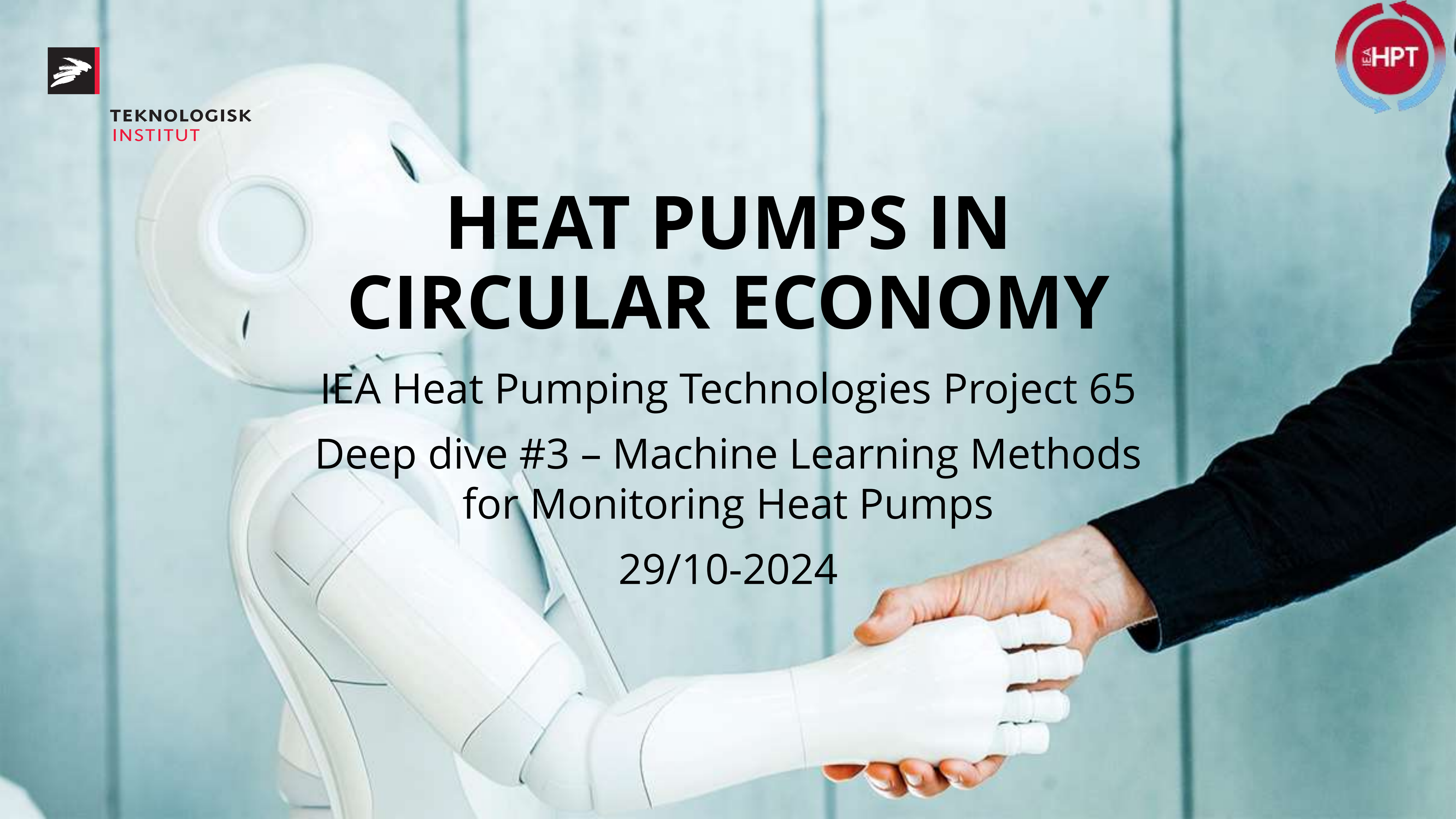

TEKNOLOGISK INSTITUT

HEAT PUMPS IN CIRCULAR ECONOMY

IEA Heat Pumping Technologies Project 65

Deep dive #3 – Machine Learning Methods for Monitoring Heat Pumps

29/10-2024

AGENDA

Agenda

- Short introduction and update (Jakob, DTI)
- Presentation of results and perspectives on lifetime extension (Arvydas, DTI)
- Business perspective – (Matteo, Metro Therm)
- Discussion and questions – (all)

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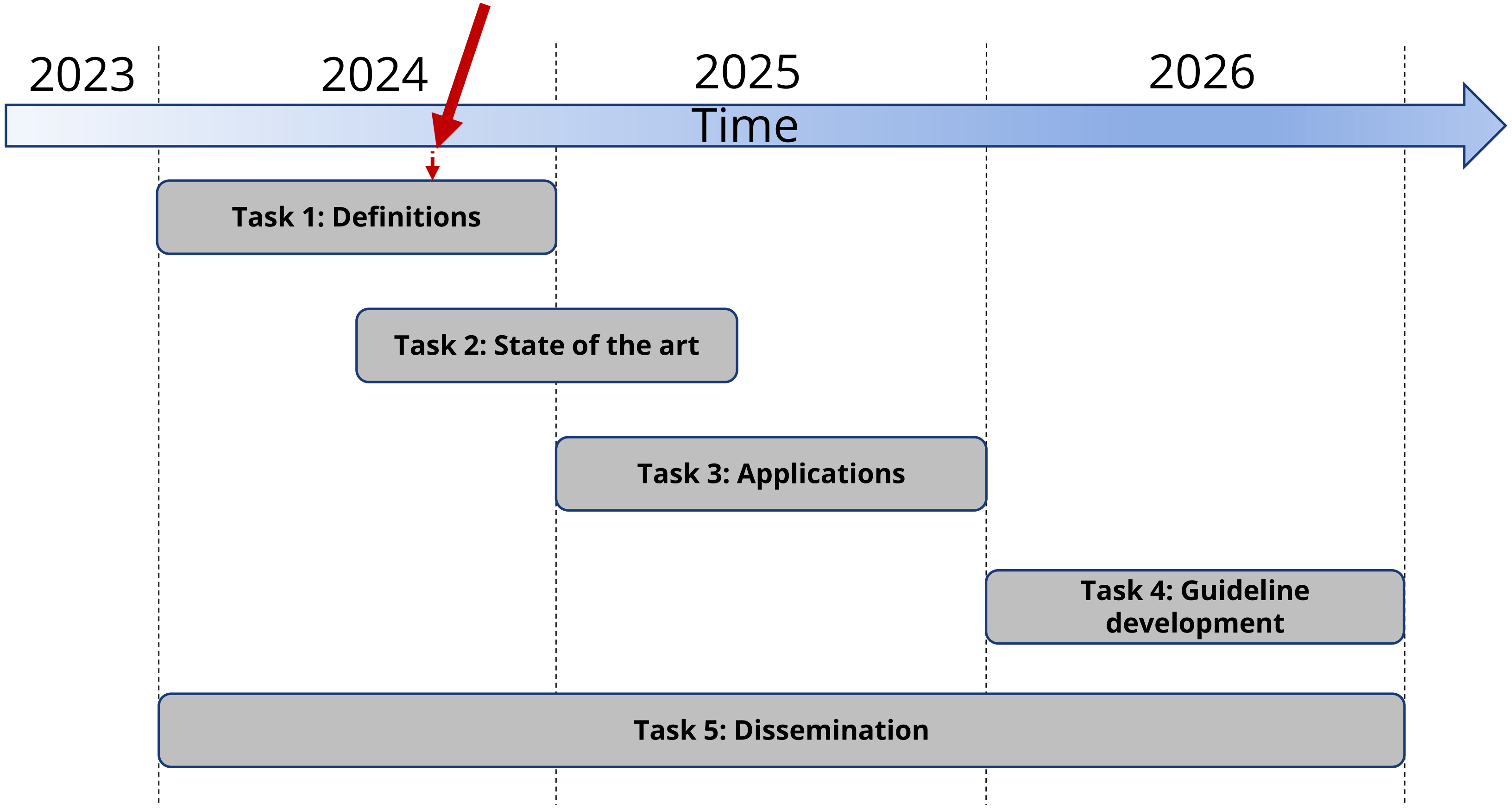
Project 65 'Heat pumps in a circular economy

