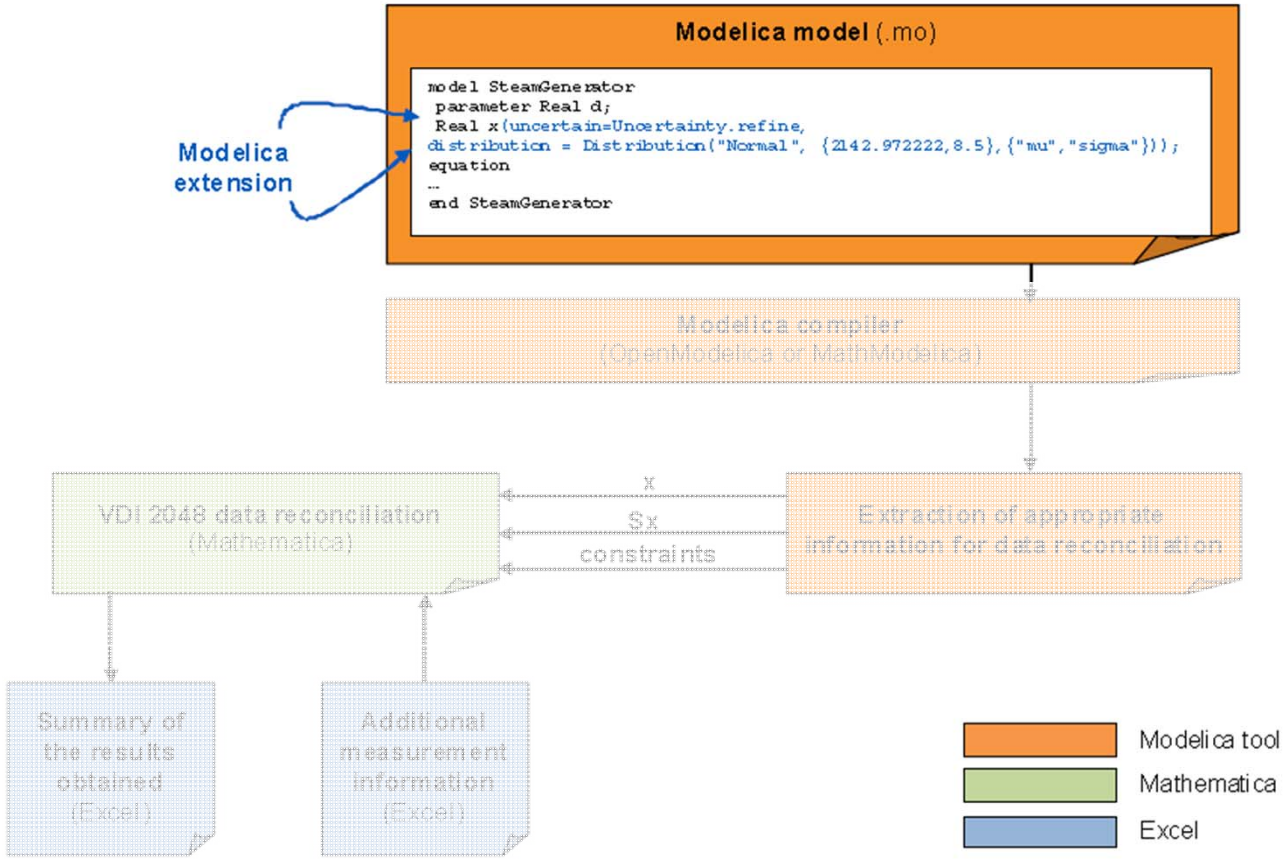

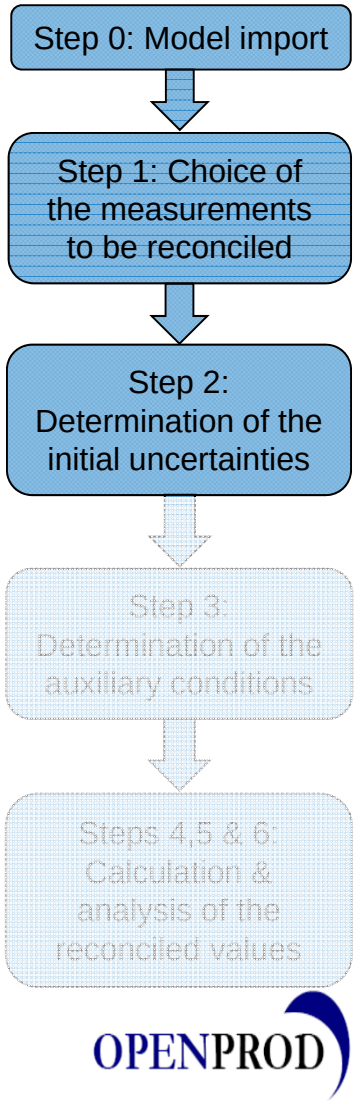

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