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Università degli Studi di Ferrara | IN4 innovazione ingegneria integrazione industria

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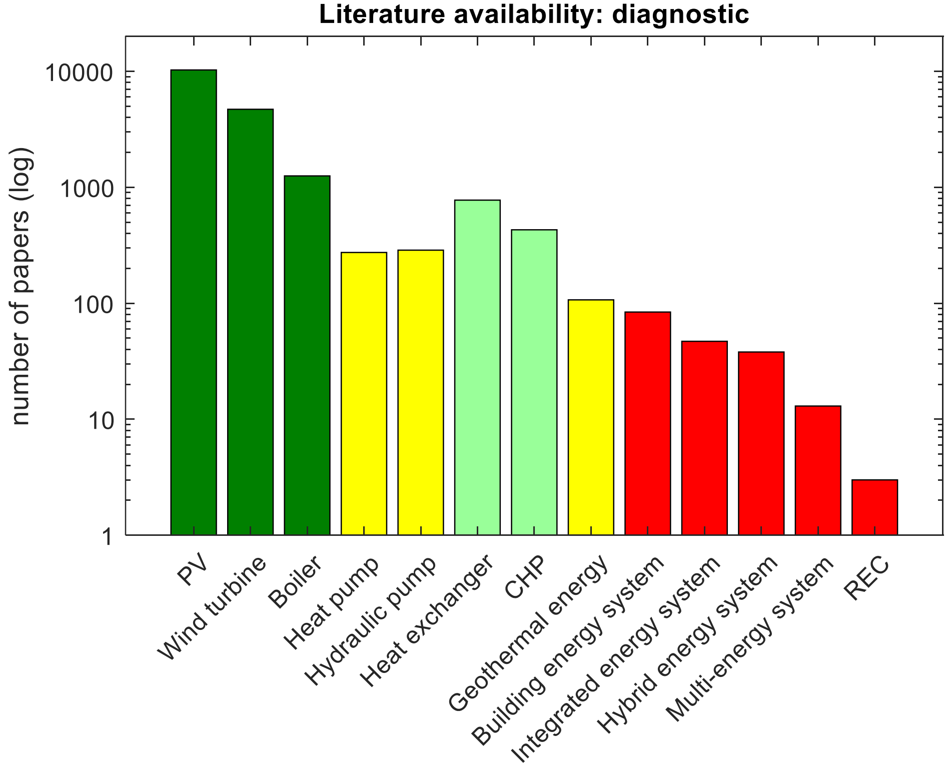
WP 2
ANALISI DELLO STATO DELL'ARTE

State of the art: REC diagnosis

Available papers

- Research source: Science Direct
- Keywords:
  - "fault detection", "diagnostic", “FDD", and "diagnosis”



List of available projects

- Research source: Cordis

Project	Duration	Focus
Energynius	2019-2021	Design and management of integrated energy systems
WEDISTRICT	2019-2023	Integration of multiple sources of renewable energy and excess heat at three demonstration sites
ESPON TANDEM	2024-2028	Creation of the largest EU-backed database of energy communities
ASCEND	2023-2027	Implementation of PCED (Positive clean energy district) in multiple cities
D4Heat	2024-2027	Data-driven diagnosis of district heating substations

Literature review: current status

	Component	Types of fault	Diagnostic methodology	Literature gap
Energy production & storage	Heat pump	✓	✓	✓
	Boiler	✓	✓	
	CHP	✓	✓	
	PV			
	Battery			
	Absorption chiller			
	Compression chiller			
Energy distribution	District heating network	✓	✓	✓
	District cooling network	✓	✓	✓
	Pump	✓	✓	
	Power grid			

Thermal energy	
Electrical energy	
Cooling energy	

Legend
In depth analyzed by IN[4] ✓

Example of literature review: heat pumps

Types of faults

Fault	Impact	Reference
Refrigerant Undercharge	COP drop, increased discharge temp, compressor risk	[1-8]
Refrigerant Overcharge	Increased compressor work, possible liquid slugging	[2-5, 9-15]
Non-condensable Gas	Increases pressure, Thermal expansion valve malfunction	[10, 15-17]
Liquid Line Restriction	Flow drop, temperature anomalies	[7, 9, 11, 13, 14, 16, 18-20]
Heat Exchanger Fouling	Reduced heat transfer, pressure drops	[4, 10, 12, 13, 20-23]
Compressor Valve Leakage	Flow rate drop, increased suction pressure	[4, 6, 14, 20]
4-way Valve Leakage	Refrigerant bypass, COP drop	[16, 17, 21, 24]
Sensor Faults	False diagnostics, compromised controls	[17, 25]

Diagnostic methodologies

Model category	Examples	Reference
Physics-based	• Thermodynamic analysis • UA factor and LMTD modification • Energy balance equation • Refrigerant state correlations	[26-30]
Data-driven	• ANN • SVM • PCA • Bayesian network • tree-based model	[26, 27, 31]
Hybrid	A combination of data-driven and physics-based models	[32, 33]

Literature gap

- Limited availability of FDD methods for multiple simultaneous faults
- Few methods with realistic reproduction of faults
- Limited literature regarding reversible heat pumps

