Towards optimal predictive maintenance in large-scale heat pumps through digital twins

José Joaquín Aguilera Prado

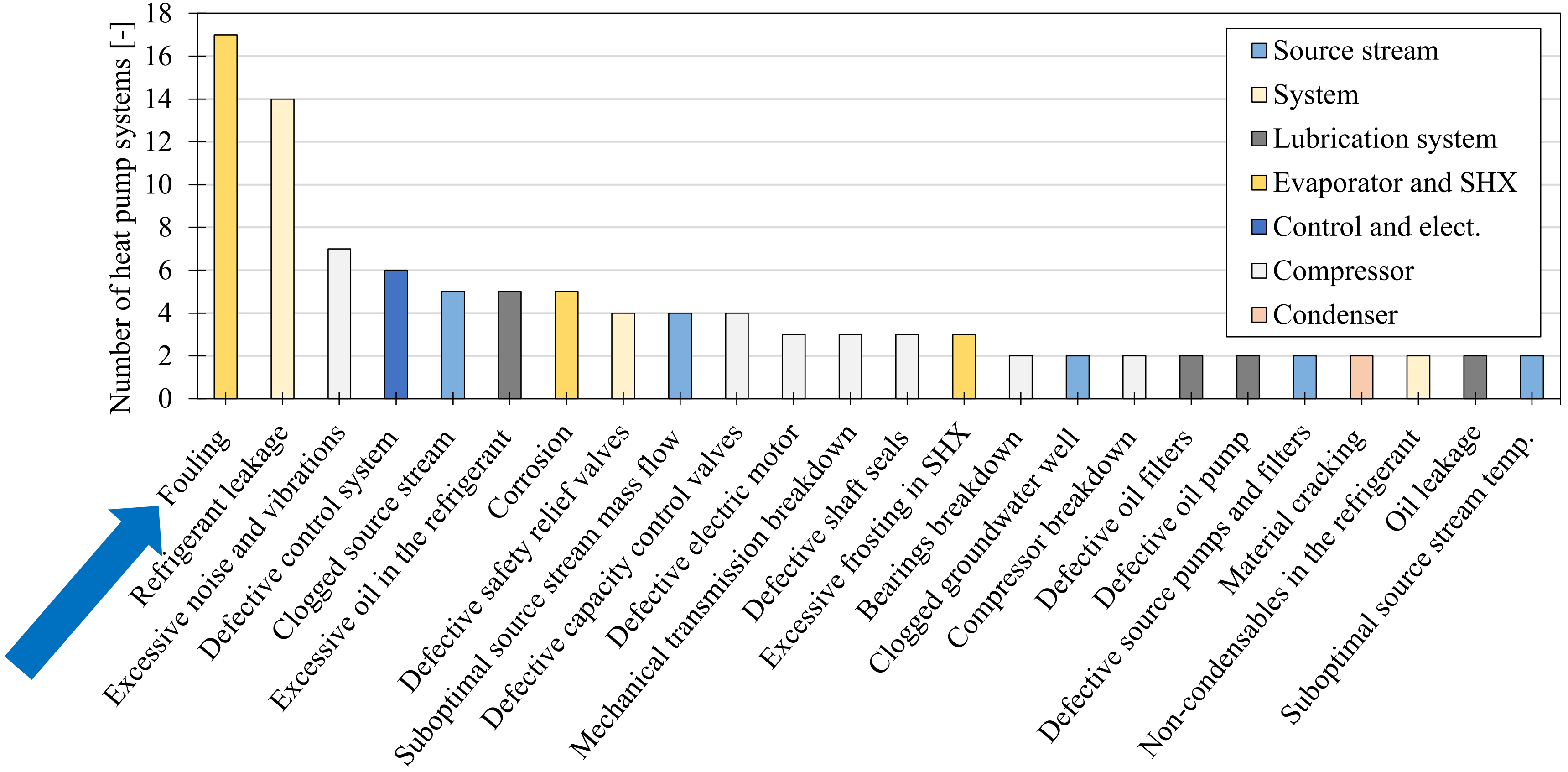
Consultant – Danish Technological Institute

Project: Digital twins for large-scale heat pump and refrigeration systems

More info in our website : https://digitaltwins4hprs.dk/

Common faults in large-scale heat pump systems

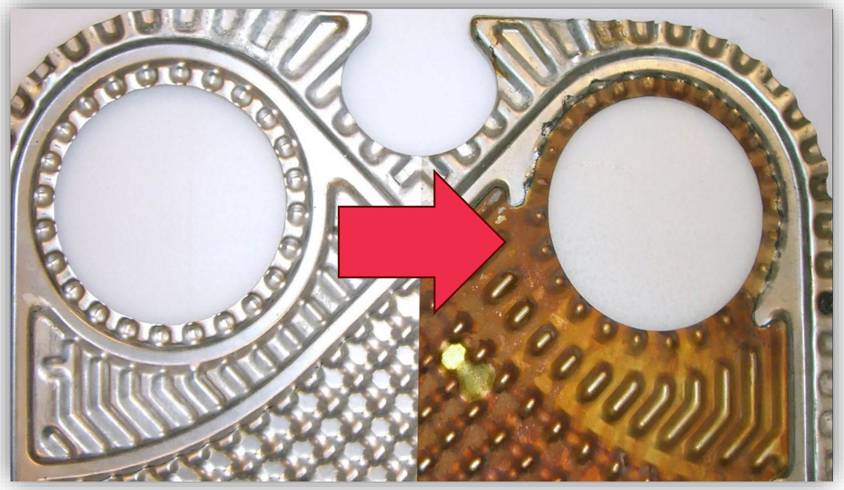
- Information from commercial systems described in the literature