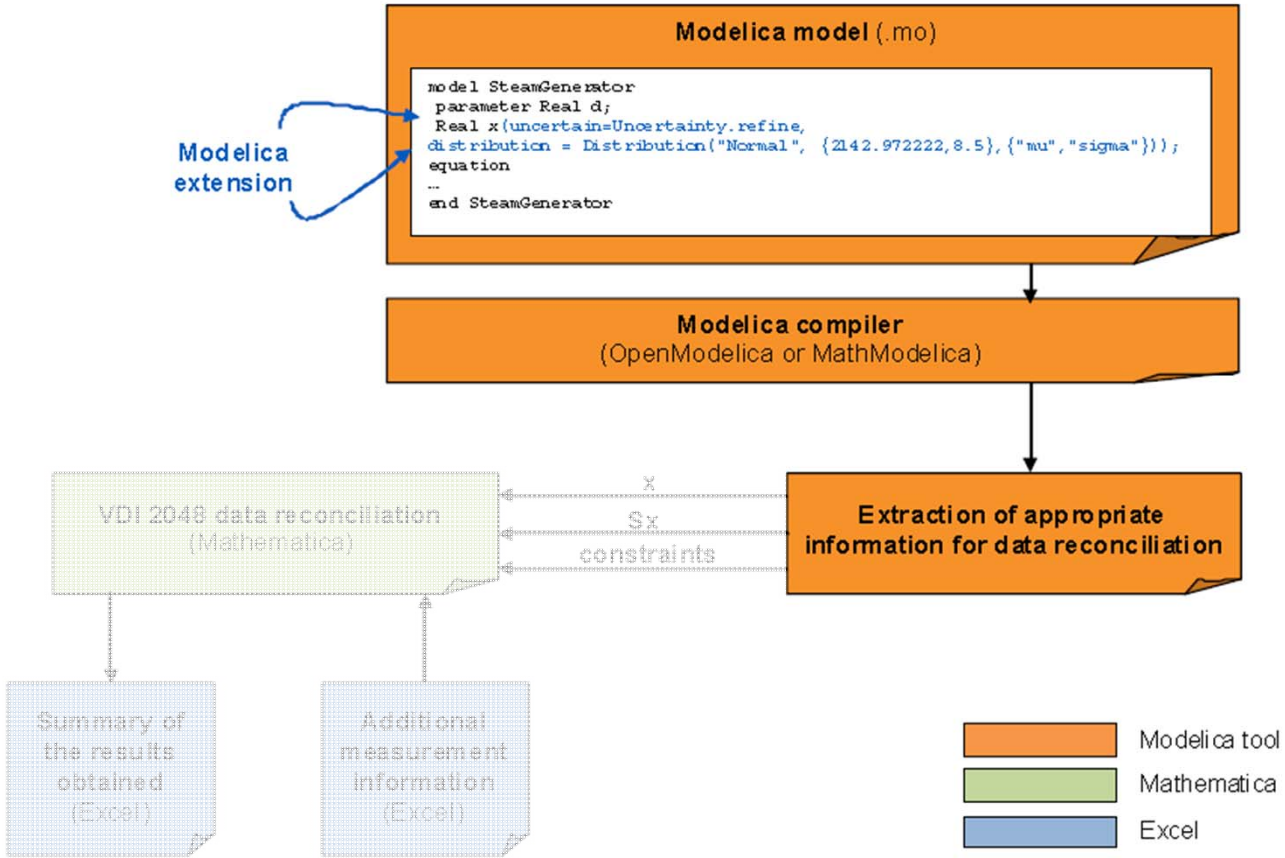
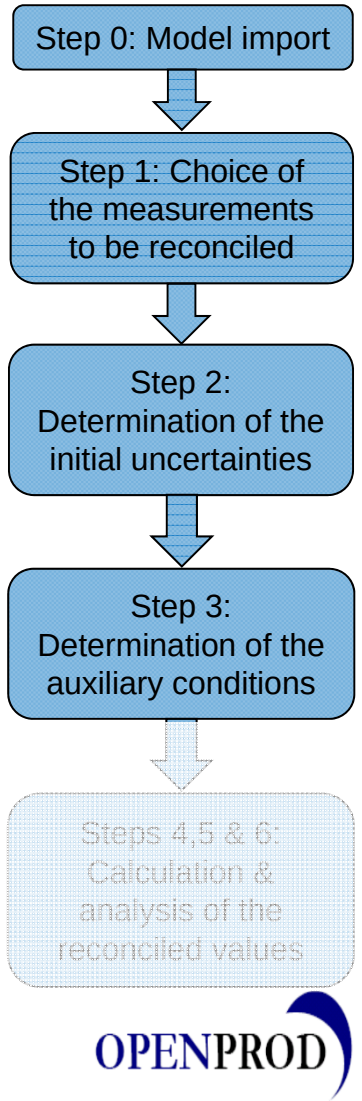
Handling of Uncertainties in Modelica
3. Application to Reconcile Data





