DANISH TECHNOLOGICAL INSTITUTE

BOOK OF PRESENTATIONS

SEMINAR

DIGITALIZATION OF REFRIGERATION AND HEAT PUMP SYSTEMS

DANISH TECHNOLOGICAL INSTITUTE

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WELCOME

Wiebke Brix Markussen

Danish Technological Institute

WELCOME

Seminar on Digitalization of Refrigeration and Heat Pump Systems

4 July 2024, Teknologisk Institut

Digital services and flexibility analysis

Operation monitoring

Predictive maintenance

Modelling and scalability

Overview of digital services and flexibility analysis

09.40 -10.00	Results from the IEA IoT Annex 56 project about digital services for IoT connected heat pumps Jonas Lundsted Poulsen, Danish Technological Institute (DTI)
10.00 - 10.20	Model predictive control and demand side flexibility through heat pumps Jan Bendtsen, Aalborg University (AAU)
10.20 - 10.40	Heat pumps providing flexibility services – the role of model-based tools Wiebke Meesenburg, DTU Construct

Coffee break

Operation monitoring

11.10 - 11.30 More than 10 years with own cloud monitoring system - before and now
Stig Petersen, LS Control

11.30 - 11.50 A cloud-assisted framework for real-time monitoring of refrigeration and heat pump systems
Johan hardt Løbner, Danish Technological Institute (DTI)

11.50 - 12.10 A digital twin for evaluating evaporation pressure fluctuations in supermarket refrigeration systems
Andreas Schulte, TU Braunschweig

Lunch

Predictive maintenance

13.00 -13.20	Automatic fault detection and diagnosis in refrigeration systems, a data-driven approach Zahrasadat Soltani, Bitzer
13.20 - 13.40	Fault detection in ultra-low temperature freezers Francesco D'Ettorre, Danish Technological Institute (DTI)
13.40 - 14.00	Towards optimal predictive maintenance in large-scale heat pumps through digital twins José Joaquín Aguilera Prado, Danish Technological Institute (DTI)

Coffee break

Modelling and scalability

14.30 - 14.50	Fast heat pump simulation model deployable anywhere Emil Navntoft Pedersen, Danish Technological Institute, (DTI)
14.50 - 15.10	Versatile simulation models of heat pump and refrigeration systems with Dymola Pierre-Jean Delêtre, Danish Technological Institute (DTI)
15.10 - 15.30	Scaling digital services for heat pump systems Lasse Nyberg Thomsen, Numerous / Energy Machines
15.30	Seminar closing

Organization and acknowledgements

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EUDP

DANISH TECHNOLOGICAL INSTITUTE

RESULTS FROM THE IEA HPT IOT ANNEX 56 PROJECT ABOUT DIGITAL SERVICES FOR IOT CONNECTED HEAT PUMPS

Jonas Lundsted Poulsen

Danish Technological Institute

TEKNOLOGISK INSTITUT

IoT for heat pumps

IEA HPT

Results from the IEA HPT IoT Annex 56 project about digital services for IoT connected heat pumps

Jonas L. Poulsen, DTI

04-07-2024

Seminar on Digitalization of Refrigeration and Heat Pump Systems

Heat Pumping Technologies (HPT) programme

- A Technology Collaboration Programme (TCP) within **the IEA** since **1978**
- An international framework of **cooperation** and **networking** for different HP actors
- A forum to exchange **knowledge** and **experience**
- A contributor to **technology improvements** by RDD&D projects

20 member countries

Austria	Denmark	Japan	Sweden
Belgium	Finland	Netherlands	Switzerland
Canada	France	Norway	United Kingdom
China	Germany	South Korea	United States
Czech Republic	Ireland	Spain	
	Italy		

Digitalisation and IoT for HPs - IEA HPT Annex 56

- Project duration: 2020-2023
- 4 main task (work packages):
  - Task 1: State-of-the art
  - Task 2: Interfaces
  - Task 3: Data Analysis
  - Task 4: Business Models
- Interviews and surveys on the state of digitalisation in the participating countries
- 40 factsheets of IoT use cases and projects
- Covers both household and industrial heat pumps

Austria (AIT (OA), TU Wien, UAS Burgenland, ÖAW)

Tilman Barz
Regina Hemm
Reinhard Jentsch
Philipp Ortmann
Christoph Reichl
Veronika Wilk
Bernd Windholz
Gerhard Zucker
Goran Music
Wolfgang Kastner
Gernot Steindl
Felix Schaber
Helmut Plank
Roman Stelzer
Christian Heschl

Denmark (DTI, DTU Compute, DTU Construct, EnergyMachines)

Wiebke Brix Markussen
Jonas Lundsted Poulsen
Tobias Dokkedal Elmøe
José Joaquín Aguilera
Christian Ankerstjerne Thilker
Henrik Madsen
Wiebke Meesenburg

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Tim Rist
Danny Günther

Norway (SINTEF)

John Clauss
Kristian Stenerud Skeie
Cansu Birgen

Switzerland (HSLU)

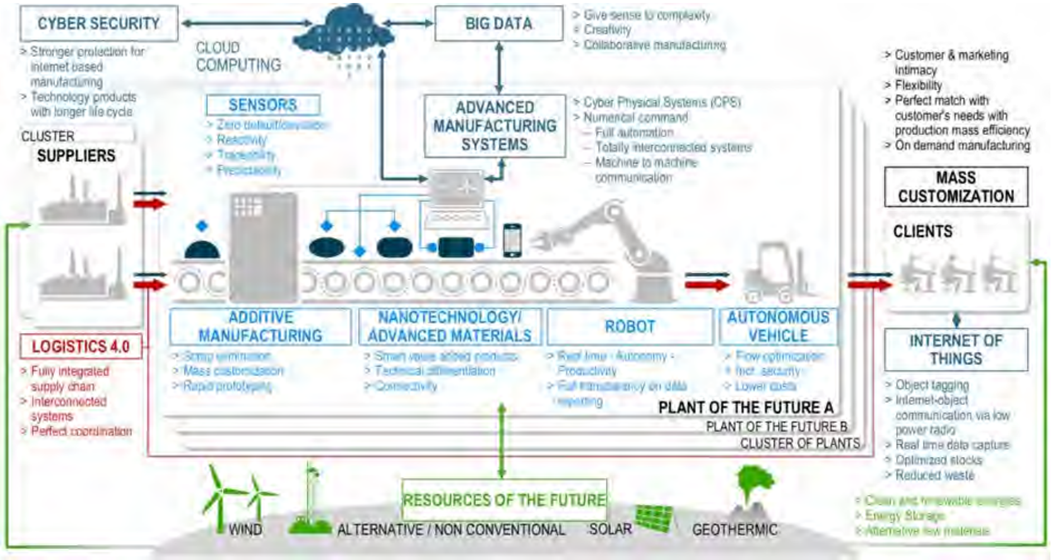
Raphael Agner
Beat Wellig

France (EDF)
Odile Cauret

Task 1 – state of the art

- One of the first definitions of "IoT" which creates a shift of paradigme from **internet of data and people** to **internet of things:**

  *<u>Internet of Things</u>: "Machine-to-machine communications and person-to-computer communications will be extended to things, from everyday household objects to sensors monitoring the movement of the Golden Gate Bridge or detecting earth tremors. Everything from tyres to toothbrushes will fall within communications range, heralding the dawn of a new era, one in which **today's internet of data and people** gives way to tomorrow's **Internet of Things**." (ITU, 2005)*



Trend in evolution of M2M to IoT, (Blanz, 2012).

- Paradigme shift lead to wider range of communication protocols:
  - Industrial Ethernet fieldbuses: Modbus, KNX, BACnet, …
  - Session layer protocols: AMQP, MQTT, …
  - Opportunities, uncertainties and characteristics for protocols described in Task 1 report.

The global push for new technologies brought by a large number of different consortia and standards, (Blanz, 2012).

Task 1 – State of the art – use cases

- 40 use cases collected by the various national teams with focus on design, development, and implementation of IoT solutions for heat pump systems. Both products and services as well as research projects.
- Fact sheets includes key aspects such as stakeholders, participants, connection type and data requirements.
- Common patterns identified, resulting in 5 main categories:
  - Heat pump operation optimization
  - Predictive maintenance
  - Flexibility provision
  - Heat pump operation commissioning
  - Heat as a service

Factsheet for "Large scale demand response of heat pumps to support the national power system – SLAV (SE)"

Factsheet for "Virtual Energy Storage Network based on Residential Heating Systems by Tiko Energy Solutions AG (CH)"

23 DANISH CASE DESCRIPTIONS

Product and Service Suppliers:
- Energy Machines – Energy machines verification
- Neogrid – PreHEAT for Heat Pumps by Neogrid Technologies ApS
- LS Control - SmartConnect Center
- Centrica Energy Marketing and Trading
- Climify – Indoor Climate Monitoring Platform
- Nærvarmeværket – Community owned Heat Pump Company
- AI-nergy – Artificial Intelligence Assisted Products
- ENFOR A/S – Energy Forecasting and Optimization Platform
- Center Denmark – The Digital Data Platform
- EnergyFlexLab
- METRO THERM - MyUpway[TM]

IoT Project Cases:
- Digital Twins for Large-scale Heat Pump and Refrigeration Systems
- EnergyLab Nordhavn - Smart Components
- Flexheat – Intelligent and Fast-regulating Control
- Smart-Energy Operating-Systems (SE-OS) framework
- OPSYS 2.0
- Cool-Data
- SVAF phase II
- HPCOM
- Flexible Energy Denmark
- Res4Build
- Development of Fast Regulating Heat Pumps using Dynamic Models
- CEDAR

11 case descriptions for product and service providers and 12 case descriptions for R&D projects about IoT and digitalization of heat pumps in Denmark.
Full descriptions of all use cases available on homepage:
https://heatpumpingtechnologies.org/annex56/factsheets/

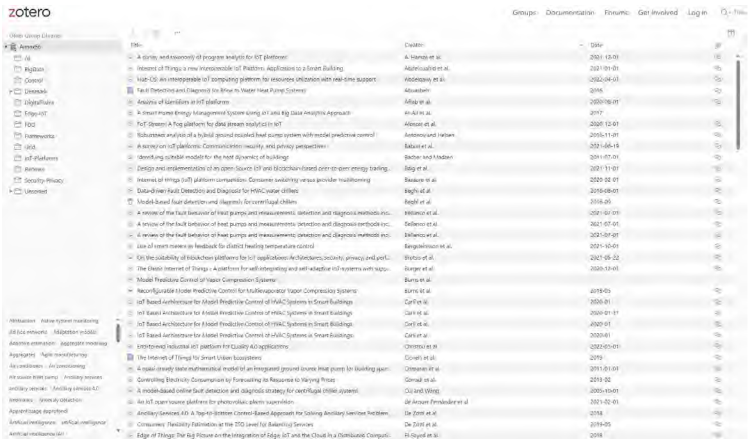
Factsheet for "Energy machines verification tool (EMV)".

Factsheet for "PreHEAT for Heat Pumps by Neogrid Technologies ApS".

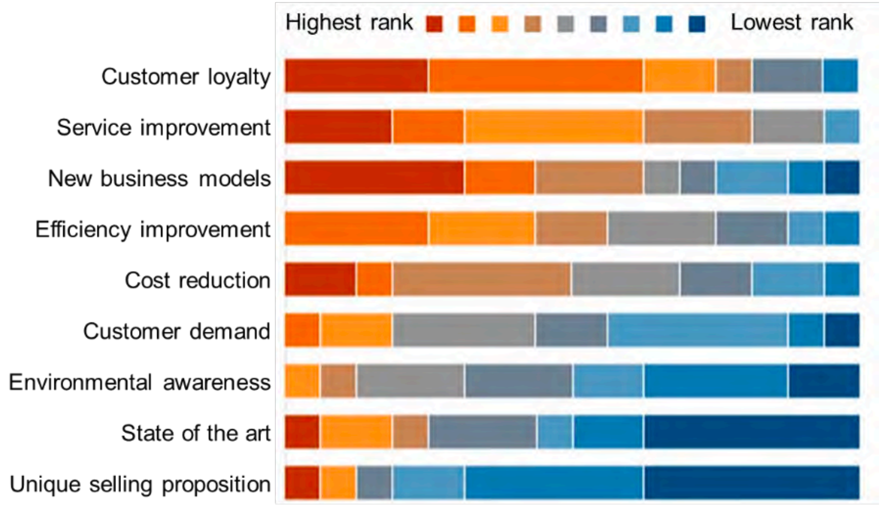
Task 1 – Litterature and survey

- To create an overview of the current state of research on IoT technologies for heat pump a large number of literature sources were collected in a public Zotero group, available at the following link: https://www.zotero.org/groups/4871439/annex56/library

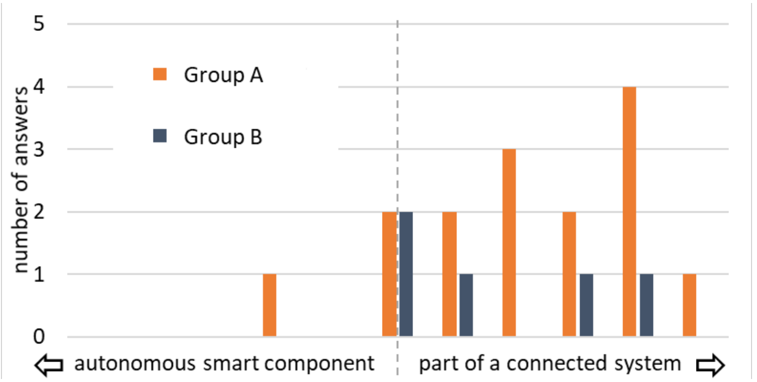
- Manufacturer survey (Austria)
  - About 50 questions to gather and evaluate the general opinion and importance of IoT and heat pumps
  - A total of 16 companies participated in the survey
  - Challenges: Data security, data protection guidelines, increase of system complexity, and availability of qualified personnel
  - Frequent answers to introduce IoT produtcs: Customer loyalty, service improvement and new business models



Zotero library with literature survey.



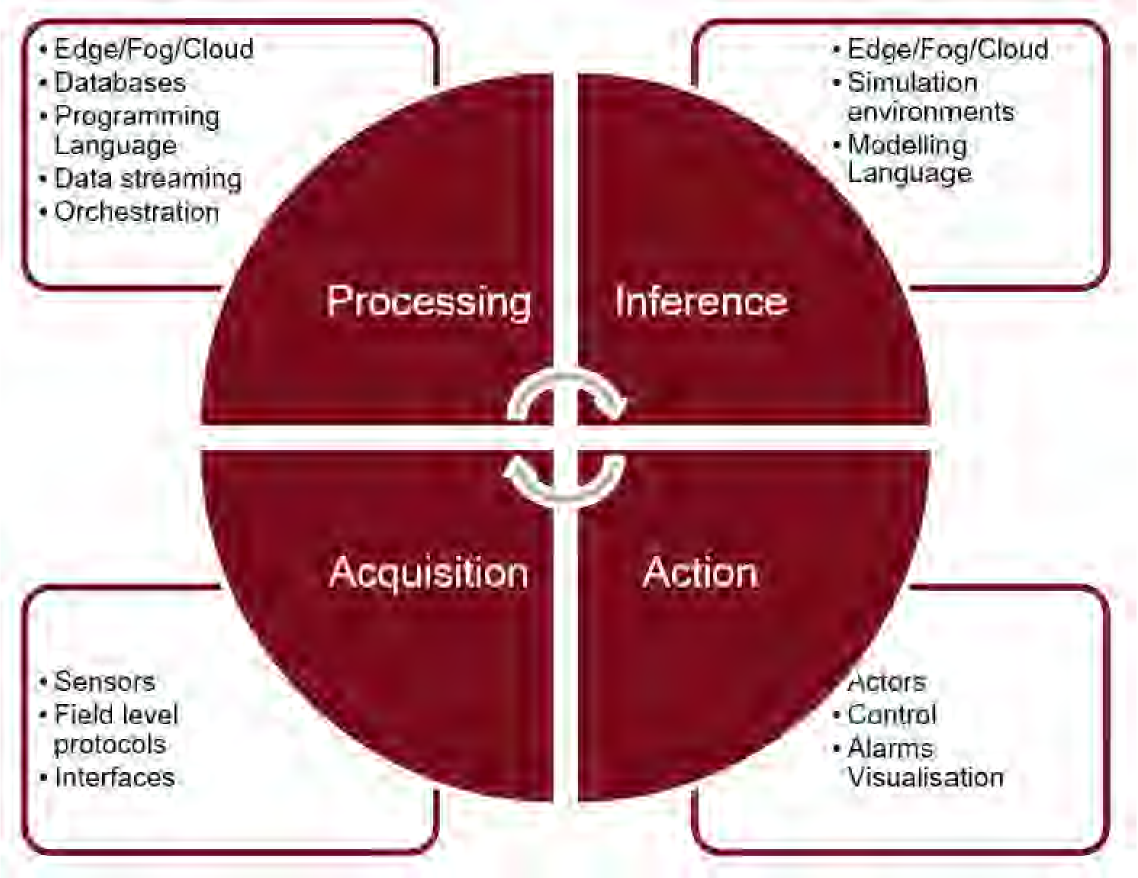
Motivation to introduce IoT products in heat pump systems.



IoT enabled heat pumps are expected to become a part of a connected energy system in the future rather than an autonomous smart component

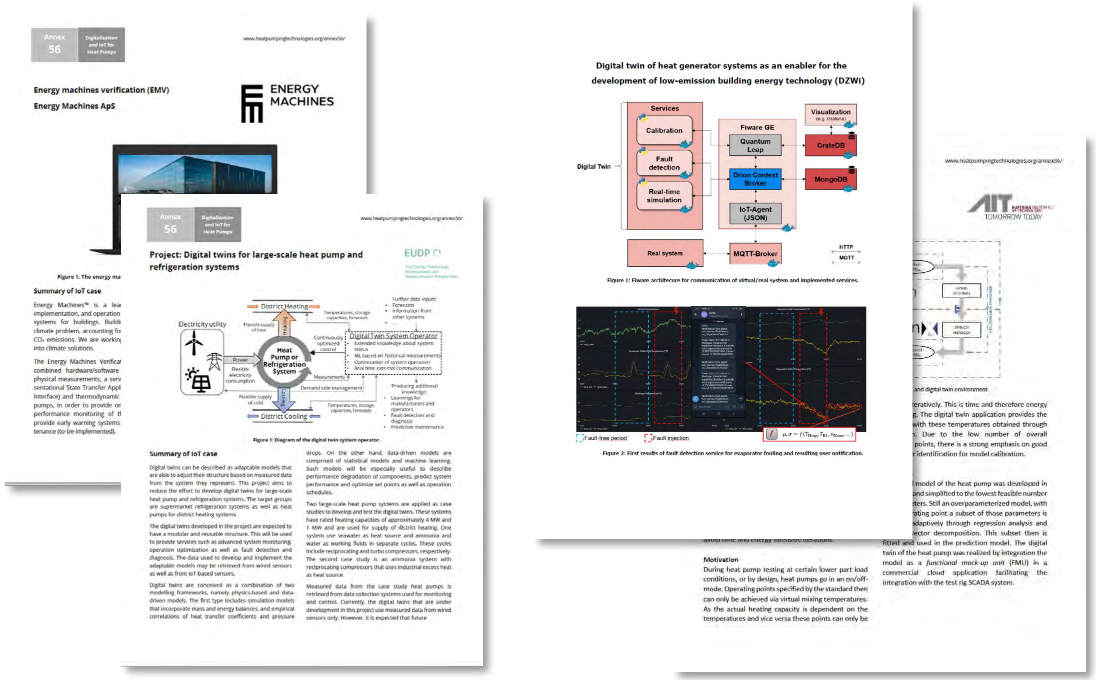
Task 2 – Interfaces, platforms and protocols

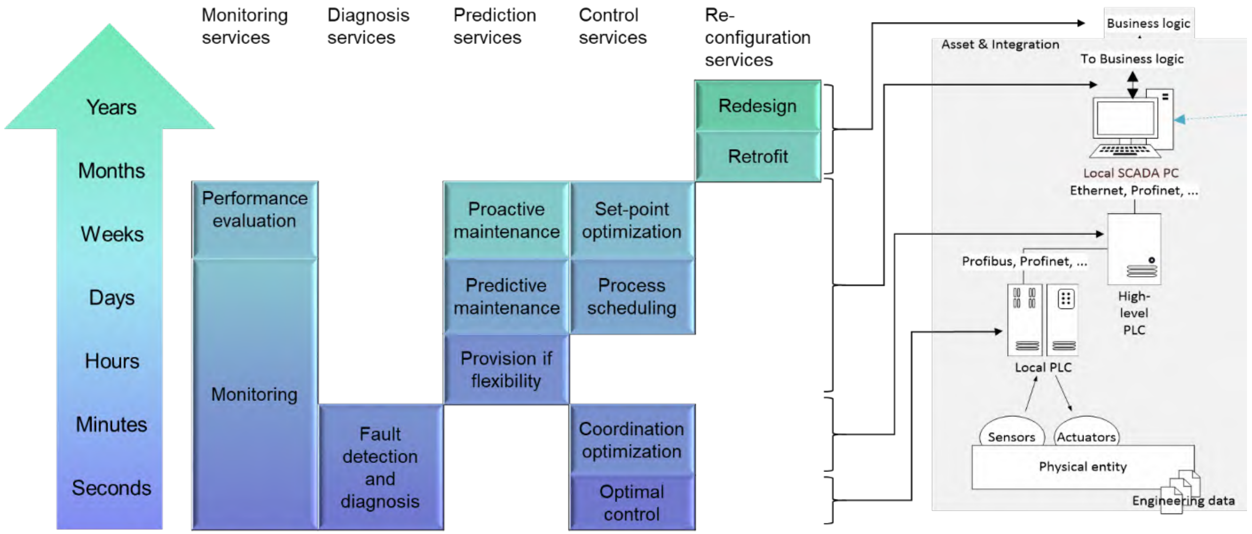
- Task 2: Provision of communication and processing capabilities.
- Common challenges and solutions analysed for different applications:
  - Digital twins of heat pumps
  - Connected heat pumps in building automation
  - Heat pumps in grid services
  - Retrofitting
- Completing a circle in the decision-making framework can add value.