Introduction and update

DANISH TECHNOLOGICAL INSTITUTE

TIMELINE


2023
2024
2025
2026
Time
Task 1: Definitions
Task 2: State of the art
Task 3: Applications
Task 4: Guideline development
Task 5: Dissemination

TASK 1 - DEFINITIONS AND DELIMITATION

The task aims to explore frameworks for circular economy and material efficiency and definitions will be established. This is expected to be based on:

- Evaluation of the standards for material efficiency in energy related products (literature study)
- Exploring the links to relevant regulation linked to materials in heat pumps such as WEEE, ROHS, etc. which will be mapped out. (literature study)
- A literature study to establish state of the art of lifecycle analyses conducted on domestic heat pumps will be carried out, and learnings from the various studies will be shared.
- Case study descriptions of previous common measures in heat pump design for domestic applications to lower the impact of materials. (literature study+interviews)

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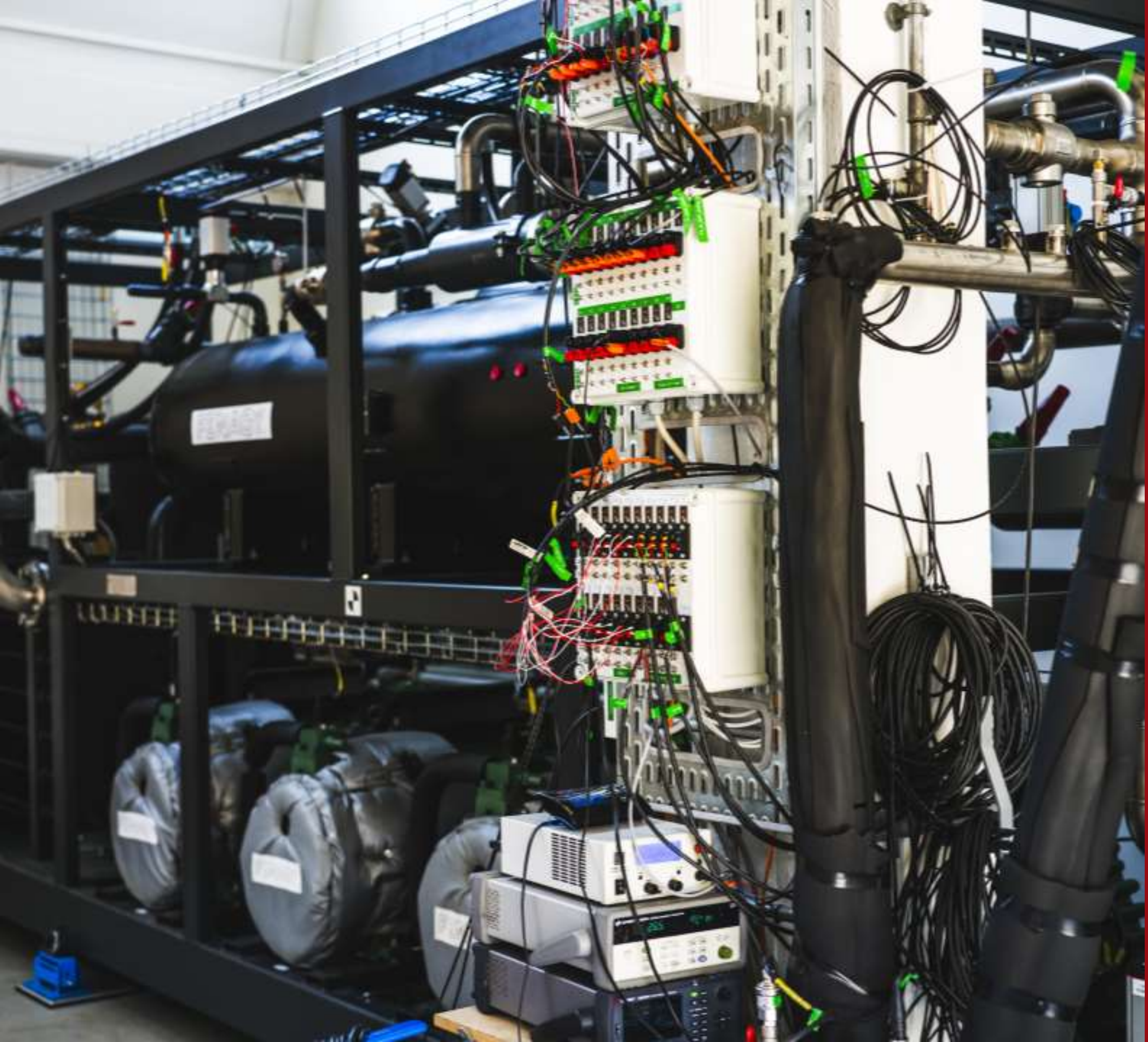


Project 65 ‘Heat pumps in a circular economy

Presentation from Arvydas Latvenas (DTI) and Matteo Caramaschi (Metro Therm)

DANISH TECHNOLOGICAL INSTITUTE

MSc Thesis - Arvydas Latvenas

Fault detection of PVT-heat pump system using machine learning methods

Introduction

Objectives:

- Fault detection and diagnosis model development
- Increase the lifetime of a product
- Reduced maintenance costs
- Improve heating system performance
- Sensors’ data analysis from a residential building HP system

Fault selection

- Early refrigerant leakage detection:

  Increase the safety of the system

  Reduce environmental impact

  Prevents loss of efficiency & heating capacity

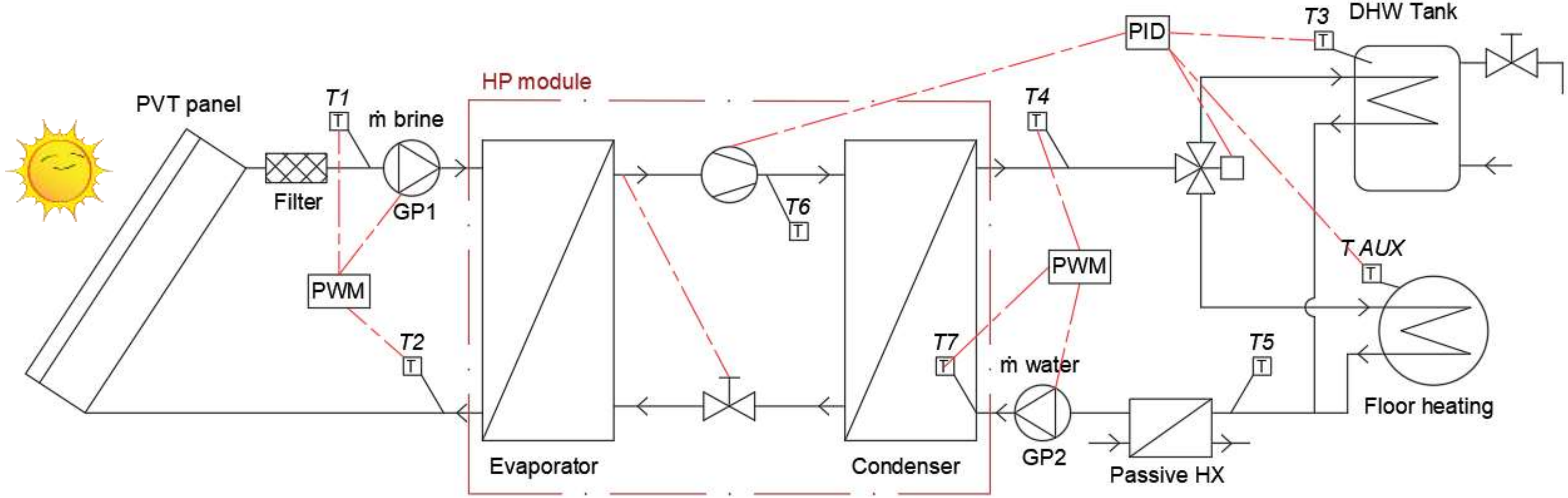
- Early clogged filter detection:

  Reduce wear of the components

  Reduce circulation pump energy consumption

PVT heat pump system

Metro DELTA [1] heat pump diagram



- Capacity 4.7 kW
- COP 4.7
- R290

- Rotary compressor
- TXV valve

- PVT panels
- dT source 3 K
- dT sink 5 K

PVT-heat pump system

- Cottage house
- 30 apartments
- 30 heat pumps
- Each heat pump connected to 4 PVT panels

Cottage house in Netherlands

Front projection of the cottage house with the apartments' number layout

3rd floor	90	91	92	93						
2nd floor	80	81	82	83	84	85	86	87	88	89
1st floor	70	71	72	73	74	75	76	77	78	79
Ground floor	63	-	-	64	-	65	66	67	68	69

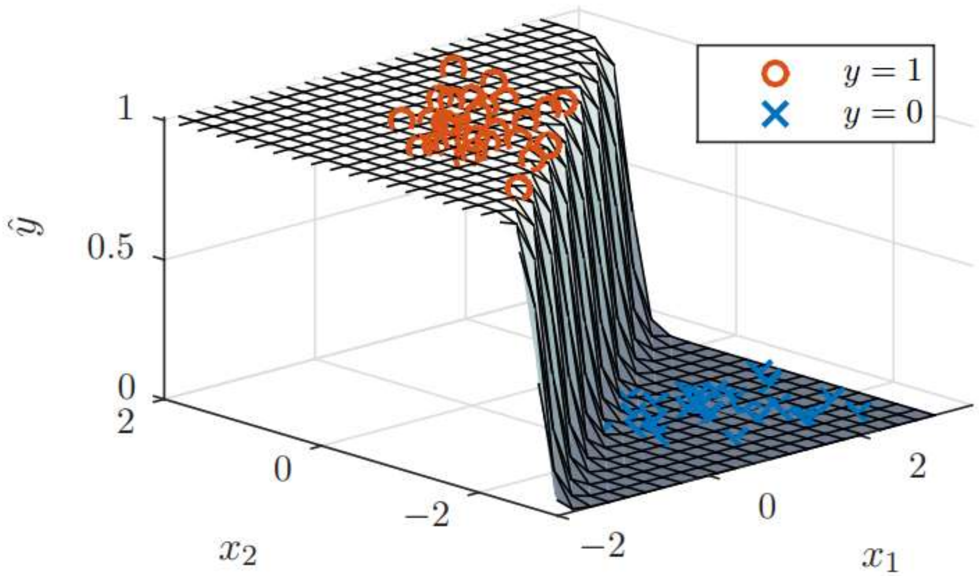
Methodology

Methodology

- Laboratory tests performed to gather training data for Machine Learning algorithms
- Two fault detection algorithms selected: Logistic regression & CUSUM
- Reduced brine flow rate fault detection model validated on the residential building dataset.
- Refrigerant leakage fault detection verified on the laboratory data set.

Logistic regression algorithm

Logistic regression sigmoid function [2]



- Supervised learning classification algorithm
- Needs faulty labeled data for training
- Input: sensors measurements
- Output: faulty operation probability
- Sigmoid function parameters w and b
- Sigmoid function:

$$\hat{y} = P(y = 1|\vec{x}; \vec{w}b) = sigmoid(\vec{w} \cdot \vec{x} + b) = \frac{1}{1 + e^{-(\vec{w} \cdot \vec{x} + b)}}$$

CUSUM algorithm

- Statistical process control
- Does not need faulty labeled data for training
- Accumulated residuals function:

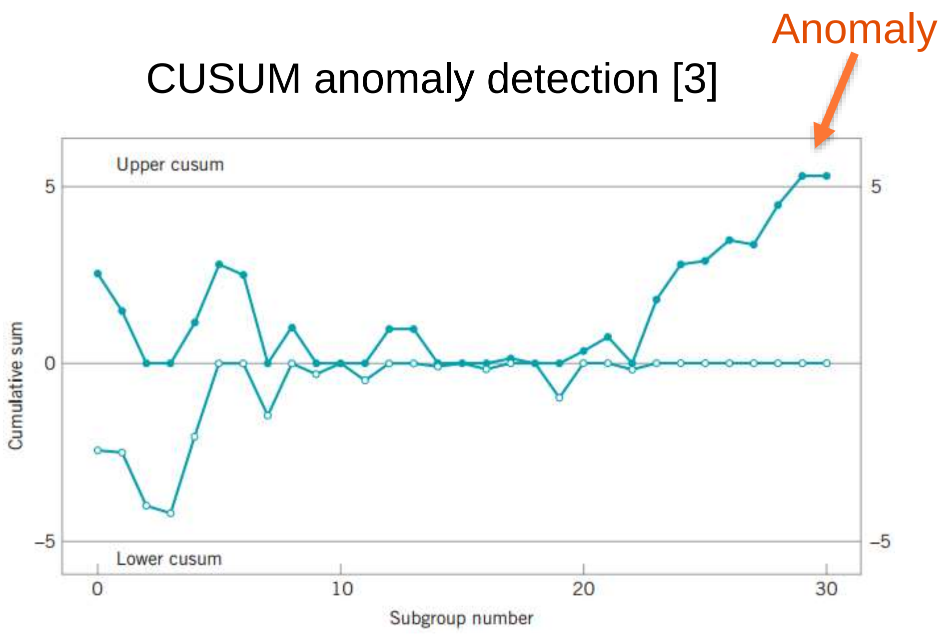
$$C_i^+ = max[0, C_{i-1}^+ + x_i - \mu_0 - K]$$