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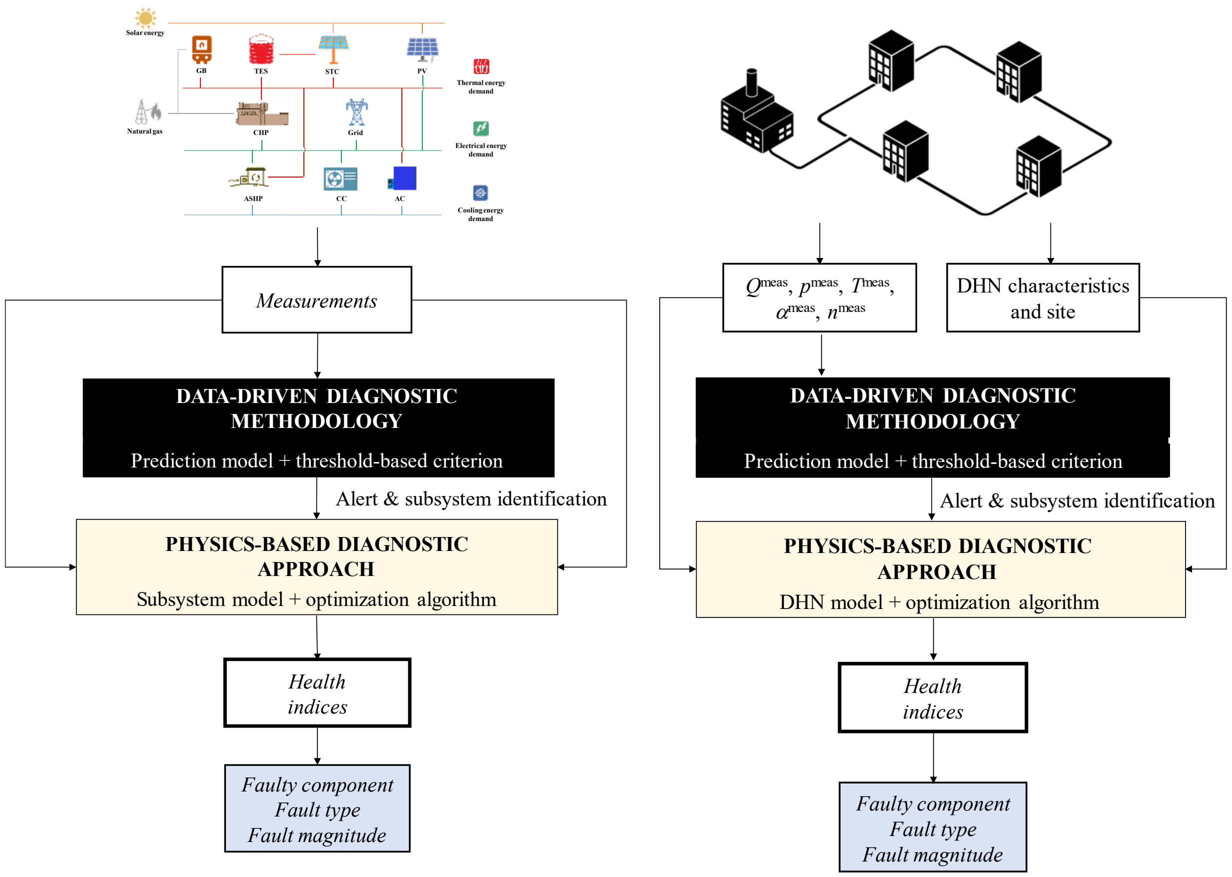
WP 3
SVILUPPO DI TOOL PER LA DIAGNOSI DI SISTEMI MULTI-ENERGIA & RETI DI TELERISCALDAMENTO

Goal

Methodology



Data-driven approach

Identification of the faulty sub-system

- Transient and steady-state operation

Physics-based approach

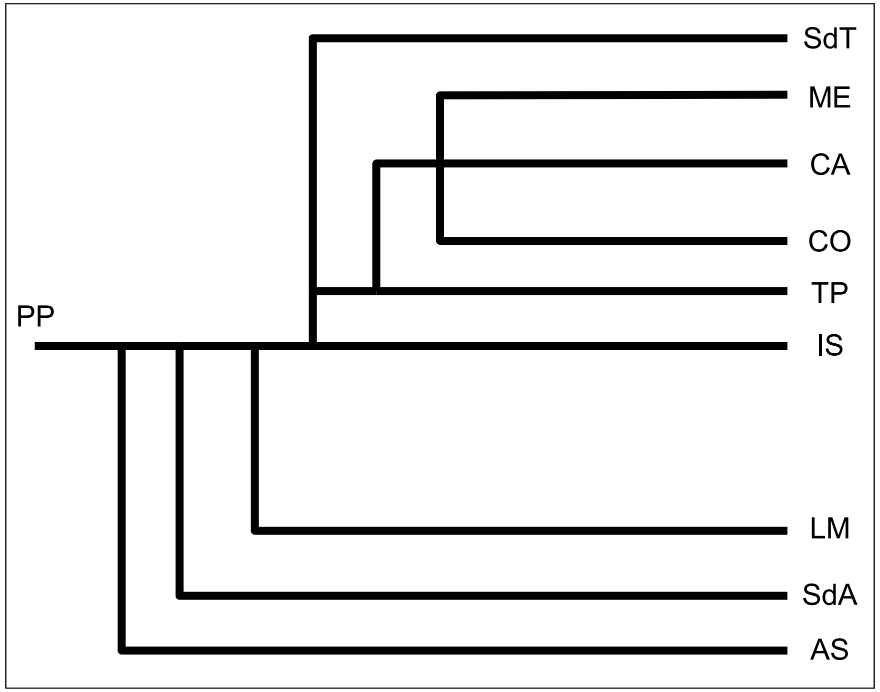
Identification of the fault type and magnitude

- Steady-state operation

SVILUPPO DI TOOL PER LA DIAGNOSI DI RETI DI TELERISCALDAMENTO

Case study

District heating network of the Campus of University of Parma



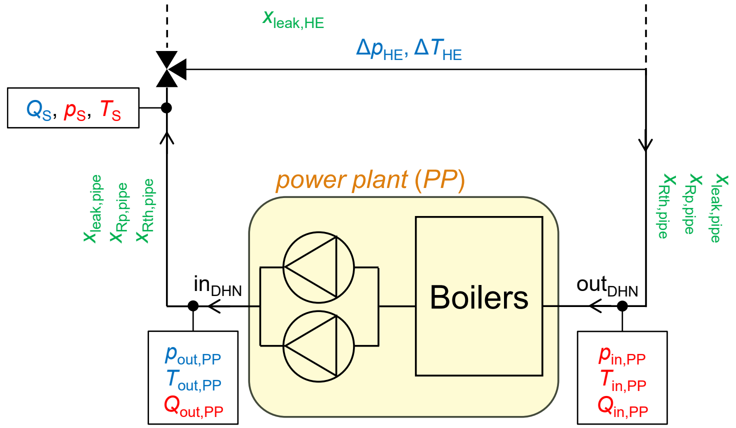
- 9 end-users
- 32 pipes (supply + return pipelines)
- 2 pumps

- 17 datasets with faults and without faults

Data-driven approach (in progress)

Physics-based approach

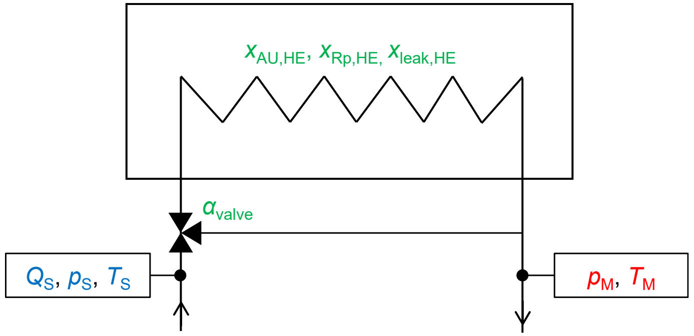
Pipes



INPUTS	
Independent variables	$Q_S, p_{out,PP}, T_{out,PP}$ $T_{soil}, \Delta T_{HE}, \Delta p_{HE}$
	$\mu_{pipe}, D_{int,pipe}, D_{int,ins}, D_{int,case},$ $L_{pipe}, \lambda_{pipe}, \lambda_{ins}, \lambda_{case}$
Dependent variables	$p_S, T_S, Q_{out,PP}, p_{in,PP}, T_{in,PP},$ $Q_{in,PP}$

