PIACER
Piattaforma Progettazione Gestione
Comunità Energetiche Rinnovabili

Meeting online

Stato di avanzamento delle attività di ricerca di IN⁴

25/06/2026

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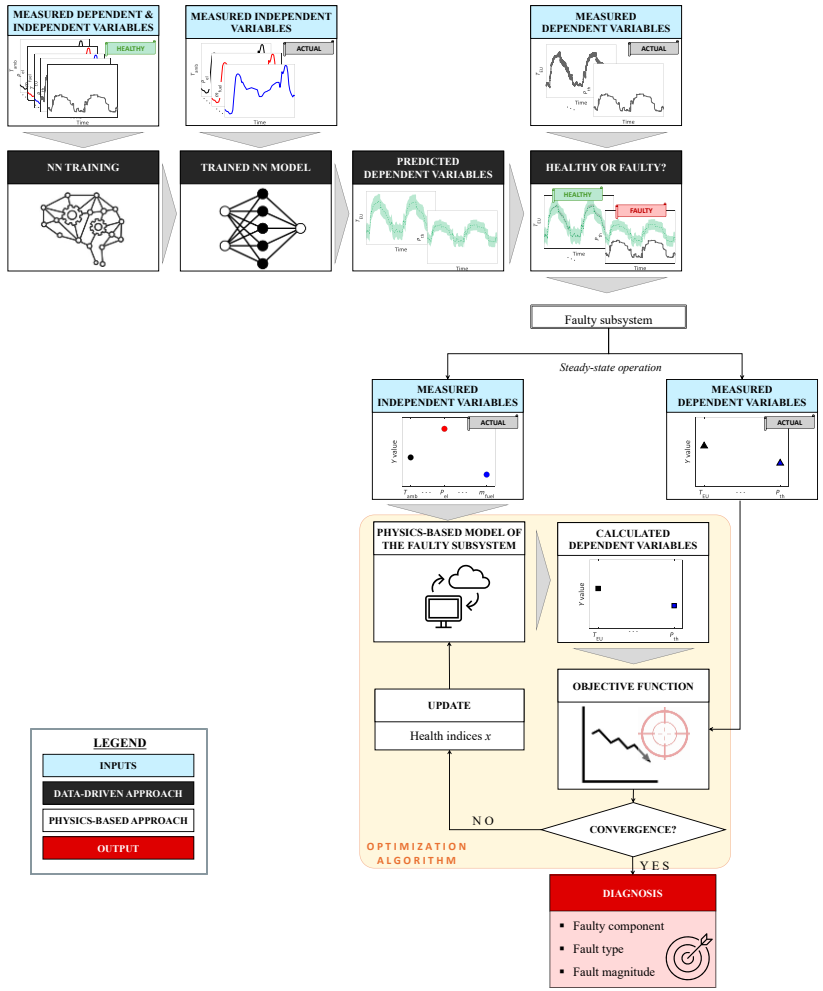
Università degli Studi di Ferrara
IN⁴ innovazione ingegneria integrazione industria