Decision making framework of an IoT application

Task 2 - Digital twins of heat pumps





Categorization of services provided by digital twins according to scope, response time and relevant system level on which the service is executed

4 examples of Digital Twins analysed:

- DIGIBatch: A digital twin for predicting operating points for test bench measurements of heat pumps (research project from Austria)
- Distributed Digital Twin: Architecture of a distributed digital twin (research project "Digital Twins", DK)
- DZWI: Digital twin of heat generating systems as a pioneer for the development of low emission building energy technology (research project from Germany)
- Digital twins by EnergyMachines (IoT product from Denmark)

Challenges:

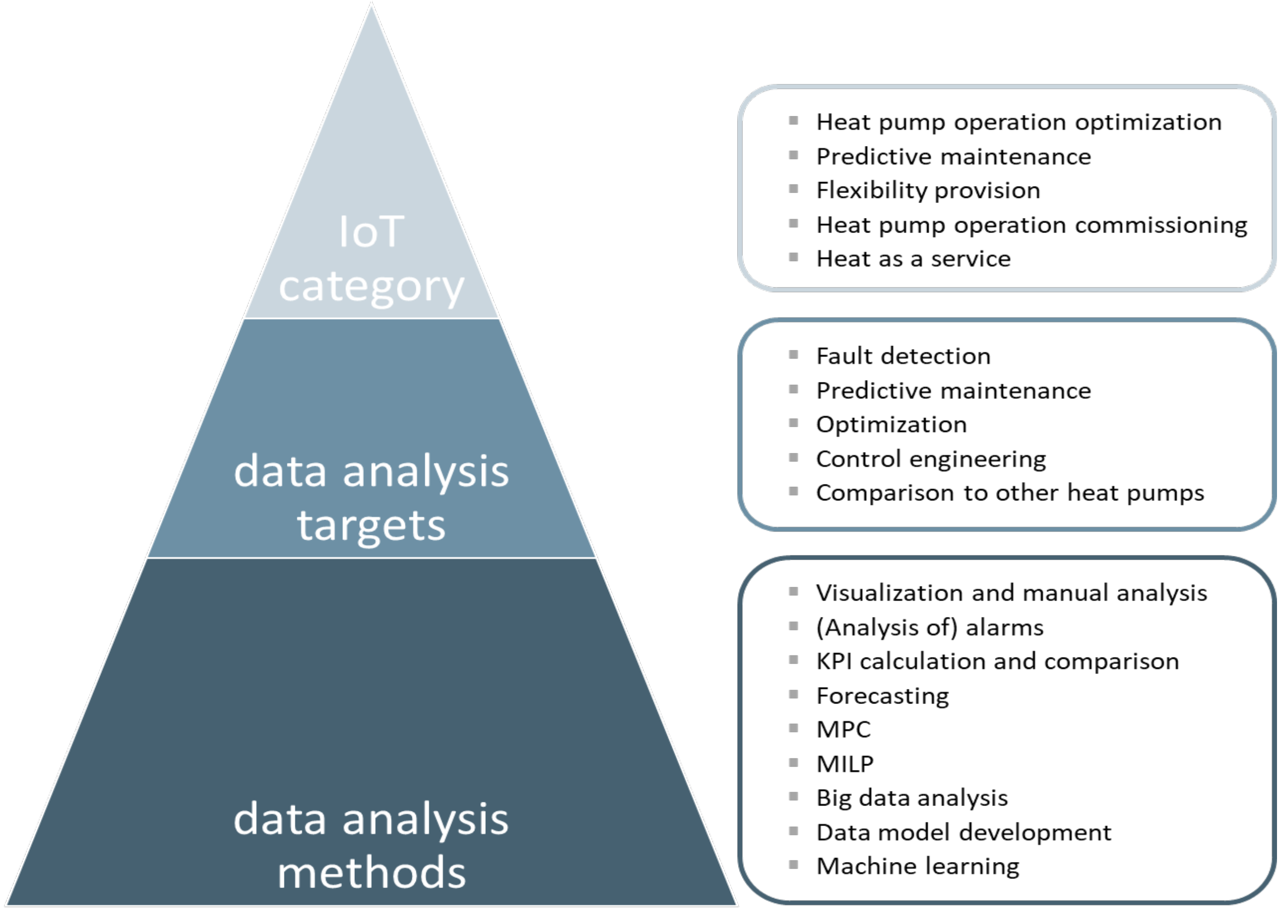
- Distributed data
- Timescales
- Simulation req.
- Configuration

Solutions:

- Data Broker (MQTT)
- Containers
- FMU
- Frameworks

Task 3 – Data Analysis

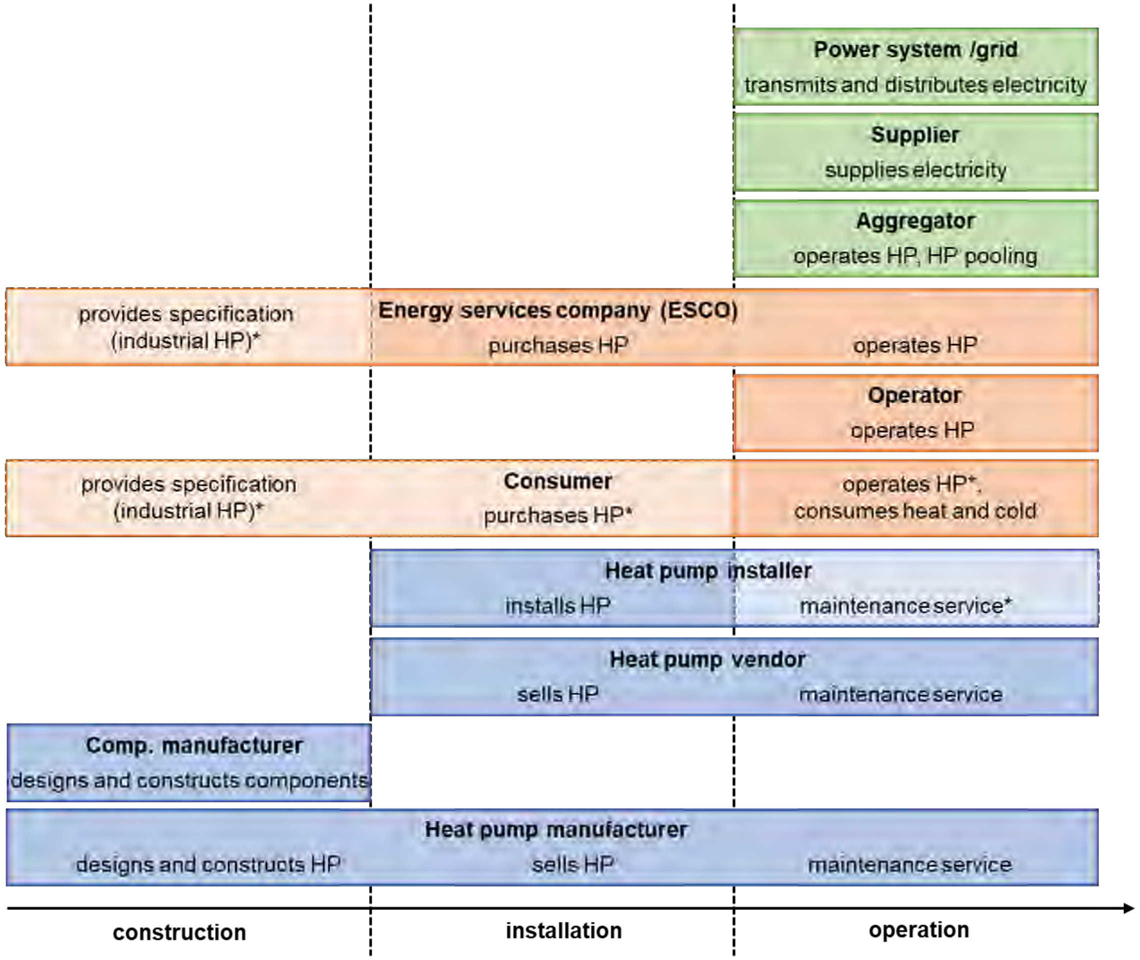
- Categorization of data analysis methods and targets based on use cases.
- Best practices given on: Pre-treatment of data, usage of data models, meta data and building information models (BIM).
- Applicable data analysis methods for certain use cases identified.



Hierarchy derived from the use cases: IoT category, data analysis targets and data analysis methods

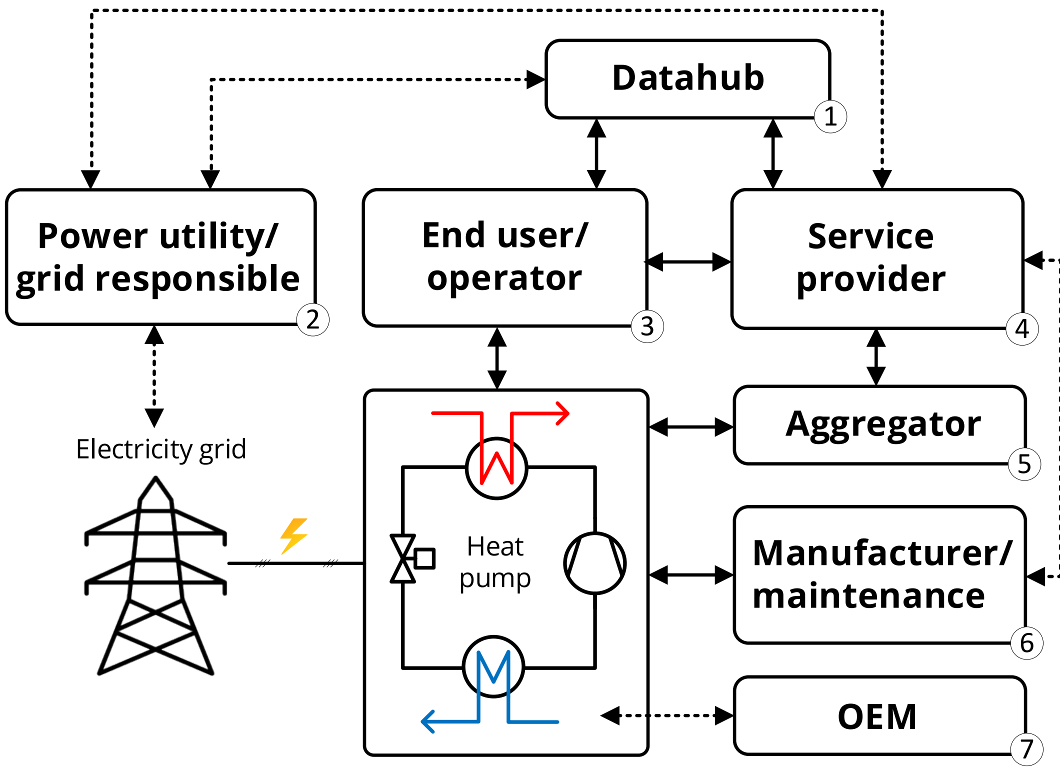
Task 4 – Business Models

- 19 examples of business models analyzed
- SWOT analysis to compare business models, e.g.:
  - Predictive maintainance vs. Fixed interval or on demand maintenance
  - Heat as a service vs. Traditional model
  - Providing flexibility with heat pump pooling vs. Using a heat pump as an autonomous component in a building
- Key findings:
  - Value proposition for the consumers: Lower costs, higher efficiency, higher reliability
  - More responsibility for efficiency than in traditional business models.
  - Energy system (aggregators, suppliers, grid, etc.): Strong need for flexibility to compensate for fluctuating generation. Sector coupling with heat pumps (power/heat) possible.



Overview on stakeholders in the life cycle of IoT enabled heat pumps (indicates optional tasks).*

IoT-based energy system around heat pump(s)



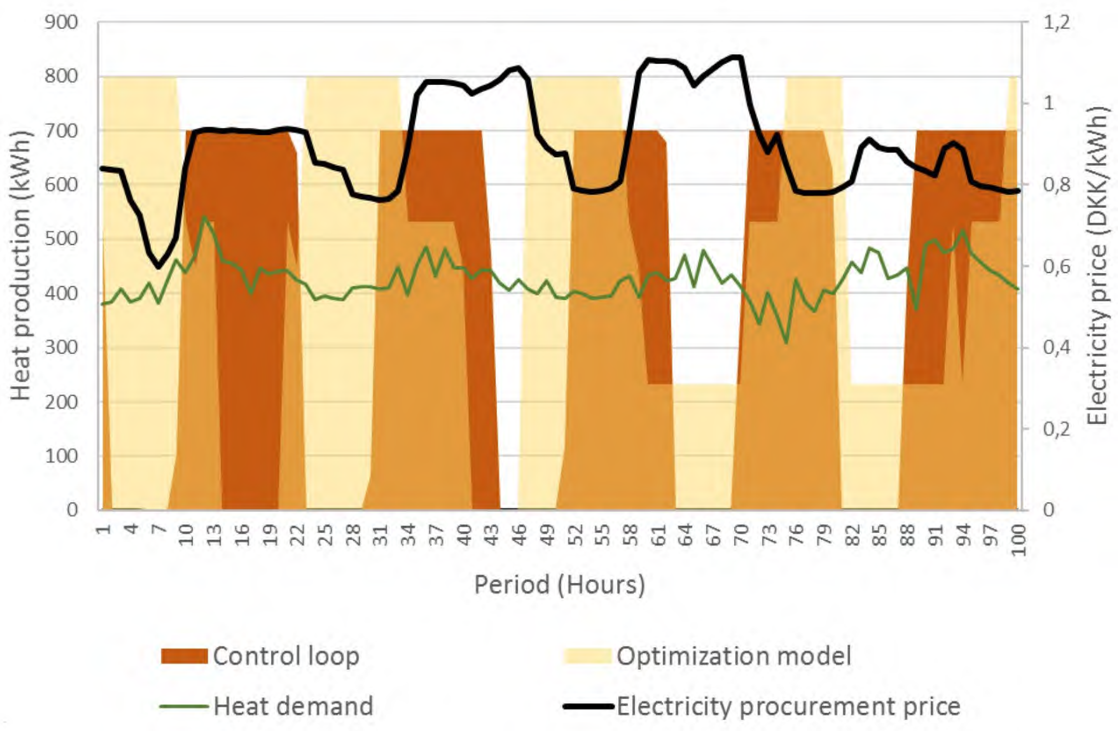
Selected examples in Denmark:

1. Center Denmark
2. Energinet
3. HOFOR, Nærvarmeværket, Best Green
4. Climify, Centrica, ENFOR, IBM, EnergyFlexLab, AI-Energy, EWII
5. Neogrid
6. Energy Machines, JCI, DVI, METRO THERM, Bosch, Nilan
7. LS Control, Grundfos, Kamstrup

Visualization of supplier groups and examples of associated suppliers in an IoT-based energy system for heat pumps – based on review results from collected case studies in Denmark.

- Several stakeholders at different levels in the heat pump industry are focusing on enhancing and deploying digital and IoT-enabled solutions for heat pumps in Denmark.
- Cooperation between groups important to further develop the digitalization of the energy system around the heat pump(s).
- Overlap for companies being present in more groups, but general grouping visualized (various other companies not included in review also exists).

Task 4 - FLEXHEAT (use case example)



Flexible heat production during winter [HOFOR, 2021].

- Grid services are provided with a flexible energy system consisting of an 800 kJ/s ammonia-based ground-water heat pump with reciprocating compressors, 200 kJ/s electric boiler and a thermal storage tank of 100 m^3.
- System is optimized by a linear-optimization model supported by a dynamic model of the heat system to schedule optimal planning production with a real-time communication setup to control the heat pump accordingly. Furthermore, the heat pump has been modified to provide fast regulation services to the grid.
- Preliminary results indicate that operating costs can be reduced by 7 % by introducing intelligent operation with the linear optimization model, and an additional 6 % costs reduction can be achieved by delivering grid services.

Annex 56 homepage

Annex 56 homepage, link:
- https://heatpumpingtechnologies.org/annex56

Available reports:
- Annex 56 – Digitalization and IoT for Heat Pumps Final Report
- Annex 56 Digitalization and IoT for Heat Pumps Executive Summary
- Annex 56 Digitalization and IoT for Heat Pumps 2-page Summary
- Task 1 Report: State of the Art
- Task 2 Report: Interfaces and platforms
- Task 3 Report: Data analysis
- Task 4 Report: Business Models
- Country summary report for Denmark on digitalization and IoT for heat pumps

40 project and use case descriptions about IoT and digitalization of heat pumps:
- https://heatpumpingtechnologies.org/annex56/factsheets/

Acknowledgement

EUDP

The Energy Technology Development and Demonstration Programme

The project ”Danish participation in IEA HPT Annex – IoT Annex – Digitalization and IoT for Heat Pumps” is funded by EUDP – The Energy Technology Development and Demonstration Programme.

IoT for heat pumps

IEA HPT

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LONG-TERM EXPERIMENTAL STUDY OF PRICE RESPONSIVE PREDICTIVE CONTROL IN A REAL OCCUPIED SINGLE-FAMILY HOUSE WITH HEAT PUMP

Jan Dimon Bendtsen

Aalborg University

Long-term experimental study of price responsive predictive control in a real occupied single-family house with heat pump

Simon Thorsteinsson,
Alex Kalaee,
Pierre Vogler-Finck,
Henrik Stærmose,
Ivan Katic,
Jan Dimon Bendtsen

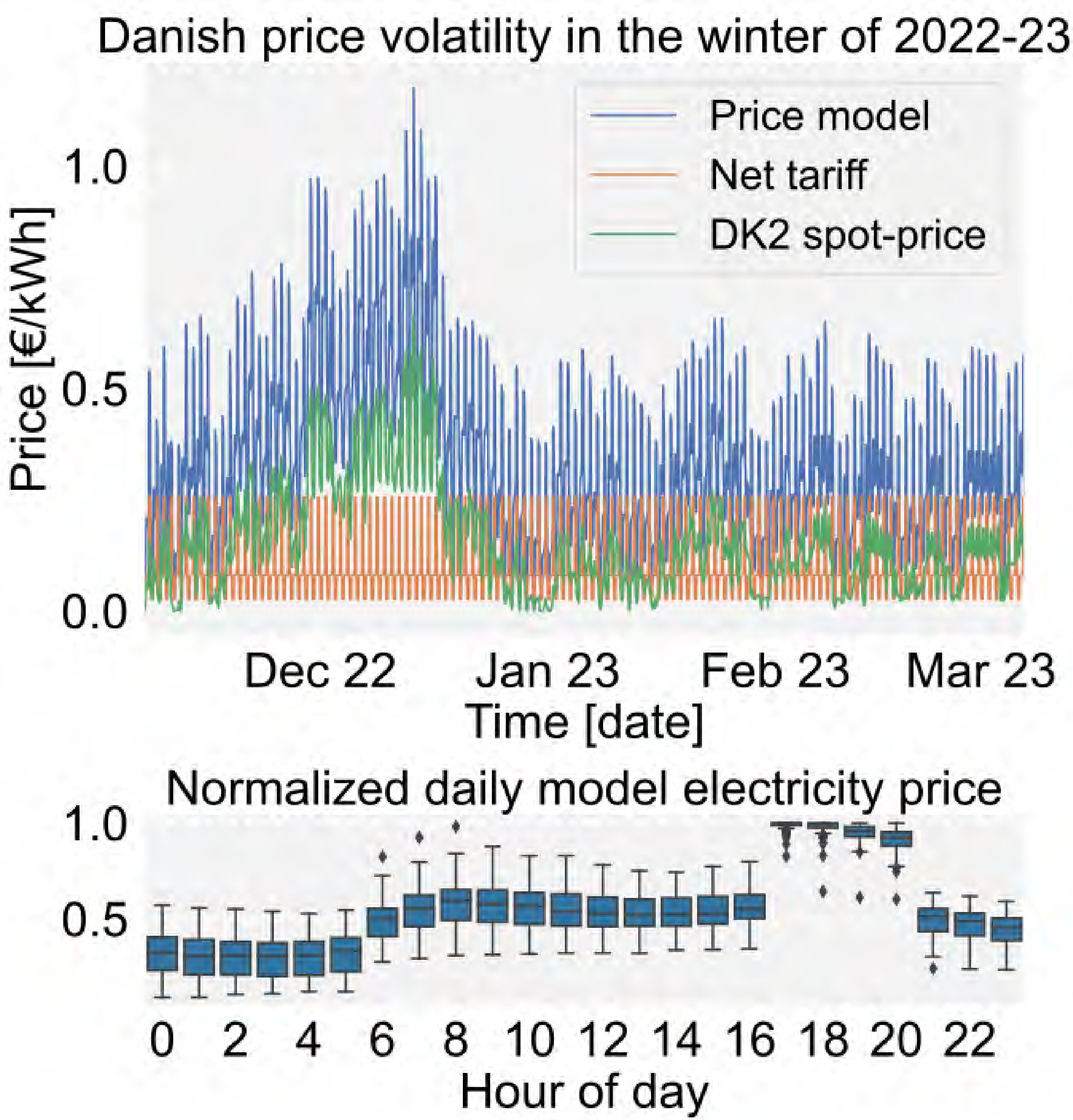
Overview

- Load shifting through demand side management
- *Four-month* experimental study in a near-zero emission *occupied* single-family house in Denmark.
- The control algorithm uses price signals, weather forecast, a single-zone building model, and a non-linear heat pump efficiency model.
- *Cost reduction* from the controller ranging from 2-17% depending on the chosen comfort level.
- Study carried out as part of the EUDP project "OpSys 2.0".