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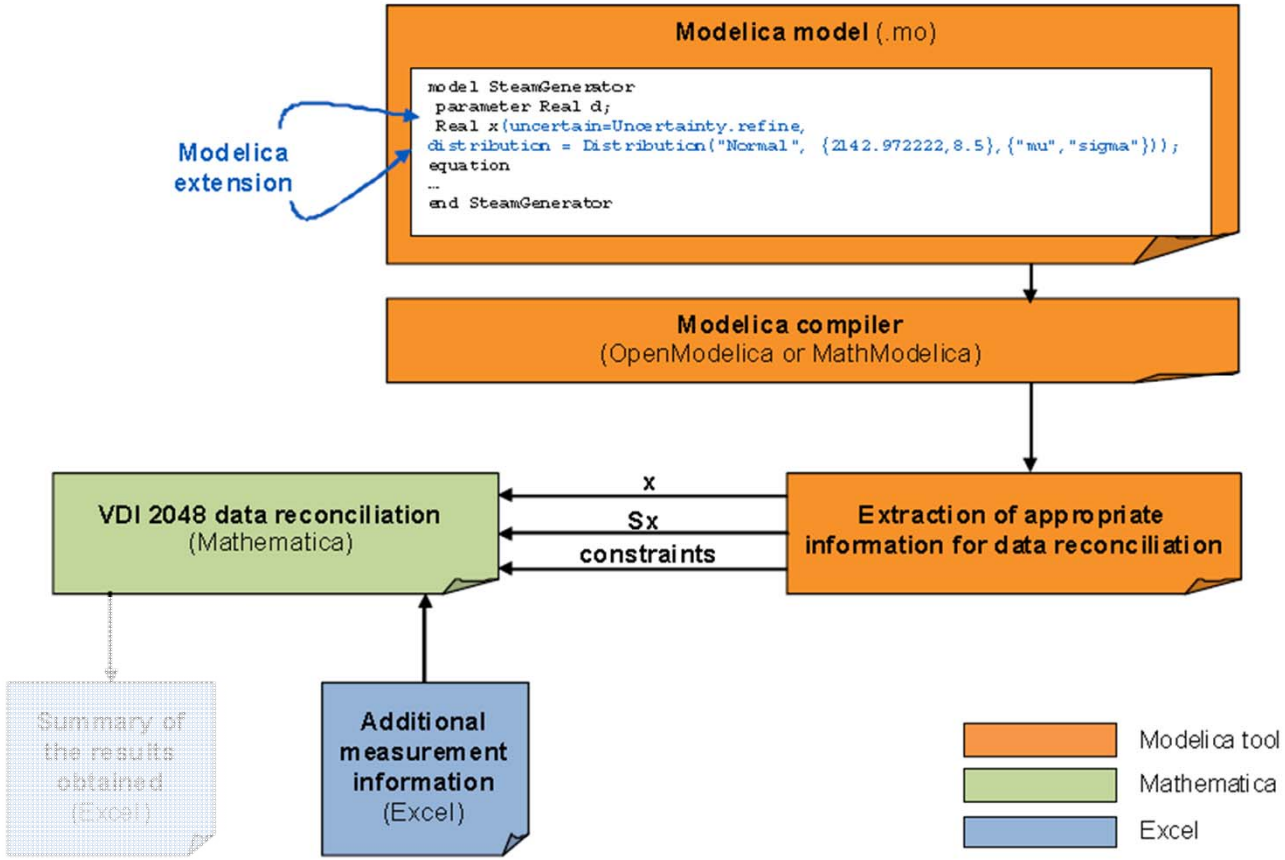