OUTPUTS
$x_{Rth,pipe}, x_{Rp,pipe}, x_{leak,pipe}, x_{leak,HE}$

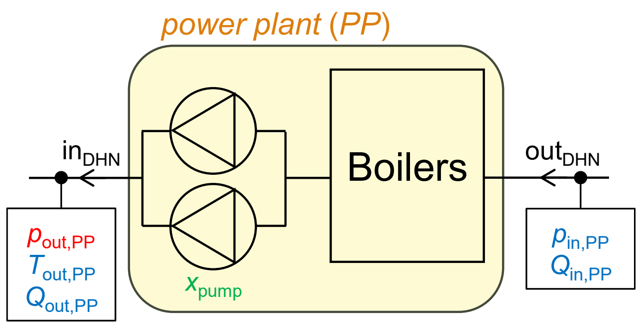
Valves and heat exchangers



INPUTS	
Independent variables	Q_S, p_S, T_S $T_{soil}, T_{EU}, \alpha_{signal}$
	$k_{valve},$ $\mu_{HE}, D_{HE}, L_{HE}, AU_{HE},$ $\mu_{BY}, D_{BY}, L_{BY}, \lambda_{BY}$
Dependent variables	p_M, T_M

OUTPUTS
$\alpha_{valve}, x_{AU,HE}, x_{Rp,HE}, x_{leak,HE}$

Pumps

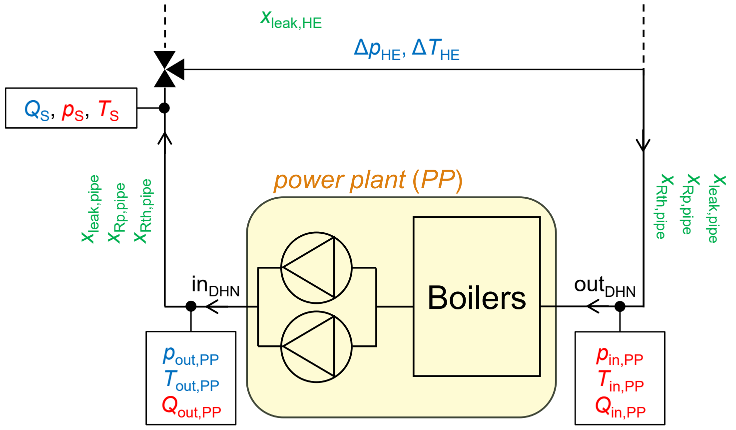


INPUTS	
Independent variables	$p_{in,PP}, Q_{in,PP}, T_{out,PP}, Q_{out,PP}$
	$k_{Boilers}, H_{pump} = f(Q_{out,PP})$
Dependent variables	$p_{out,PP}$

OUTPUTS
x_{pump}

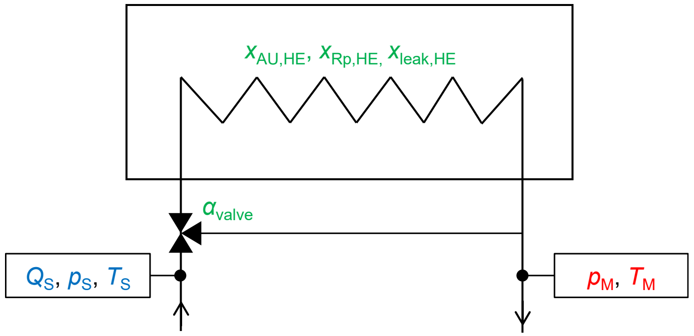
Physics-based approach

Pipes



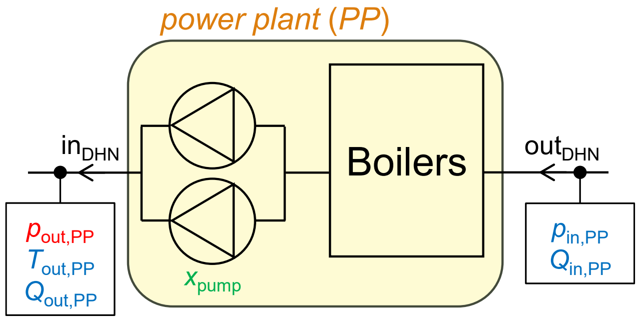
$$OF = \left(\frac{T_{in,PP} - T_{in,PP}^{calc}}{T_{in,PP}^{calc}}\right)^2 + \left(\frac{p_{in,PP} - p_{in,PP}^{calc}}{p_{in,PP}^{calc}}\right)^2 + \left(\frac{Q_{in,PP} - Q_{in,PP}^{calc}}{Q_{in,PP}^{calc}}\right)^2 + \left(\frac{Q_{out,PP} - Q_{out,PP}^{calc}}{p_{out,PP}^{calc}}\right)^2 + \sum_{i=1}^{N_{EU}} \left(\frac{T_{S,i} - T_{M,i}^{calc}}{T_{S,i}^{calc}}\right)^2 + \left(\frac{p_{S,i} - p_{S,i}^{calc}}{p_{S,i}^{calc}}\right)^2$$

Valves and heat exchangers



$$OF = \sum_{i=1}^{N_{EU}} \left(\frac{T_{M,i} - T_{M,i}^{calc}}{T_{M,i}^{calc}}\right)^2 + \left(\frac{p_{M,i} - p_{M,i}^{calc}}{p_{M,i}^{calc}}\right)^2$$

Pumps



$$OF = \left(\frac{p_{out,PP} - p_{out,PP}^{calc}}{p_{out,PP}^{calc}}\right)^2$$

Minimize the *OF*s by using an optimization algorithm based on a gradient-based method

Physics-based approach: challenge #1

Dataset in which pipes are healthy

(all health indices x must be found equal to 1)

	$x_{Q,s}$	$x_{Rth,s}$	$x_{Rp,s}$	$x_{Q,r}$	$x_{Rth,r}$	$x_{Rp,r}$
CT-S04	1.00	0.92	1.00	1.00	0.95	1.00
S04-AS	1.00	1.00	1.00	1.00	1.00	1.00
S04-S07	1.00	0.93	1.00	1.00	0.95	1.00
S07-SdA	1.00	0.97	1.00	1.00	0.99	1.00
S07-S15	1.00	0.87	1.00	1.00	0.89	1.00
S15-LM	1.00	0.97	0.99	1.00	0.99	1.00
S15-S16	1.00	0.99	1.00	1.00	0.99	1.00
S16-IS	1.00	0.92	1.00	1.00	0.93	1.00
S16-S26	1.00	0.88	1.00	1.00	0.83	1.00
S26-SdT	1.00	0.98	1.00	1.00	0.98	1.00
S26-S27	1.00	1.00	1.00	1.00	1.00	1.00
S27-TE	1.00	0.98	1.00	1.00	0.97	1.00
S27-S34	1.00	0.99	1.00	1.00	0.99	1.00
S34-ME	1.00	0.98	0.99	1.00	0.99	1.00
S34-CA	1.00	0.98	1.00	1.00	0.97	1.00
S34-CO	1.00	0.98	1.00	1.00	0.99	1.00