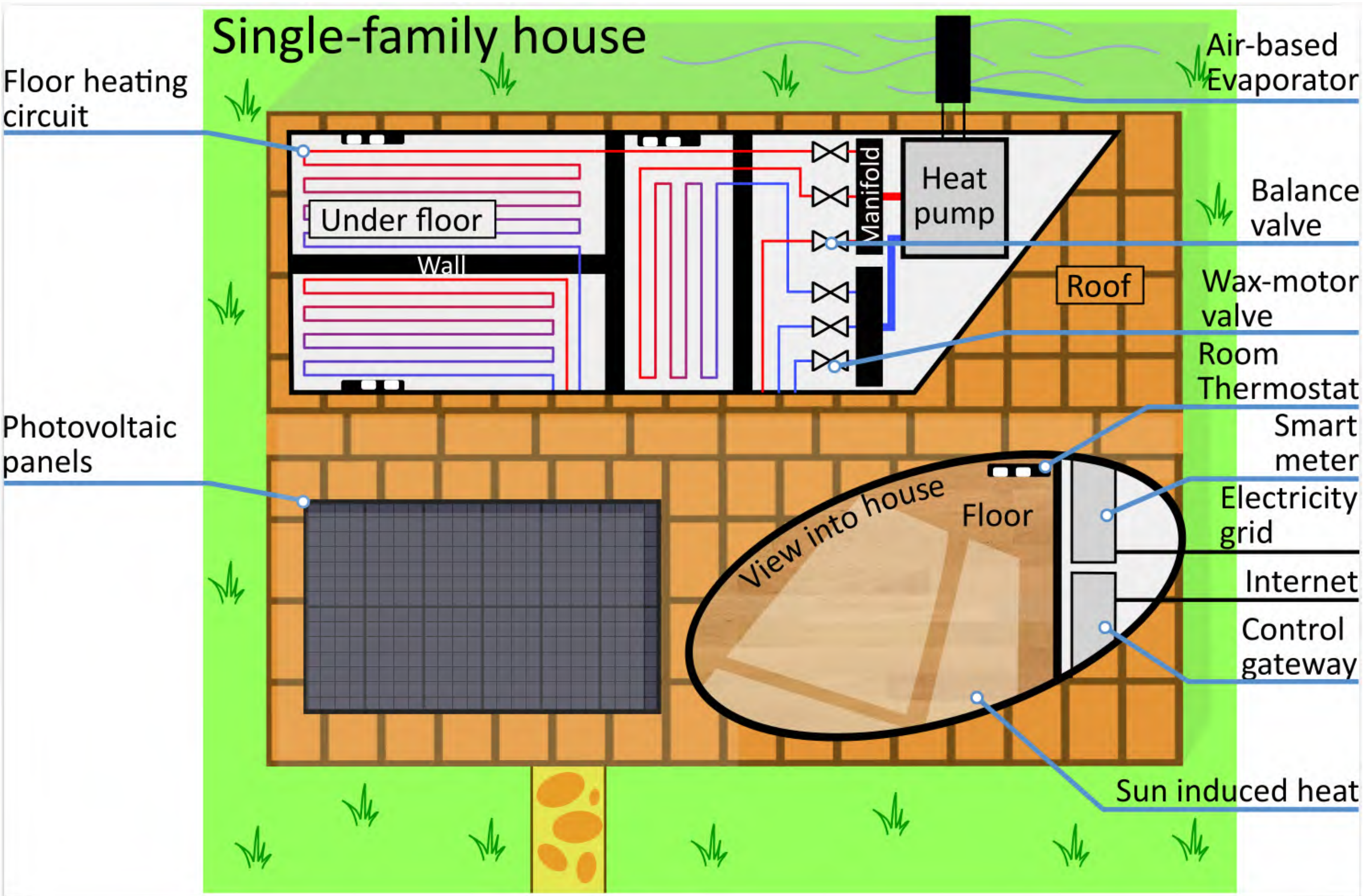
Outline

- Case study
- System setup
- Control architecture
- Main results
- Conclusion

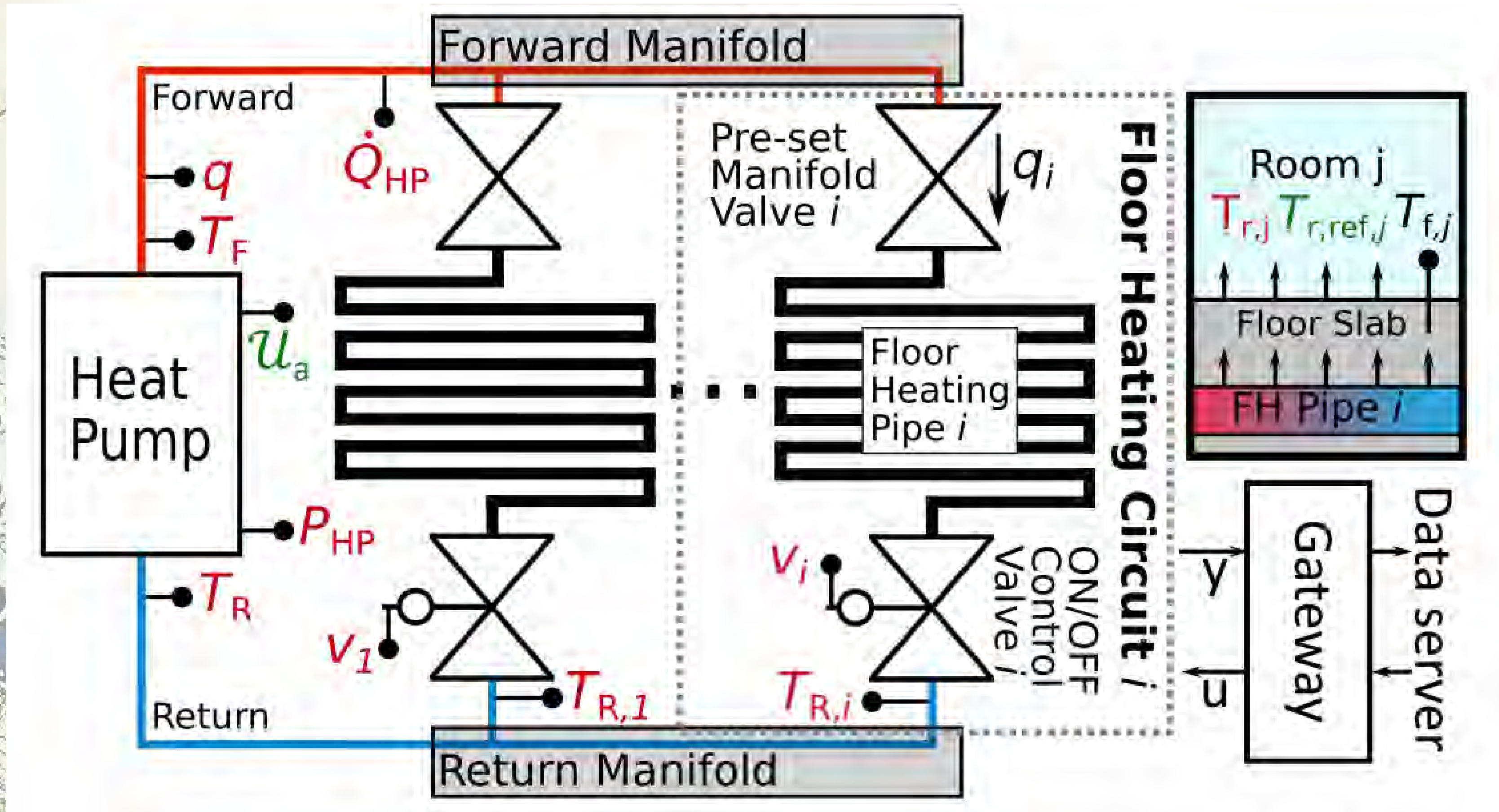
Why care about load shifting?



Case study: Modern low-energy single-family house

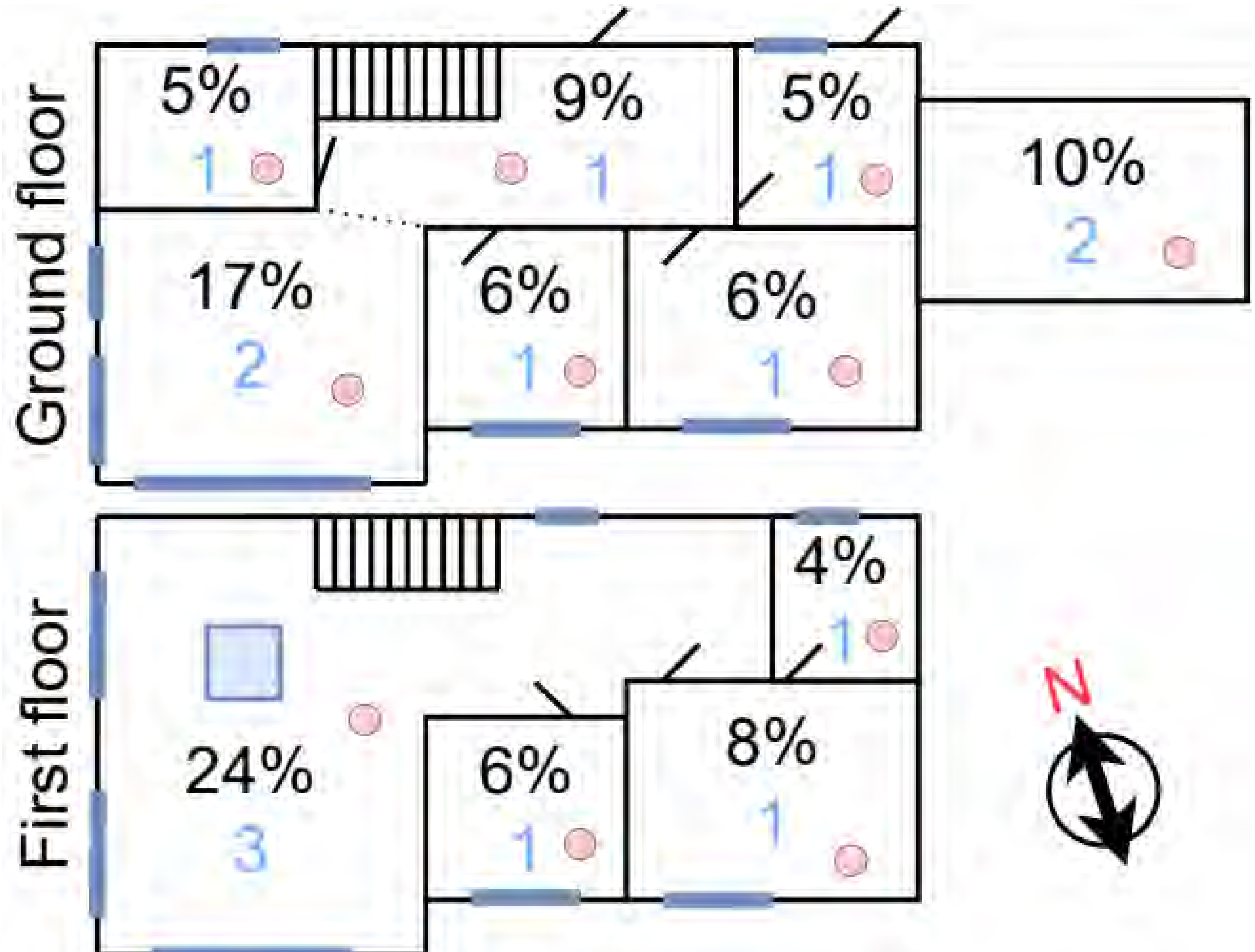


Heating system

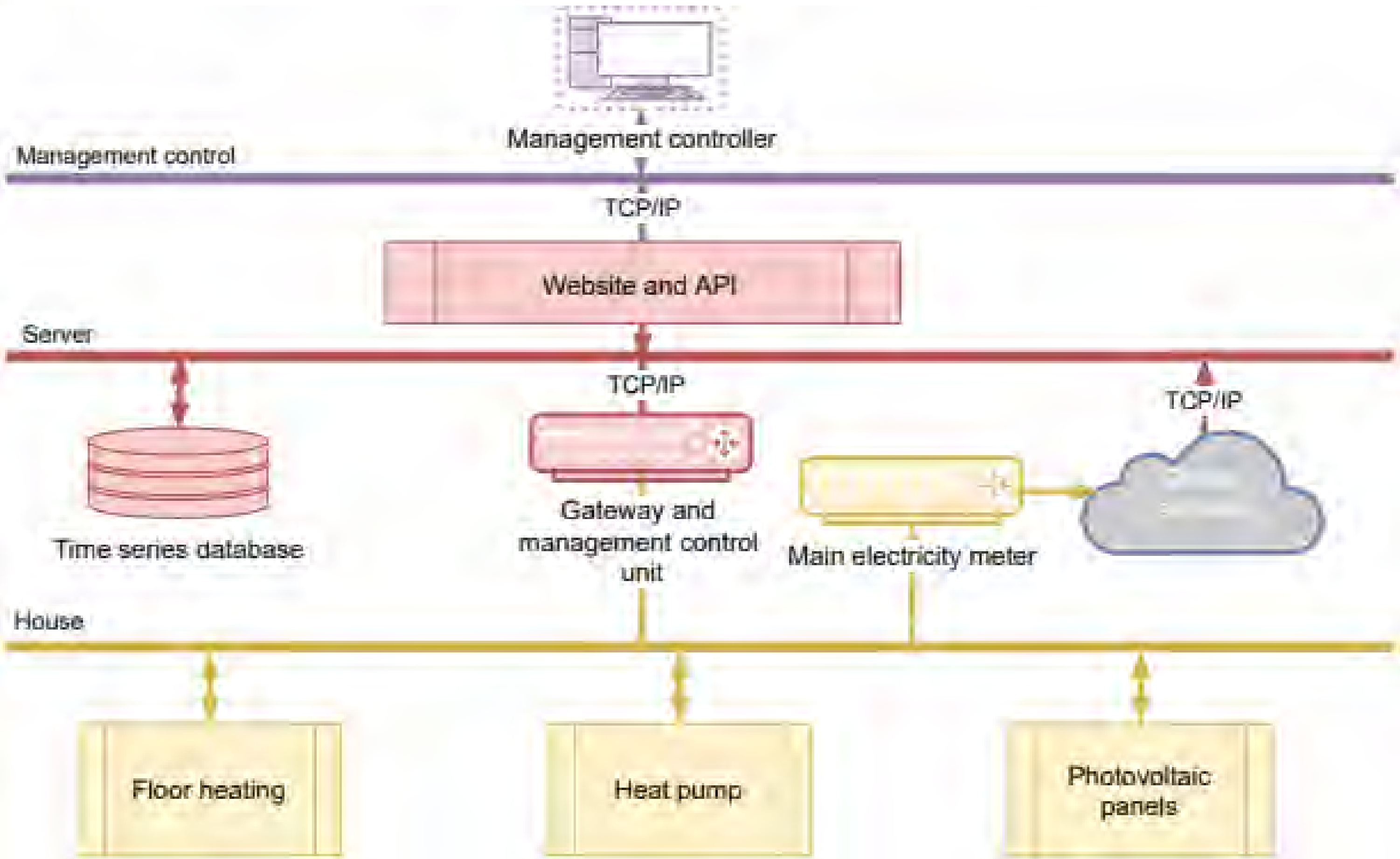


- Heat pump: Bosch Air/water, 7kW capacity
- Floor heating managed by Wavin controller – individual circuit flows governed by ON/OFF valves
- Photovoltaic panels on roof deliver up to 5.5 kW electric power, remaining electricity is supplied from electric grid