WP 3

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

Goal



Data-driven approach

Detection of the faulty sub-system

- Transient and steady-state operation

Physics-based approach

Identification of the fault signature and magnitude

- Steady-state operation

FAULT DETECTION

- *Is there a fault?*
- *Which is the faulty component?*

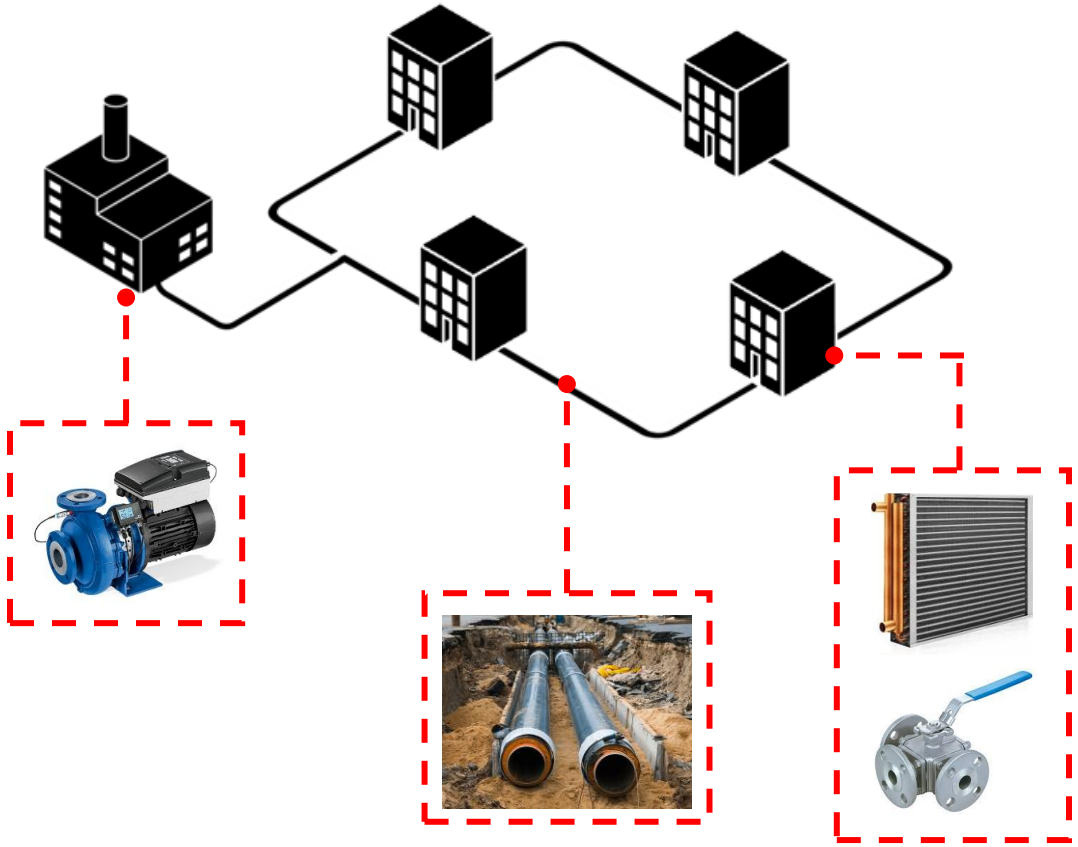
FAULT IDENTIFICATION

- *What is the fault signature?*
- *What is the fault magnitude?*

SVILUPPO DI TOOL PER LA DIAGNOSI DI RETI DI TELERISCALDAMENTO

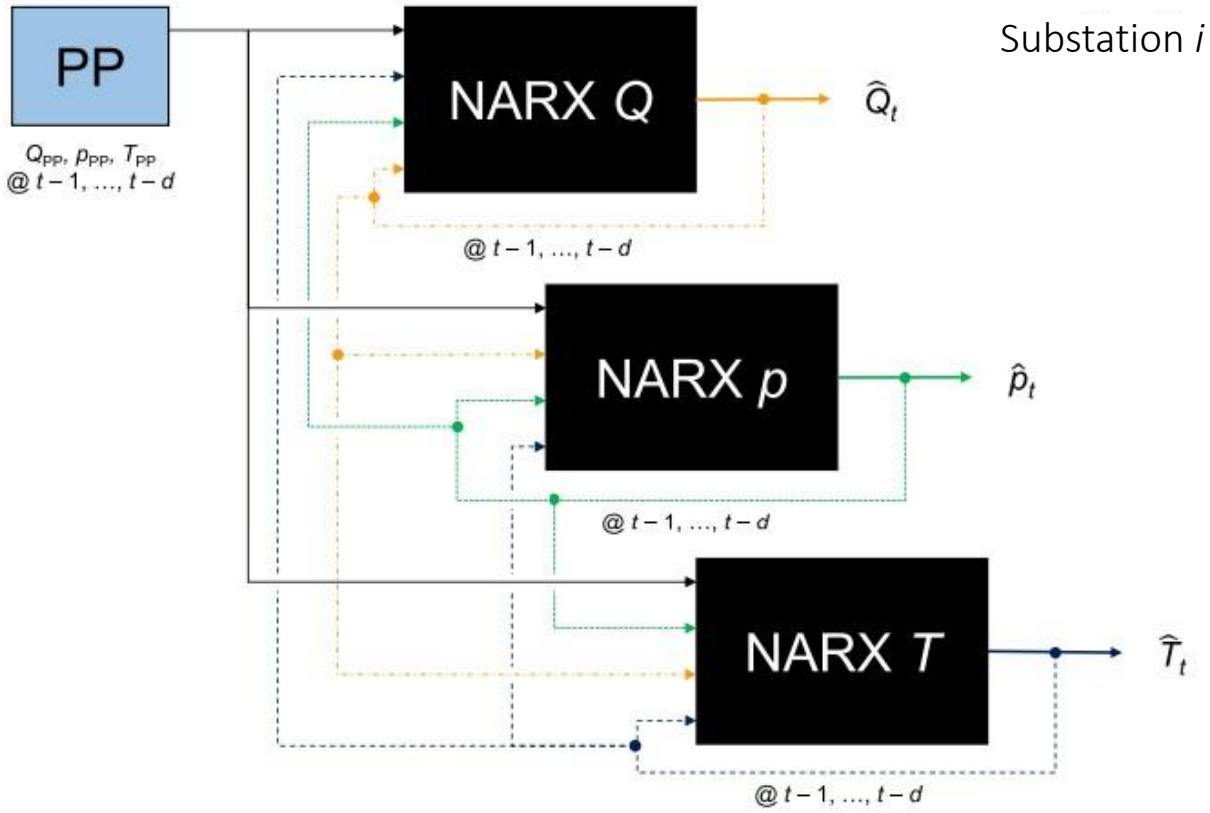
Detectable faults

Faulty component	Fault signature
Pump	▪ Head reduction
Pipe	▪ Leakages ▪ Anomalous heat losses ▪ Anomalous pressure losses
Valve	▪ Incorrect opening ▪ Leakages
Heat exchanger	▪ Leakages ▪ Anomalous heat losses ▪ Anomalous pressure losses



Data-driven approach

For each substation



Substation *i*

if

$$|\hat{y}_t - y_t^{meas}| < 3\sigma$$

then

y_t^{meas} healthy

if

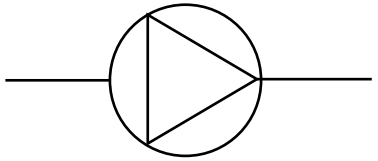
$$|\hat{y}_t - y_t^{meas}| > 3\sigma$$

then

y_t^{meas} faulty

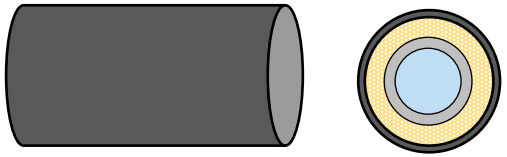
Physics-based approach

Pumping station model



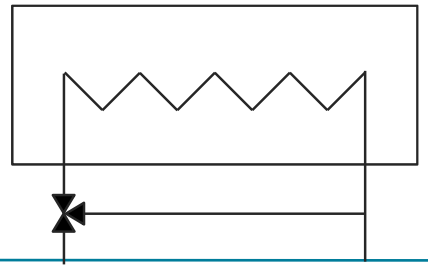
- (*Q*,*H*) curve

Distribution network model



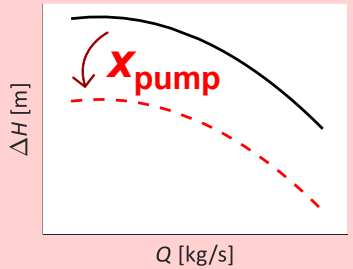
- Mass conservation equation
- Energy conservation equation
- Momentum conservation equation

Substation model



- Mass conservation equation
- Energy conservation equation
- Momentum conservation equation

Health indices

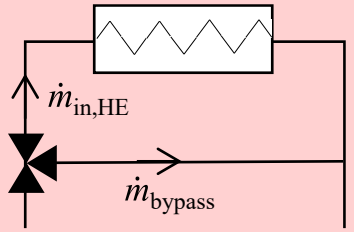


$$\sum x_{leak}\dot{m}_{in} - \sum \dot{m}_{out} - \dot{m}_{in,sub} = 0$$

$$R_{th} = x_{th,loss}\left(\frac{1}{\pi L D_{int} k} + \sum \frac{1}{2\pi L \lambda} \ln \frac{D_{ext}}{D_{int}}\right)$$

$$\Delta p = x_{p,loss} R_p \dot{m}^2$$

Valve opening



$$\dot{m}_{in,HE} = \alpha_{valve}\dot{m}_{in,sub}$$

Physics-based approach

Pumping station model

pump head

Distribution network model

leakages

anomalous heat losses

anomalous pressure losses

Substation model

leakages

valve position

anomalous heat losses

anomalous pressure losses

Physics-based approach

Pumping station model

Health index < 1 ⇒ faulty
Health index = 1 ⇒ healthy

anomalous heat losses

anomalous pressure losses

Distribution network model

Valve opening ≠ setpoint ⇒ faulty
Valve opening = setpoint ⇒ healthy

anomalous heat losses

anomalous pressure losses

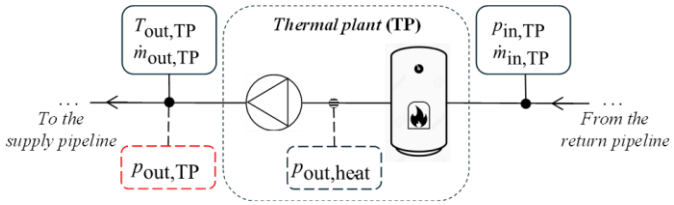
Substation model

anomalous heat losses

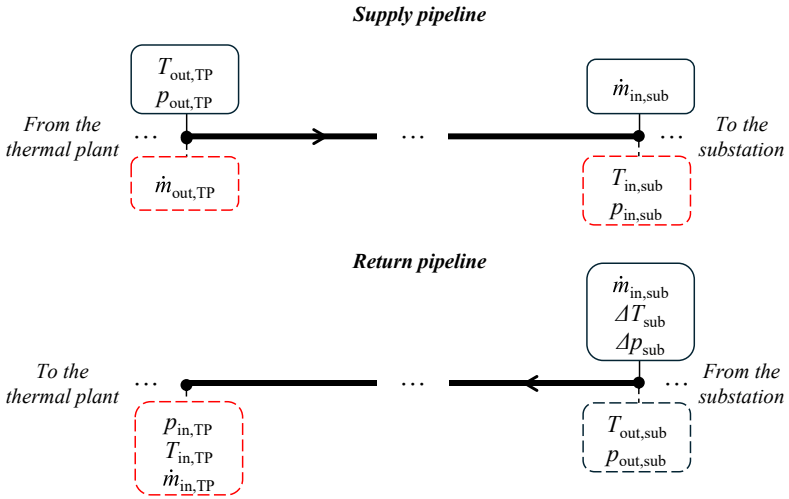
anomalous pressure losses

Physics-based approach

Pumping station model



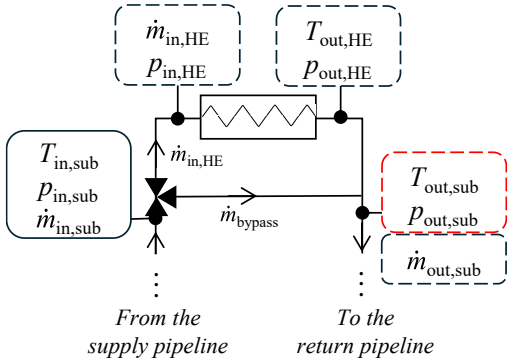
Distribution network model



$$OF = \sum_{i=1}^{N} \left(\frac{Y_i^{target} - Y_i^{calc}}{Y_i^{target}} \right)^2$$