Colour scale: 1, 0.99, 0.98, 0.97, 0.96, 0.95, 0.94, 0.93, 0.92, 0.91, 0.9

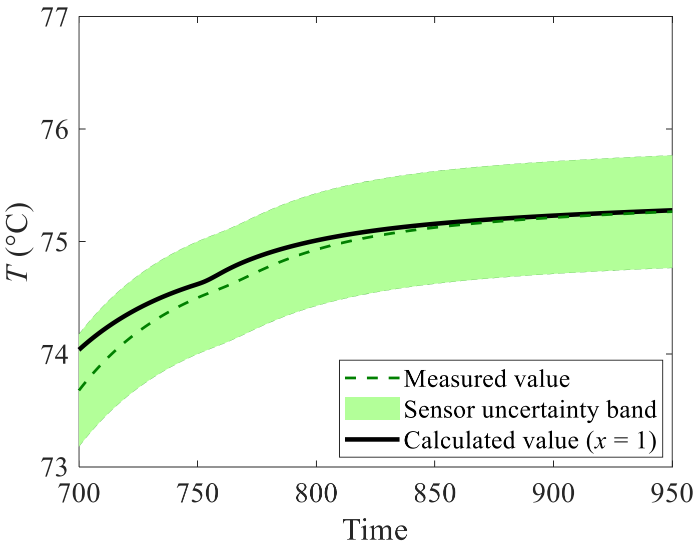
If all health indices *x* are set equal to 1, the difference between (i) the measured temperatures and (ii) the calculated temperatures is lower than 0.1 °C.

The optimization approach significantly reduces the health indices that are associated to thermal dissipations.

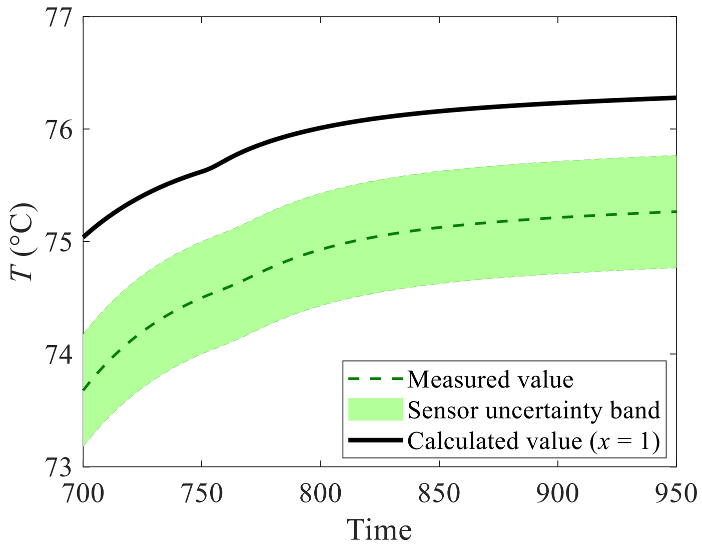
Physics-based approach: challenge #1

Identification of sensor uncertainty bands:

- temperature: ±0.5 °C
- pressure: ±0.25 % full-scale
- mass flow rate: ± 0.3 % reading value



The **calculated value** is ***inside*** the sensor uncertainty band: use the ***calculated value*** in objective function

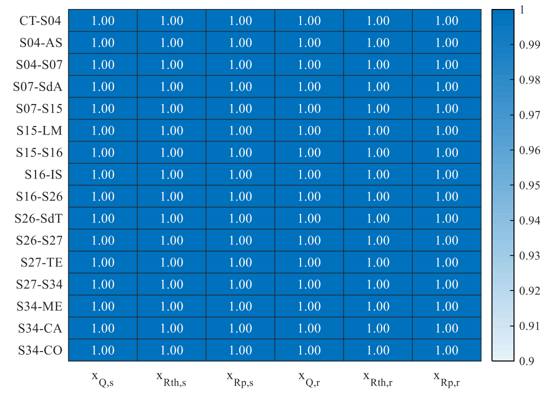


The **calculated value** is ***outside*** the sensor uncertainty band: use the ***measured value*** in objective function

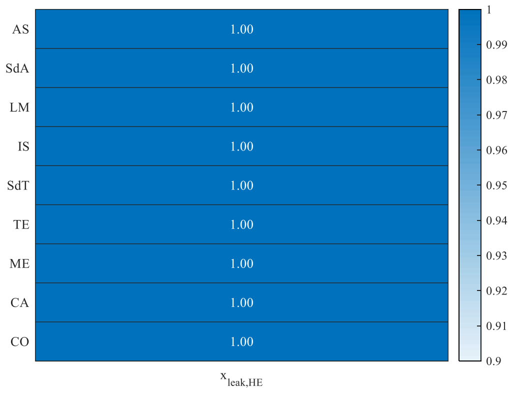
Example of diagnosis

Dataset «VB_50_IS»: due to a fault, the valve located in IS is always open at 50 %