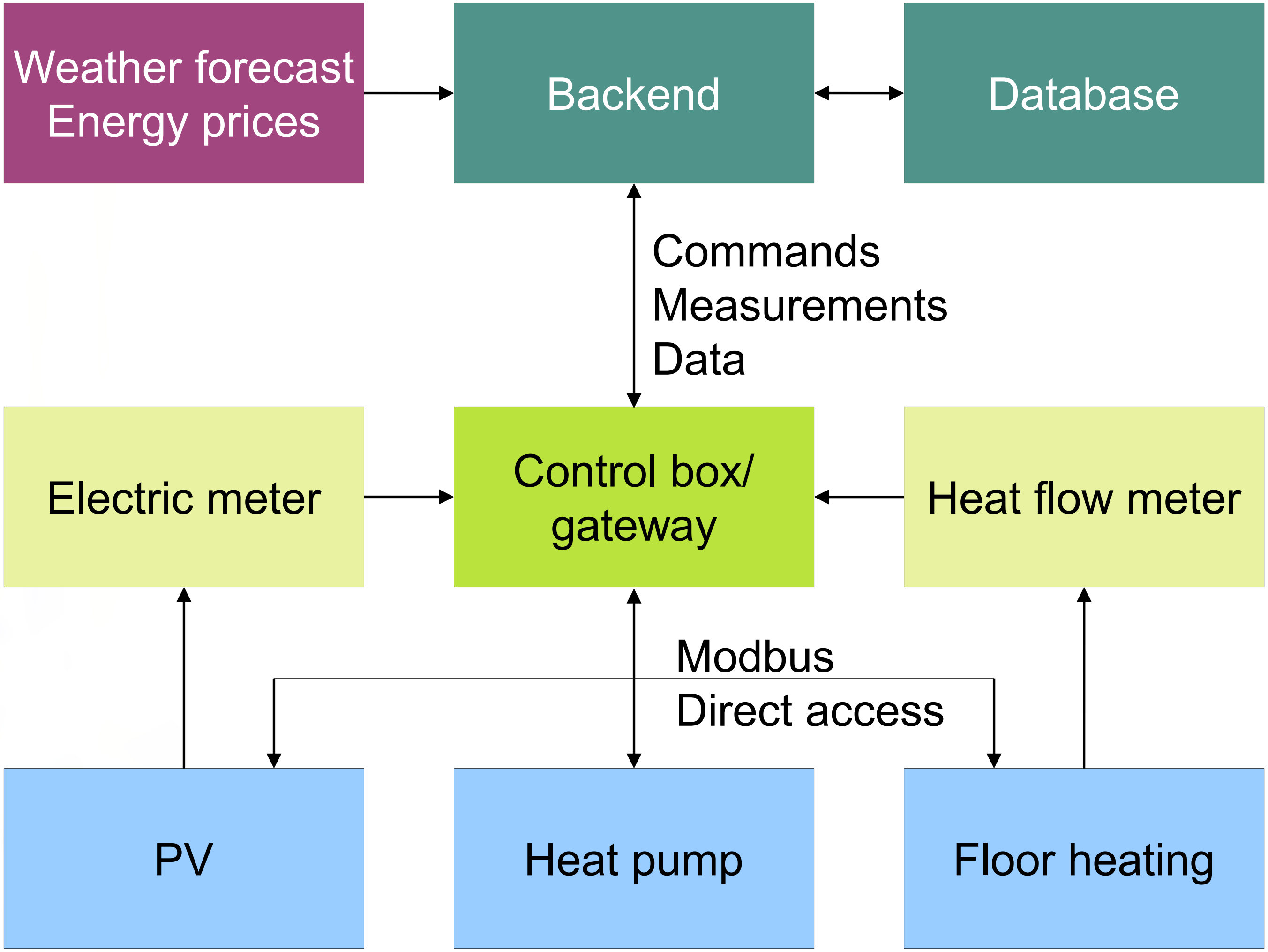
Floor layout



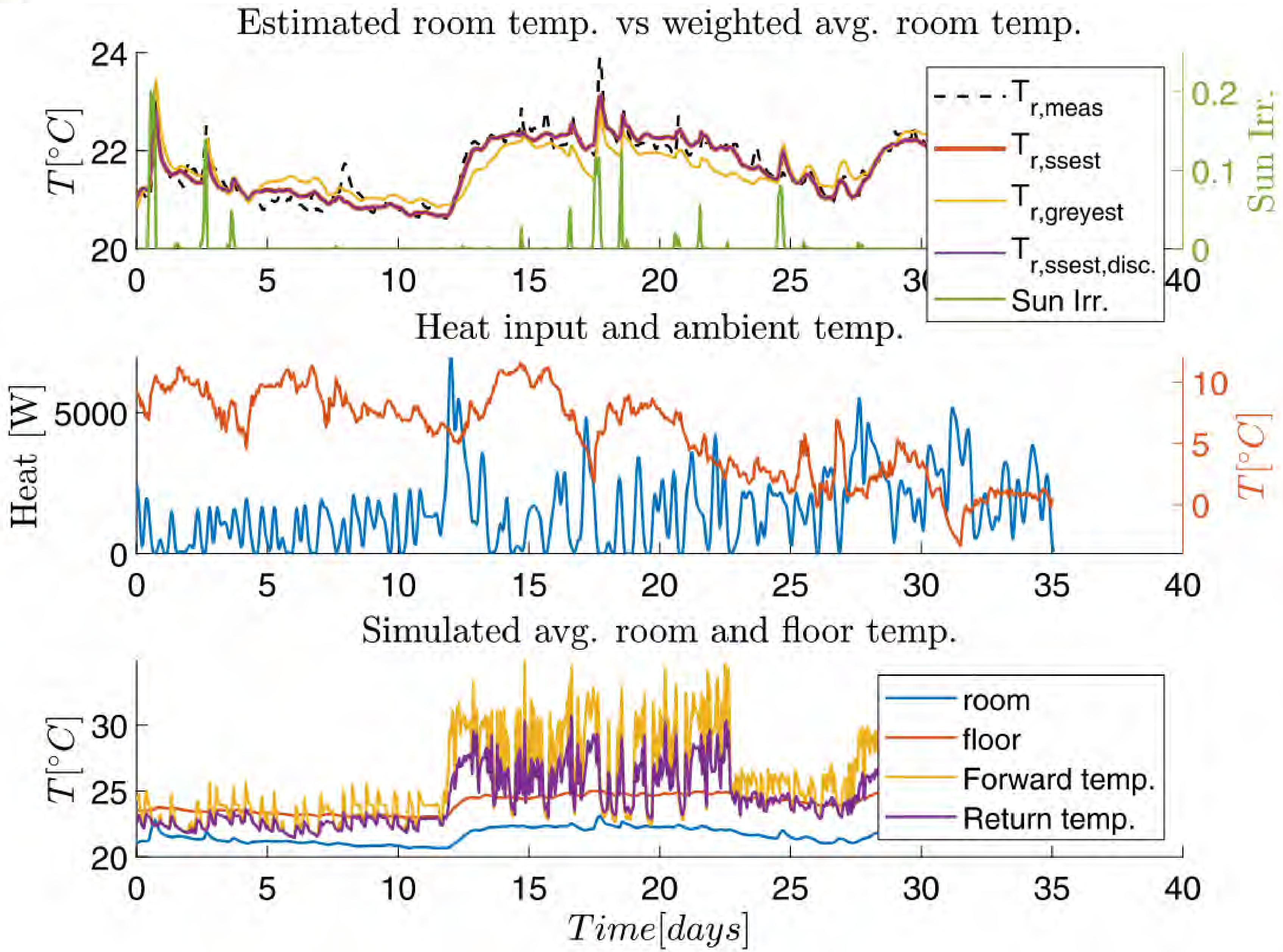
System setup – data management



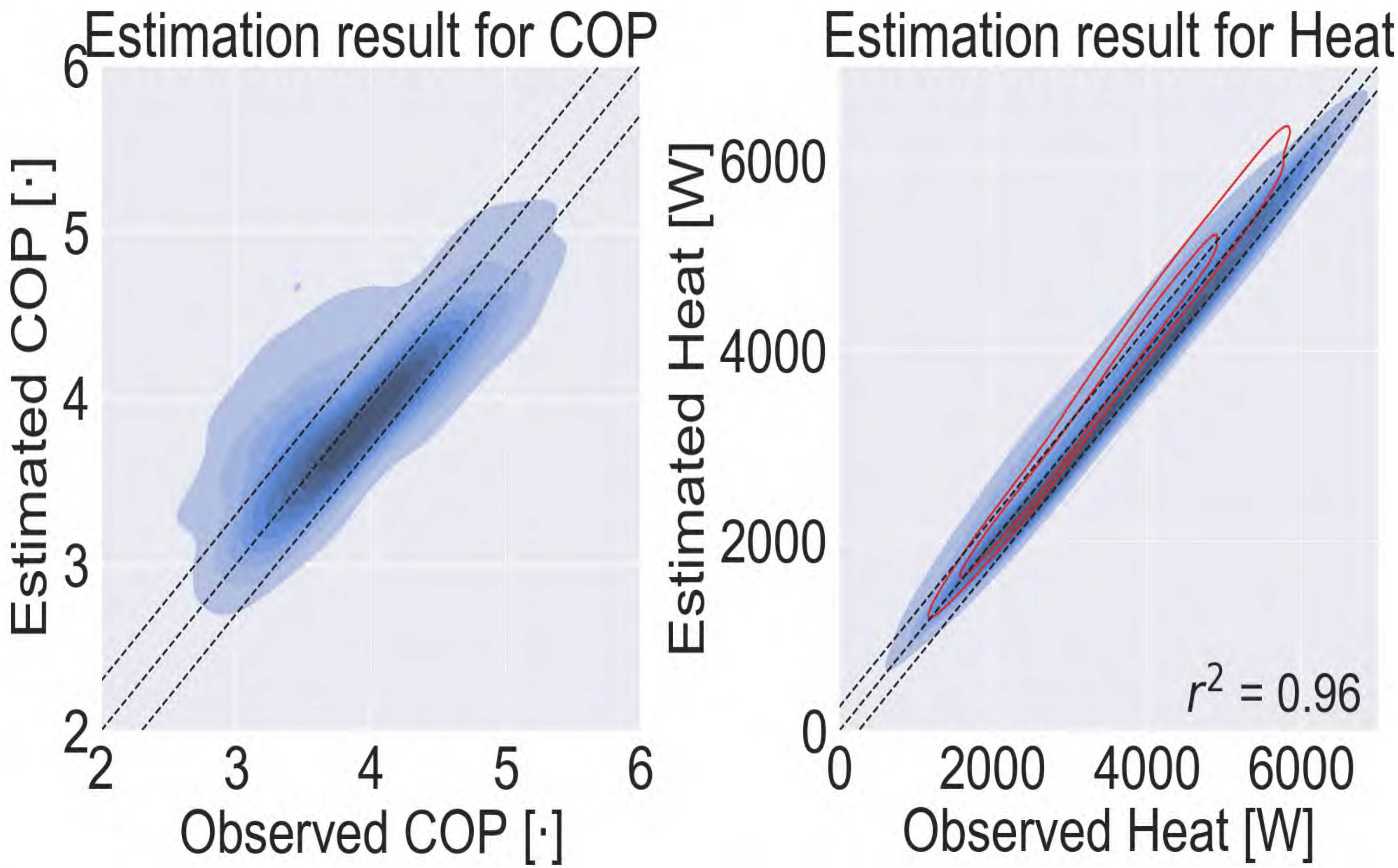
Communication infrastructure



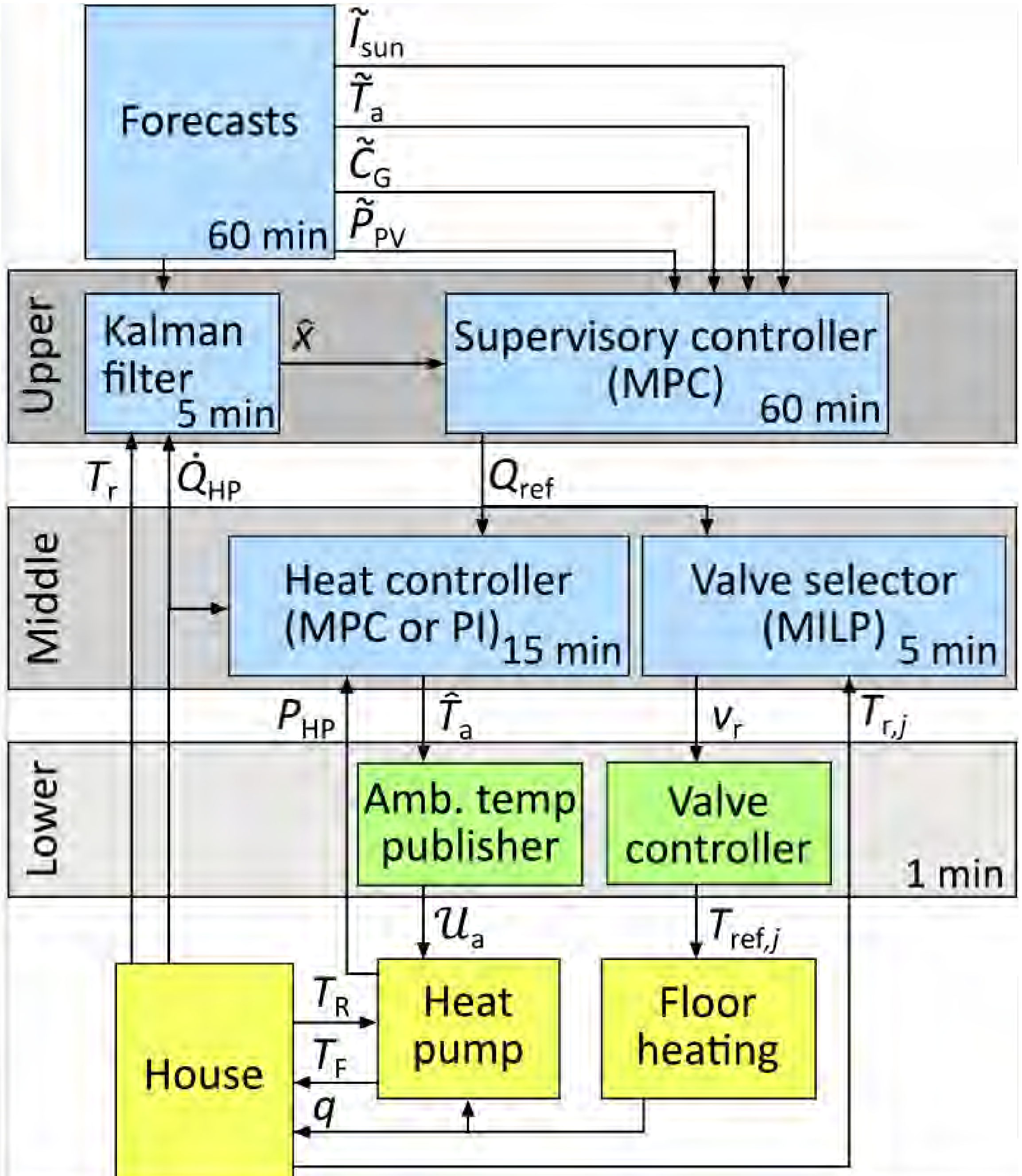
Room temperature model fit



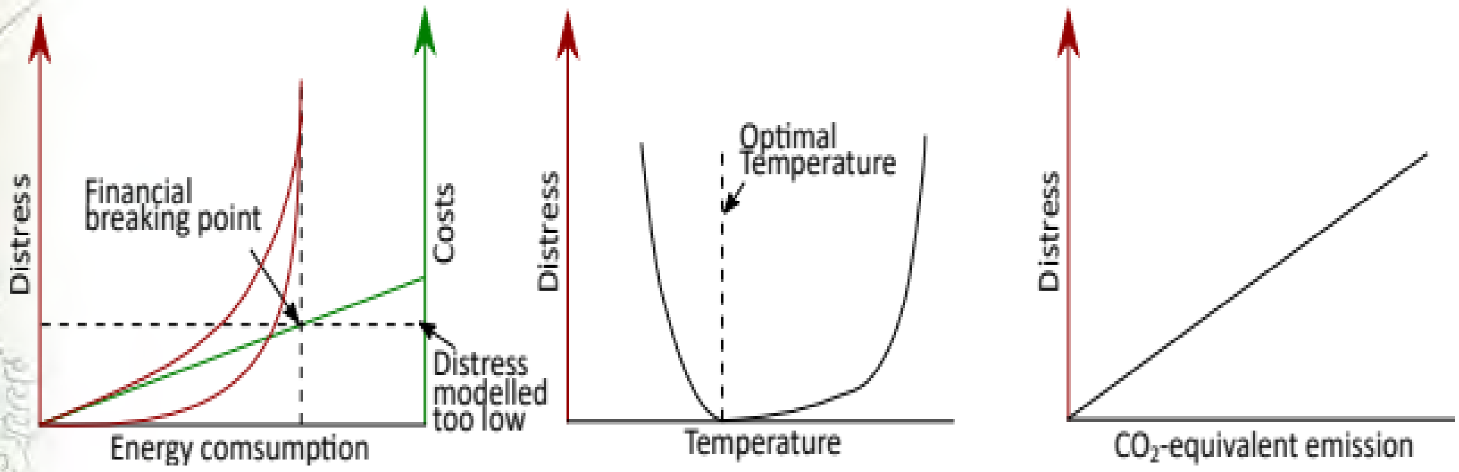
Heat pump model



Control architecture

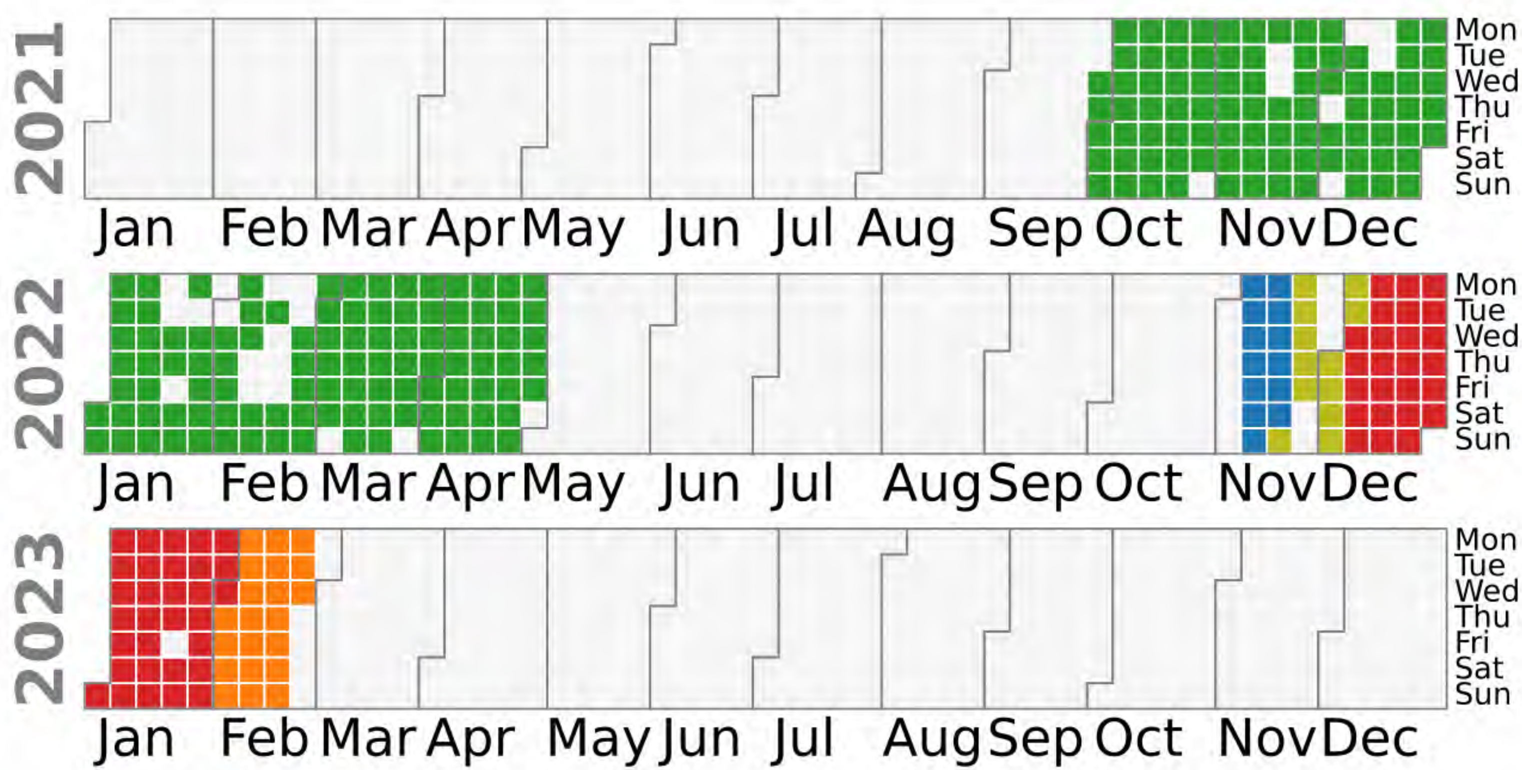


'Tuning' supervisory MPC



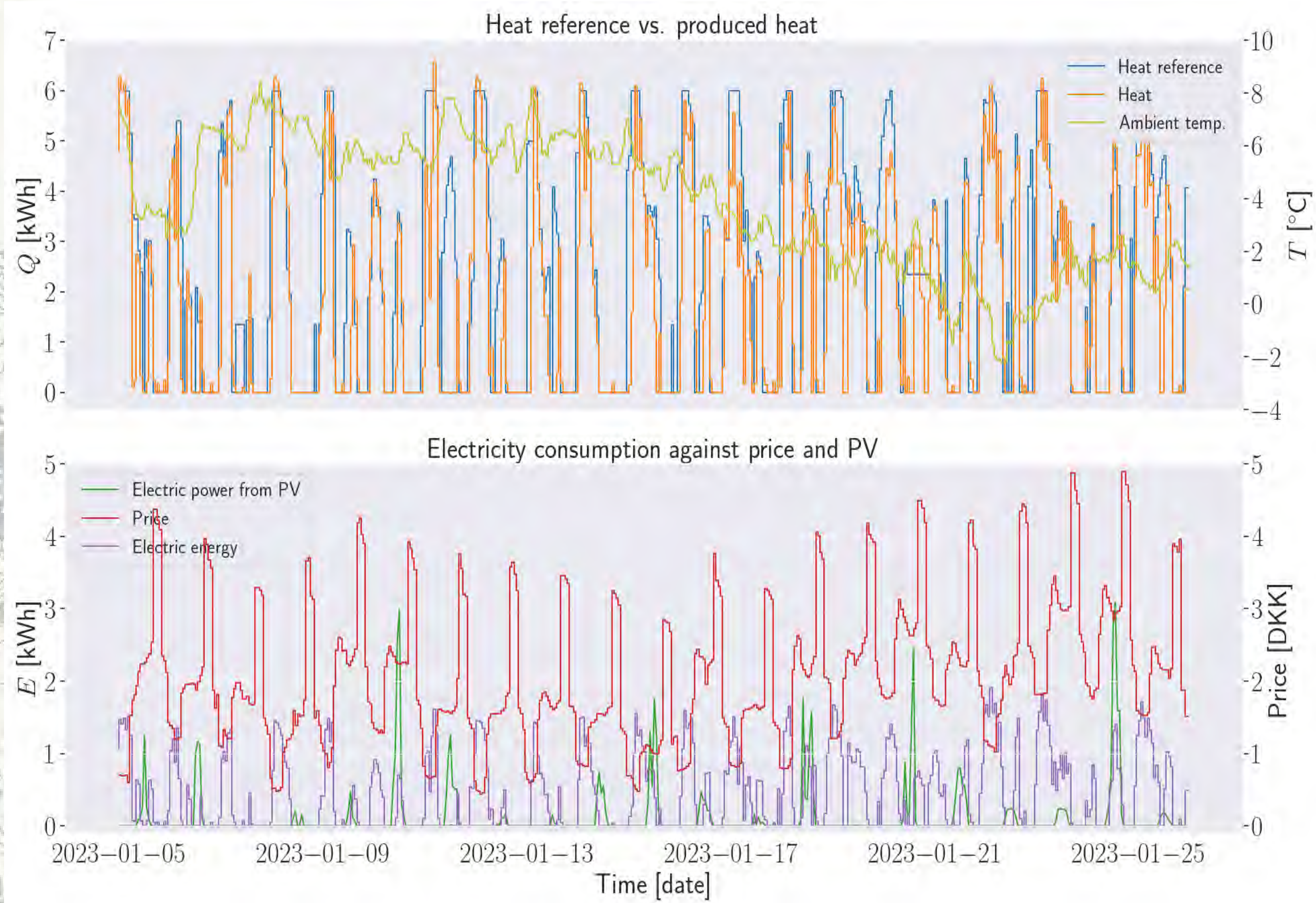
- The supervisory MPC solves a *Mixed Integer/Linear Programming* optimization problem based on a weighted sum of performance curves like the ones shown above.
- Instead of "comfort," high values indicate "distress."
- Lower-level controllers manage the actual flows, turning the heat pump ON/OFF, etc.

Experiment and benchmark days

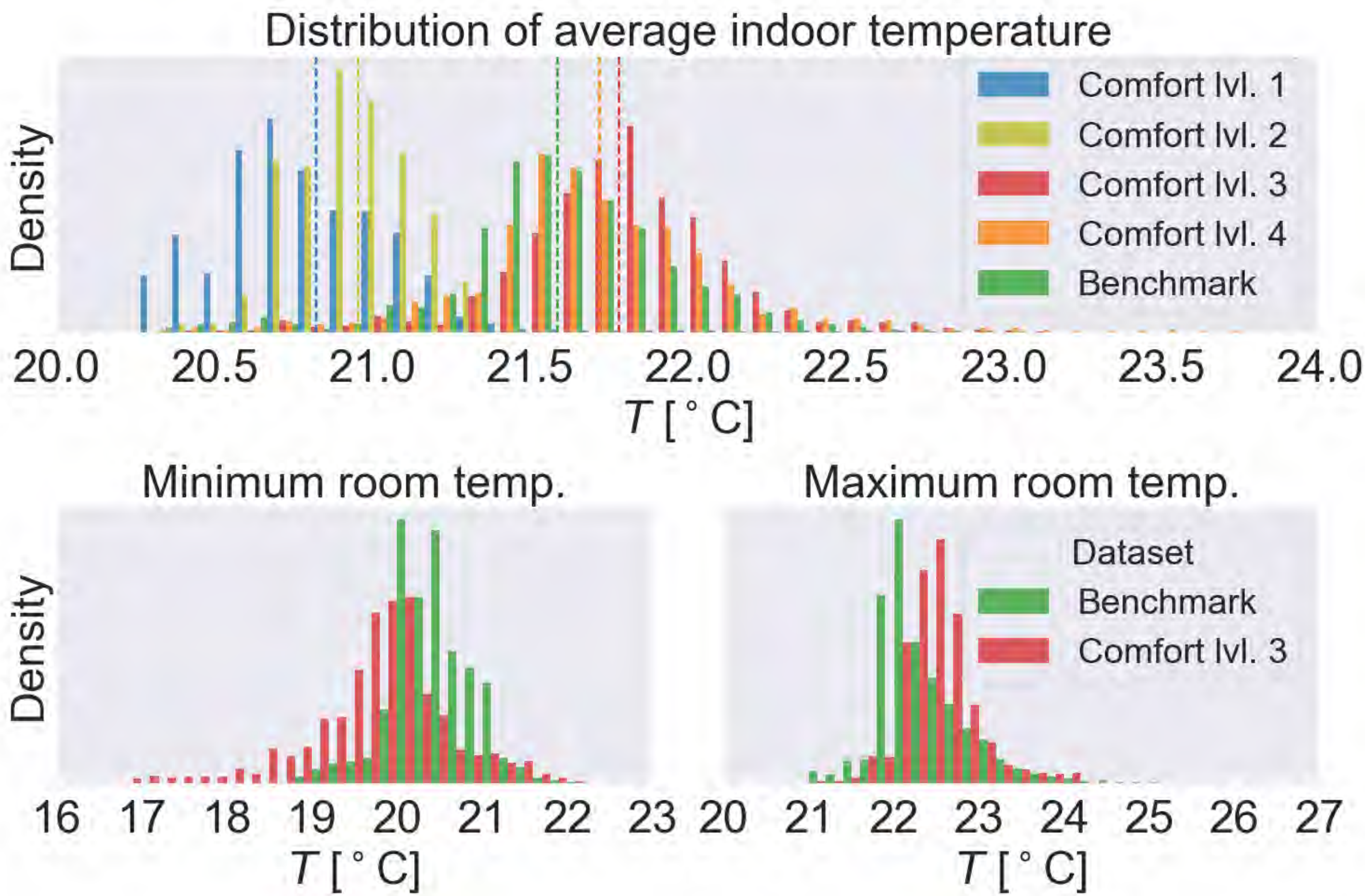


Green – benchmark
Blue – Comfort level 1
Yellow – Comfort level 2
Red – Comfort level 3
Orange – Comfort level 4