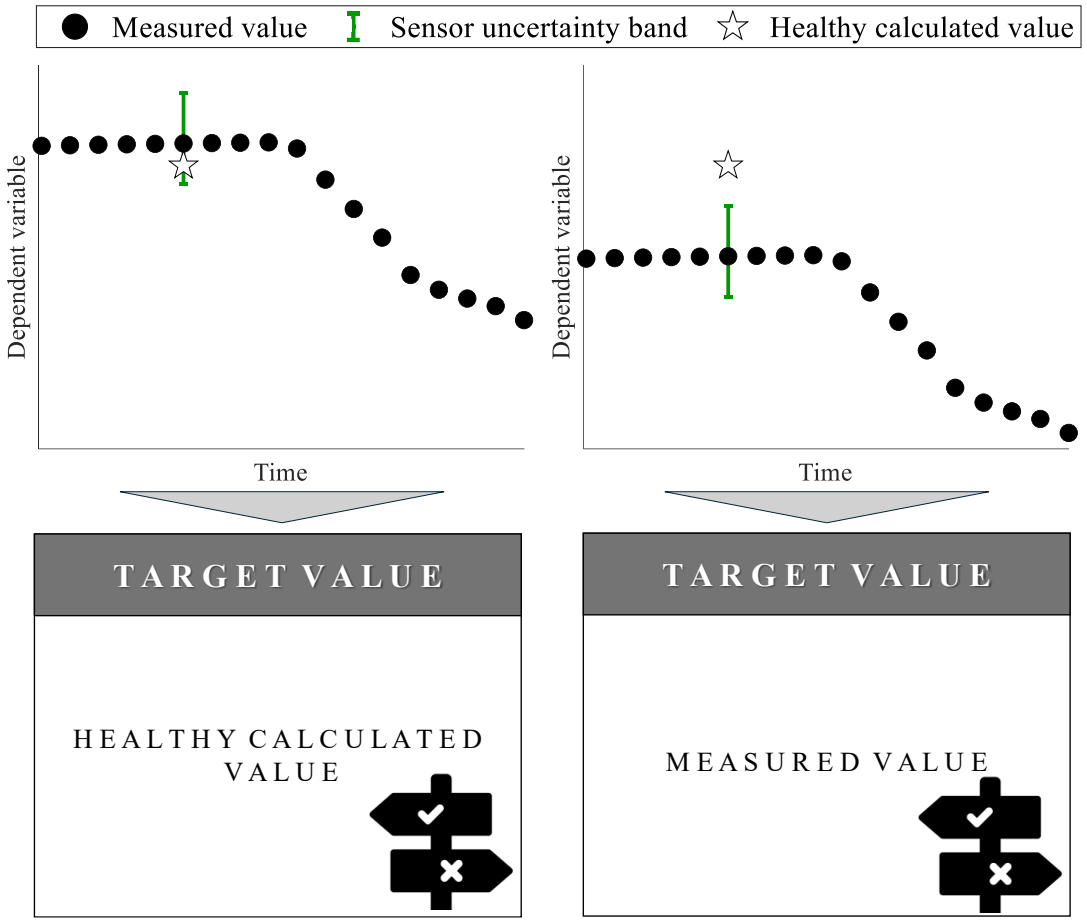
where Y is ṁ, T or p

Substation model



Minimize by using an optimization algorithm based on a gradient-based method

Physics-based approach



Sensor	Uncertainty band
Flow meter	± 0.3 % of reading value
Thermocouple	± 0.5 °C
Pressure gauge	± 0.25 % of the full-scale

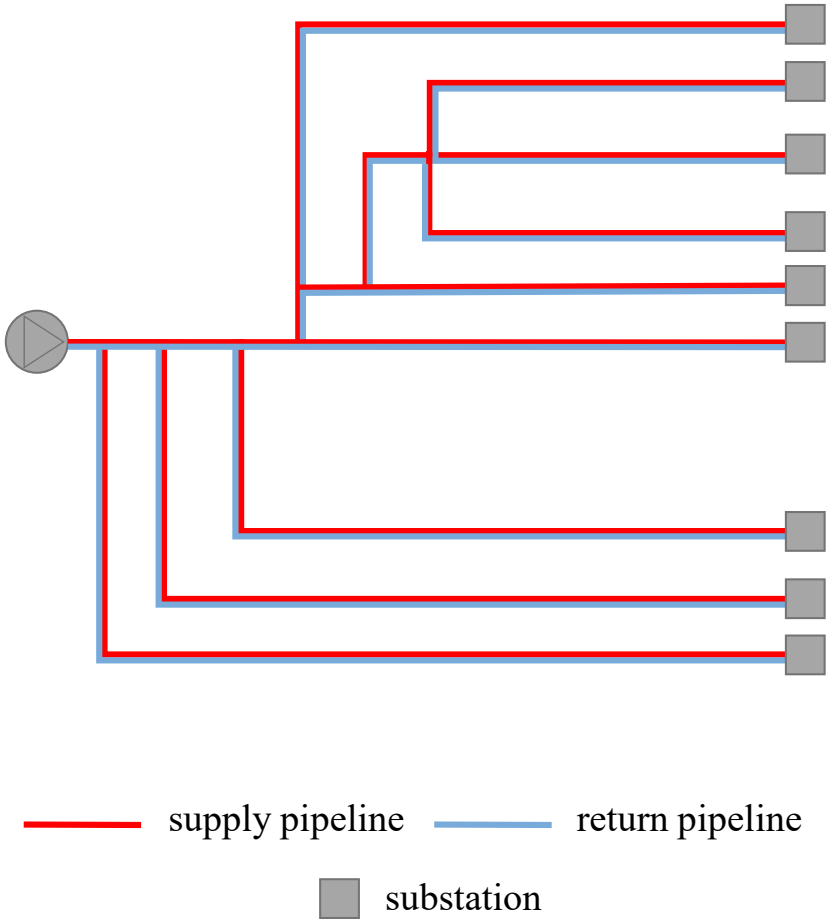
Suitable for real-word applications

robust against measurement noise

minimize false positives

Case study

District heating network of the Campus of University of Parma



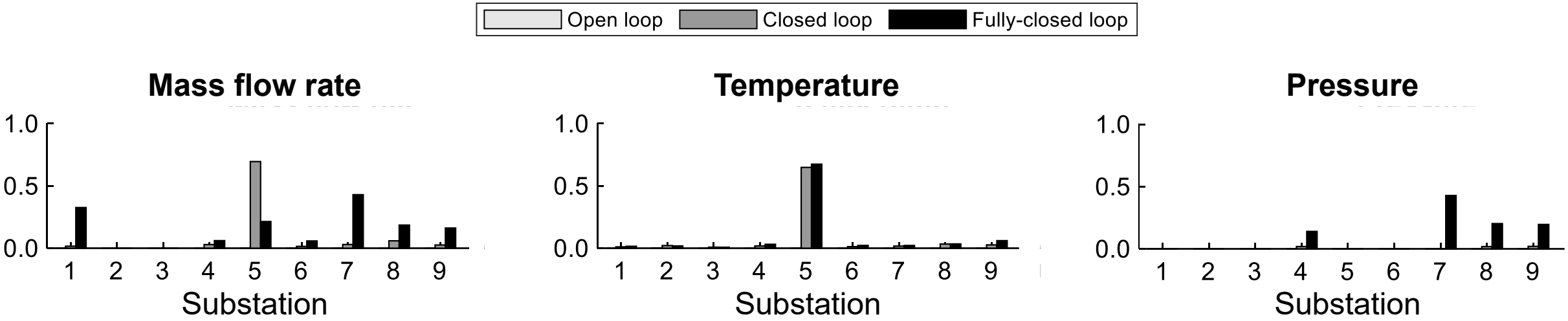
CIDEA
Centro Interdipartimentale per l'Energia e l'Ambiente
UNIVERSITÀ DI PARMA

Datasets	No.
Healthy DHN	1
Faulty valve (locked)	6
Faulty valve (partial opening)	4
Faulty heat exchanger	2
Faulty pump	1
Faulty pipe	4
Total	18