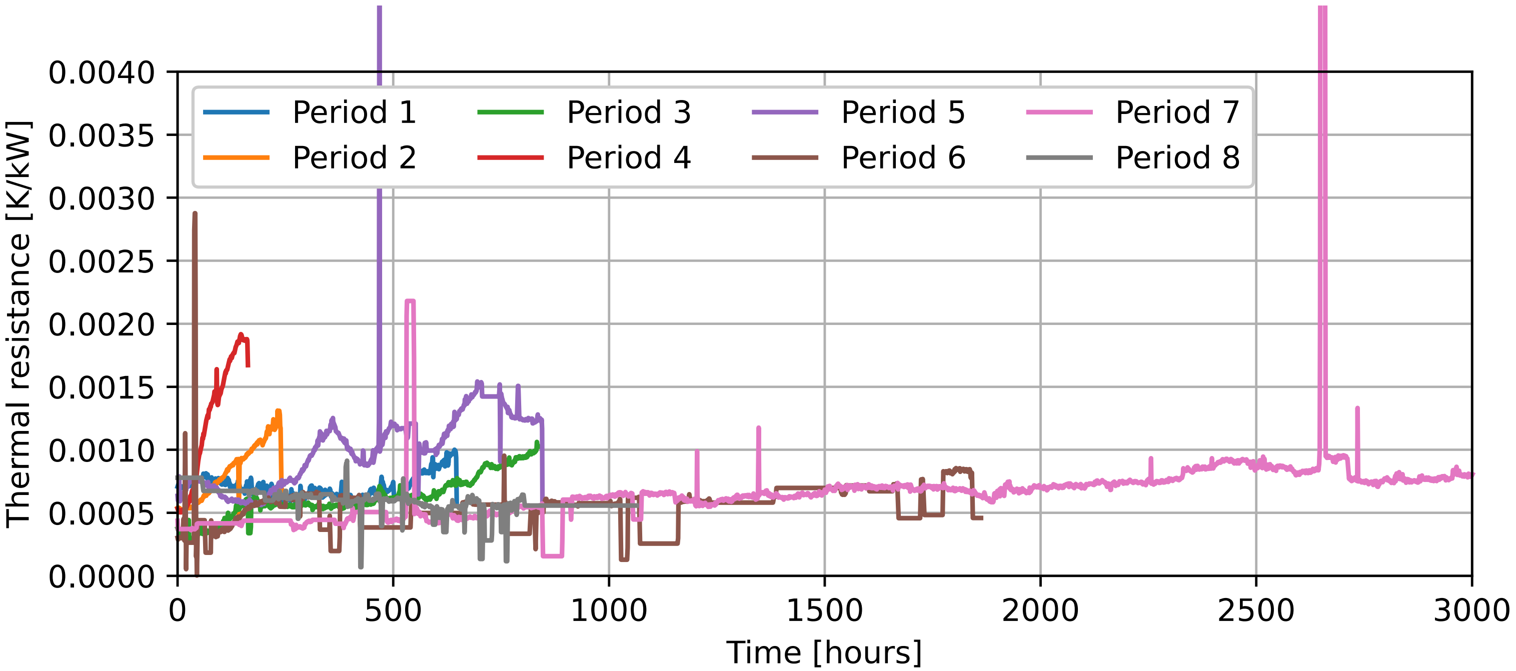


Source: J.J. Aguilera, W. Meesenburg, T. Ommen, W. B. Markussen, J.L. Poulsen, B. Zühlsdorf, and B. Elmegaard, "**A review of common faults in large-scale heat pumps**", Renewable and Sustainable Energy Reviews, 2022.

The challenge of fouling and its mitigation

- Growth of fouling-related thermal resistance on the same system

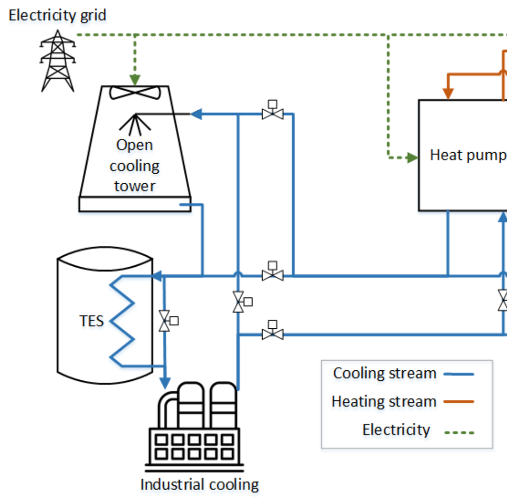


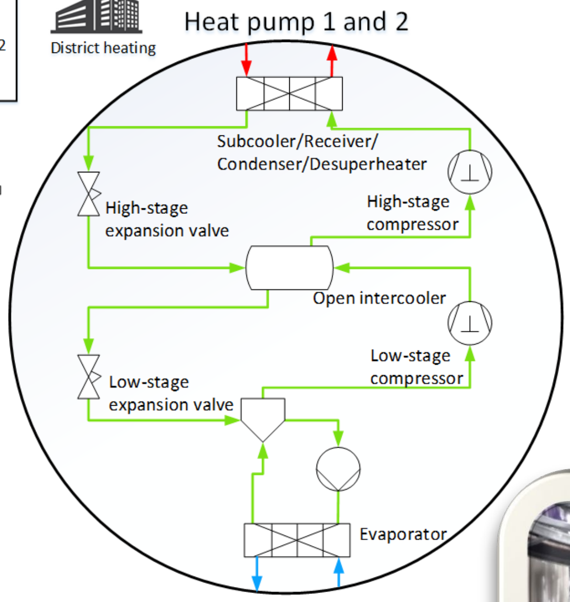


Source: (left) https://www.apexengineeringproducts.com, (right) W. Meesenburg, J.J. Aguilera, R. Kofler, W. B. Markussen, and B. Elmegaard, "**Prediction of fouling in sewage water heat pump for predictive maintenance**", Proceedings of ECOS 2022;