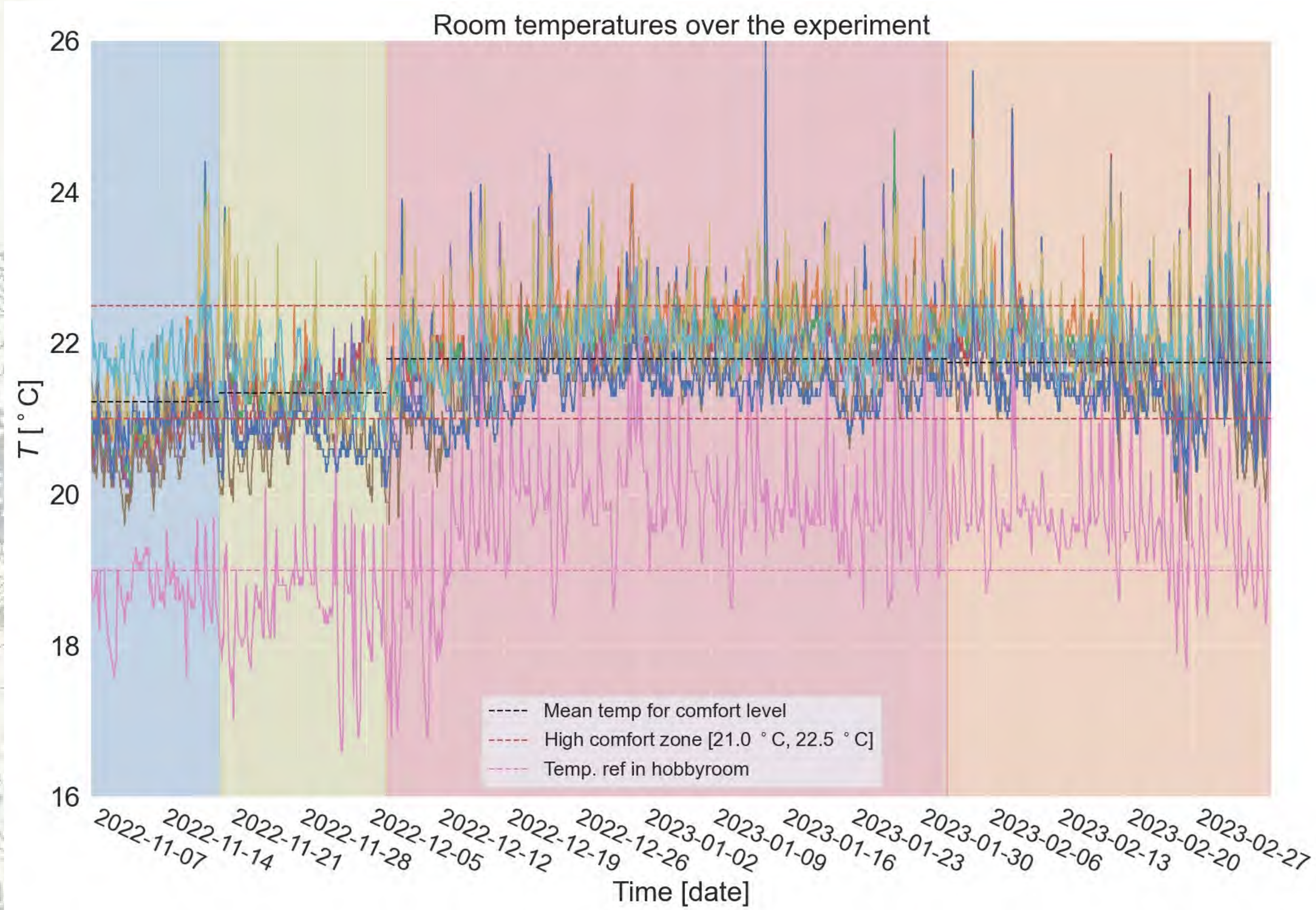
Control performance



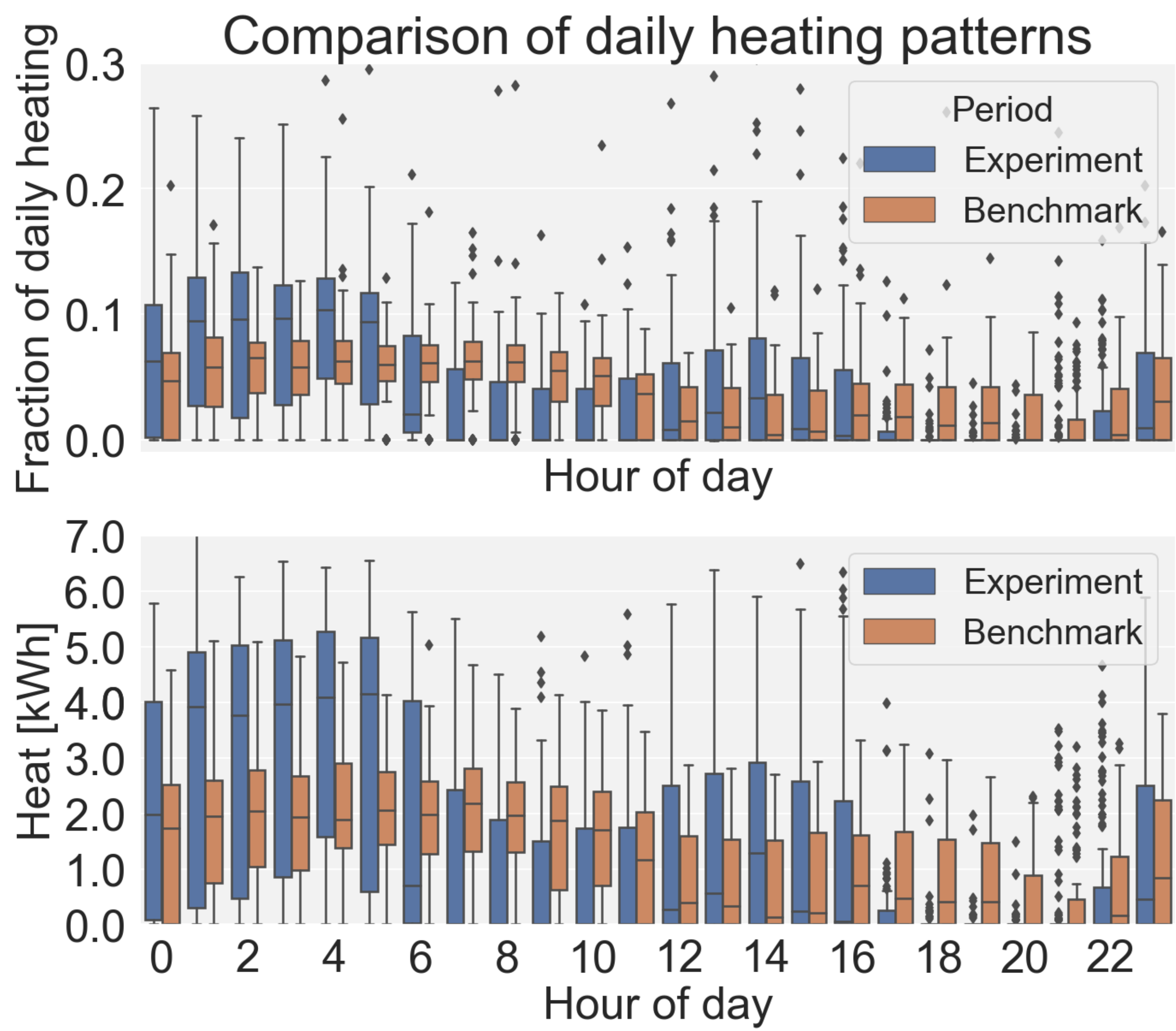
Control performance



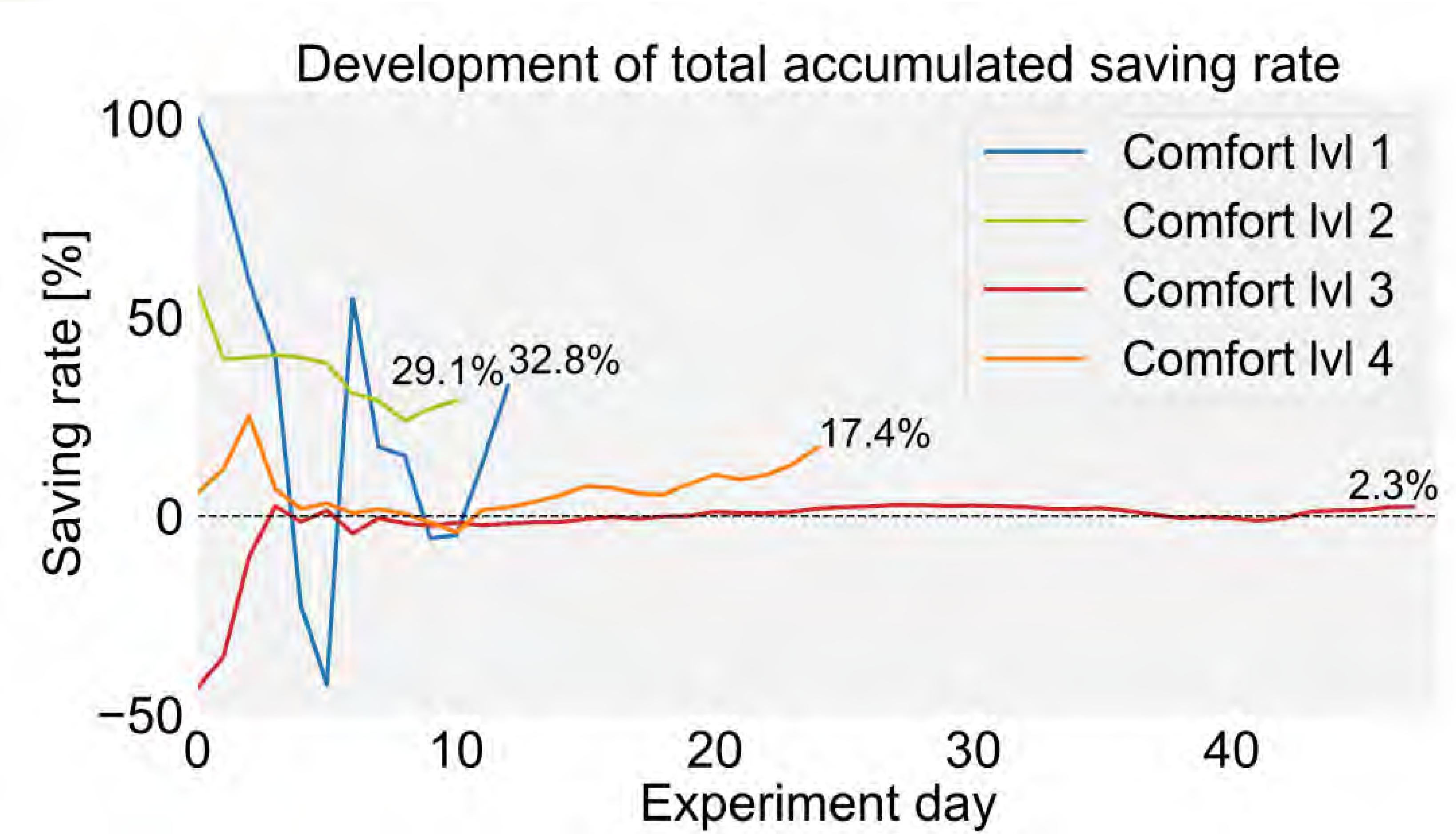
Long term performance



Benefit of using MPC?



Savings depend on comfort level



Nice percentage-wise savings ...
but limited financial benefit

Comfort level	Average benchmark cost [€]	Exp. cost [€]	Reduction [€]	Saving rate [%]
1 (▲)	10.92	7.33	3.59	32.8
2 (▲)	49.84	35.34	14.50	29.1
3 (▲)	126.42	123.49	2.93	2.3
4 (▲)	42.65	35.23	7.42	17.4
3 and 4	169.07	158.72	10.35	6.1
All	229.83	201.39	28.43	12.4

Conclusion

- We presented a four-month experimental study in a near-zero emission occupied single-family house in Denmark.
- The control algorithm was able to provide energy savings by coordinating the available hardware, including running the heat pump closer to its COP optimum and exploiting the roof photovoltaic panels more efficiently.
- The cost reduction achieved was found to rang from 2-17% depending on the chosen comfort level.
- Crucially, the experiment did not result in any discernible discomfort to the occupants.

DANISH TECHNOLOGICAL INSTITUTE

HEAT PUMPS PROVIDING FLEXIBILITY SERVICES - THE ROLE OF MODEL BASED TOOLS

Wiebke Meesenburg

Technical University of Denmark

DTU

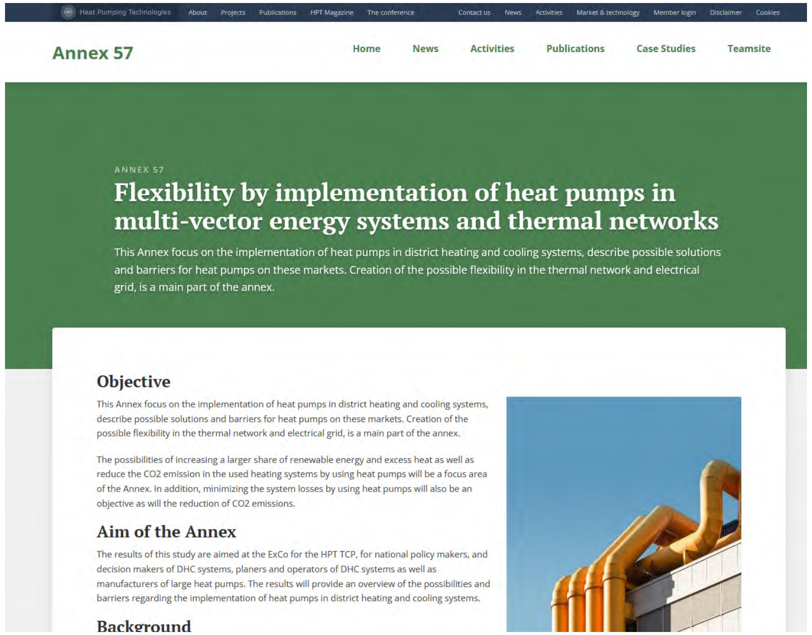
Seminar on Digitalization of Refrigeration and Heat Pump Systems, DTI, 04-07-2024

Heat pumps providing flexibility services - the role of model-based tools

Wiebke Meesenburg, DTU Construct, Section of Thermal Energy

Agenda

- What do we mean by flexibility and why do we talk about it?
- How can heat pumps provide flexibility?
- What are the barriers?
- What is the role of model – based tools?



What do we mean by flexibility?

Thermal flexibility

- Adaption of heat uptake or heat output
- Adaption of delivered temperatures

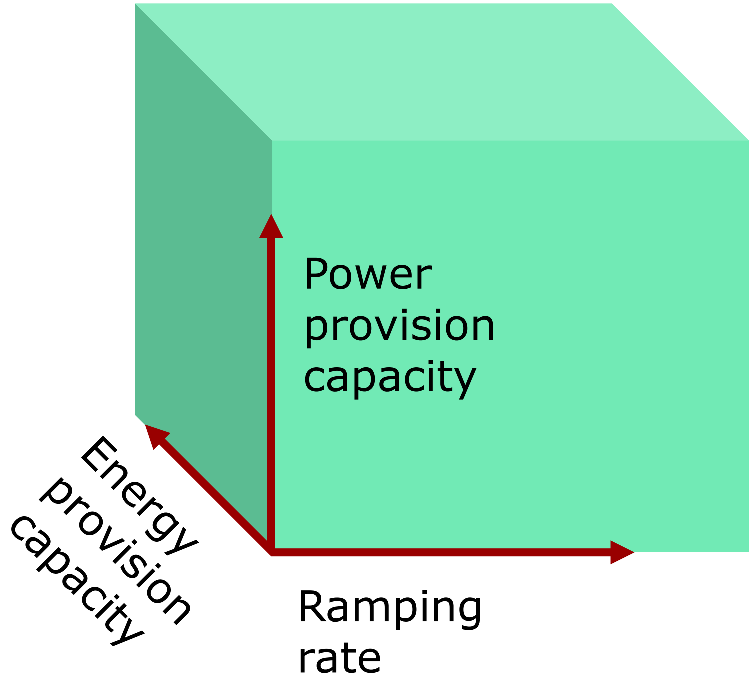
Electric flexibility

Capability to adapt the consumed electricity at a defined node in the grid

Short-term

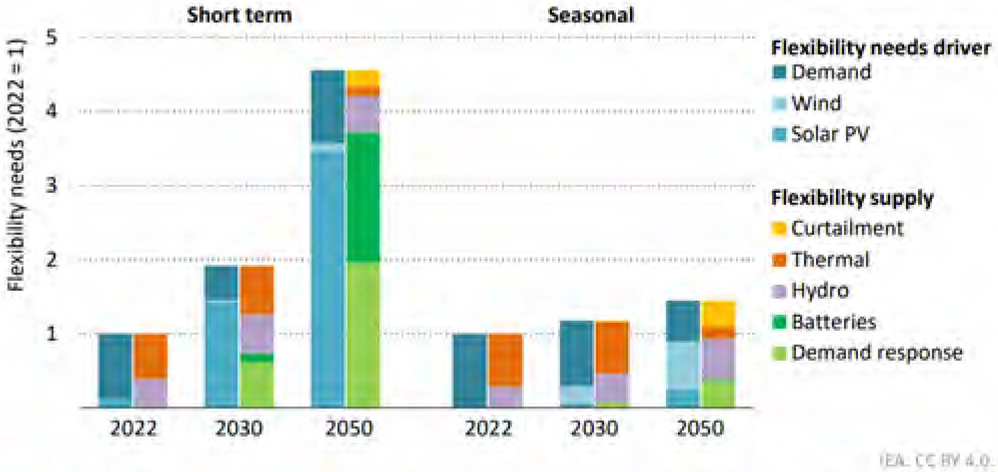
Mid-term

Long-term



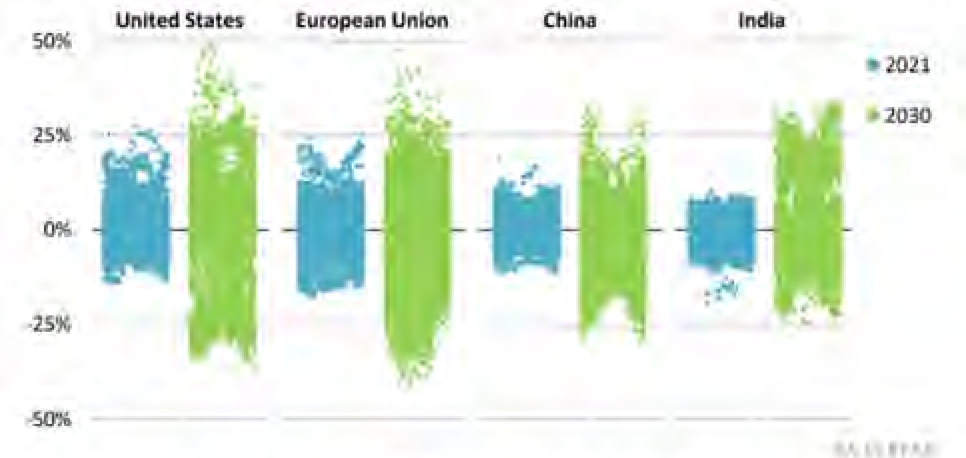
Adapted from: Ulbig A, Andersson G. Analyzing operational flexibility of electric power systems. Int J Electr Power Energy Syst 2015;72:155e64. https://doi.org/10.1016/j.ijepes.2015.02.028.

Need for electric flexibility



Short-term needs increase significantly, mainly due to solar PV, with batteries and demand response emerging as crucial suppliers of flexibility; seasonal needs rise less sharply

Notes: Flexibility needs are computed for 2030 and 2050 taking into account changes in electricity supply and demand and weather variability over 30 historical years. Demand response includes the flexible operation of electrolysers.



Hour-to-hour flexibility needs rise significantly by 2030 in major markets driven by increasing shares of variable renewables and changes in demand patterns

Note: Flexibility needs are represented by the hour-to-hour ramping requirements after removing hourly wind and solar PV production from hourly electricity demand, divided by the average hourly demand for the year.

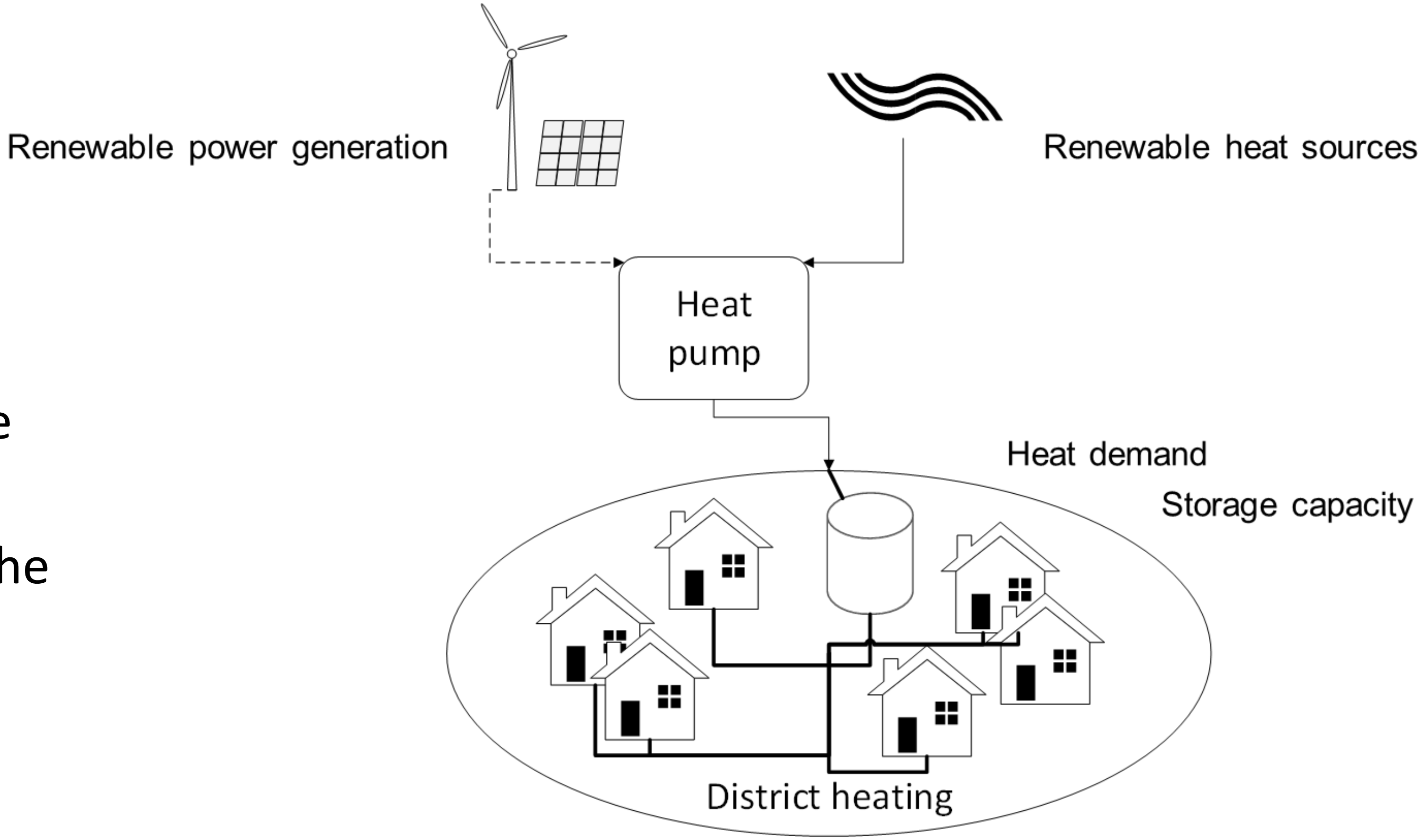
Source: IEA World Energy Outlook 2023

How can heat pumps provide flexibility?

Large-scale: Here, centralized heat pumps in thermal grids

Requirements

- Integration with thermal storage
- Efficient part-load operation
- Higher number of starts- and stops
- Fast reaction time (dependent on the service)
- Measurement and direct control of the power uptake



Flexibility services to the power grid

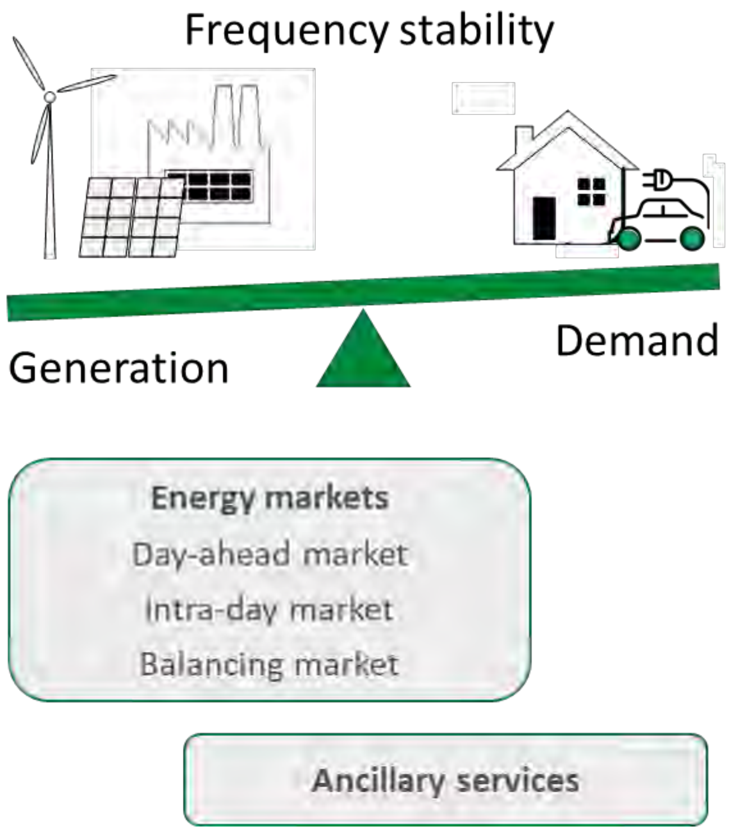
Implicit flexibility

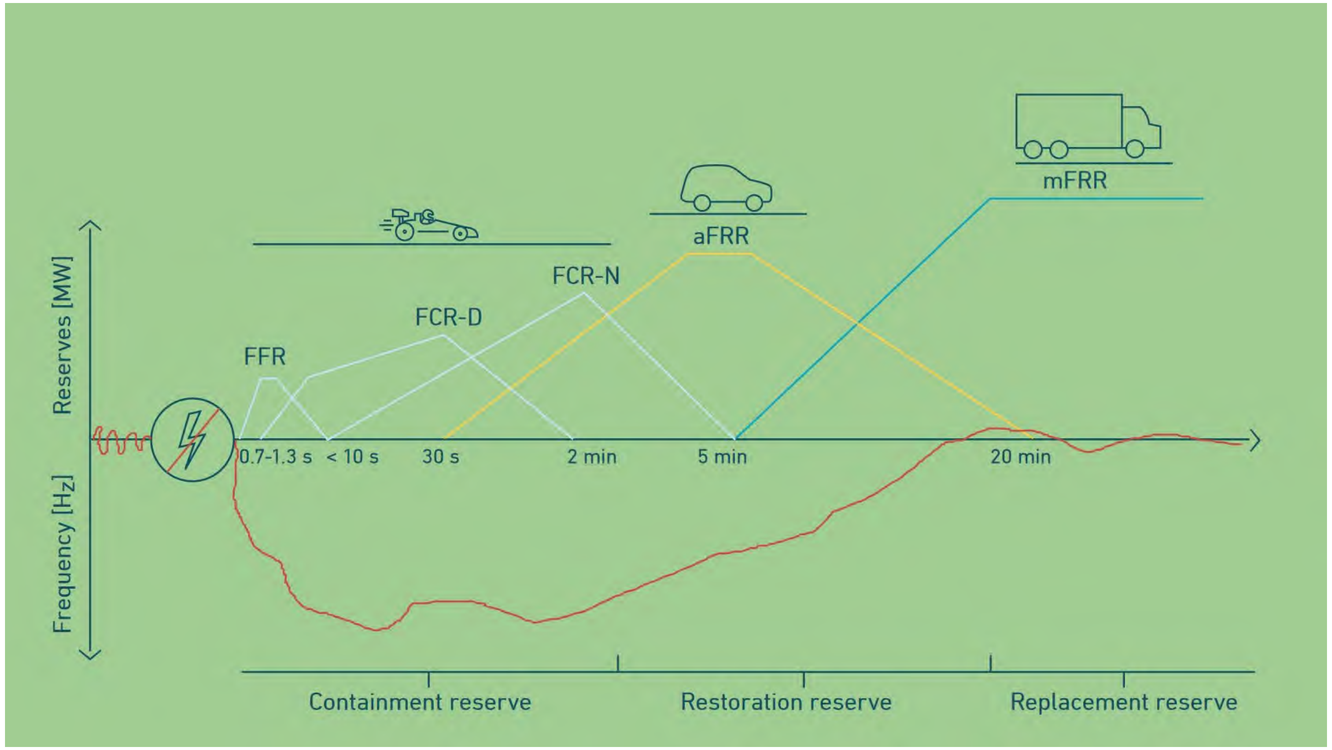
- Variable electricity price
- Variable grid tariffs

Explicit flexibility

Bilateral agreements	TSO ancillary services	Local flexibility market	Conditional agreements
Directly procured flexibility	Balance services, bids are activated upon calls	Flexibility market, bids are activated upon calls	Agreement with customer to adjust the power consumption when necessary