Example of application

Data-driven approach

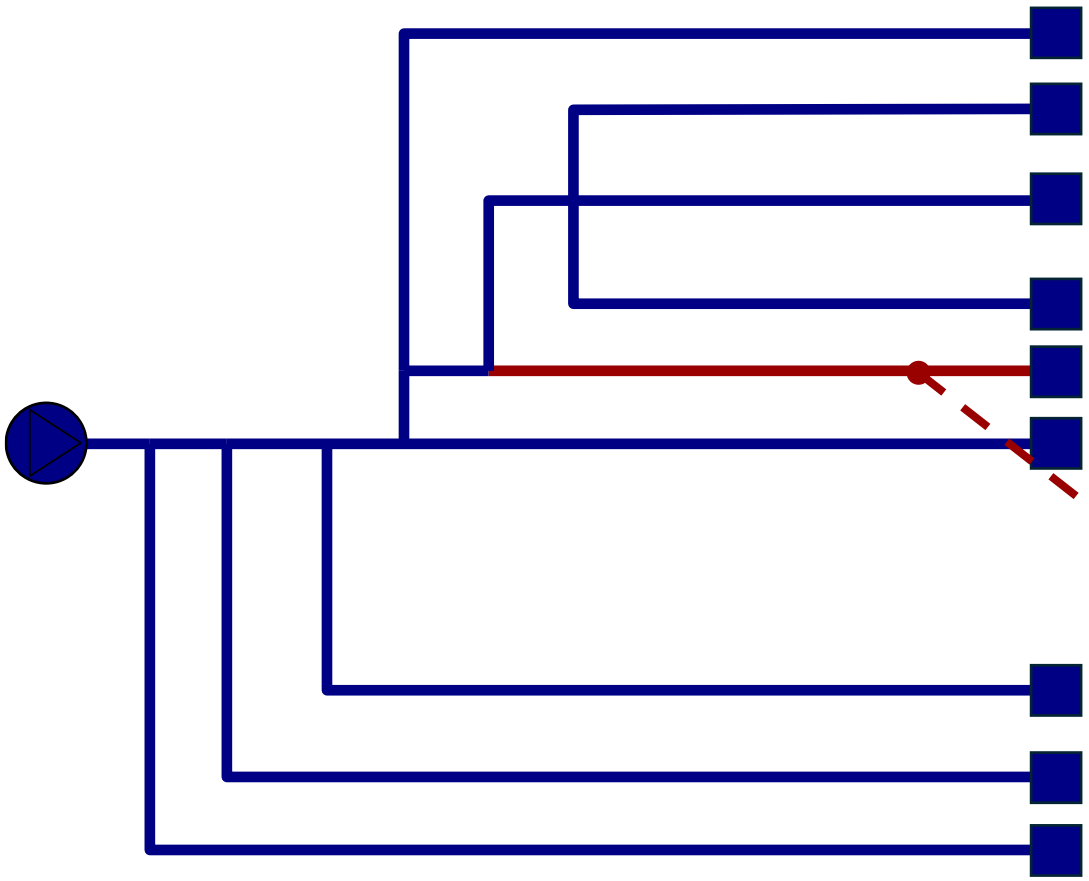
Rate of data classified as *faulty*

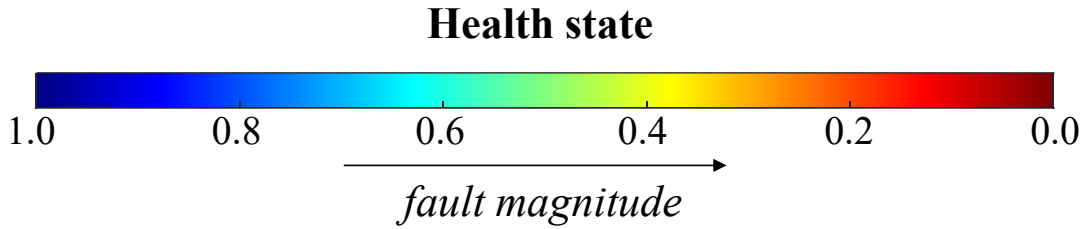


FAULT ALERT AT SUBSTATION 5

Example of application

Physics-based approach

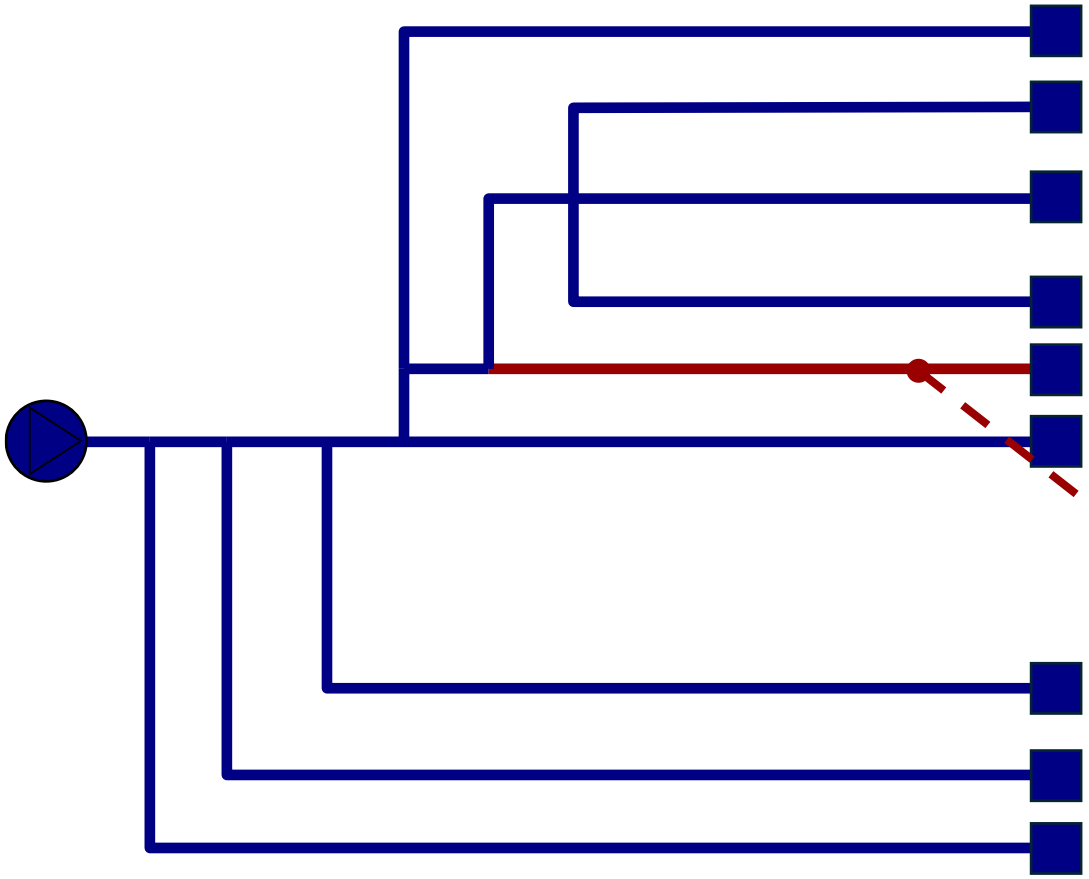




PIPE #11 (substation 5)

Example of application

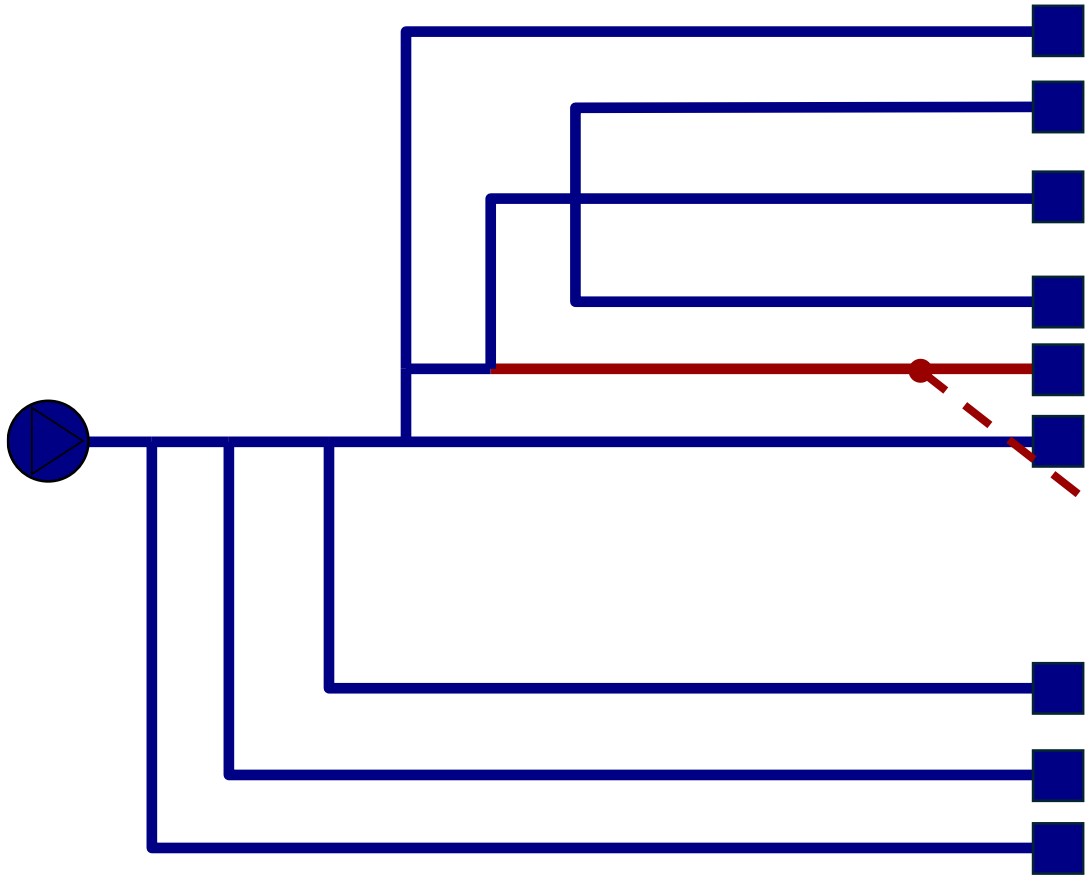
Physics-based approach



PIPE #11 (substation 5)