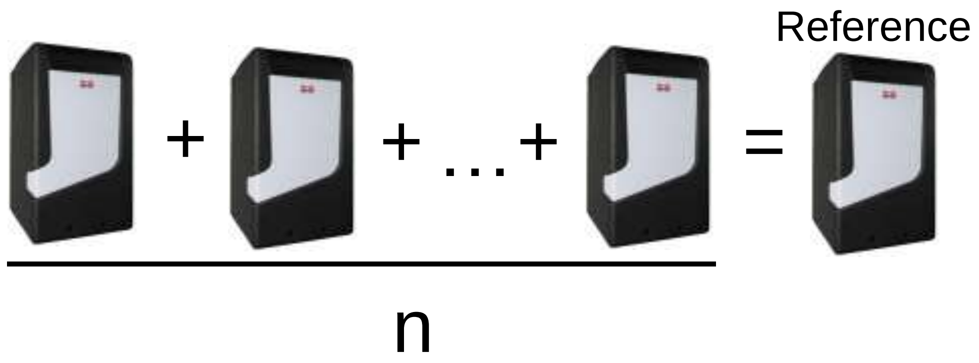
$$C_i^- = min[0, C_{i-1}^- + x_i - \mu_0 + K]$$

- Reference value μ_0:

$$\mu_0 = \frac{1}{n}\sum_{i=1}^{n} x_i$$

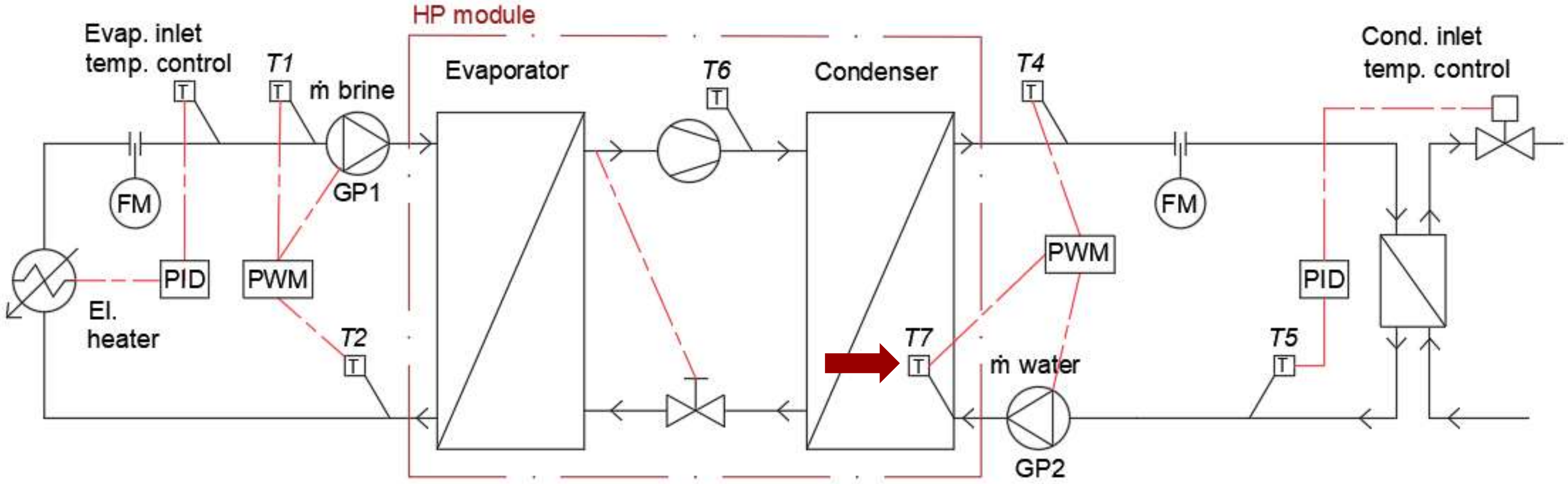
CUSUM anomaly detection [3]





Laboratory testing

Refrigerant leakage laboratory test



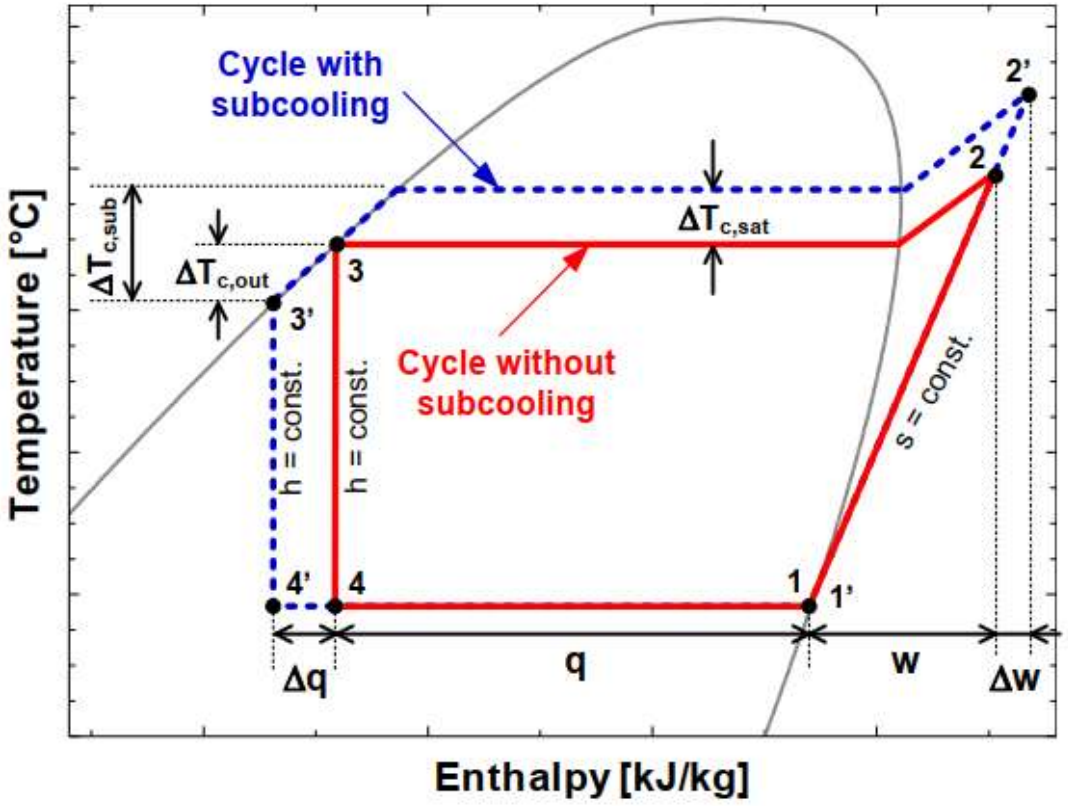
4 tests with different refrigerant charge levels:

- RL00 – normal charge
- RL10 – 10% reduced charge
- RL20 – 20% reduced charge
- RL40 – 40% reduced charge