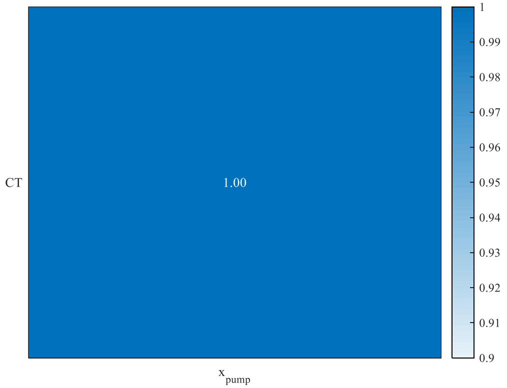
Pipes



Leakages in HEs

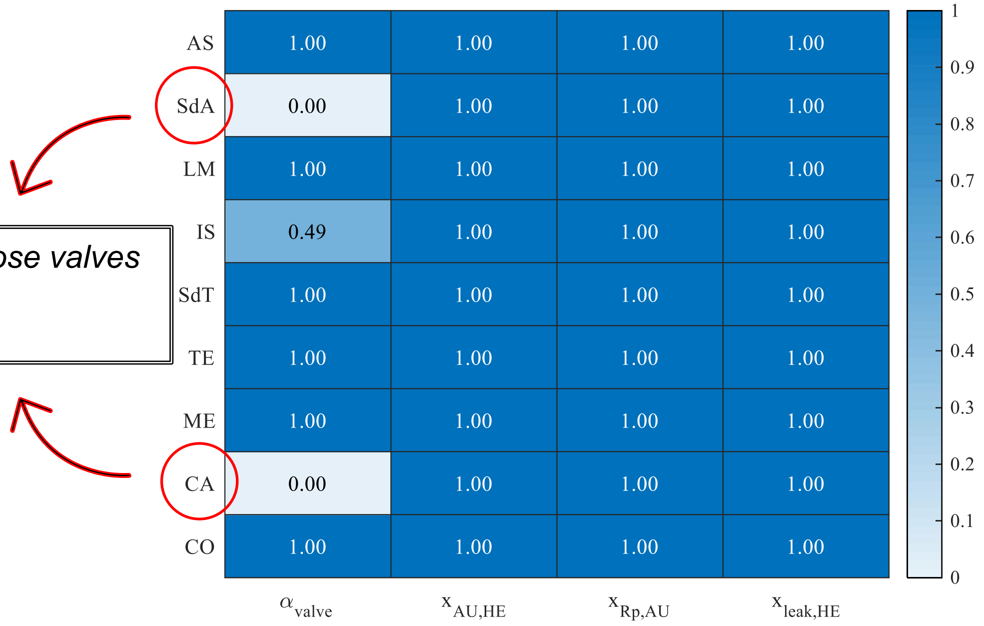


Pumps



- Physics-based approach: *close valves*
- Signal: *close valves*
- Reality*: close valves*

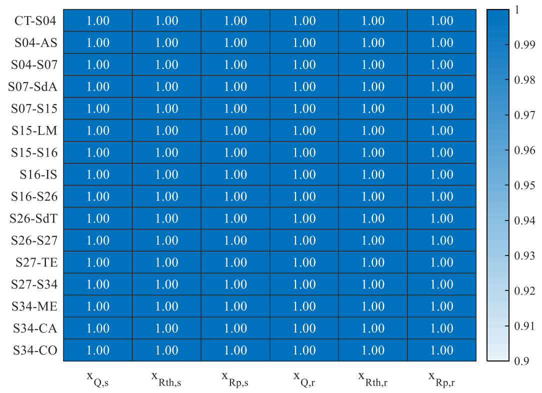
Valves & HEs



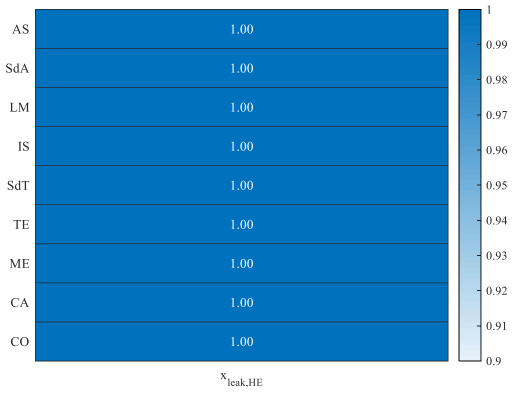
Example of diagnosis

Dataset «VB_50_IS»: due to a fault, the valve located in IS is always open at 50 %

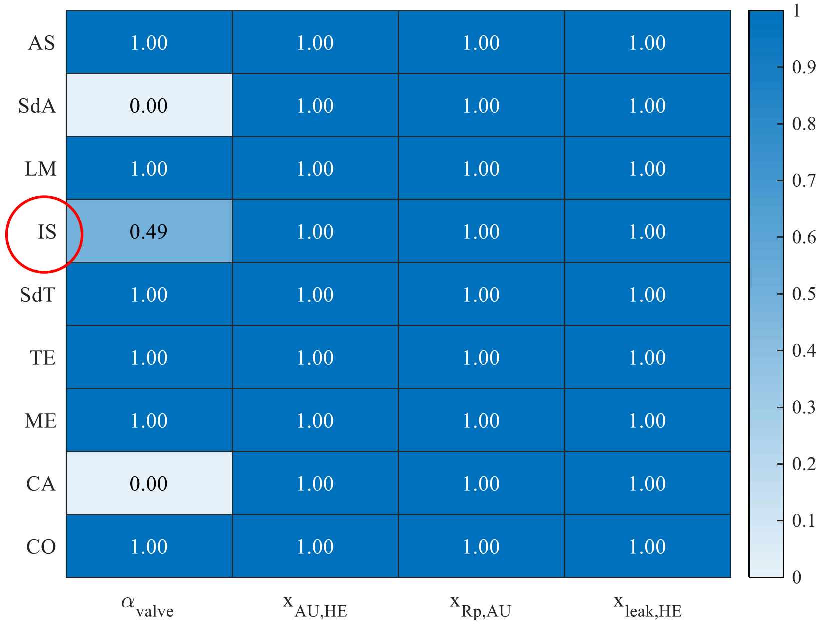
Pipes



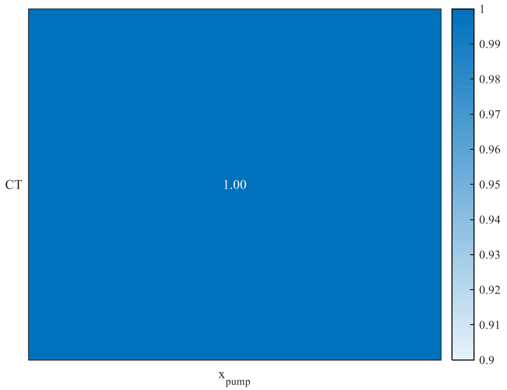
Leakages in HEs



Valves & HEs



Pumps

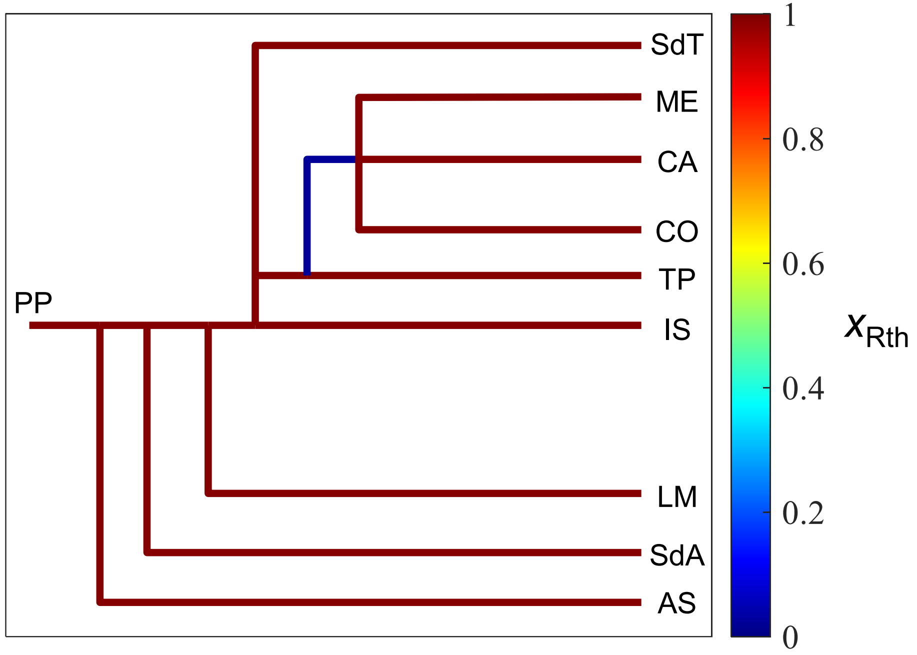


- Physics-based approach: *valve open at 49 %*
- Signal: *open valve*
- Reality*: valve open at 50 %*