Case study

- Large-scale heat pump system affected by fouling



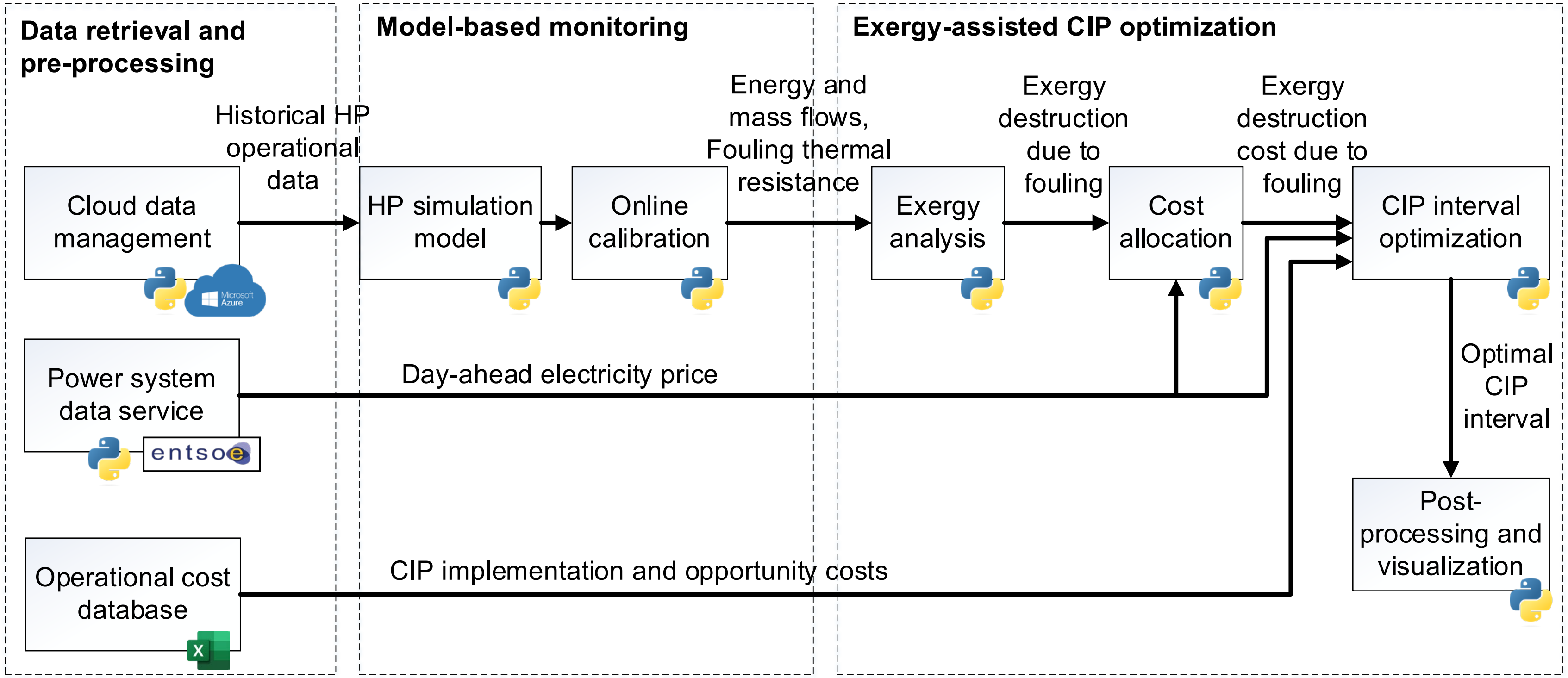


Heat pump characteristics:

- **Nominal heating capacity:** 2 MW
- **Refrigerant:** R-717
- **Compressor type:** Reciprocating
- **Evaporator and condenser type:** Plate-and-shell
- **Heat source:** Industrial waste heat
- **Heat sink:** District heating