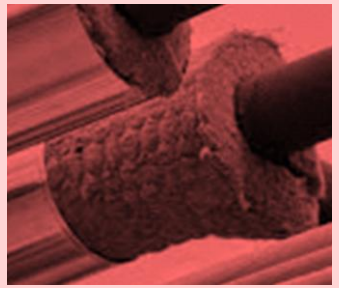
Example of application

Physics-based approach



PIPE #11 (substation 5)

x_{leak} = 1.00

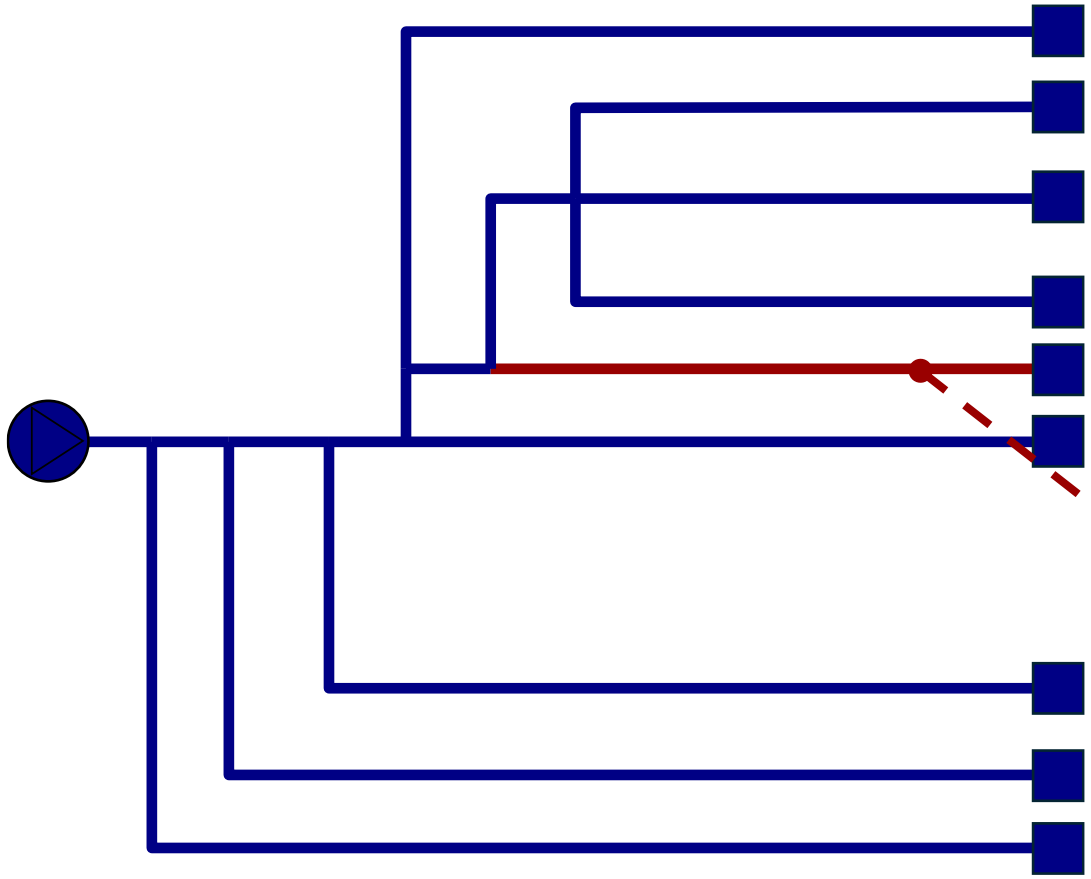


$x_{th.loss}$ = 0.02

$x_{p.loss}$ = 1.00

Example of application

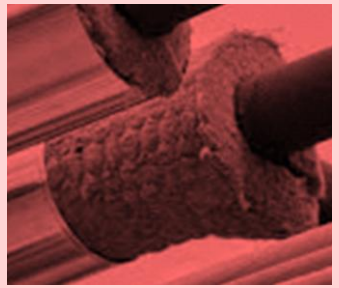
Physics-based approach



FAULT ALERT CONFIRMED

PIPE #11 (substation 5)