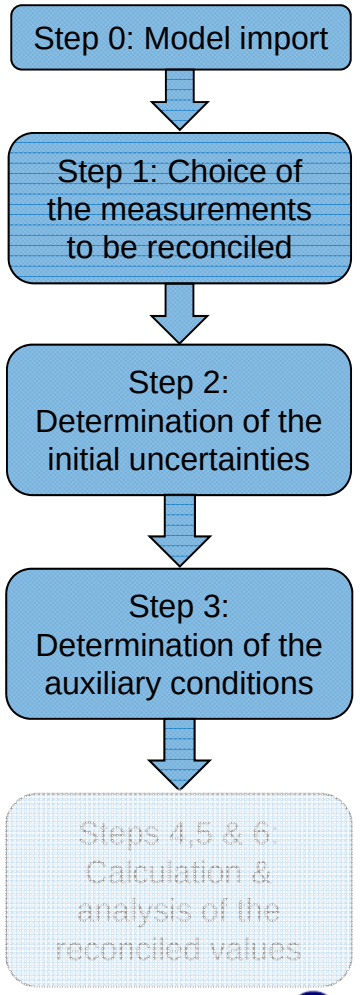

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Handling of Uncertainties in Modelica
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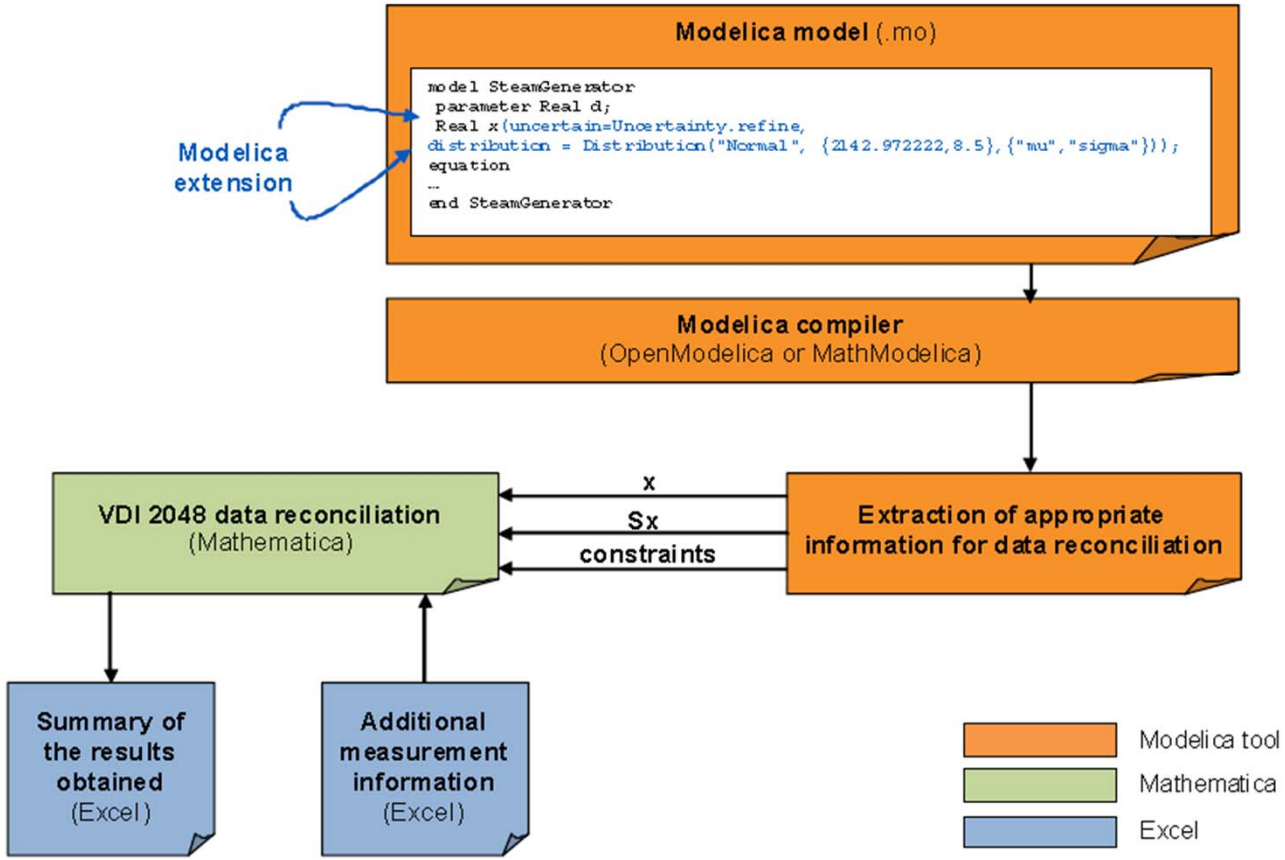
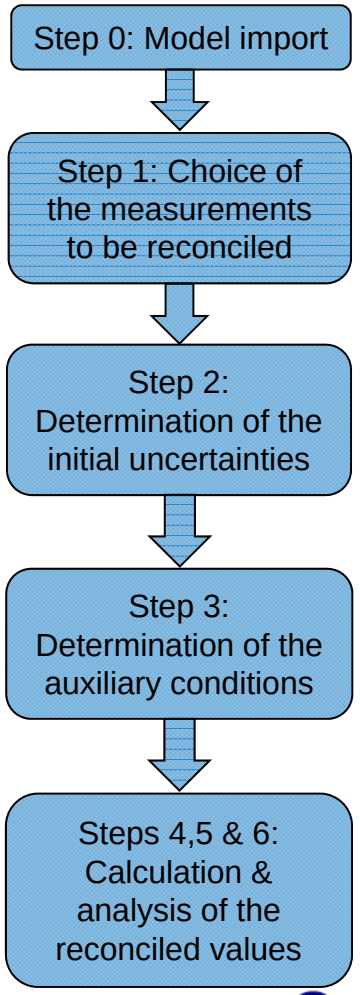