Digital twin-based CIP interval optimization

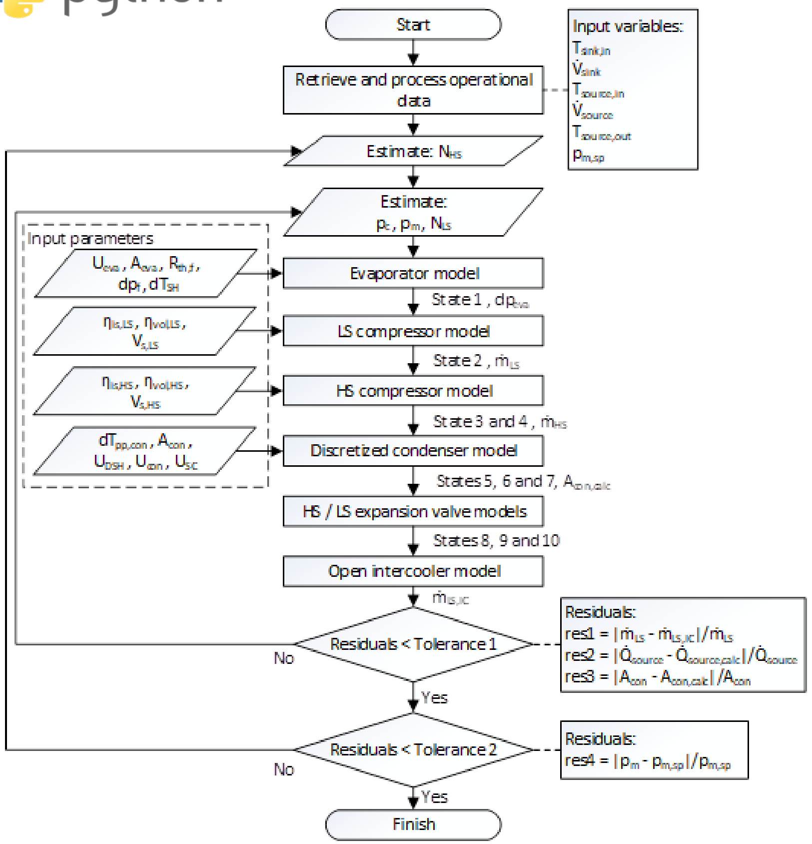
- Framework overview

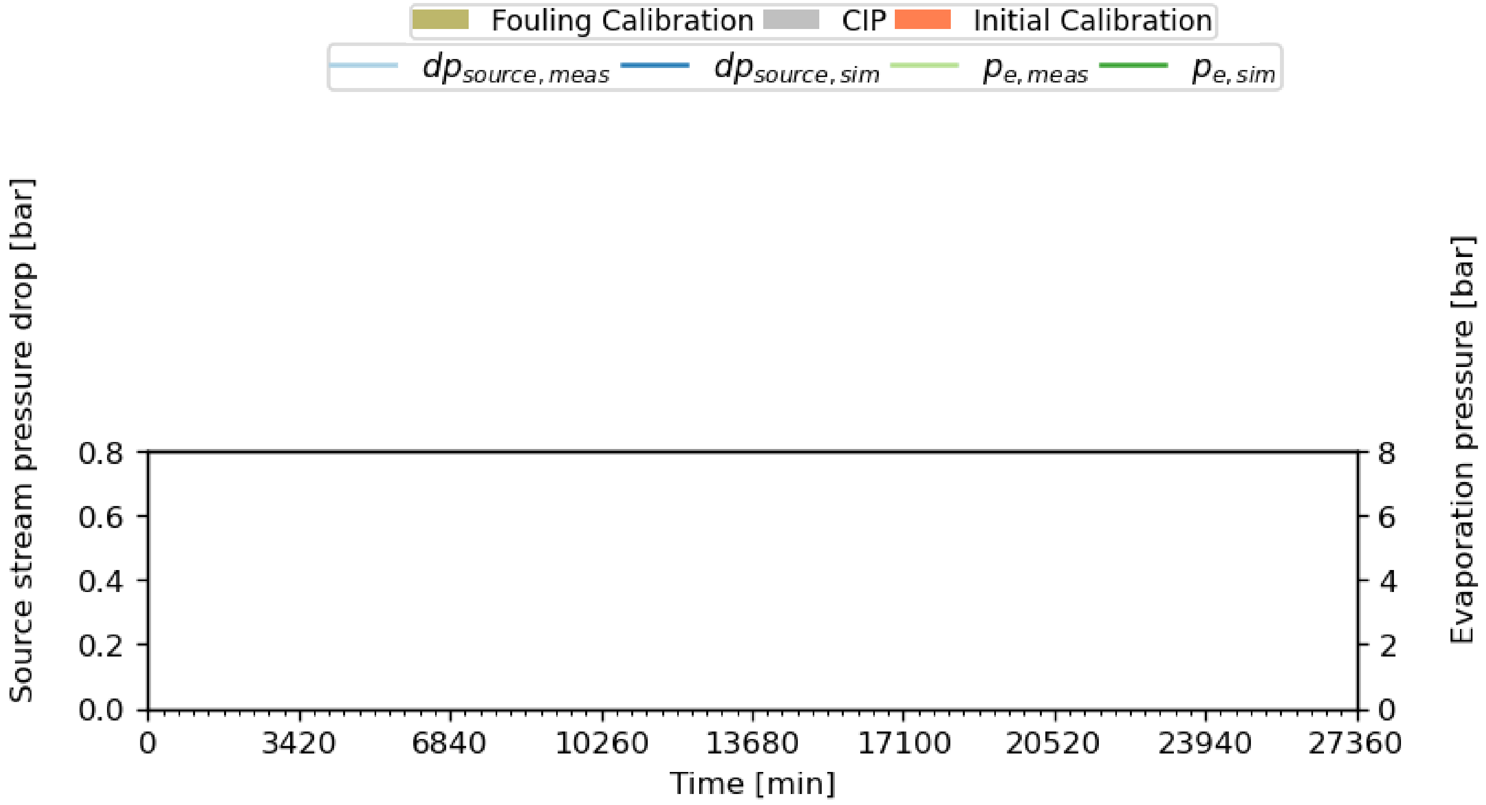


Source: J.J. Aguilera "**Digital twin-based services for large-scale heat pump systems**", Ph.D. thesis, Technical University of Denmark, 2024.