x_{leak} = 1.00

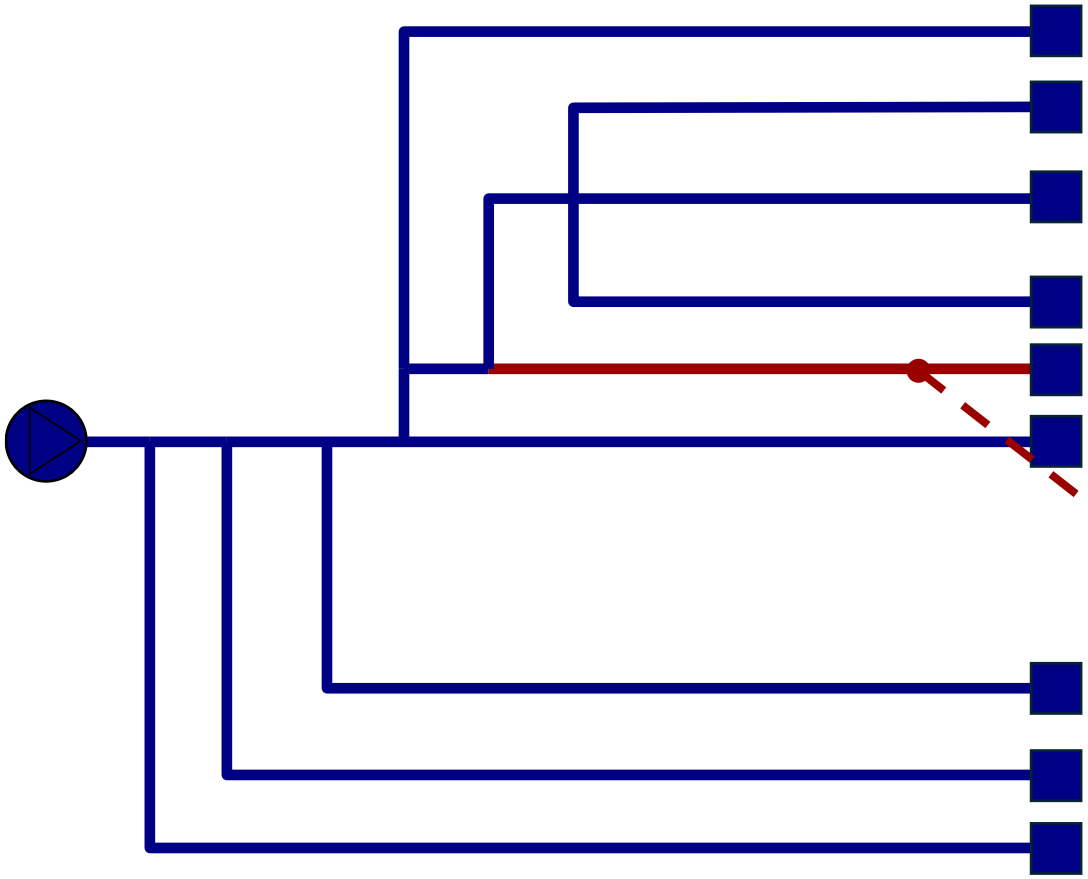


$x_{th.loss}$ = 0.02

$x_{p.loss}$ = 1.00

Example of application

Physics-based approach

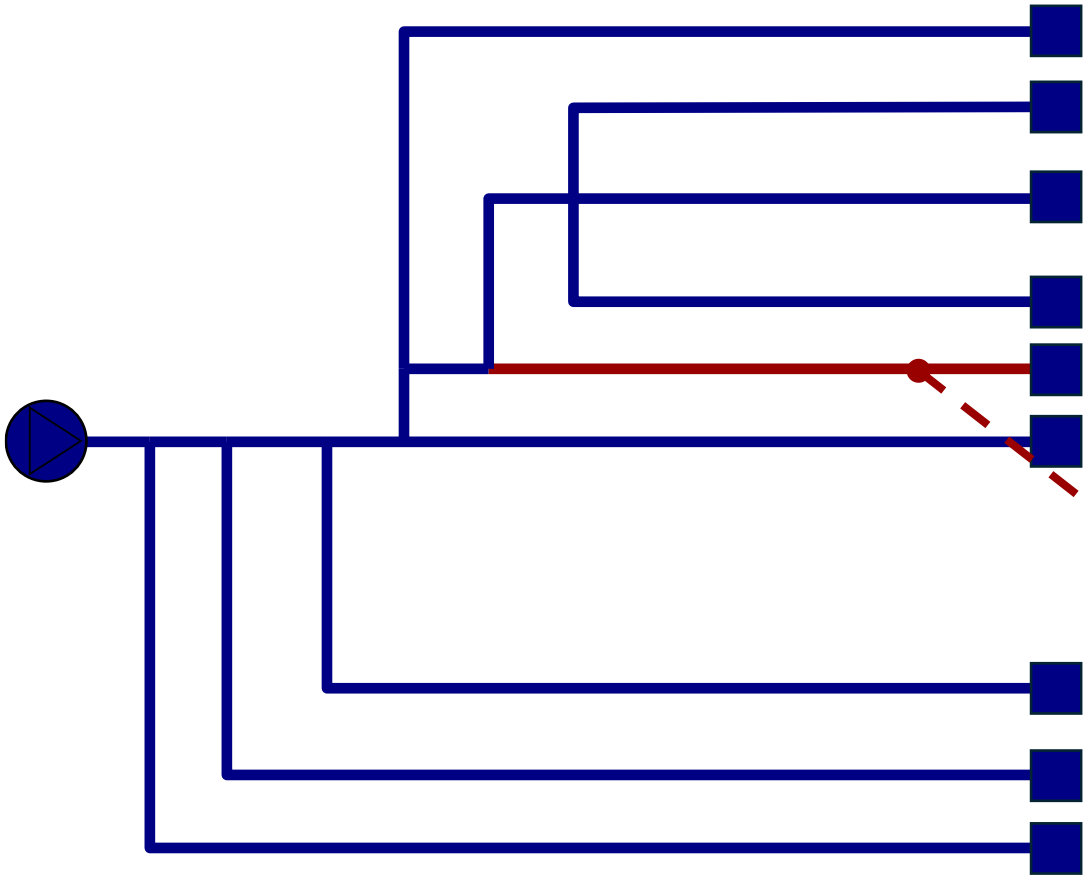


$x_{th.loss}$ = 0.02

λ_{ins} [W·m^{-1}·K^{-1}]	
Calculated	1.9

Example of application

Physics-based approach

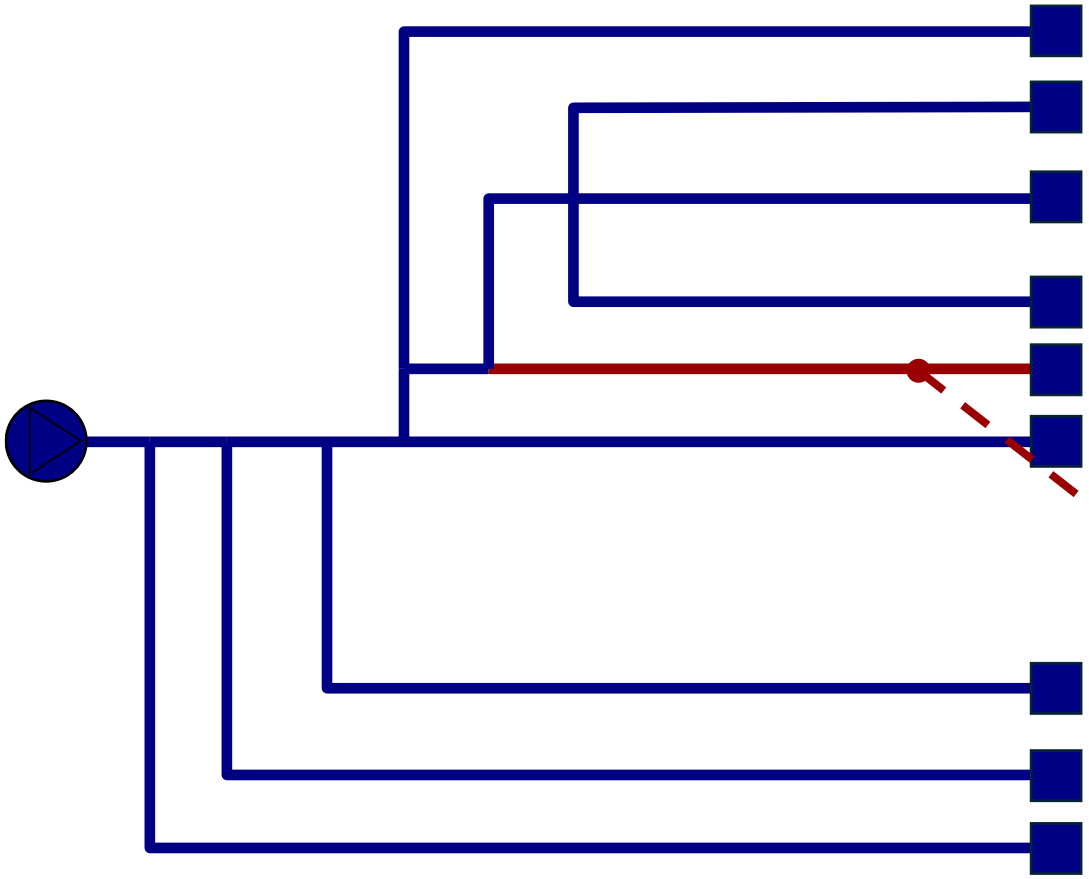


$x_{th.loss} = 0.02$

λ_{ins} [W·m^{-1}·K^{-1}]	
Calculated	1.9
Healthy	0.04

Example of application

Physics-based approach

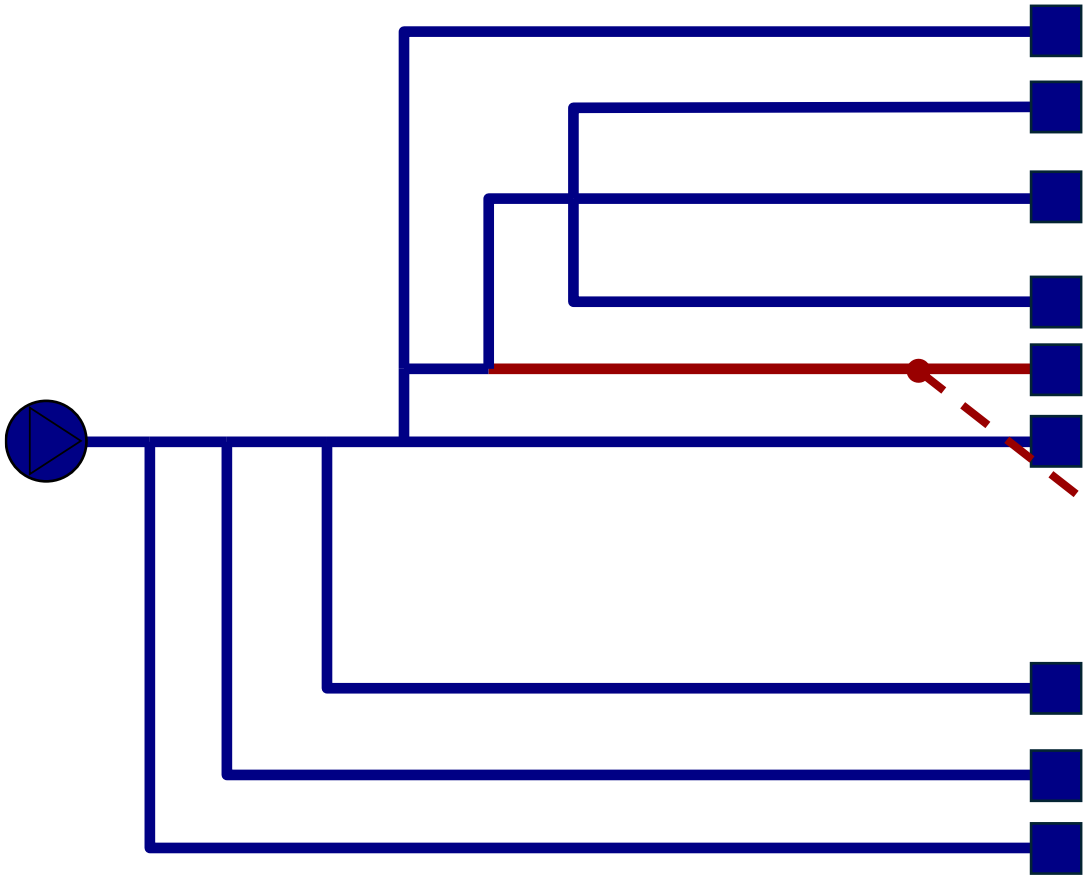


$x_{th.loss} = 0.02$

λ_{ins} [W·m^{-1}·K^{-1}]	
Calculated	1.9
Healthy	0.04
Actual	2.0

Example of application

Physics-based approach



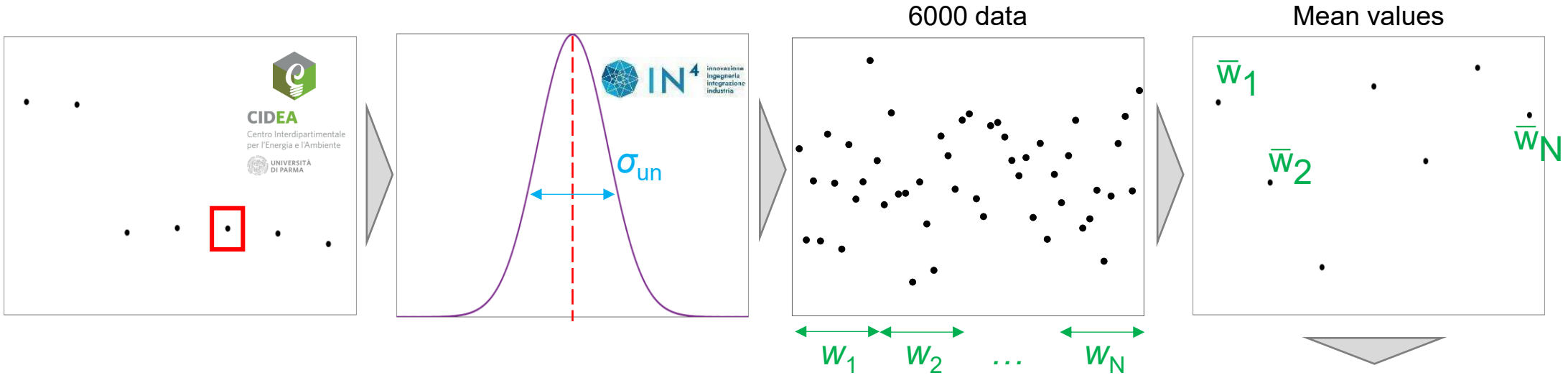
FAULT DETECTED & IDENTIFIED

$x_{th.loss}$ = 0.02

λ_{ins} [W·m^{-1}·K^{-1}]	
Calculated	1.9
Healthy	0.04
Actual	2.0

Robustness against noisy data

Physics-based approach



Diagnosis on *N* values

Health indices with noisy data

Robustness against noisy data

Physics-based approach

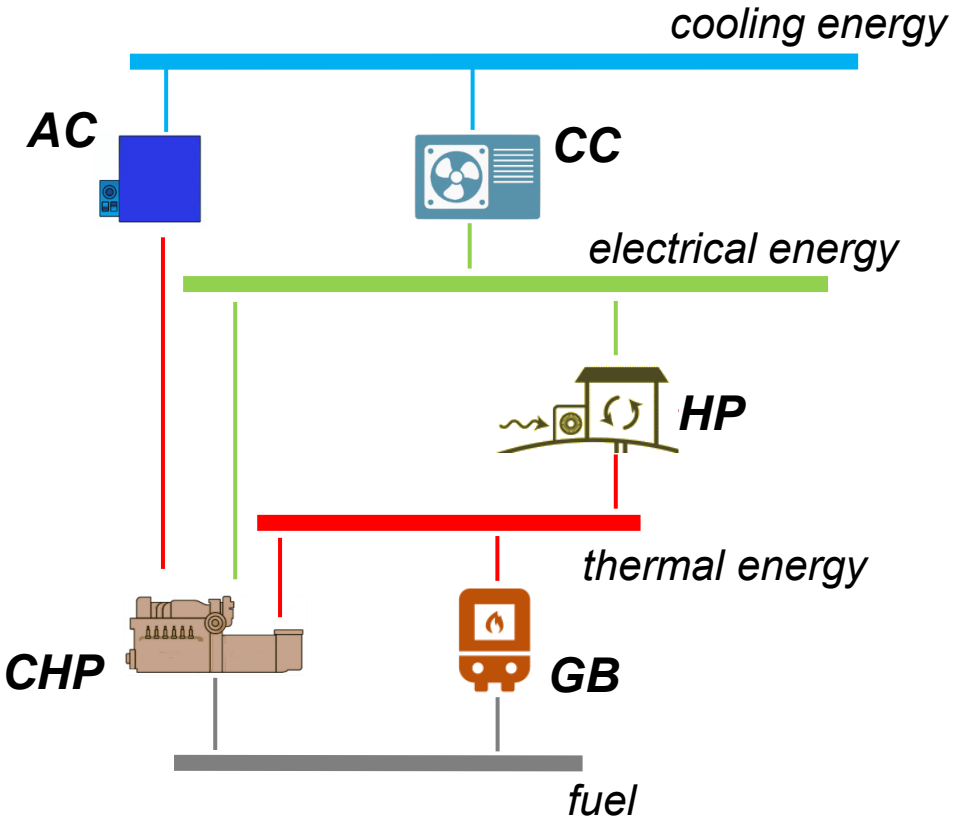