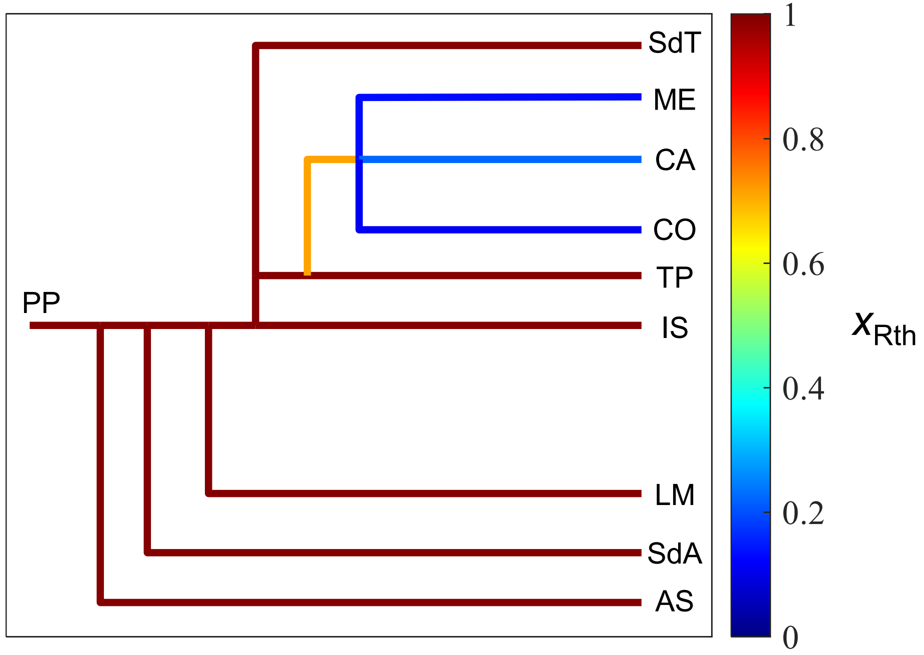
Physics-based approach: challenge #2

Fault located into intermediate pipes

Expected diagnosis



Diagnosis

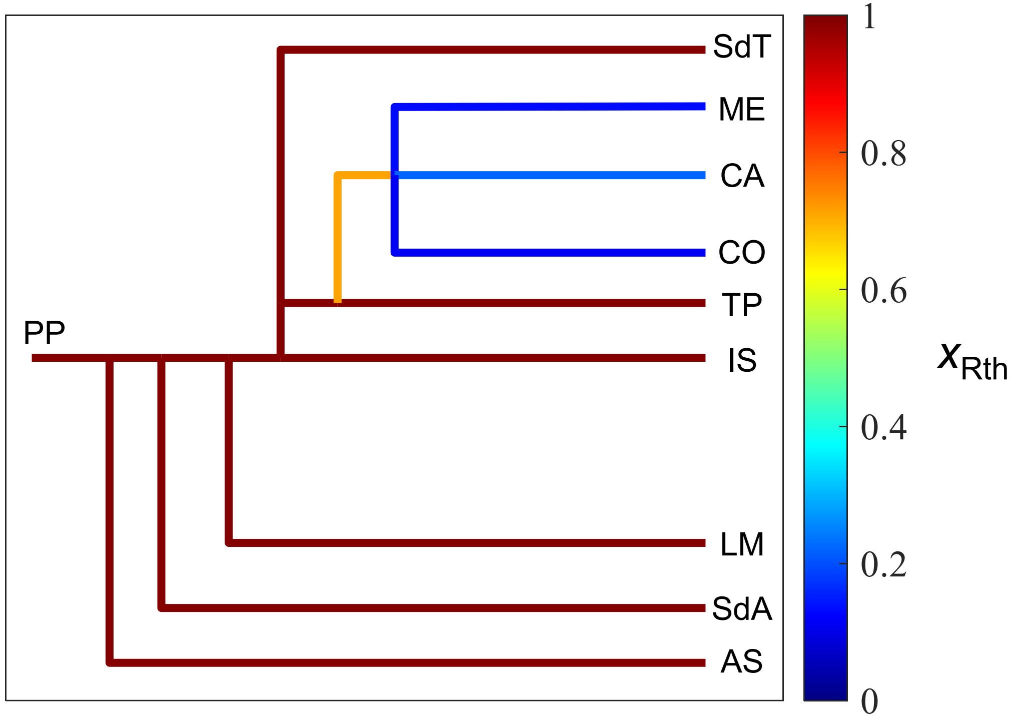


unknown variables > # equations

⚠ The fault magnitude is spread among consecutive pipes