System monitoring

- Digital twin for online monitoring of performance and fouling effects

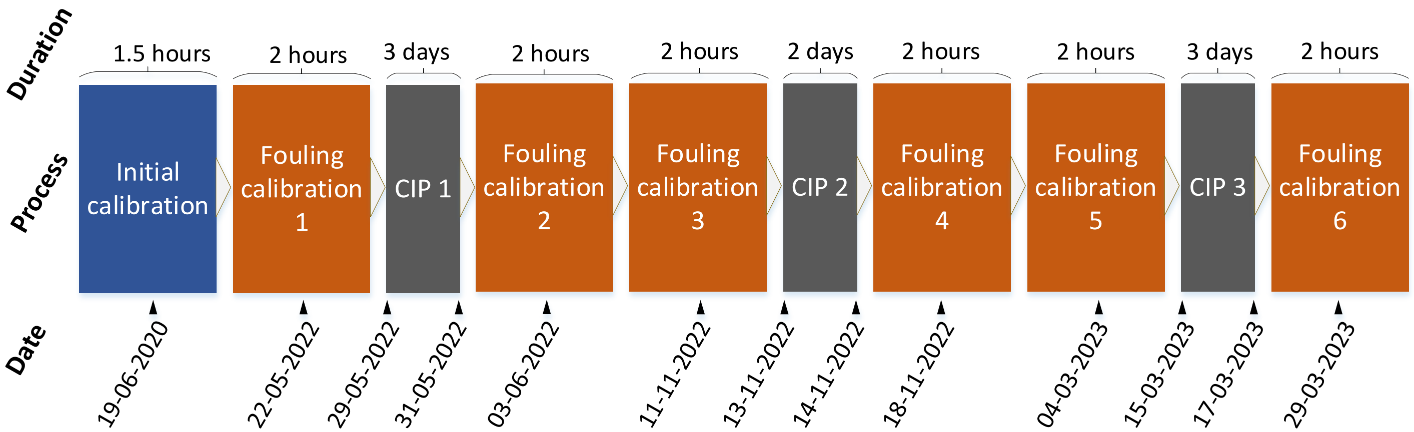




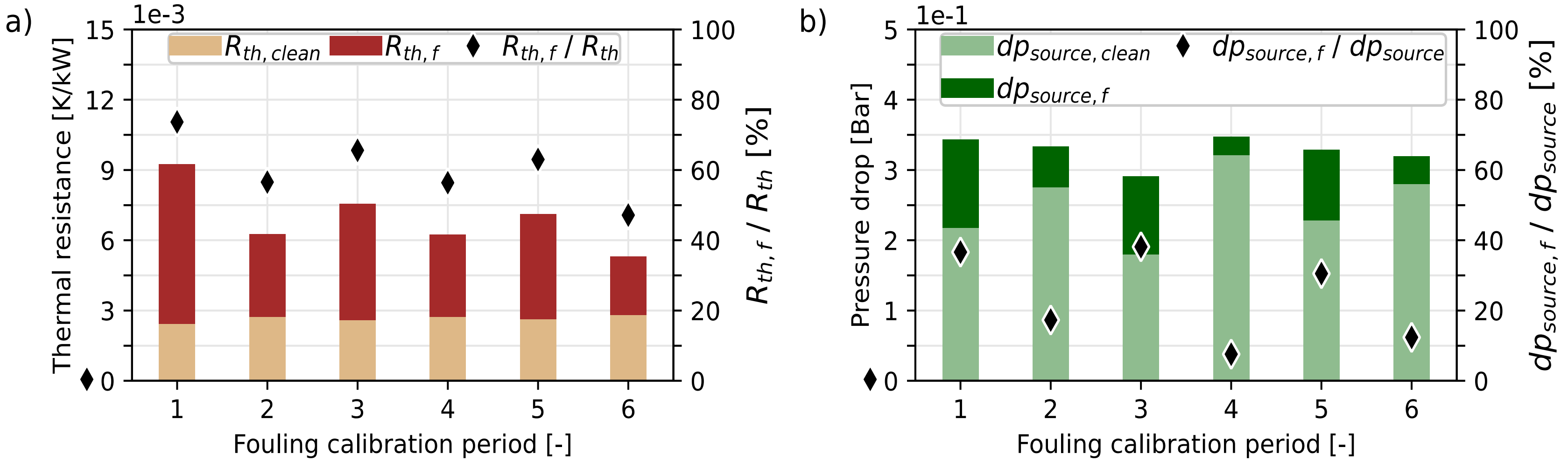
Source: J.J. Aguilera, W. Meesenburg, W. B. Markussen, B. Zühlsdorf and B. Elmegaard, "**Online model-based framework for operation and fouling monitoring in a large-scale heat pump**", Proceedings of ECOS 2023