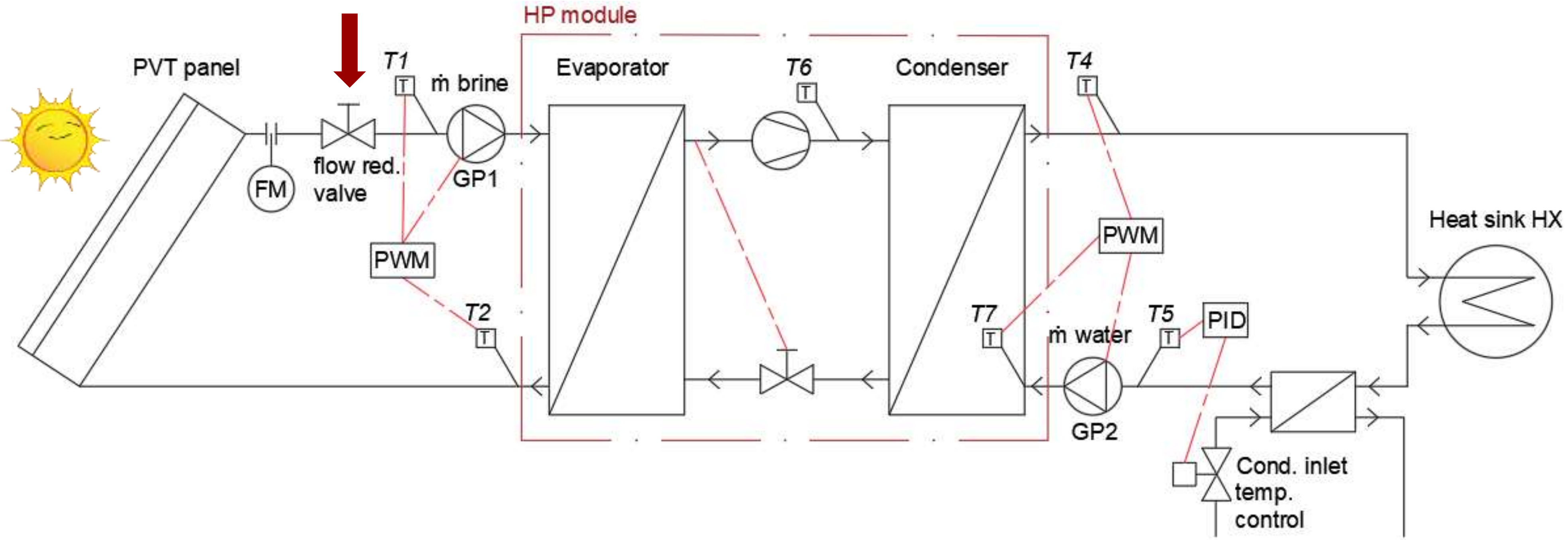
Largest effect: temperature in condenser subcooling zone

Refrigerant leakage laboratory test

T-h diagram of fault-free and refrigerant undercharge cycles [4]



Reduced brine flow laboratory test



- 40% reduced brine flow test
- Largest effect: dT evaporator temperature $\dot{Q}_E = \downarrow \dot{m}_{source} c_p (T1 - T2) \uparrow$

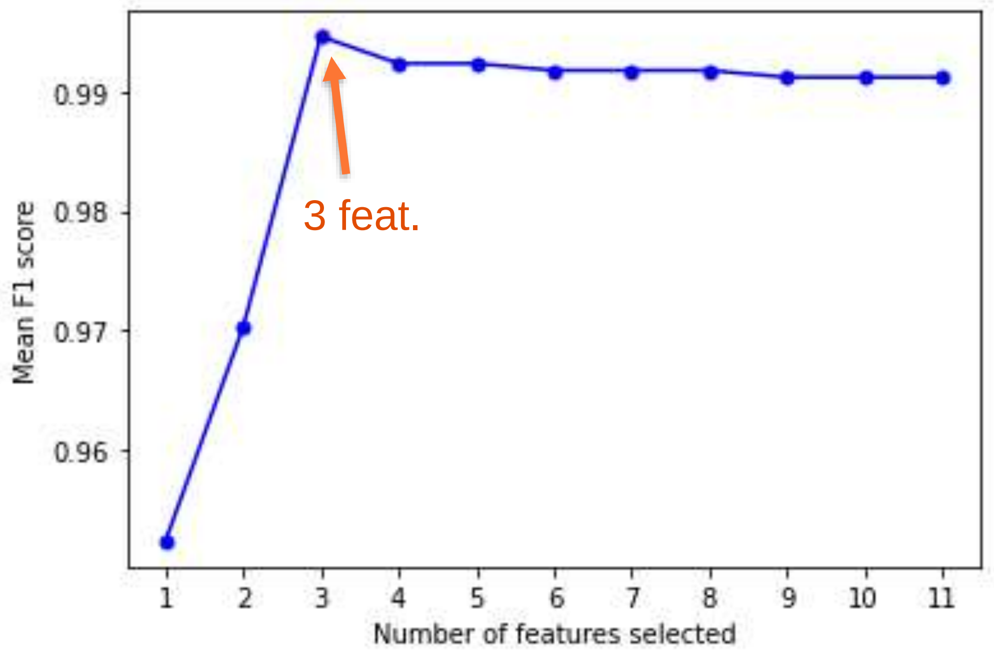
FDD model development

Logistic regression algorithm training

Reduced brine flow relevant features and weight coefficients:

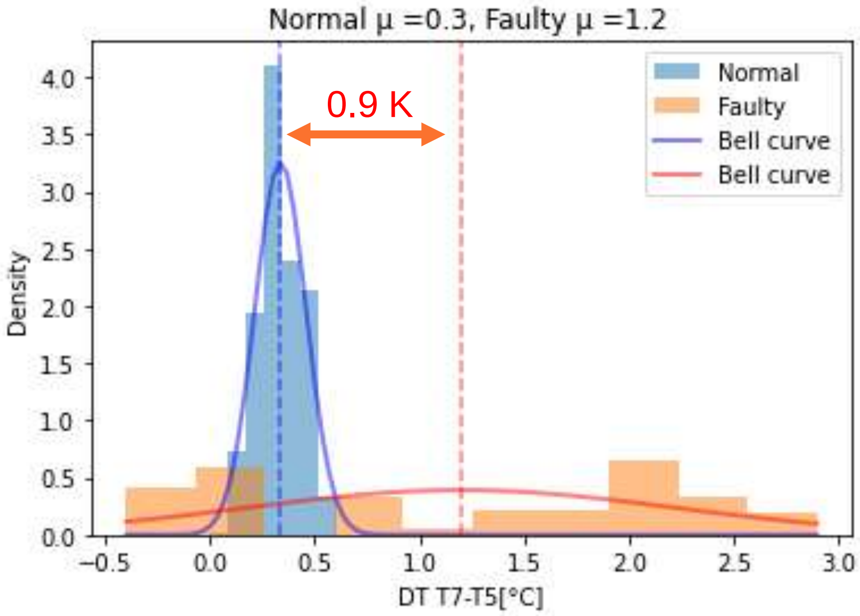
Rank	Feature	w, [-]
1	$dT_{source} T1 - T2$	6.18
2	$T2$ Source Outlet	-1.73
3	GP2 Pump sink PWM	-0.94
4	$T6$ Compressor discharge	0.83
5	GP1 Pump source PWM	0.82
6	$dT\ T7 - T5$	-0.77
7	$dT_{sink} T4 - T5$	-0.43
8	$T5$ Sink return	0.34
9	$T4$ Sink supply	0.32
10	$T7$ Sink inlet	0.31
11	$T1$ Source Inlet	-0.24