Example of diagnosis

Diagnosis



Four health indices are found lower than 1

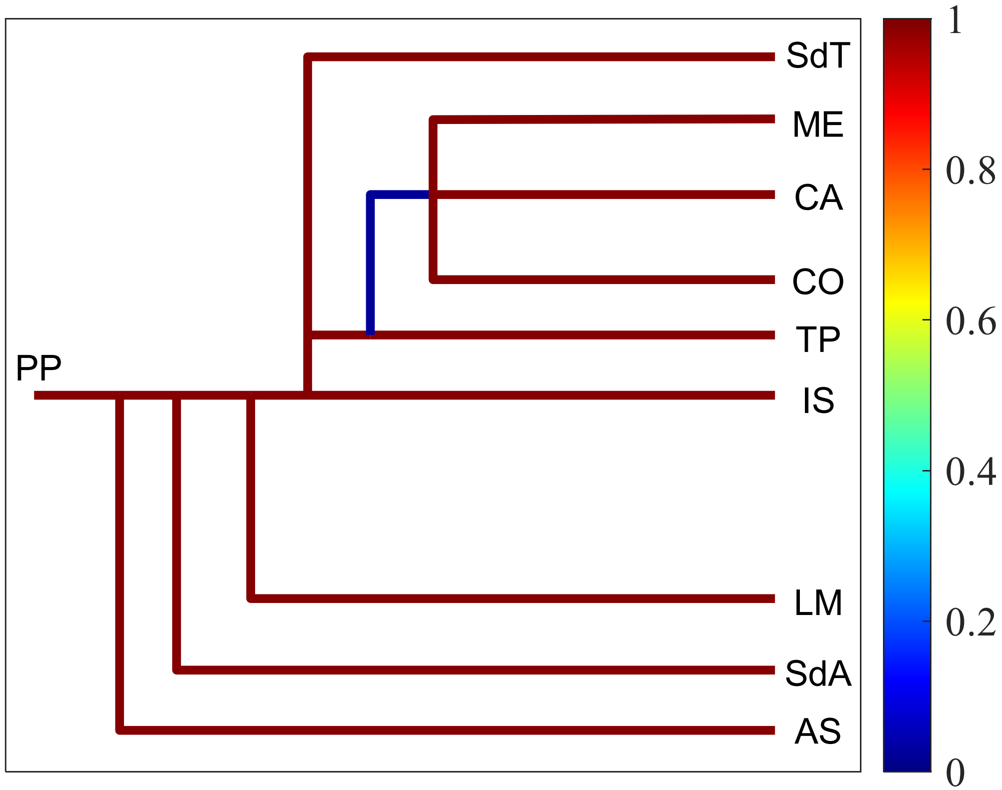
↓

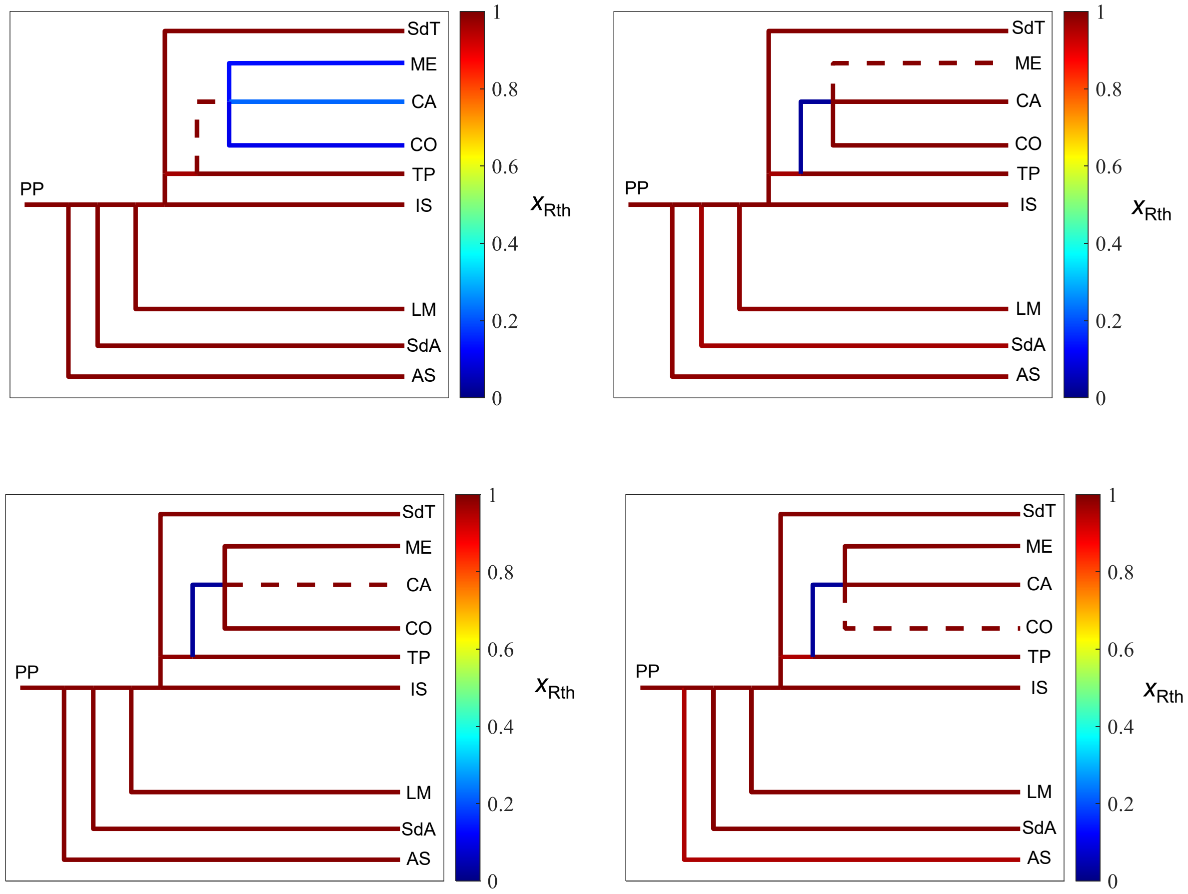
a) In turn, one out of four health indices is set equal to 1
b) In turn, three out of four health indices are set equal to 1