System monitoring

- Characterization of fouling-related effects



Cleaning-in-place (CIP) system

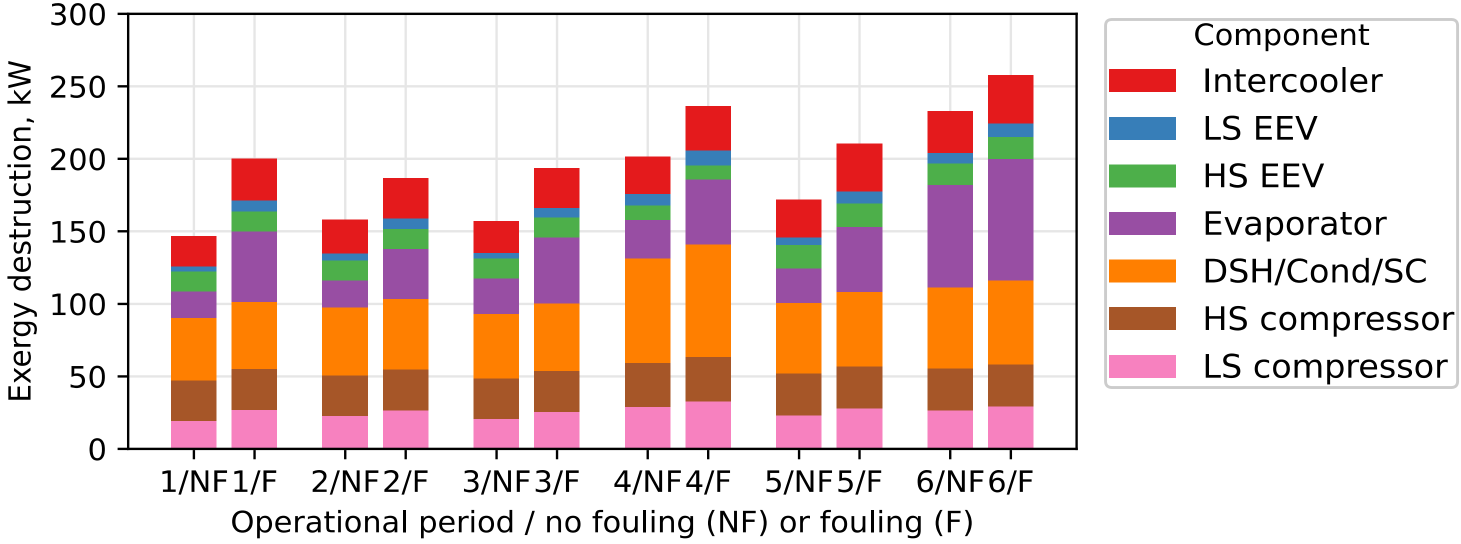


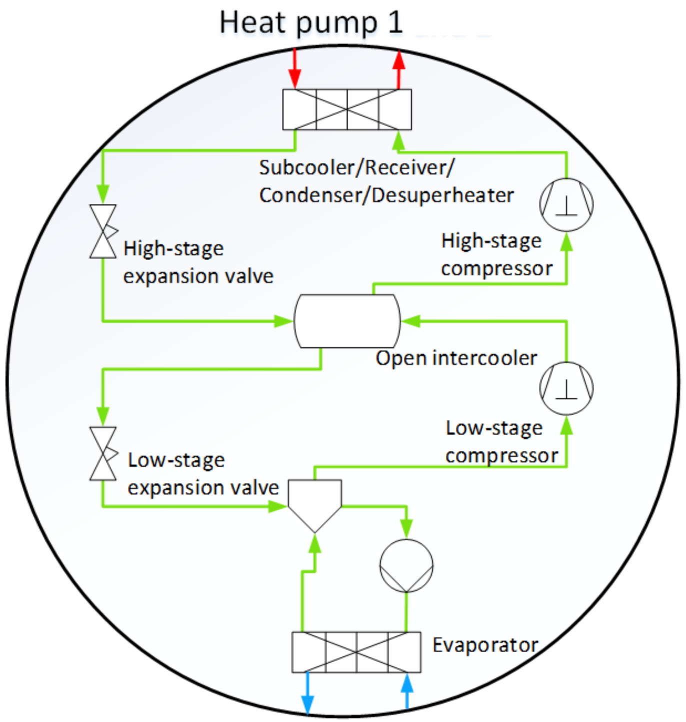
Exergy analysis derived from monitoring results

- Exergy -> Maximum useful work from an energy carrier
- Exergy destruction ($\dot{E}_{\mathrm{D}}$), assuming steady state:

$$\dot{E}_{\mathrm{D}} = \dot{E}_{\mathrm{F}} - \dot{E}_{\mathrm{P}} - \dot{E}_{\mathrm{L}}$$

- $\dot{E}_{\mathrm{D}}$ for operational periods with different fouling levels:





Source: J.J. Aguilera "**Digital twin-based services for large-scale heat pump systems**", Ph.D. thesis, Technical University of Denmark, 2024.

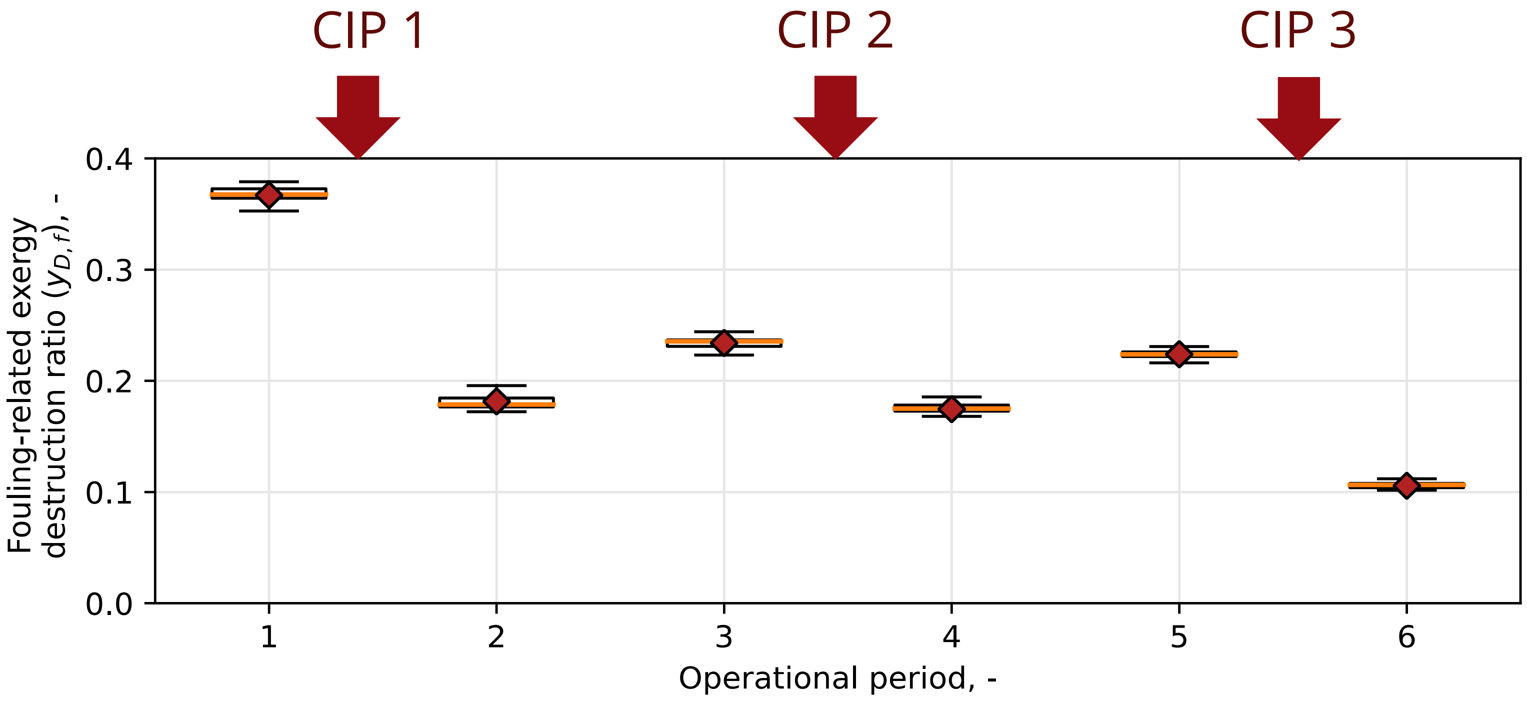
Fouling contribution to exergy destruction