F1 score (blue) for feature elimination



CUSUM algorithm feature selection

RL10 faulty-free (blue) and faulty (orange) dT T7-T5 measurements



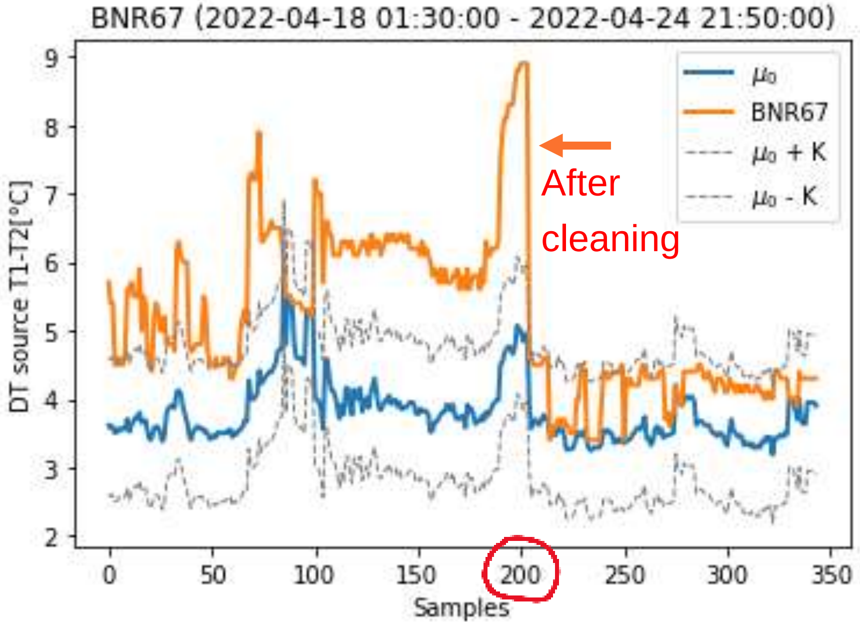
FDD results

FDD results for the building

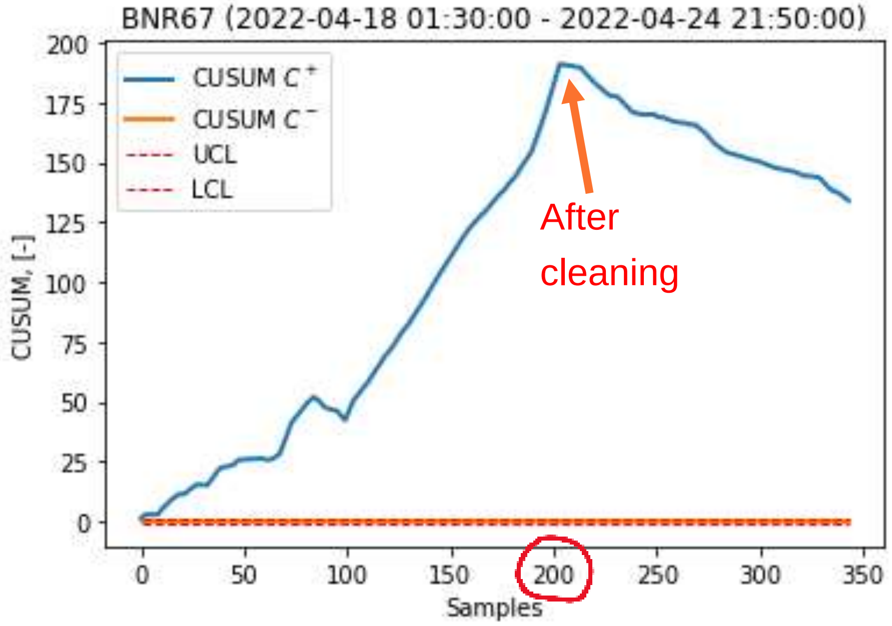
- Filter clogging in residential building, apartment 67

90	91	92	93						
80	81	82	83	84	85	86	87	88	89
70	71	72	73	74	75	76	77	78	79
63	-	-	64	-	65	66	67	68	69

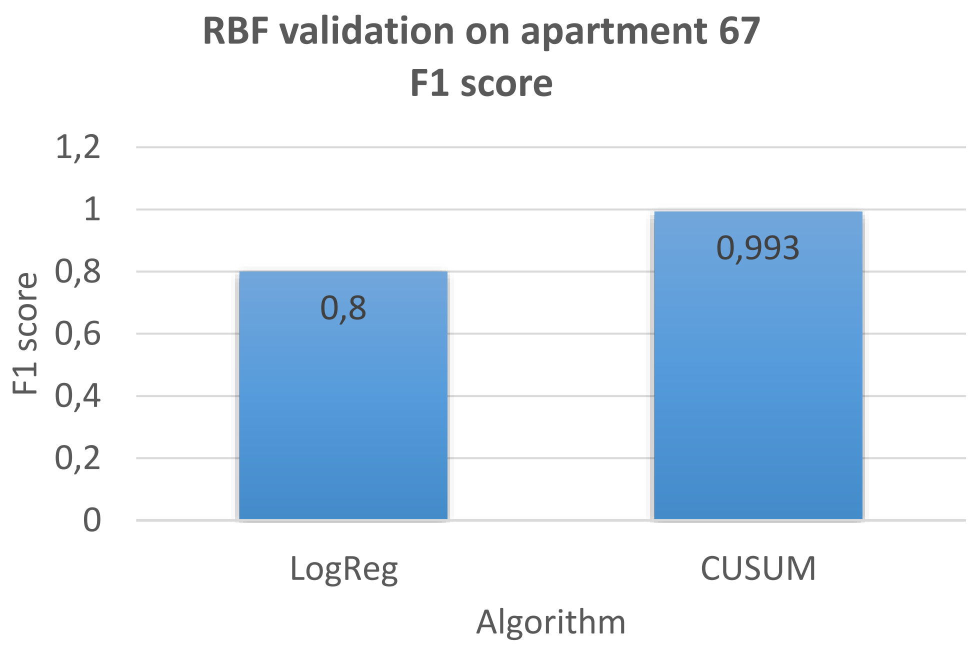
Sensor measurements of dT T1-T2 (orange), reference value μ_0 (blue), threshold K (grey)