Maximum deviation of x and α_{valve} with respect to noise-free measurements

	N	**100**	**300**
Faulty component	Pump	$7.6 \cdot 10^{-4}$	$7.0 \cdot 10^{-4}$
	Pipe #6	$1.4 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
	Valve #4	$2.5 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$
	Heat exchanger #4	$1.1 \cdot 10^{-2}$	$2.7 \cdot 10^{-2}$

Robustness against noisy inputs

SVILUPPO DI TOOL PER LA DIAGNOSI DI SISTEMI MULTI-ENERGIA

Physics-based approach



Combined heat and power system (CHP)

$P_{el,meas}$ T_a $P_{el,nom}$ $\eta_{el,nom}$ $P_{th,nom}$ $x_{el.CHP}$ $x_{th,CHP}$

$$load_{el} = f(P_{el,meas}, T_a, P_{el,nom})$$

$$\eta_{el} = f(x_{el,CHP}, T_a, load_{el}, \eta_{el,nom})$$

$$load_{th} = f(x_{th,CHP}, load_{el})$$

$$P_{th,calc} = f(load_{th}, T_a, P_{th,nom})$$

$$P_{fuel,calc} = f(P_{el,meas}, \eta_{el})$$

$$\eta_{tot} = f(P_{el,meas}, P_{th,calc}, P_{fuel,calc})$$

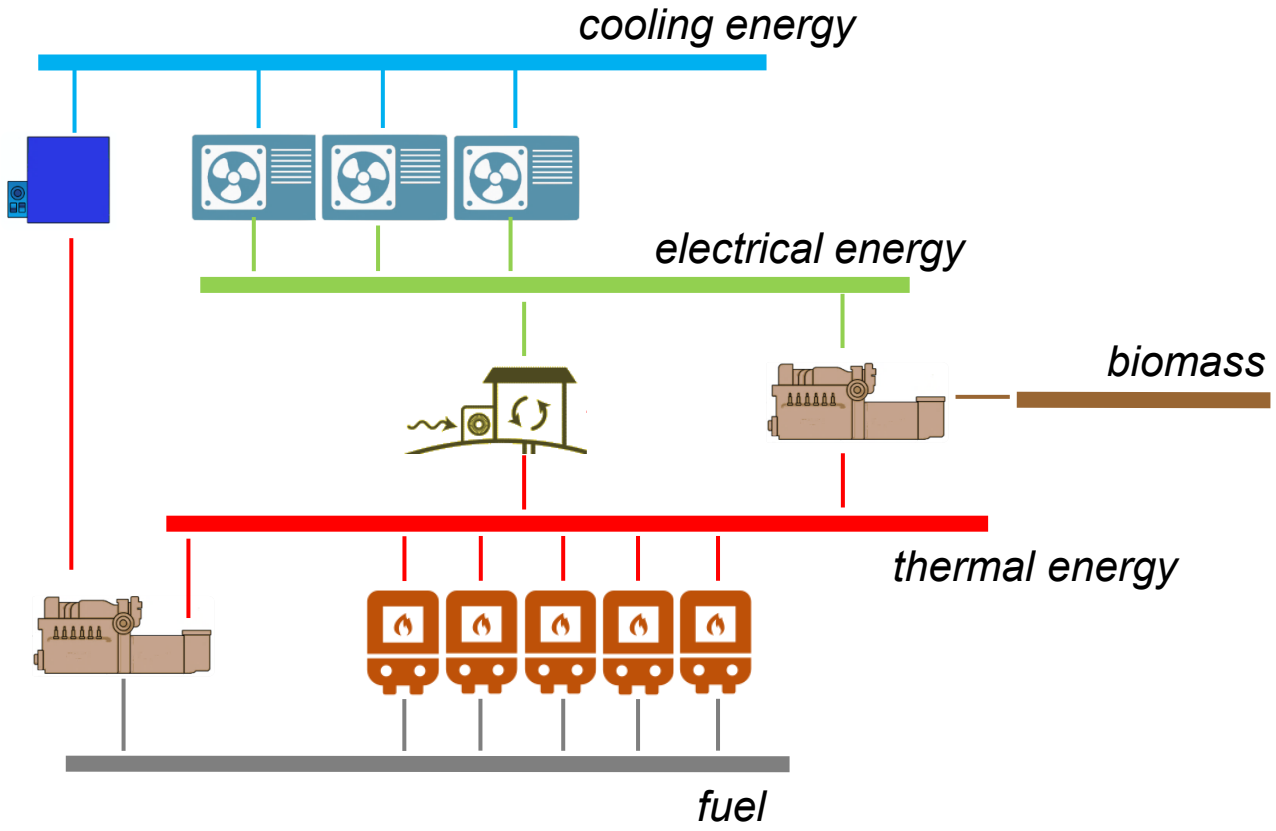
$$\eta_{th} = f(\eta_{tot}, \eta_{el})$$