- Fouling-related exergy destruction ratio:

$$y_{\mathrm{D,f}} = \dot{E}_{\mathrm{D,f}} / \dot{E}_{\mathrm{D}}$$

with

$$\dot{E}_{\mathrm{D,f}} = \dot{E}_{\mathrm{D}} - \dot{E}_{\mathrm{D,clean}}$$



Source: J.J. Aguilera "**Digital twin-based services for large-scale heat pump systems**", Ph.D. thesis, Technical University of Denmark, 2024.

Characterization of O&M costs

- **Total CIP costs**

$$C_{\text{CIP,total}} = C_{\text{CIP}} + C_{\text{CIP,OC}} + C_{\text{D,f,cum}}$$

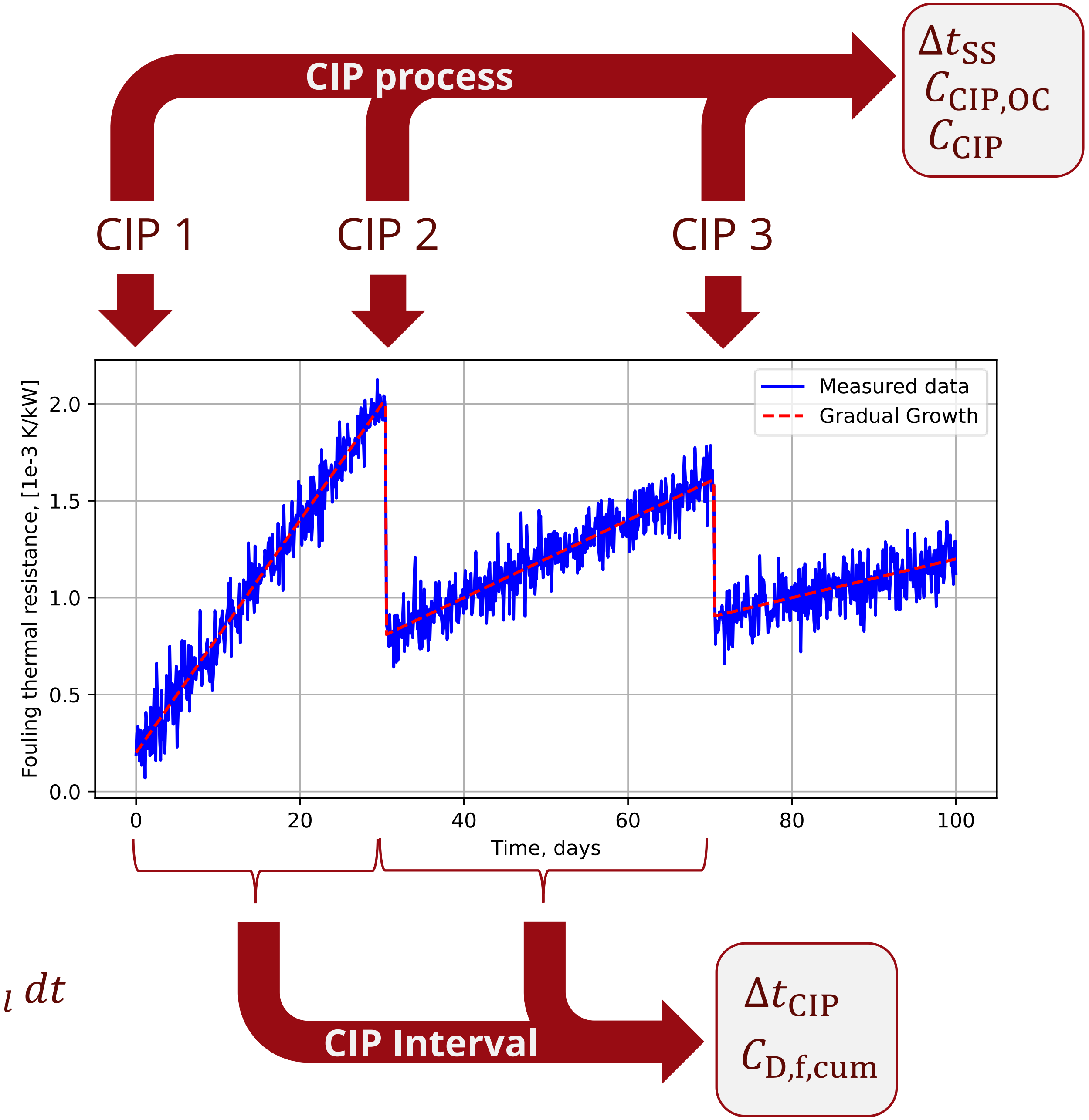
- **Cumulative cost of fouling**

$$C_{\text{D,f,cum}}(\Delta t_{\text{CIP}}) = \int_{t=0}^{t=\Delta t_{\text{CIP}}} \dot{C}_{\text{D,f}}(t)\, dt$$

with: $\dot{C}_{\text{D,f}} = c_{\text{el}} \cdot \dot{E}_{\text{D,f}}$

- **Opportunity cost of CIP**

$$C_{\text{CIP,OC}}(\Delta t_{\text{SS}}) = \int_{t=0}^{t=\Delta t_{\text{SS}}} \dot{Q}_{\text{sink}}(t) \cdot c_{heat} - \dot{W}_{\text{total}}(t) \cdot c_{el}\, dt$$



Source: J.J. Aguilera "**Digital twin-based services for large-scale heat pump systems**", Ph.D. thesis, Technical University of Denmark, 2024.