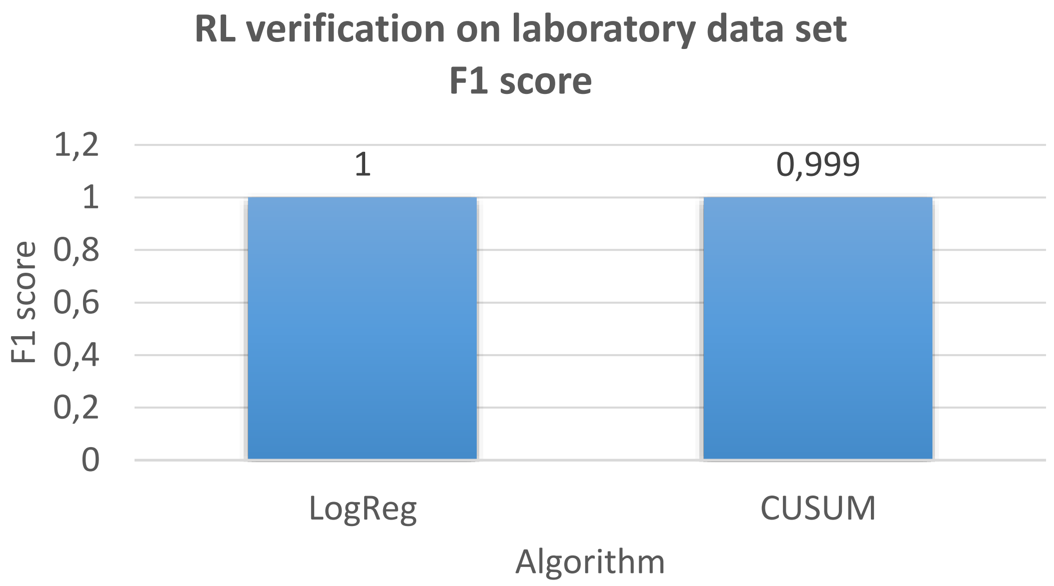


CUSUM residual sum of dT T1-T2 (blue)



FDD results





RBF best F1 score:

- RBF validation: CUSUM 0.99

RL best F1 score:

- RL training: LogReg 1.0

Reduced brine flow detection results for the building

- RBF in residential building
- Apartments 67, 69, 83

Table 4.14: RBF Fault detection

R. [-]	Week no, [-]	BNR [-]	Sample total, [-]	Sample faulty, [-]	Fault [%]
1	14	67	399	399	100
2	15	67	182	182	100
3	16	67	344	344	100
4	13	67	436	433	99.3
5	15	69	580	563	97.1
6	14	83	1256	1133	90.2
7	13	83	756	606	80.2

Cottage house in Netherlands

- RBF fault detected apartments

90	91	92	93						
80	81	82	83	84	85	86	87	88	89
70	71	72	73	74	75	76	77	78	79
63	-	-	64	-	65	66	67	68	69

Refrigerant leakage results for the building

- RL in residential building,
- Apartment 80

R. [-]	Week no, [-]	BNR [-]	Sample total, [-]	Sample faulty, [-]	Fault [%]
1	21	80	74	31	41.9

Cottage house in Netherlands

- RL fault detected apartments

90	91	92	93						
80	81	82	83	84	85	86	87	88	89
70	71	72	73	74	75	76	77	78	79
63	-	-	64	-	65	66	67	68	69

FDD results

Algorithms' comparison

LogReg	CUSUM
Pros:	Pros:
✓ Fast training	✓ Sensitive to small changes
✓ Automatic feature selection	✓ Does not need faulty dataset
Cons:	Cons:
▪ Inaccurate outside training dataset range	▪ Manual training
▪ Needs faulty dataset	▪ Needs reference value calculation

Conclusion

- Novel CUSUM algorithm application for the FDD
- Validated on residential building operational data set
- High performance score for both LogReg and CUSUM
- Easy scalable
- Increase lifetime of the system components
- Early fault detection and diagnosis
- Lower maintenance costs
- Better HP performance
- Models work for Metro DELTA HPs

References

[1] Metro Therm A/S. METRO Delta heat pump. URL: https://www.metrotherm.dk/produkter/varmepumper/metro-delta. (accessed: 17.06.2023).

[2] Mikkel N. Schmidt Tue Herlau and Morten Mørup. Introduction to Machine Learning and Data Mining. Technical University of Denmark, 2022.

[3] C. Montgomery Douglas. Introduction to Statistical Quality Control, Sixth Edition. John Wiley Sons, 2009. ISBN: 978-0470169926.

[4] Gustavo Pottker and Pega Hrnjak. "Effect of the condenser subcooling on the performance of vapor compression systems: Experimental and Numerical Investigation". In: 50 (2015), pp. 156–164. ISSN: 0140-7007. DOI: 10.1016/j.ijrefrig.2014.11.003

MSc Thesis Defence - Arvydas Latvenas

Thank you for your attention

MSC THESIS ON FAULT DETECTION - BUSINESS PERSPECTIVE

NIBE GROUP MEMBER

METRO THERM

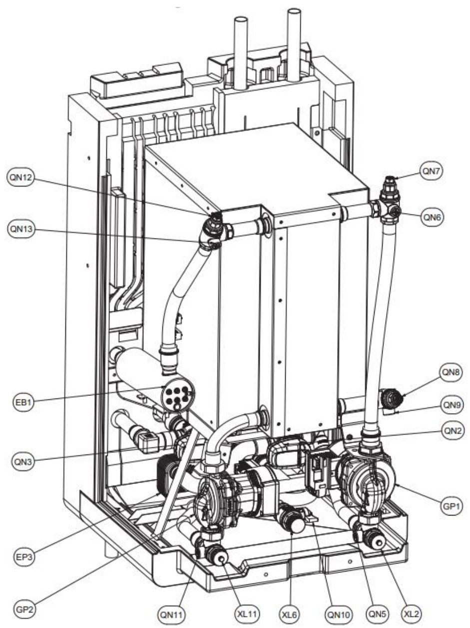
LEARNINGS

Product

✓ Unit behaviour under reduced flow

✓ Performance vs charge characterization

✓ Performance robustness
- 10 % leak → COP variation < 5 %



150 g R-290

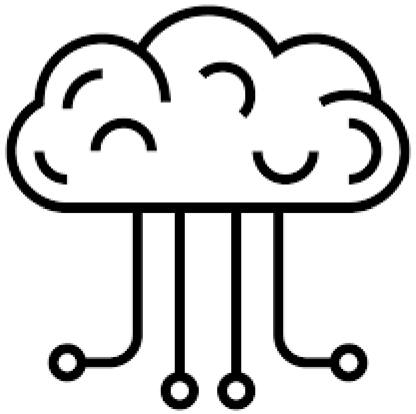
METRO THERM

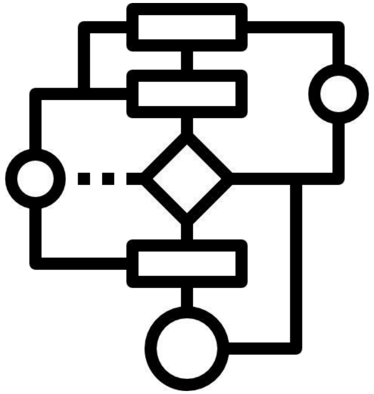
LEARNINGS

Methods

- ✓ Exploring Machine Learning
- ✓ Alternative fault-finding techniques

- ✓ Detection (new) most sensitive parameters
- ✓ New fault detection algorithms (simplified)