Example of diagnosis

a) In turn, one out of four health indices is set equal to 1

Expected diagnosis



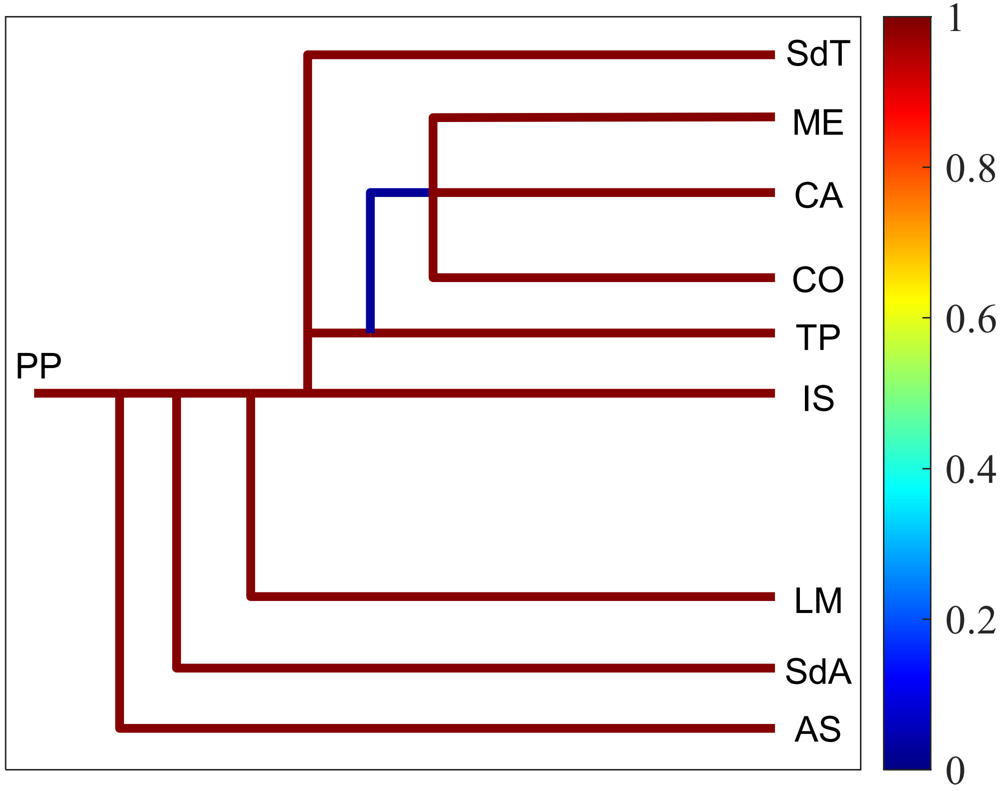


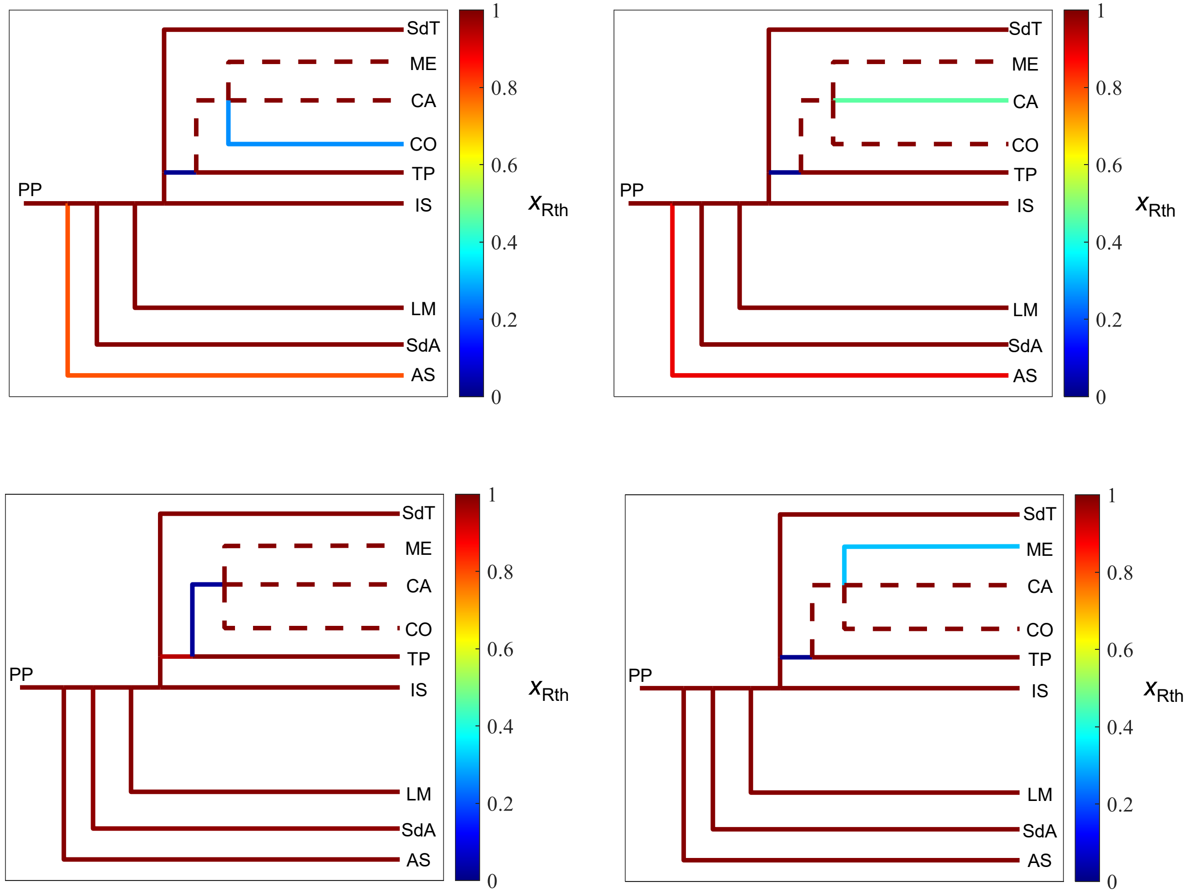
x_{Rth} set equal to 1

Example of diagnosis

b) In turn, three out of four health indices are set equal to 1

Expected diagnosis



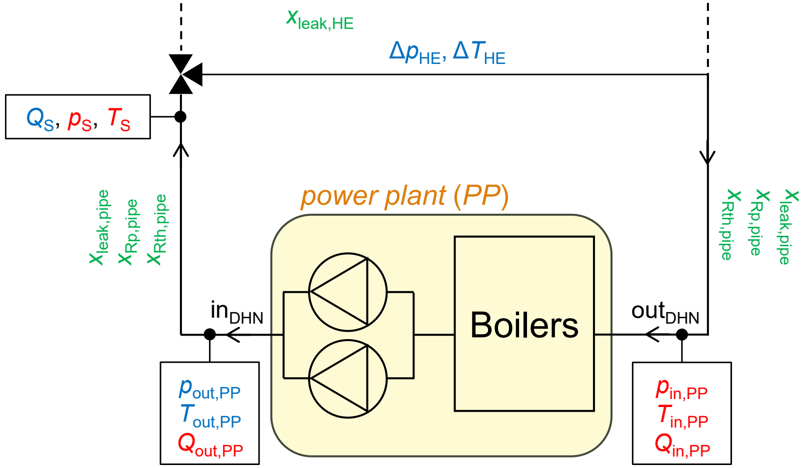


x_{Rth} set equal to 1

Physics-based approach (in progress)

Objective function that accounts for the contribution of both (i) physical quantities (i.e., Q, p, T) and (ii) health indices x

For example



$$OF = \left(\frac{T_{in,PP} - T_{in,PP}^{calc}}{T_{in,PP}^{calc}}\right)^2 + \left(\frac{p_{in,PP} - p_{in,PP}^{calc}}{p_{in,PP}^{calc}}\right)^2 + \left(\frac{Q_{in,PP} - Q_{in,PP}^{calc}}{Q_{in,PP}^{calc}}\right)^2 + \left(\frac{Q_{out,PP} - Q_{out,PP}^{calc}}{p_{out,PP}^{calc}}\right)^2 + \sum_{i=1}^{N_{EU}} \left(\frac{T_{S,i} - T_{M,i}^{calc}}{T_{S,i}^{calc}}\right)^2 + \left(\frac{p_{S,i} - p_{S,i}^{calc}}{p_{S,i}^{calc}}\right)^2$$

$$OF_{tot} = OF + \text{penalty factor} \times \sum_{i=1}^{N} (1-x_i)^2$$