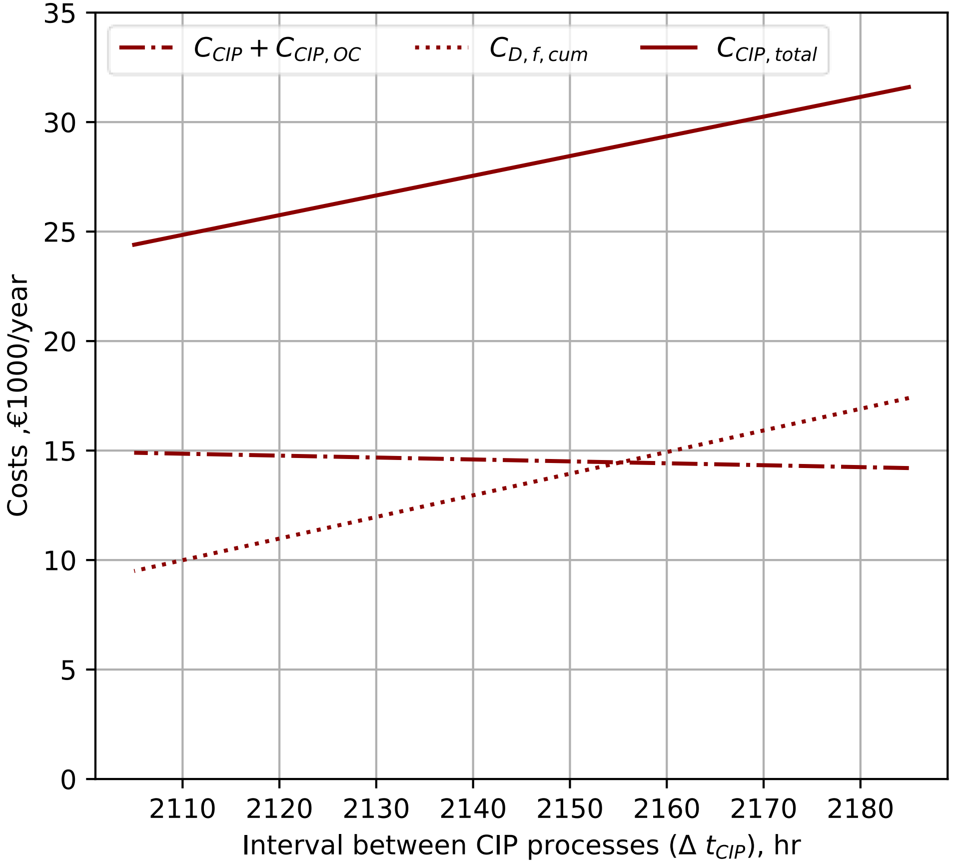
Definition of optimal CIP interval

- **Objective function based on total CIP costs**

$$min\ C_{\mathrm{CIP,total}} = C_{\mathrm{CIP}} + C_{\mathrm{CIP,OC}} + C_{\mathrm{D,f,cum}}$$

- **Cost results for CIP 2 and CIP 3**

CIP process	Δt_{CIP} (h)	C_{CIP} (€1000/year)	$C_{\mathrm{CIP,OC}}$ (€1000/year)	C_{CIP} + $C_{\mathrm{CIP,OC}}$ (€1000/year)	$C_{\mathrm{D,f,cum}}$ (€1000/year)	$C_{\mathrm{CIP,total}}$ (€1000/year)
CIP 2	2185	4.7	9.5	14.2	17.4	14.4
CIP 3	2105	4.8	10.1	14.9	9.5	15.0



Final remarks

- Additional operational data is required for the calculation of the optimal CIP interval.
- Possible to compare O&M costs for defining a cost-optimal CIP schedule.
- Possible to describe the influence of fouling on main HP components.
- Results can assist in redesigning HP components and control systems.
- The framework could be extended to address other faults leading to performance degradation.

Thank you for your attention

José Joaquín Aguilera Prado

Consultant

jjpr@teknologisk.dk

+45 7220 2903