Services to the transmission system operator (TSO)

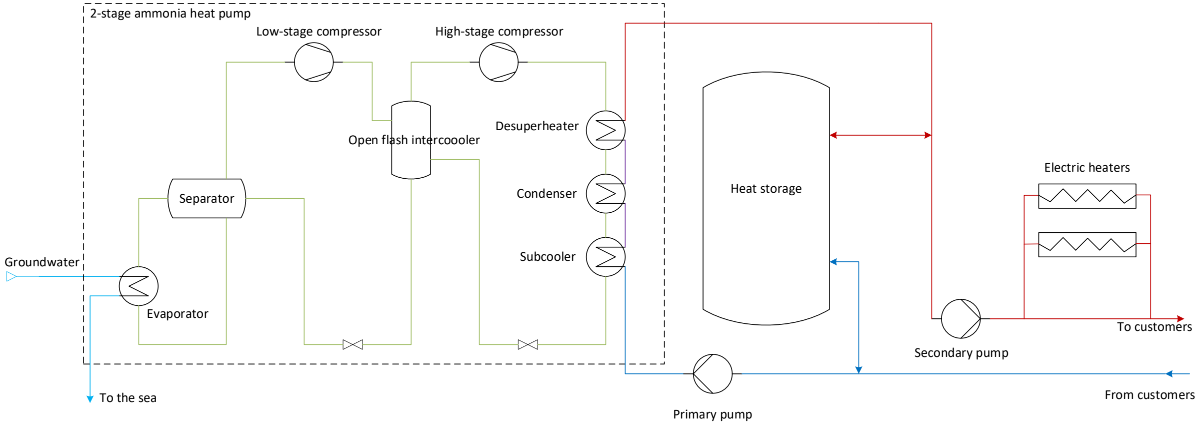


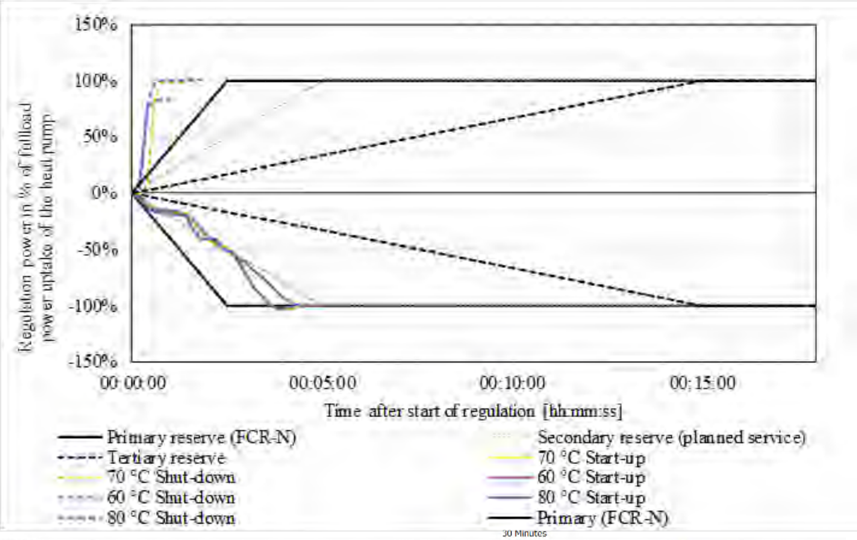


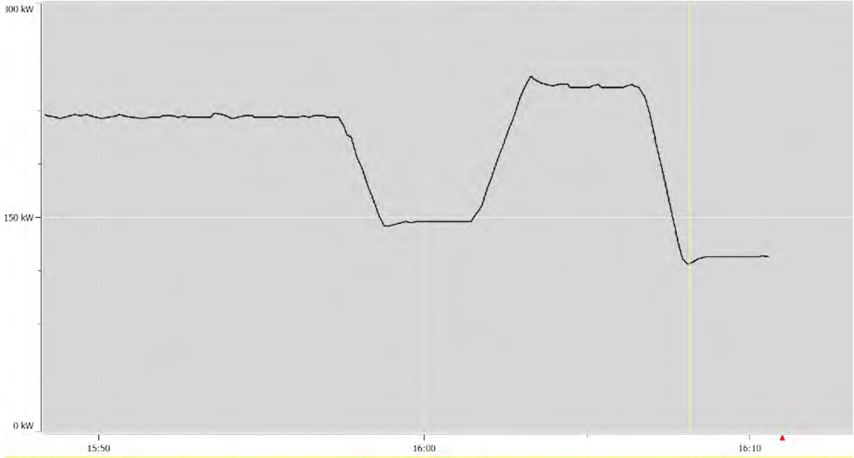
Source: Energinet (2023). Outlook for ancillary services 2023-2040

Example 1: FlexHeat, Copenhagen, DK

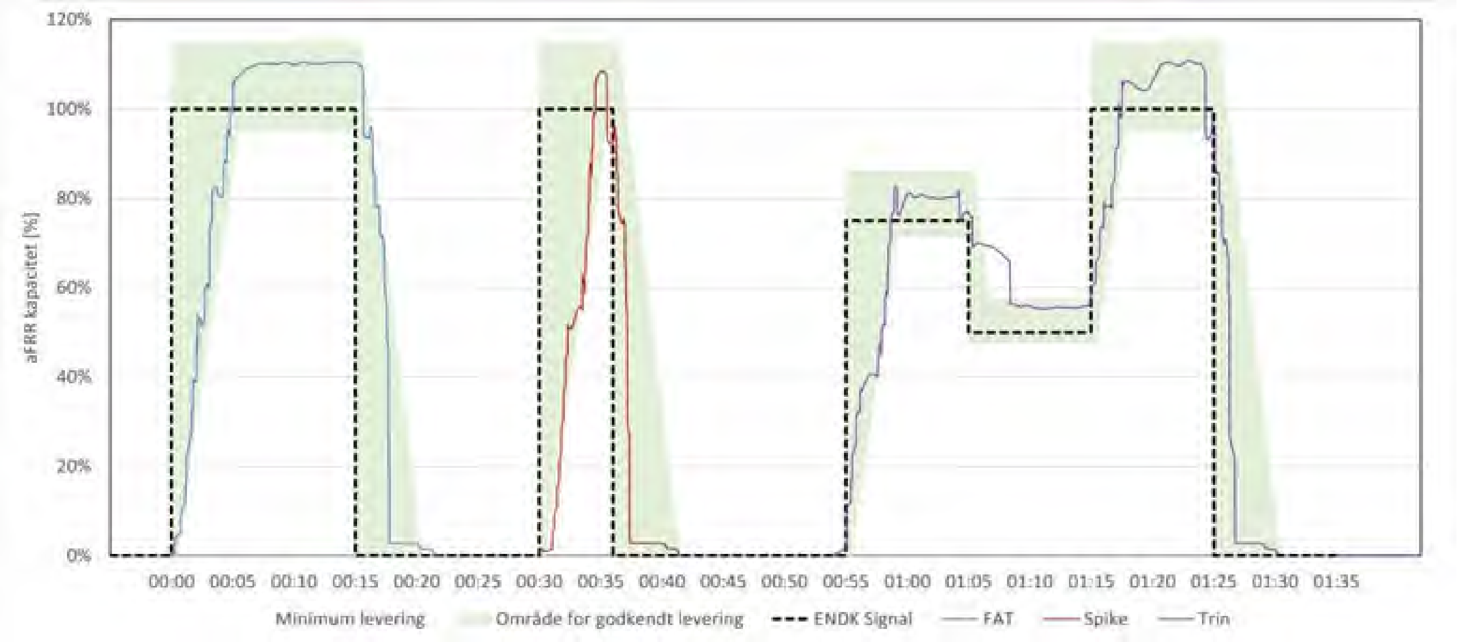
- 2-stage ammonia heat pump
- 800 kW thermal
- DH supply: 60-84 ℃
- Part-load: 20-100 %



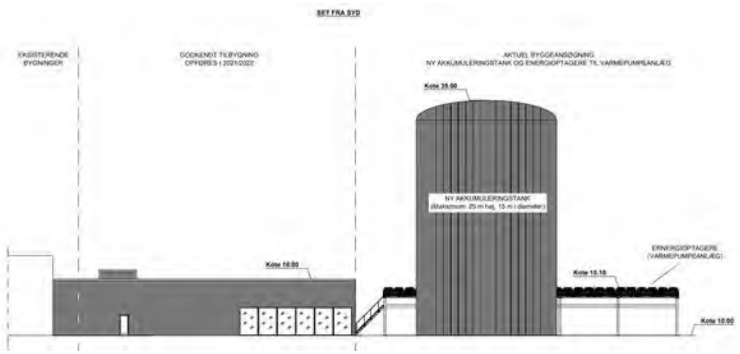




Example 2: CO_2 heat pump in Søndre Felding, DK



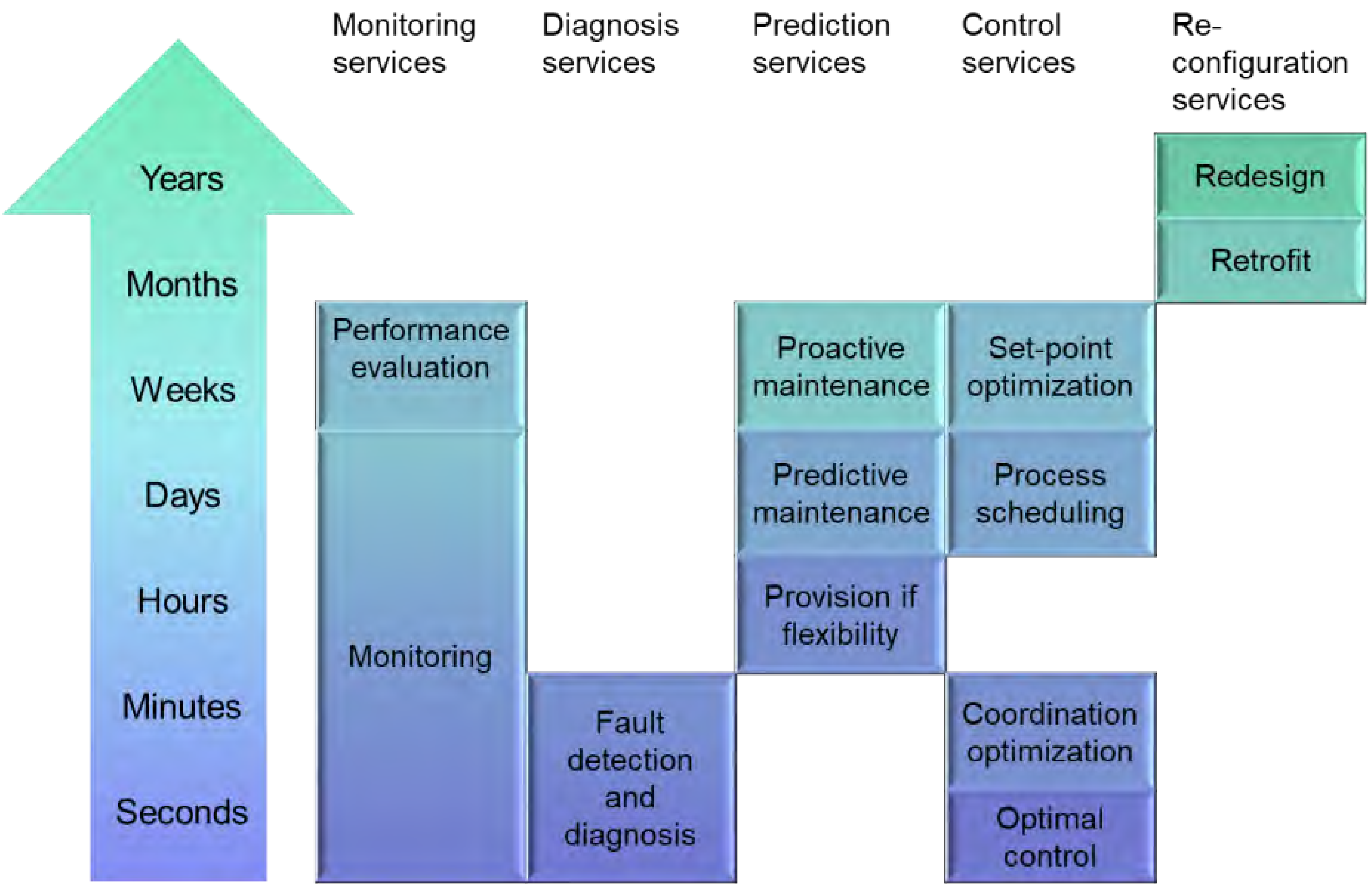
- CO_2 Heat pump
- Multiple parallel compressors
- 3.3 MW thermal
- Source: Ambient air



What are the barriers?

- Ramping times
- No direct measurement and control of power uptake
- Communication and aggregation
- Coordination with neighbouring systems
- Lack of experience
- Add-on service vs. system design requirements

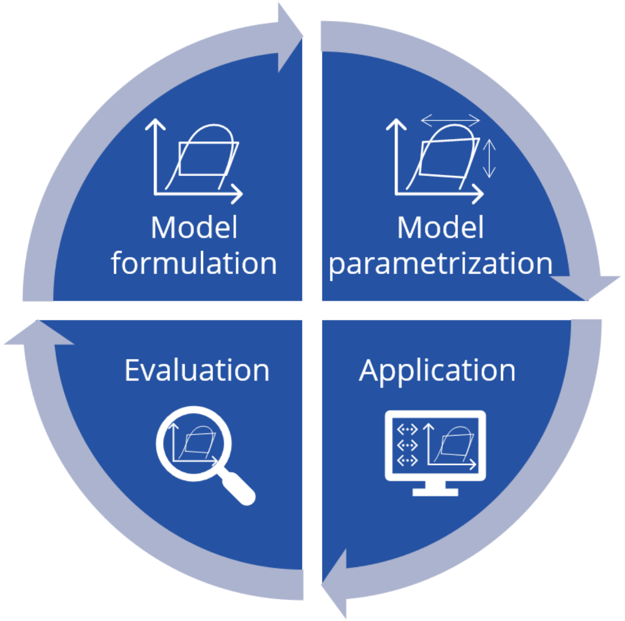
Model-based tools supporting flexible operation of heat pumps



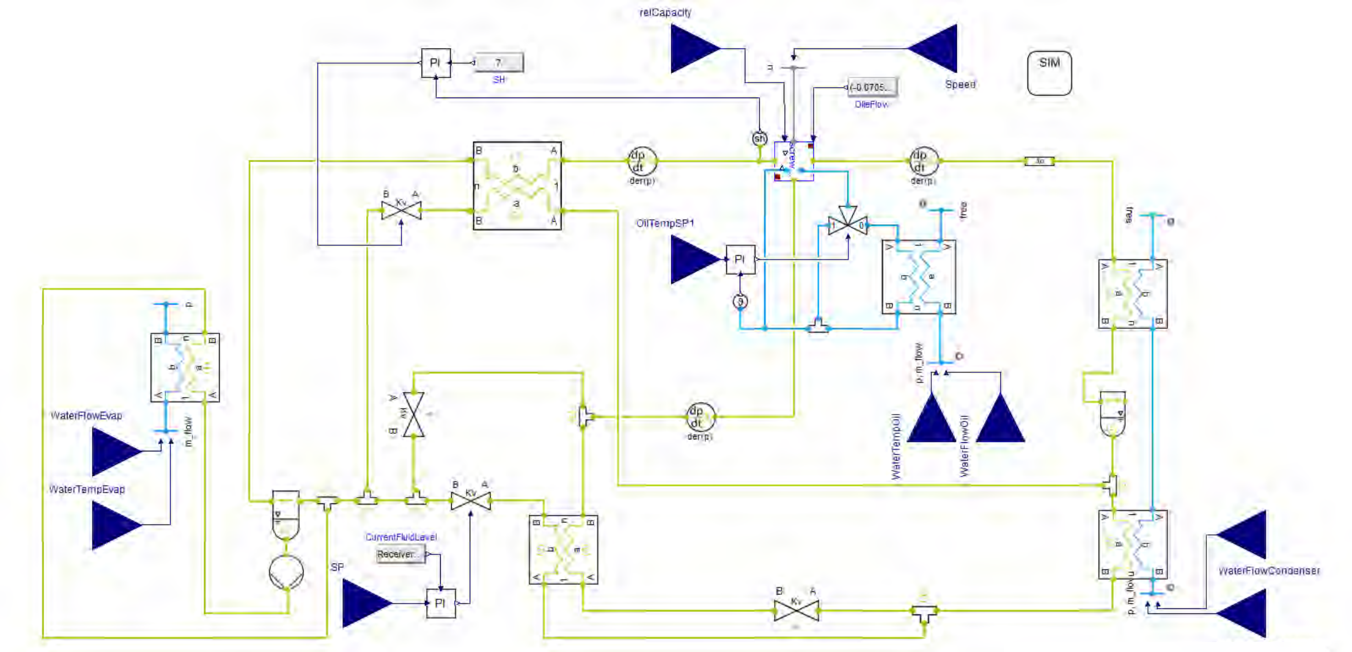
- Design and control optimization using dynamic models
- Monitoring: Current “flexibility potential” and “cost of flexibility”
- Process scheduling: when should the service act on which market
- Control: Adaption of control signal to ensure the desired flexible load adaption
- Coordination with neighbouring systems (secondary streams, industrial processes, storages, etc.)
- …

Example: DEVELOPMENT OF FAST REGULATING HEAT PUMPS USING DYNAMIC MODELS, EUDP

Modelling procedure:

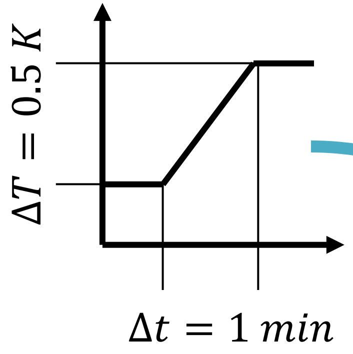


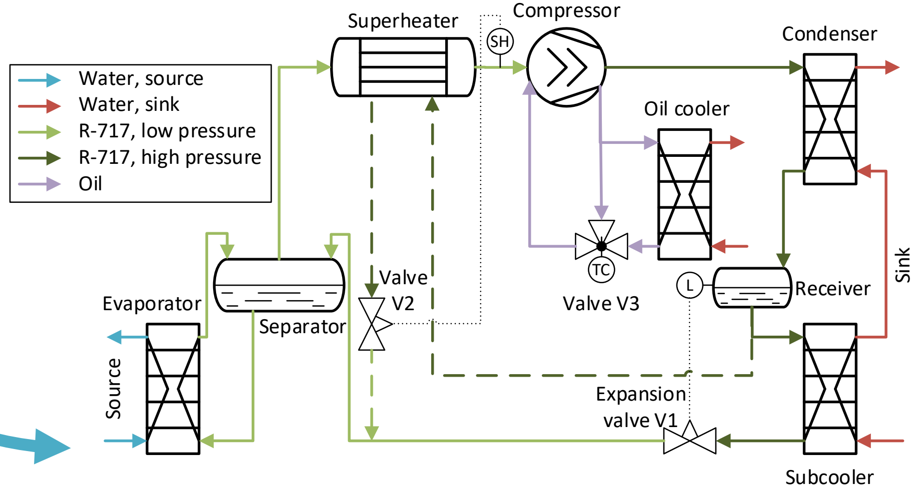
- Challenge
  - Screw compressor
  - PI-controller
  - Thermosyphon



Example: DEVELOPMENT OF FAST REGULATING HEAT PUMPS USING DYNAMIC MODELS

Experiments





- Response of pressure levels
- Response of superheating in suction line
- Risk of liquid floodback (indicator: gasvelocity in separator)

Use of validated dynamic models to optimize system control taking secondary streams into account

Optimization of system design regarding the dynamic behaviour of the system

Perspectives

Already today

- The need for ancillary services from demand side units is increasing
- Heat pumps can react within seconds to minutes
- Heat pumps offer connection to a large energy storage capacity
- Manufacturers begin to take the required flexibility and robust operation under dynamic conditions into account when designing new systems

Future developments and open questions

- Coordination of heat pump control with neighbouring systems
- Digital services targeting flexible operation (scheduling, monitoring,…)

DTU

Teaser: Digital Heat Pump Lab at DTU Construct

Digital Heat Pump Lab

- Vision: A place where research and education meet, targeting both the need for digital solutions and for skilled graduates
- State-of-the art laboratory for small-scale heat pumps enabling real time interaction between models and units
- Expected start of operation: August 2025

Contact:

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Jonas Kjær Jensen, jjkje@dtu.dk

Thank you ☺

Contact: Wiebke Meesenburg, Ph.D., wmeese@dtu.dk

DANISH TECHNOLOGICAL INSTITUTE

ELECTRONICS FOR THE FUTURE

Stig Petersen

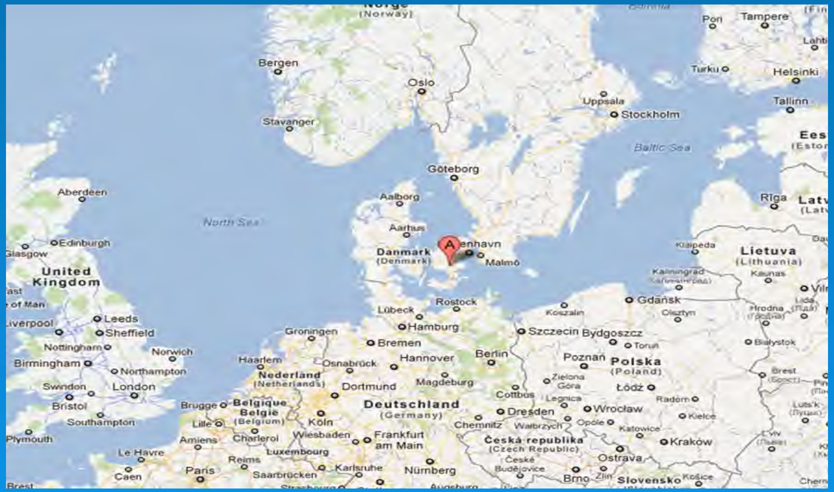
LS Control A/S

LSCONTROL

LS Control A/S

- Electronics for the Future

- One-stop shop for development and production of HW and SW.
- Danish company, which has been on the marked since 1969.
- 55 employees in Denmark and subcontractors in Poland and Slovakia.
- In 2023, we supplied over 300.000 controller PCBs for different solutions.
- Mainly for use in products provided by European manufacturers.
- HVAC ventilation industry; Heat pumps, ventilation and air-conditioning.
- Own internet cloud
- EMC test
- 3rd part certification
- ISO9001:2015 and ISO14001:2015 certified.



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Traditional control system / 10 Years ago

- Display on unit
- Not possible to update / or updates are made cabled on site
- Service must be performed on site by skilled service technician

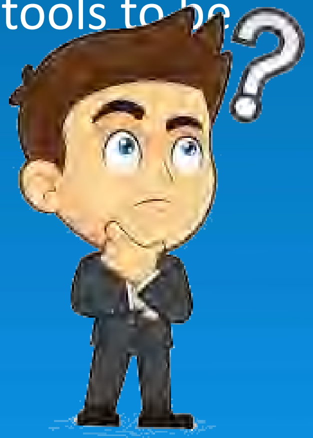
LSCONTROL

Why IoT Heat Pump Controls?

The speed of the green transition and the complexity of new products have shown that specialized assistance is often required when systems need to be

- Installed – start up
- Set-up – calibrated
- And afterwards serviced
- Electrical Grid optimization require online products

The increasing complexity means that heat pump technicians require IoT tools to be able to quickly install systems.
If a problem occurs help must be there promptly and directly.