$P_{fuel,calc}$ $P_{th,calc}$

Developed physics-based models: gas boiler, CHP, heat pump, compressor chiller, absorption chiller

Case study

Campus of University of Parma



34 datasets

1 healthy **33 faulty**

Validation of the physics-based model under healthy operation

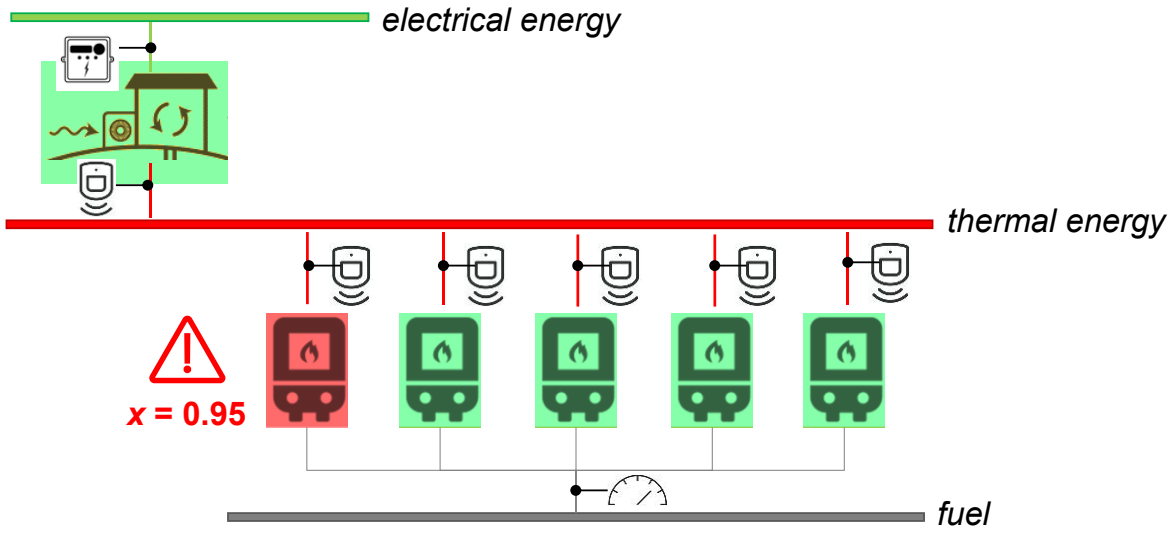
model

data

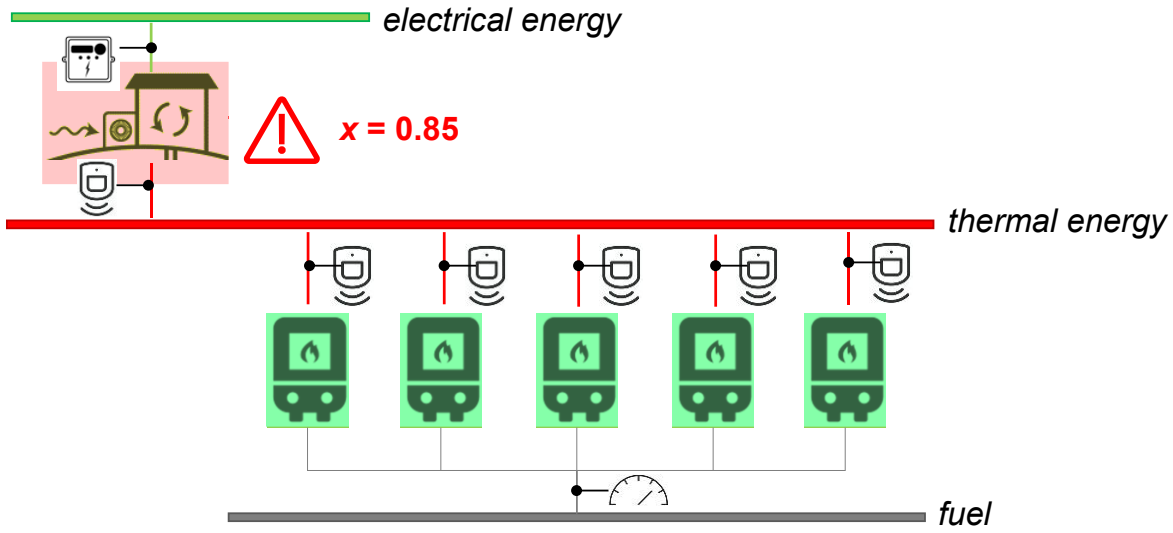
Relative error always lower than 0.1 %

Example of faulty datasets

Dataset F01



Dataset F07



IN^4 goals

Activities

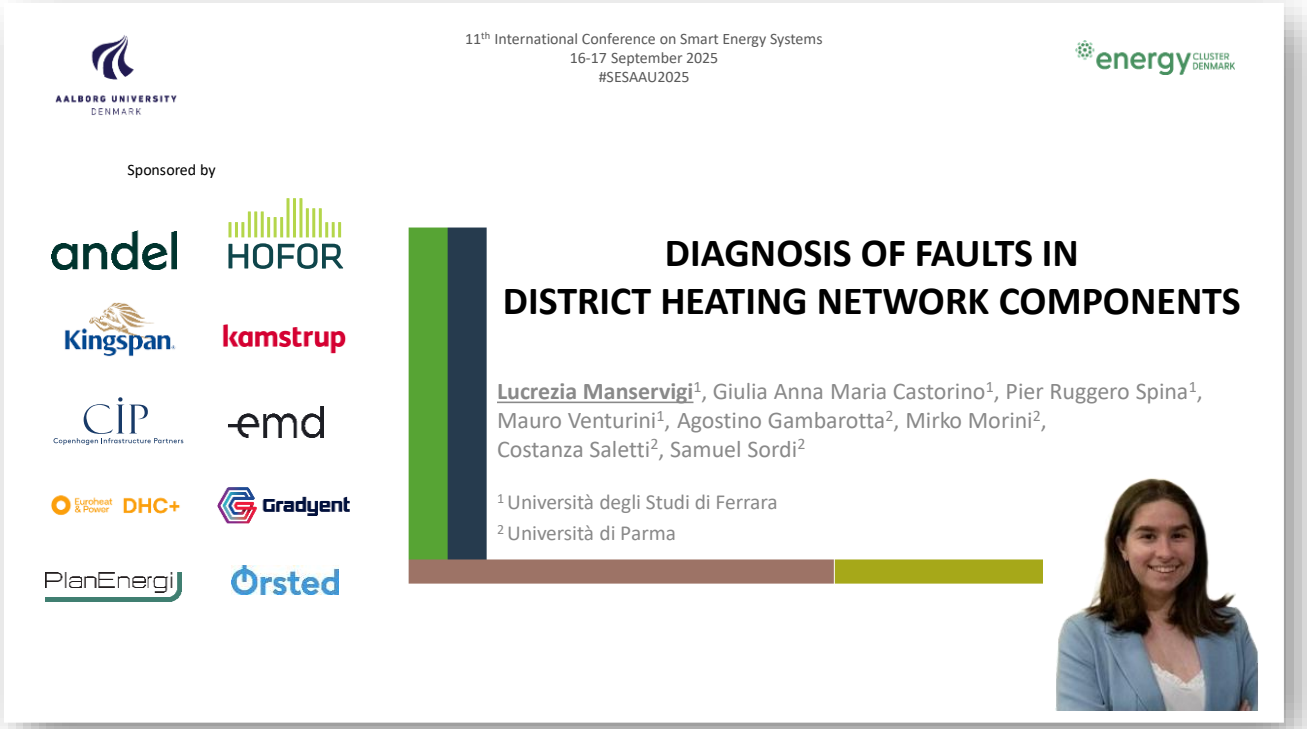
- ☑ *Literature review*
- ☑ *Data-driven approach*
- ☑ *Physics-based approach*
  - ✓ *Validation of the DHN*
  - ✓ *Diagnosis of the DHN*
  - ✓ *Validation of the MES*
  - ✓ *Diagnosis of the MES*

✓ done

✓ in progress

DISSEMINAZIONE

Conferences & papers



Invitation to submit the paper to special issue of Energy

Conferences & papers

Component-level·fault·diagnosis·in·district·heating·networks·by·using·a·physics-based·approach

Lucrezia·Manservigi[1],·Carlo·Antonio·Caputo[1],·Pier·Ruggero·Spina[1],·Mauro·Venturini[1],·
Costanza·Saletti[2],·Samuel·Sordi[2],·Mirko·Morini[2],·Agostino·Gambarotta[2]

[1]·Università·degli·Studi·di·Ferrara

[2]·Università·degli·Studi·di·Parma

Second round of review (special issue of Energy)