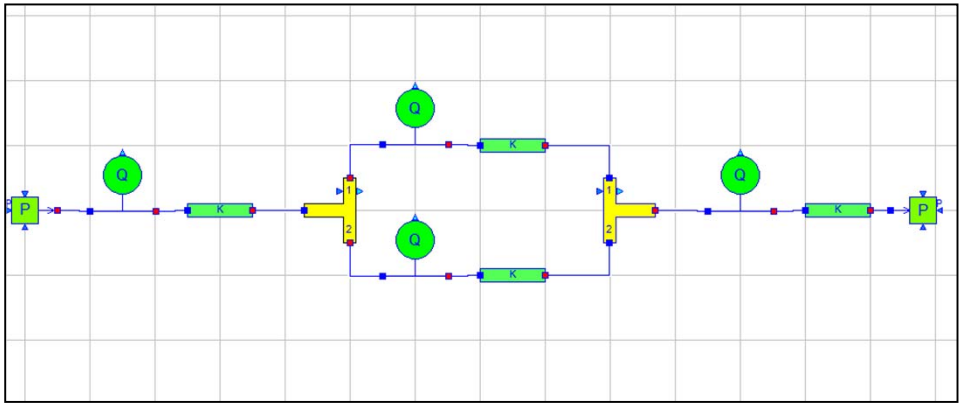


Handling of Uncertainties in Modelica
3. Application to Reconcile Data

- Demo on which model?

  A simple hydraulic circuit

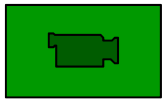
- For what? To validate and refine flow rate measurements



Demo scenario for data reconciliation

Four flow rate measurements are reconciled using only the mass balance equations

ALTHOUGH the initial model contains more physics (i.e. more equations)



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Conclusion & Prospects (1/2)

- Technical results
  - Better support of the EDF thermohydraulic library by OMC & MathModelica
  - Extensions of the Modelica language
    - New attributes to the built-in classes `Real` and `Integer`: `uncertain`, `distribution`
    - New enumeration type `Uncertainty`: `given`, `sought`, `refine`
    - Collection of records to define several types of distribution laws
    - Set of equations to define correlation and covariance matrices
  - Specific model processing for data reconciliation
    - Tagging of the approximated equations
    - Extraction of adequate equations
    - Connection to Mathematica for formal computation
  - Automatic coupling with OpenTURNS for propagation methods

- Dissemination
  - Article published for the 8th International Modelica Conference
  - Communication at the 68th Modelica Design Meeting

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Conclusion & Prospects (2/2)

- Prospects
  - Improve the support of ThermoSysPro by OMC (initialization problems still remain)
  - Continue the standardization effort about extending Modelica to stochastic aspects
  - Consolidate the extraction algorithm for data reconciliation…

    …and extend the concept to other state estimation algorithms (data assimilation…)

- Potential industrial exploitation
  - Plant diagnostics (assessment of clogging in steam generators)
  - System monitoring (improve the knowledge of the operating point)

→ Internal EDF projects + european ITEA2 MODRIO project

Acknowledgements

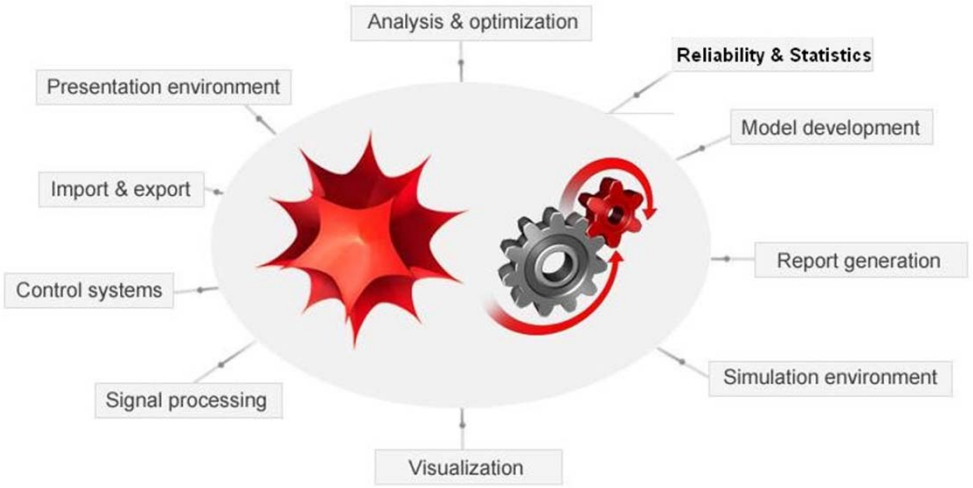
Work achievement was only possible through international european collaboration