It can be somewhat compared to the automotive industry, where cars today are online and can be serviced and especially updated online.

In our opinion, this is an absolutely necessary part of modern products.

What Are We Offering in Products Today?

Read about our IOT Fleet Management System and other online options on our website lscontrol.dk/en

Discover the Future with LS SmartConnect: The Secure Connection of Your Products to the Internet.

It is an expectation that today's products are connected to the internet and can be controlled and monitores regardless of where you are. We have developed LS SmartConnect wich is a secure web-solution for connecting your products to the internet, either directly or through our gateway. This opens the possibility for monitoring and controlling your product using a PC, smart phone or tablet, no matter where you are.

Security by LS SmartConnect

Many are worried about hacking and leaking personal data when using IoT. LS SmartConnect guarantees a secure peer-to-peer-connection where an advanced code ensures a secure problem free access without compromising security. Our user-friendly app provides a detailed overview of your products ad gives you the option to start, stop and adjust them as needed.

LS SmartConnect Center

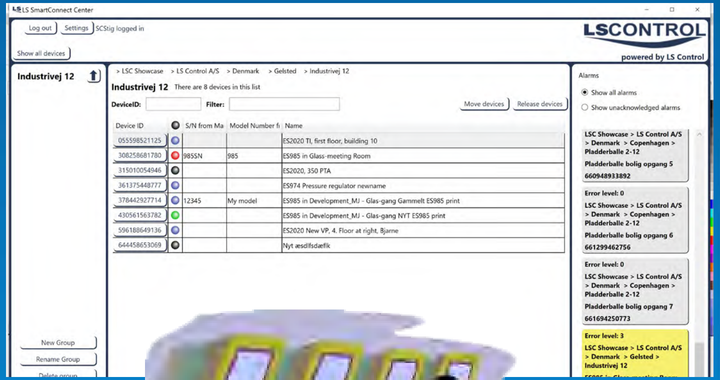
LS SmartConnect Center is an internet-based fleet management solution. Our fleet management solution is developed for PC, but is also available in a light version for smart phones and tablets. With the PC-program you can easily administer and monitor groups of products, get a performance log for a specific device, update software in devices, set-up and ajust devices. This makes LS SmartConnect Cente fleet management perfect for dealers and servide partners. You obtain full control over and insight in all the connected products and it is possible to identify and react on any alarms, such as need for filter change, even adjustments and software updates can be made without leaving the office.

What is a Service Tool, a Monitoring Tool and an End-User app?

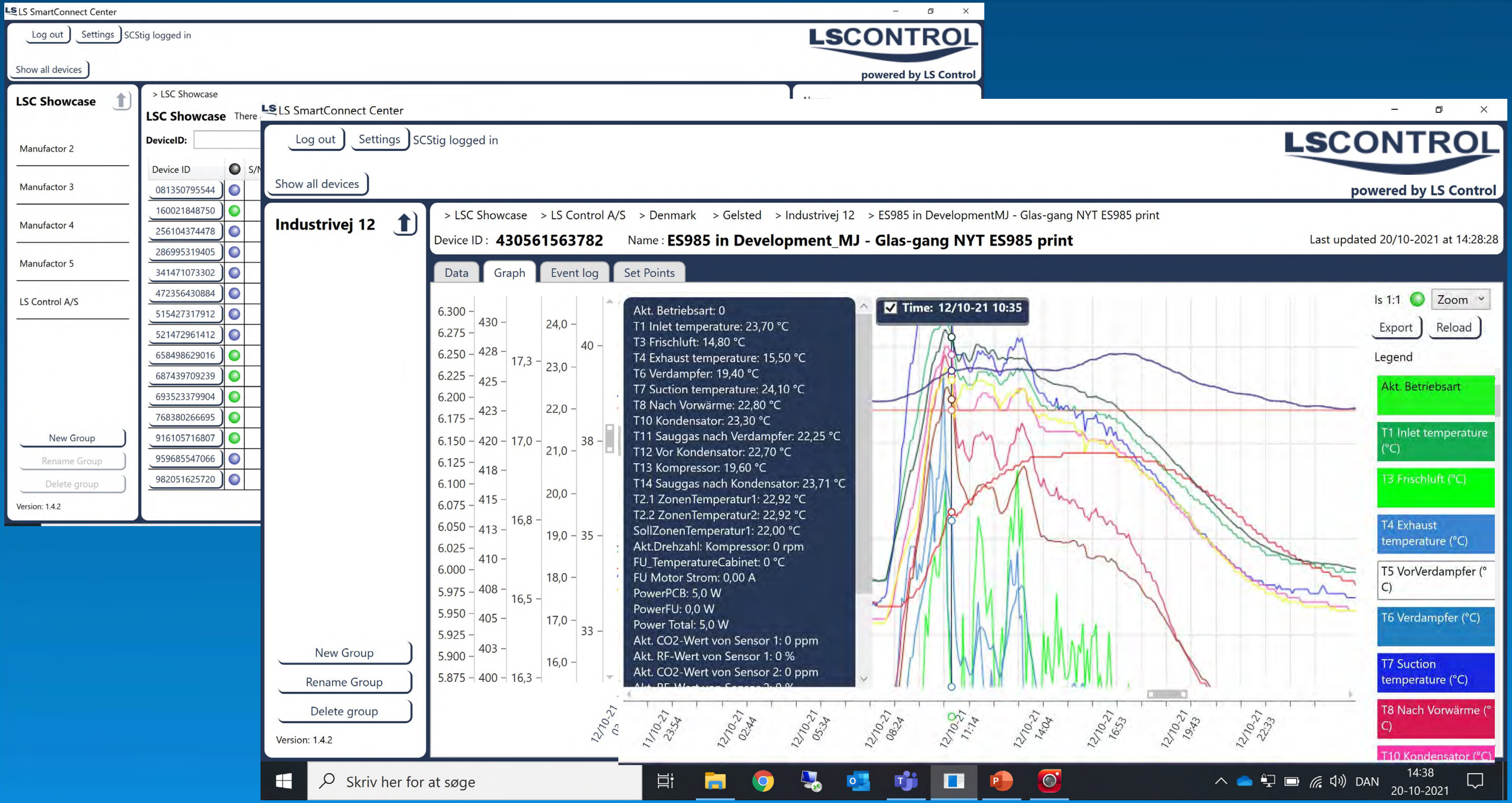
LSCONTROL

The Service Tool for PC includes

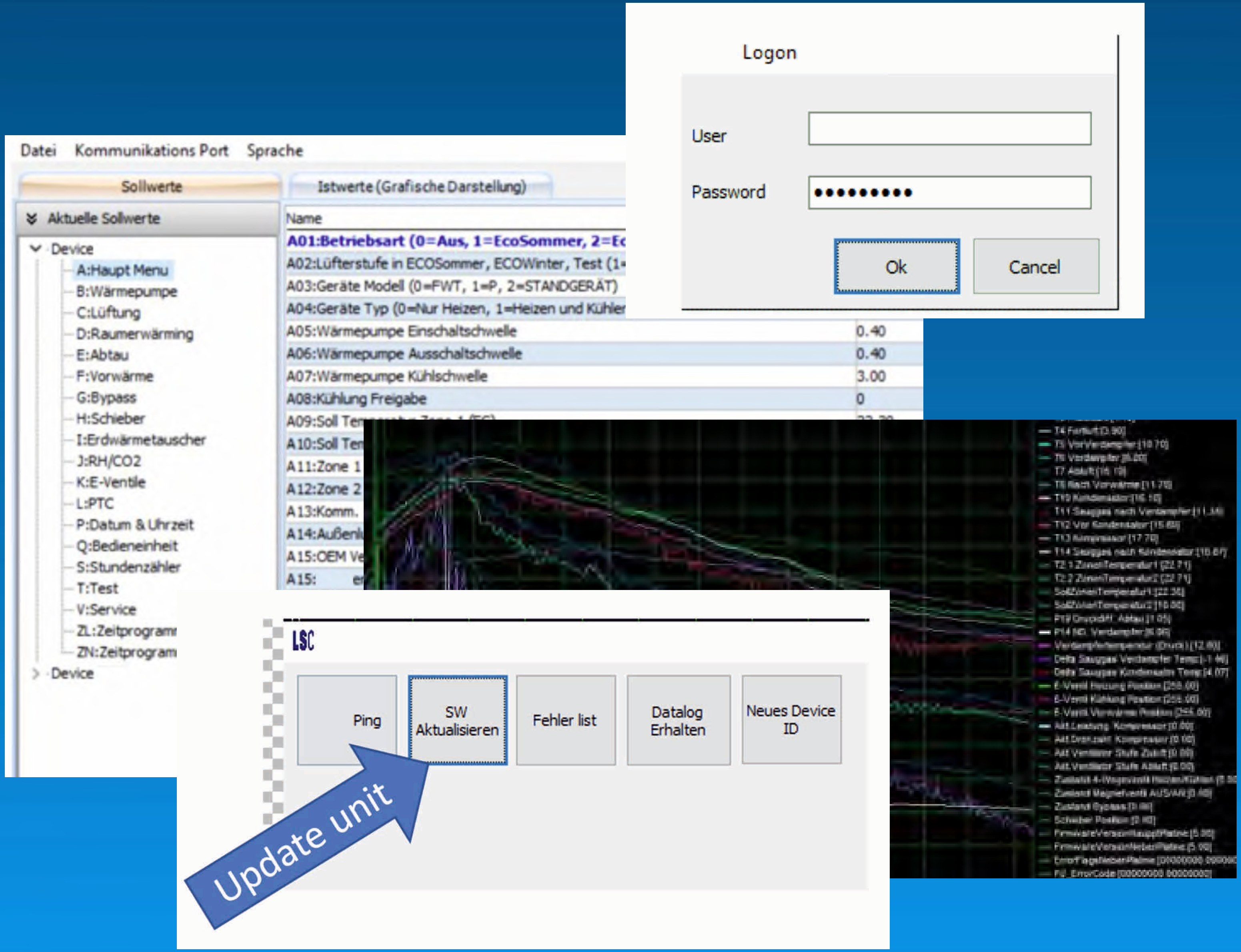
- Fleet management / administration of units
- Possibility to resell licenses to service partners and/or resellers for selection of Heat Pumps
- Starting up and adjusting units
- Assist system support and prepare necessary physical service visits
- Error overview and management



Service Tool for PC



Service Tool for PC



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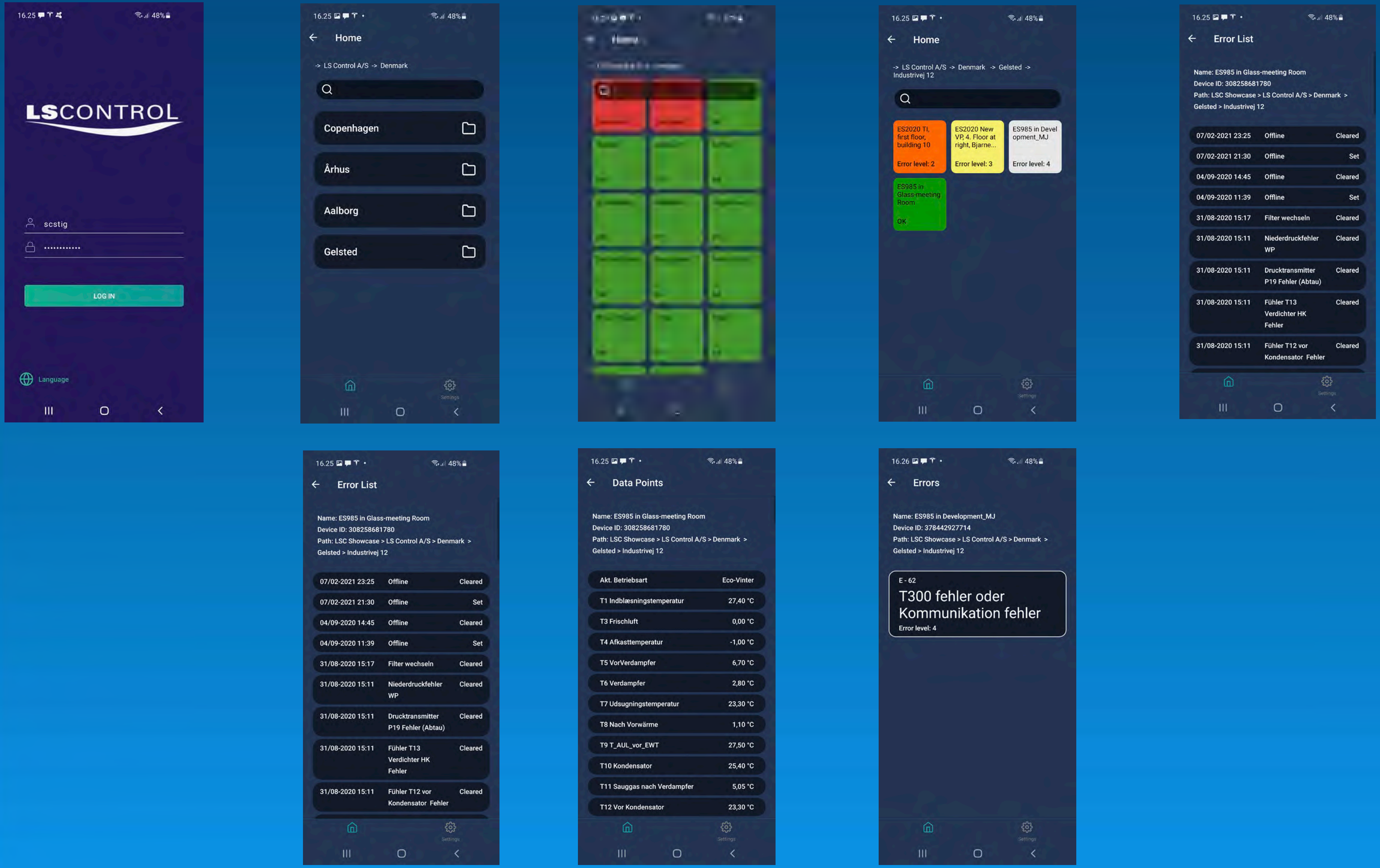
The Monitoring App

- Provide a full overview of group of Heat Pumps
- Color Coded for easy monitoring if any Heat Pumps are failing and the severity of the fault
- Ability to investigate the fault on a certain Heat Pump to establish if it is an easy fix or expert advice is needed

Monitoring App

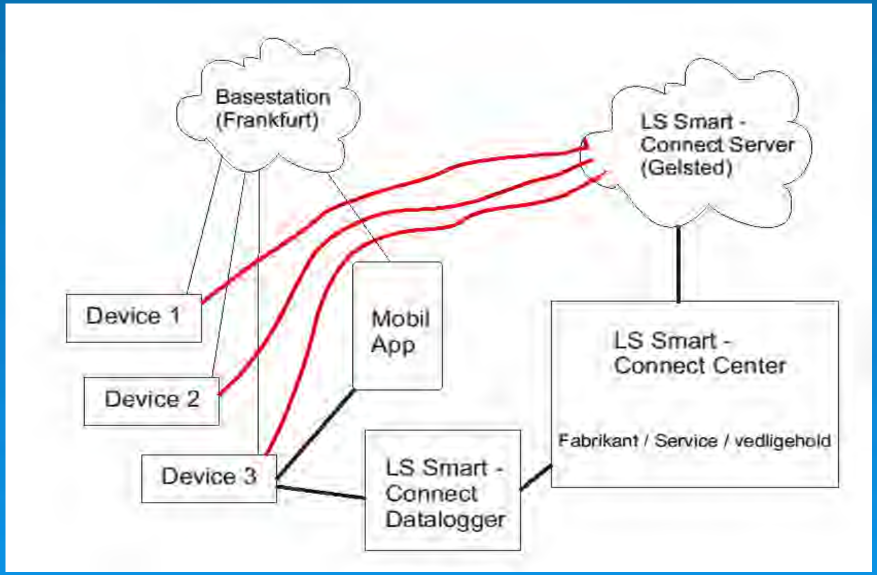


The End-User App

- Today all end-users expect to be able to monitor their home equipment – and especially Heat Pumps and Ventilation Systems
- Ability to turn the Heat Pump on/off
- Ability to adjust temperature

Security

- We ensure correct Data Controller and Data Processor Agreements to comply to the GDPR rules.
- We ensure secure cloud connection without making it troublesome for the users.
- We comply to EN 303645
- We provide a thoroughly tested system with more than 100.000 active users.



Config App

- Easy configuration and set up of a system / controller
- System / controller do not need to be connected to the internet
- Just scan the QR-code on system/ controller

- The LS Config App recognize your product from the QR-code and inserts your logo, special configuration, menu choices and colors
- Configuration is then done in the app and transferred to the system / controller via USB or Bluetooth
- Config app is operational even on offline devices

Conclusion

External factors such as lack of service personnel makes it necessary to find new ways to startup - service – and maintenance Heat Pumps – ventilation – district heating systems in buildings.

With online help / services you get better performance for units – easy and cost effective at start-up, troubleshooting and service.

Choosing a secure online system give the possibility to connect to other cloud systems through interfaces like MQTT. Products will need to be connected – and communicate to systems as EE-BUS to help with stabilize the grid, and give users the best energy price.

Our experience with more than 70.000 units online over the past 7 years tell us that our customers save a lot of service time.

All in all – it is very hard to imagine a future without having units online.

LSCONTROL

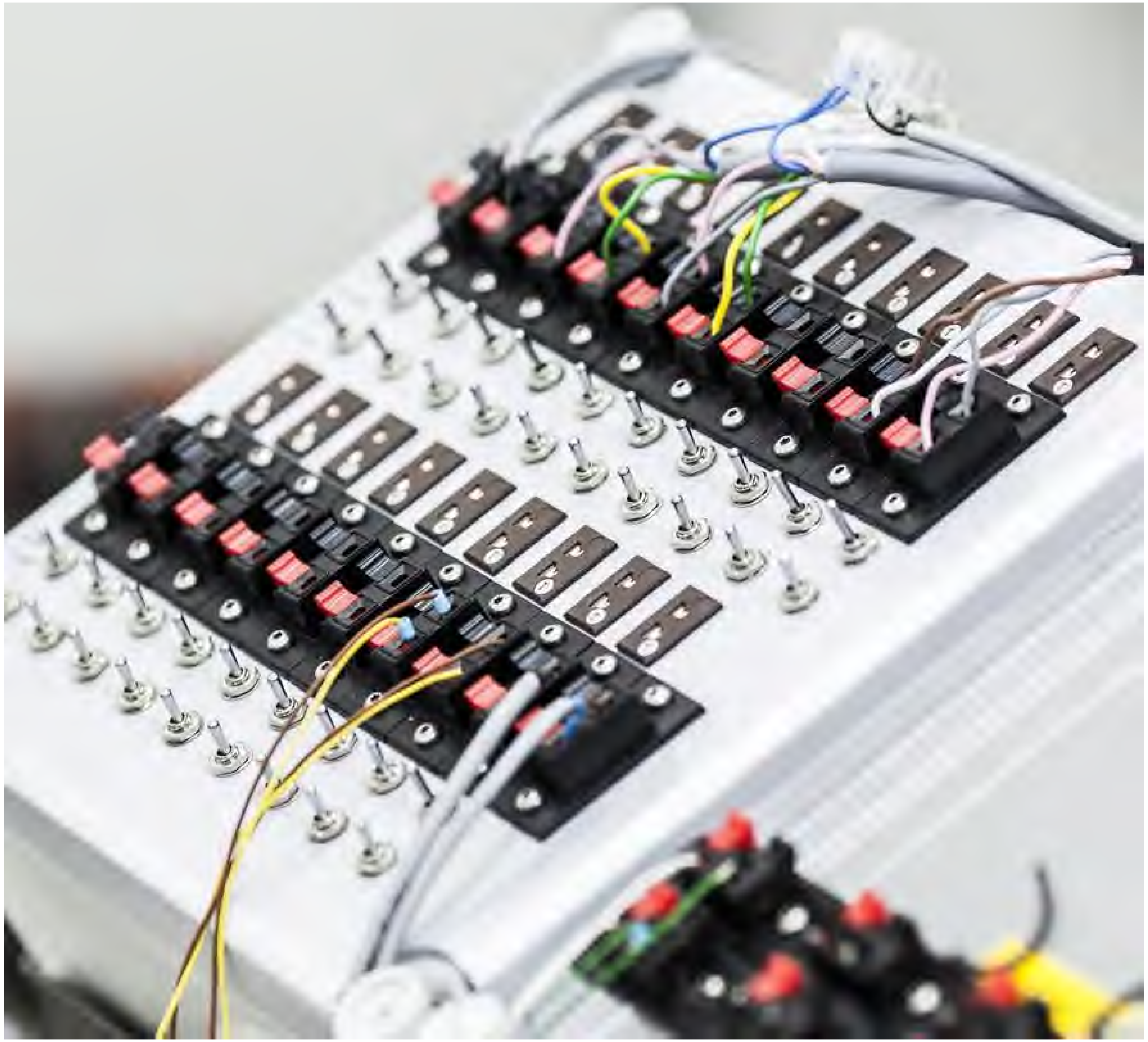
Turn your Heat Pump into a *Smart Pump*

DANISH TECHNOLOGICAL INSTITUTE

A CLOUD-ASSISTED FRAMEWORK FOR REAL-TIME MONITORING OF REFRIGERATION AND HEAT PUMP SYSTEMS

Johan Hardt Løbner

Danish Technological Institute

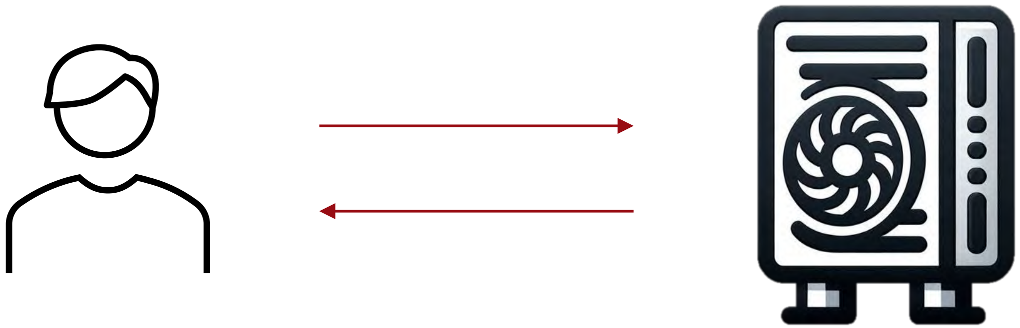


A cloud-assisted framework for real-time monitoring of refrigeration and heat pump systems

Johan Hardt Løbner, Danish Technological Institute (DTI)

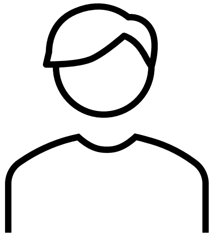
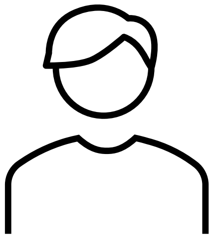
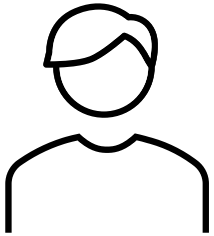
Why

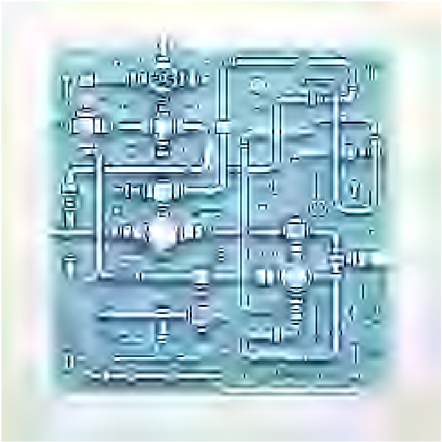
- Systems contain data
- Digital but unconnected
  - Models
  - Systems
  - Loss of data
- What do we want?
- Insights
- Cooperation between systems and people
  - Anytime anywhere