POSSIBLE IMPLEMENTATION

Monitoring, predictive mantainance & optimization

Remote – Cloud-based

PRO

myUplink Pro Web

LS Control - SCC

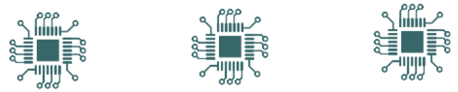
Installer

Distributor

Manufacturer

Remote & advanced

Local – Microcontroller-based



Local, simple & fast

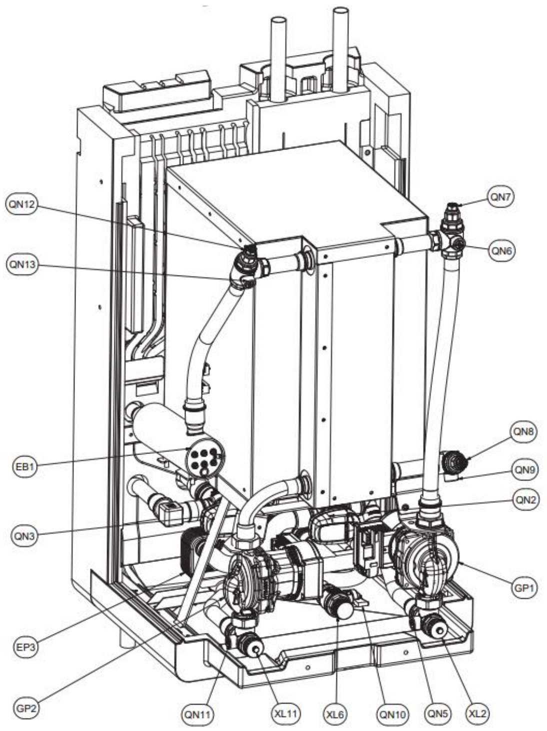
THANK YOU FOR YOUR ATTENTION

NIBE GROUP MEMBER

METRO THERM

METRO Delta

- ✓ Wall-mounted liquid-water heat pump.
- ✓ Natural refrigerant Propane 150 g.
- ✓ Possible sources: PVT panels, geothermal heat and Thermonet.
- ✓ Ideal for smaller households with strict outdoor sound requirements.



METRO THERM

Project 65 ‘Heat pumps in a circular economy

Discussion and other deep dives

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CURRENT LIST OF DEEP DIVES

Completed topics

- Lifecycle data collection to streamline data collection
- Presentation of LCA analysis of heat solutions (learnings from IEA SHC by Fraunhofer ISE)
- Lifecycle assessment and refrigerants: a case study for the German building stock
- Machine learning algorithms for fault-detection algoritms (DTI & Metro Therm)

Expected upcoming topics

- November 27th : presentation from researches from Sheffield University
  - 'Heat pump supply chain environmental impact reduction to improve the UK energy sustainability, resiliency and security'
- Presentation by Viessmann about their sustainability work (Viessmann)

Next session November 27th

Hopefully there will be one during December or early January

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LIST OF POTENTIAL DEEP DIVES

Proposal topics

- Horizontal products standards and their implications for heat pumps
- If available case descriptions of common measures to lower impact of materials
- Take-back systems for heating solutions
- Identification of priority parts for heat pumps in a lifetime perspective
- New business models in relation to circularity aspects of heat pumps
- Mapping of end-of-life handling and TRL-levels for various technologies (Danish group proposal)
- What do to with used spare parts (Danish group proposal)
- Impact of limitation on PFAS substances on circularity.

Questions

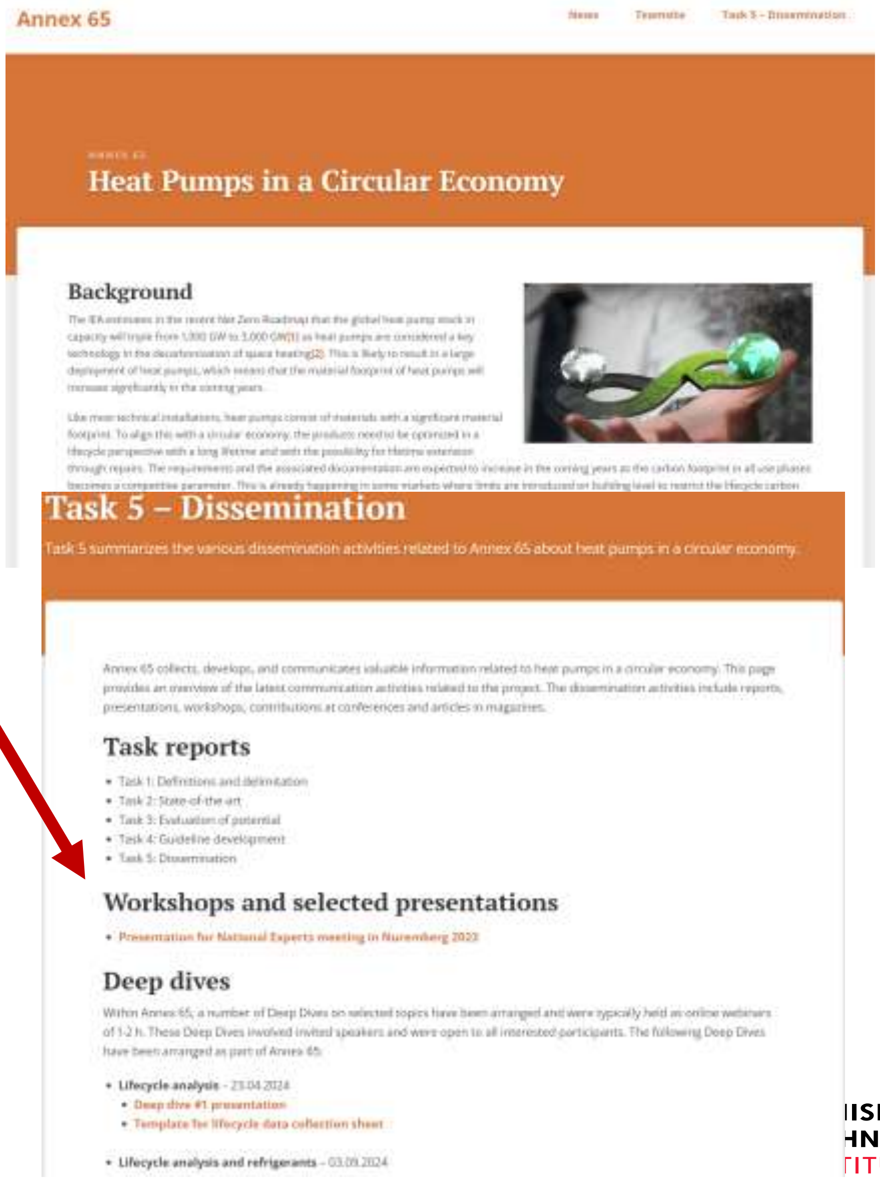
- Any other topics that would be interesting?
- Does anybody have any input to share for a topic?
- Any topics that should have increased focus?

IEA HPT ANNEX 65 WEBSITE

The website for the annex can be found here: [Link]

Public presentation including deep dive presentations are uploaded under 'Task 5 – Dissemination'. I will also include articles if you let me know.

News post is posted when I find relevant topics – You are also welcome to send relevant topics if you would like me to make a post. The news post are referenced in HPC's newsletter.



THANK YOU FOR PARTICIPATING

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