Many thanks to all contributors

- **Linköping University**
  - Adrian Pop
  - Peter Fritzson …
- **Wolfram MathCore**
  - Peter Aronsson
  - Leonardo Laguna …
- **IFP Energies Nouvelles**
  - Zakia Benjelloun-Touimi …

APPENDIX

Exploitation - Uncertainty tool chain in Wolfram SystemModeler



Modelica model with uncertainties

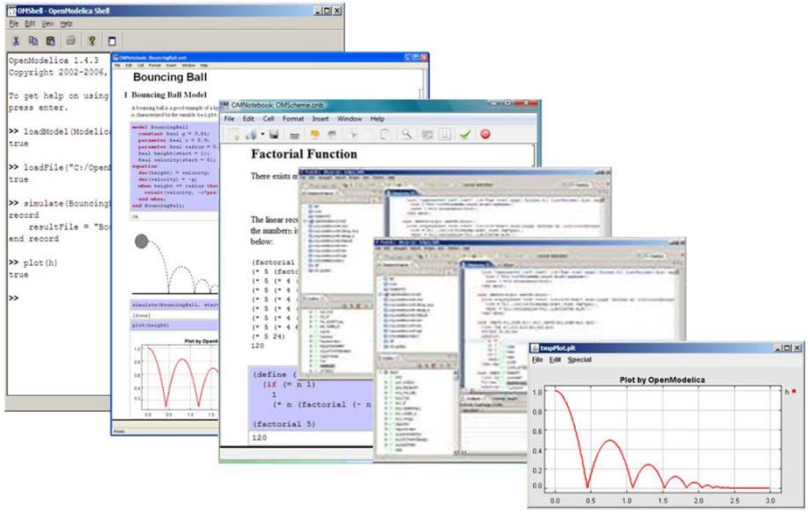
OpenProd:

- Data reconciliation

Near Future:

- Uncertainty propagation (prototype done & available in OpenModelica)
- Model calibration (MODRIO)
- Parameter & State estimation (MODRIO)

Exploitation - Uncertainty tool chain in OpenModelica



Modelica model with uncertainties

- Data reconcilation
  - Equation extraction in OpenModelica backend
- Data propagation
  - Connection with OpenTURNS through Modelica scripts

Handling of Uncertainties in Modelica
List of Requirements

- [R1] Identify the uncertain variables
  (as both inputs and outputs for data reconciliation or as pure inputs or pure outputs for propagation)
- [R2] Assign different types of distribution laws to uncertain variables
  (with their associated parameters)
- [R3] Specify dependencies between uncertain variables
  (in the form of covariance or correlation matrices)
- [R4] Identify the approximated equations
  (data reconciliation uses only constraints that are assumed as perfect)

Modelica extensions

- [R5] Handle redundant information and extract the auxiliary conditions
  (by selecting the appropriate subset of model equations that relate variables to be reconciled)
- [R6] Compute the Jacobian matrix of the auxiliary conditions
- [R7] Perform the data reconciliation algorithm

Connection to VDI 2048 algorithm coded in Mathematica

- [R8] Define the decision criterion of the uncertainties study
  (e.g. central dispersion, probability of failure, …)
- [R9] Specify the chosen propagation algorithm and sensitivity analysis
  (as well as their parameters)
- [R10] Perform propagation algorithms and run sensitivity analysis

Connection to OpenTURNS