The end points

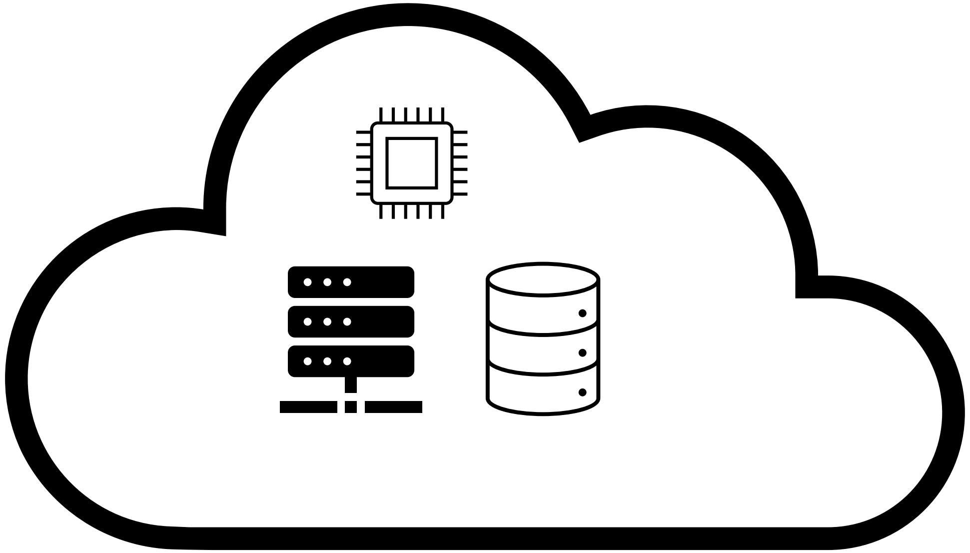
- The user(s)
  - Different user different need
  - Anywhere anytime
- The systems
  - DAQ systems
  - Test devices
  - The weather
- Making it all play together



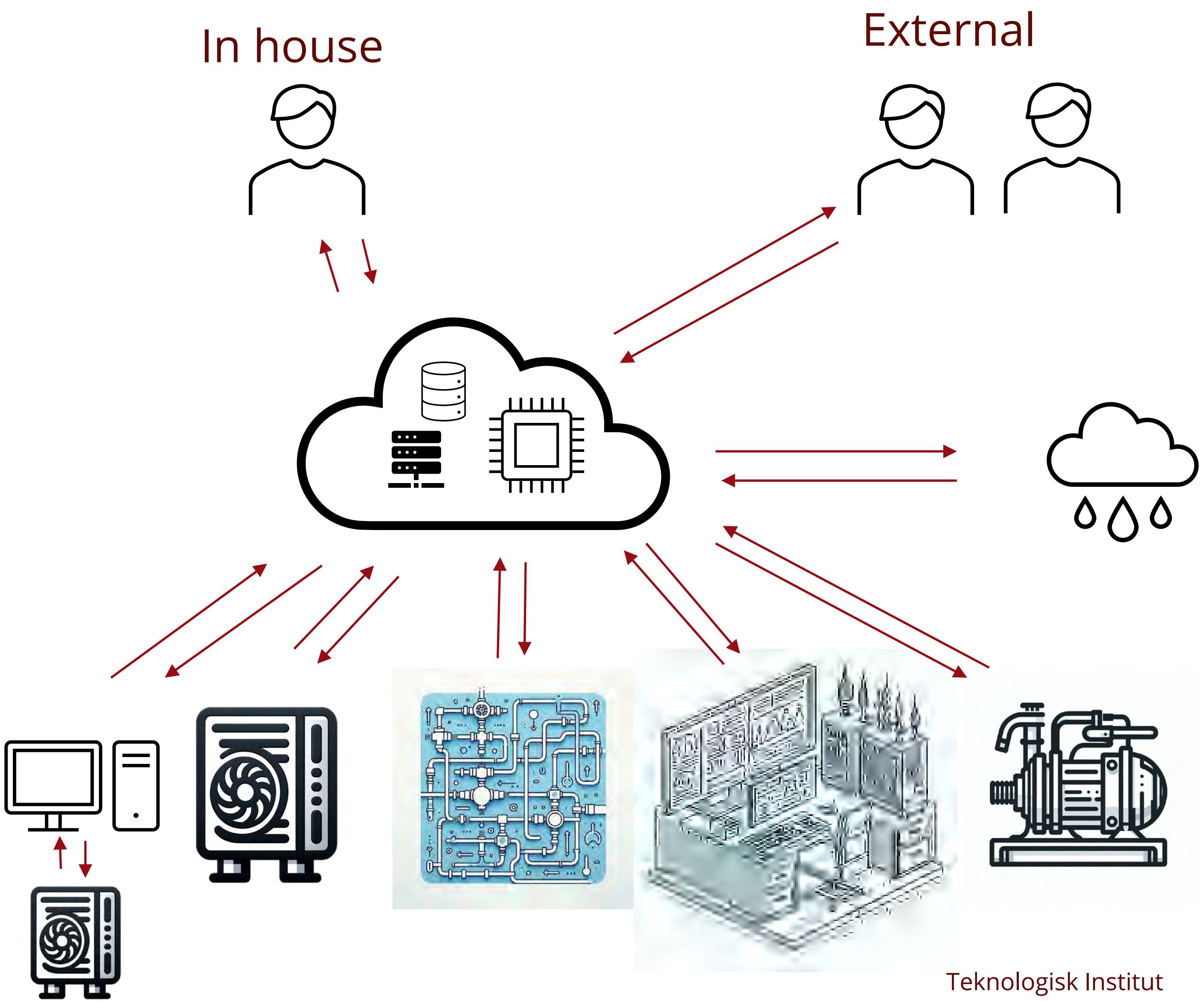

How and the cloud

- A common connection point
- Anywhere anytime
  - Real time data streams
  - Models and simulations
- Databases
- Server side processing



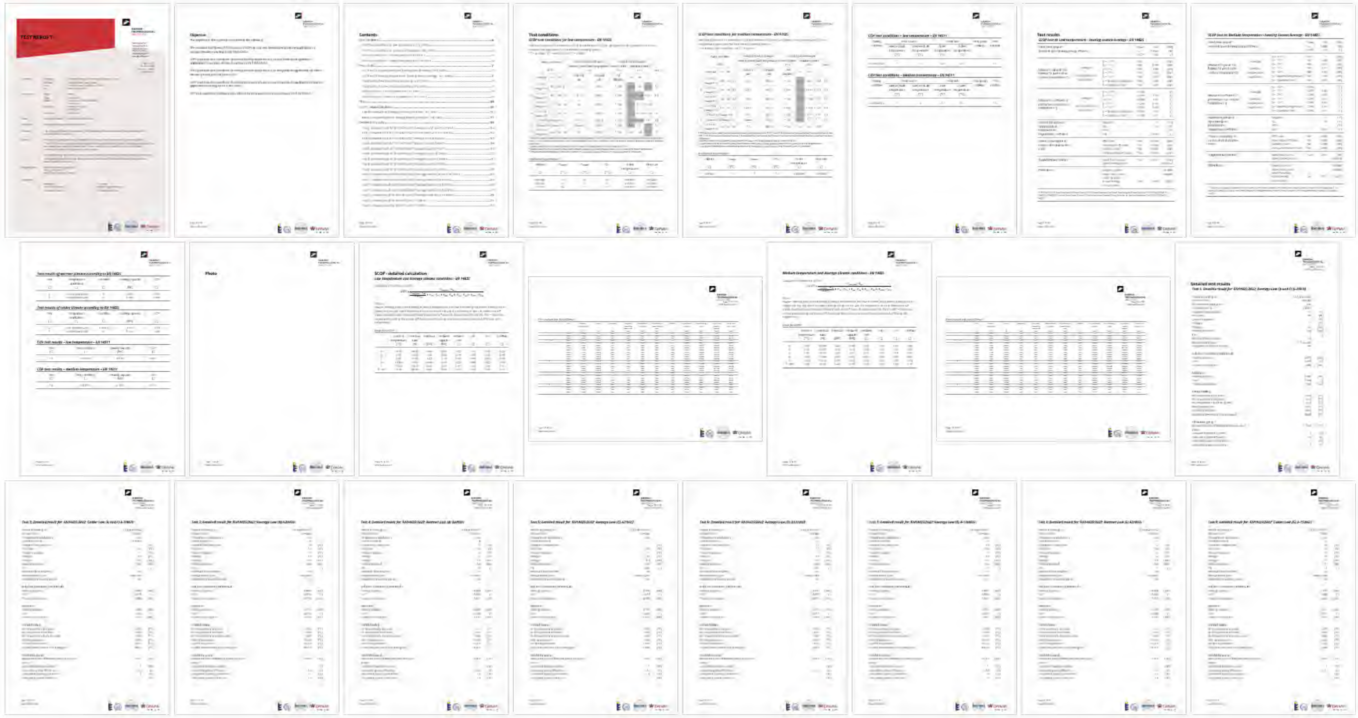
The framework

- Connecting the dots
- Translation layers
  - Lifting established legacy systems
- Relying on established protocols
  - MQTT, HTTPS, MODBUS, OPC, SQL..
- Two-way communication
- Real time



The “finished” product

- Cohesive presentation of multiple data sources
- Growing with the challenges
- The importance of flexibility
- Leveraging DTI’s excellent IT department
- Custom webapps
- A tailor-made testing environment
- Psst it’s never finished



Questions?

DANISH TECHNOLOGICAL INSTITUTE

A DIGITAL TWIN FOR EVALUATING EVAPORATION PRESSURE FLUCTUATIONS IN SUPERMARKET REFRIGERATION SYSTEMS

Andreas Schulte

Technical University of Berlin

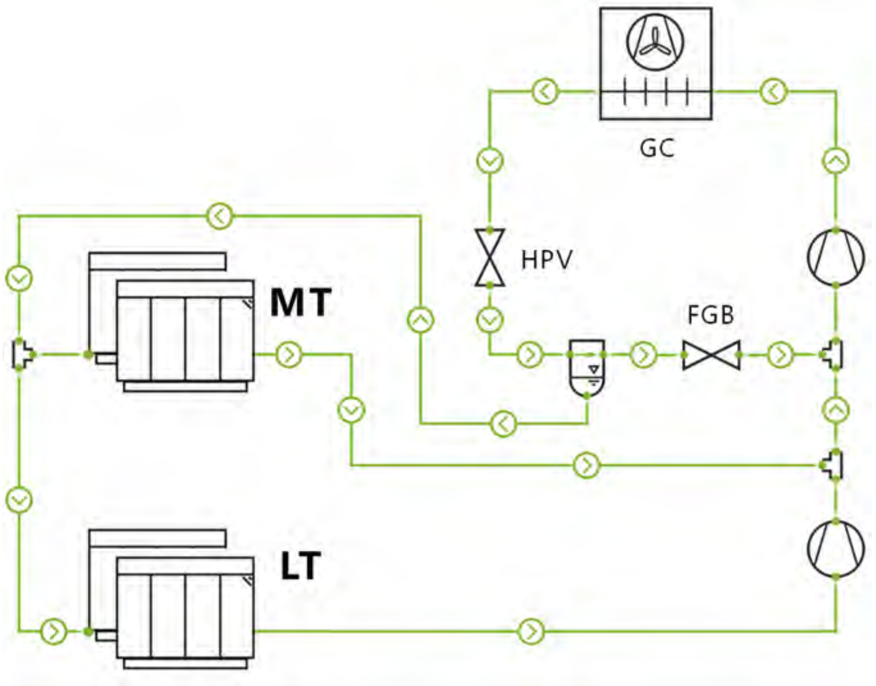
A digital twin for evaluating evaporation pressure fluctuations in supermarket refrigeration systems

Andreas Schulte, TU Braunschweig

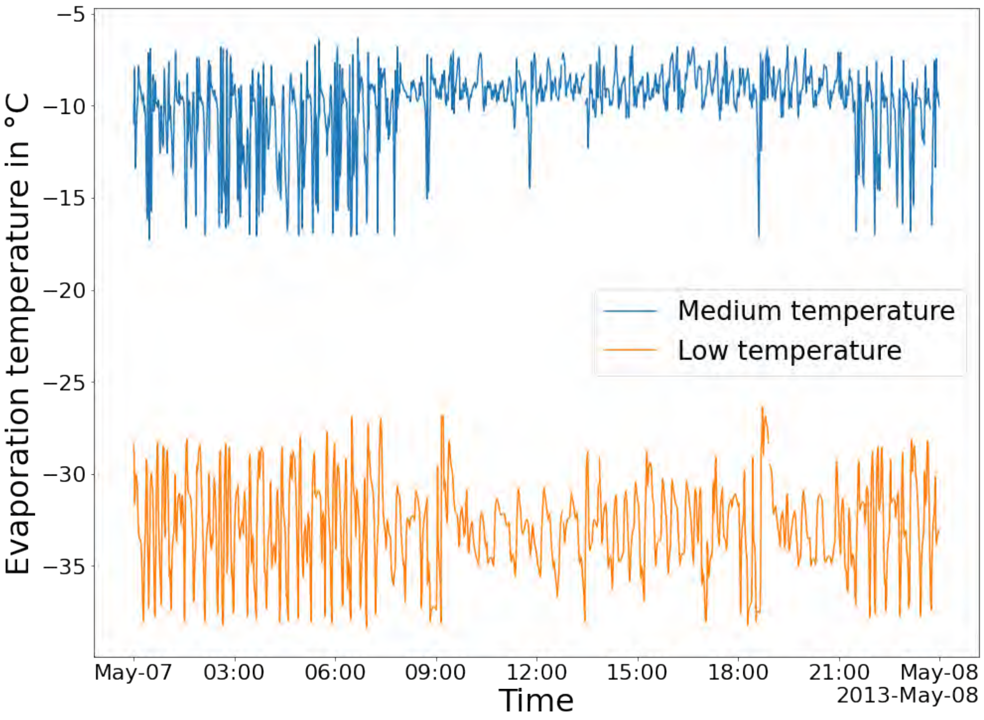
Agenda

1. Why did we want a digital twin for the evaporation pressure?
2. How did we go about building the digital twin?
3. What potential for automated model generation exist?
4. Where else can these methods be applied?

CO_2-Supermarket Refrigeration System



Typical evaporation pressure



Motivation

- We assumed a more stable operation would lead to some energy benefits
- Different controller options influence the evaporation pressure dynamics
- The interactions within the system are very complex
- A digital twin is a good option to investigate this

Building a digital twin

- The digital twin will be build in Modelica (Refrigeration cycle) and Simulink (Controllers)
- The digital twin can be build by hand or automated
- We explored some ways of automated creation
- Ultimately we build the digital twin in a mix of automation and hand

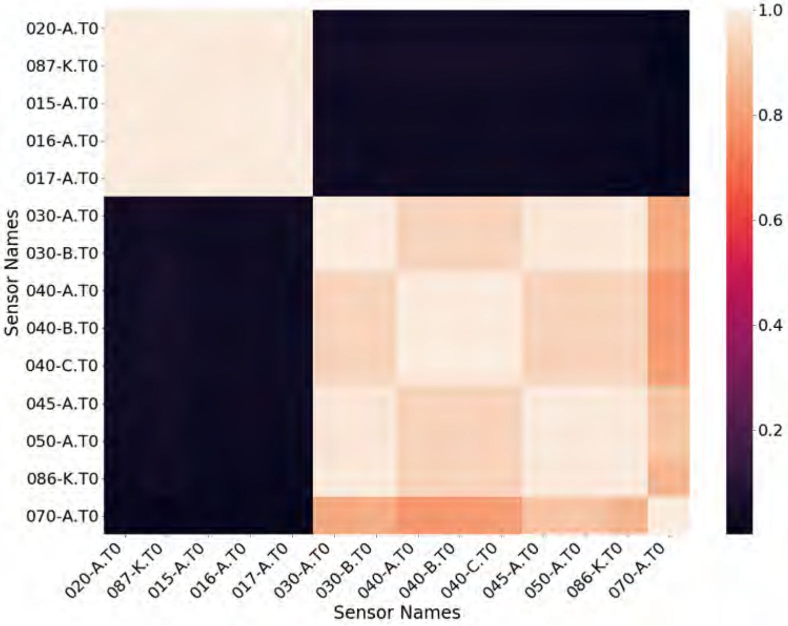
Exploration of semi-automated model creation

Basic process for automatic model creation

1. Identify components
2. Determine system layout
3. Create Modelica code for the model:
    1. Build connections between components
    2. Add Parameter for the components

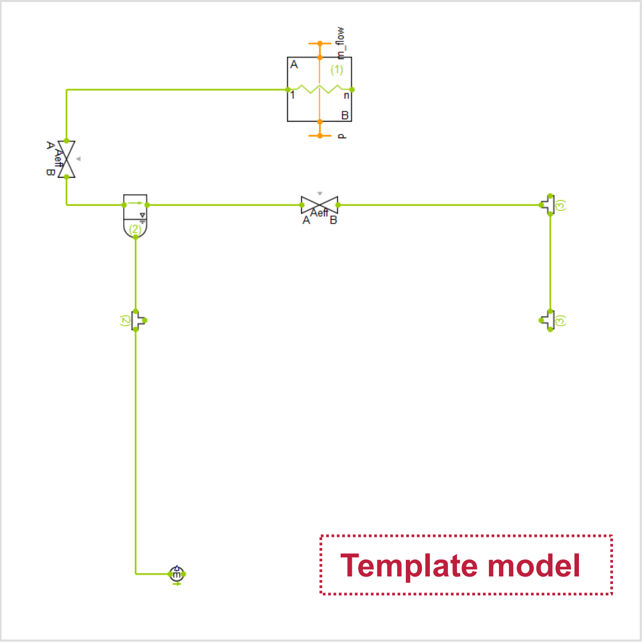
Determine system layout

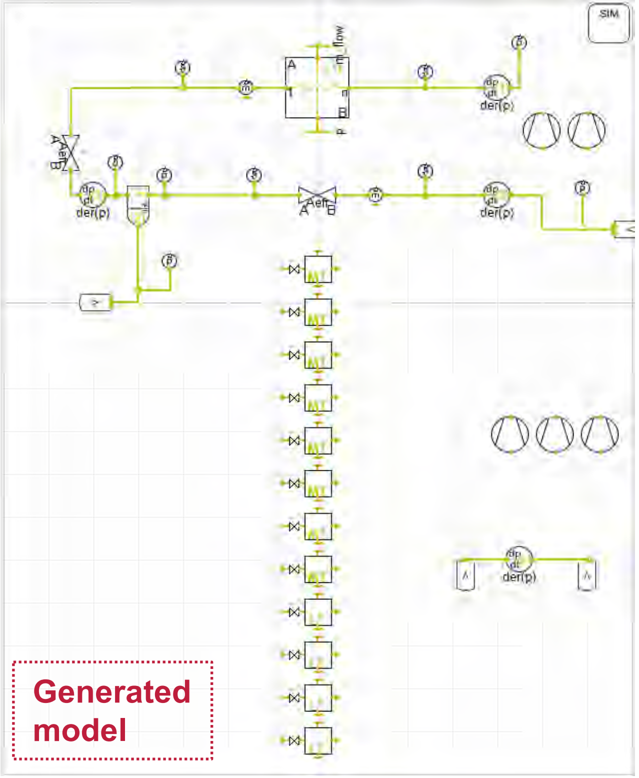
- Finding all evaporators/ compressors that belong to a pressure level
- Correlation analysis and clustering
- Other clustering/ grouping algorithms may also work



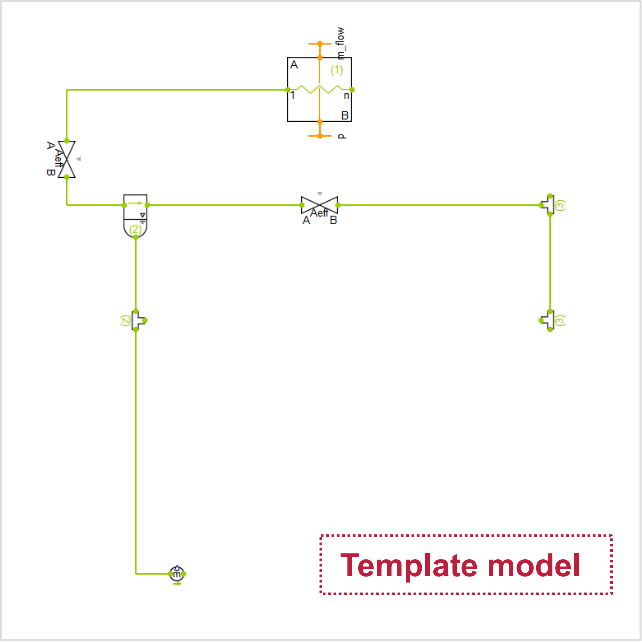
Schulte, A., Tegethoff, W., Köhler, J.: Correlation Analysis of evaporation pressure readings in CO2 supermarket refrigeration systems. 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants, Trondheim, 13.-15. Juni 2022.

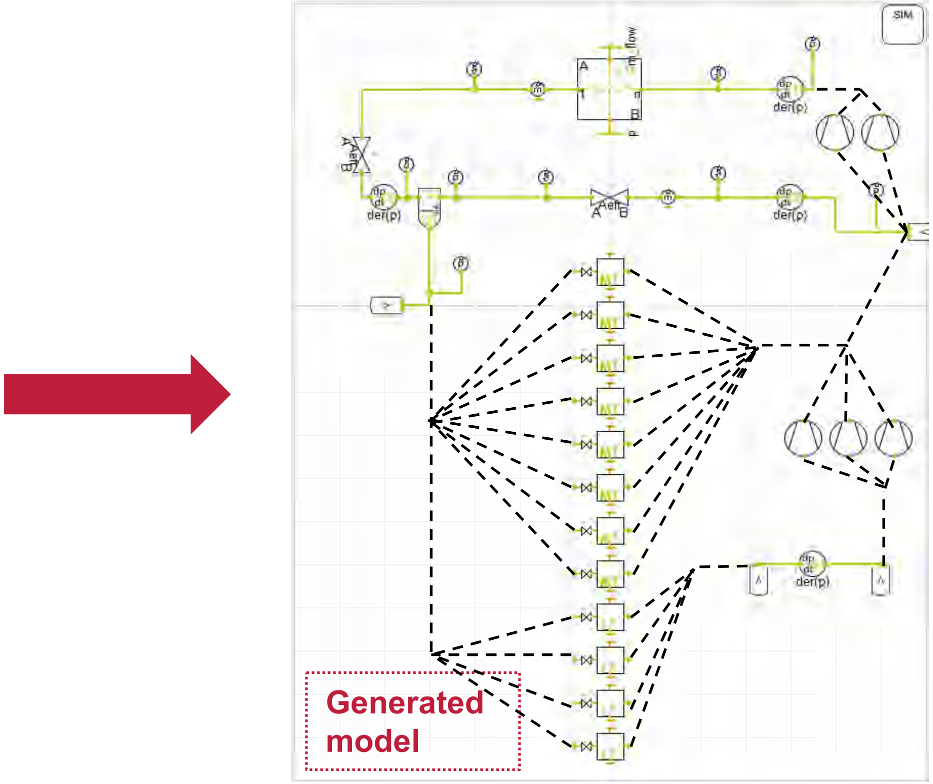
Example





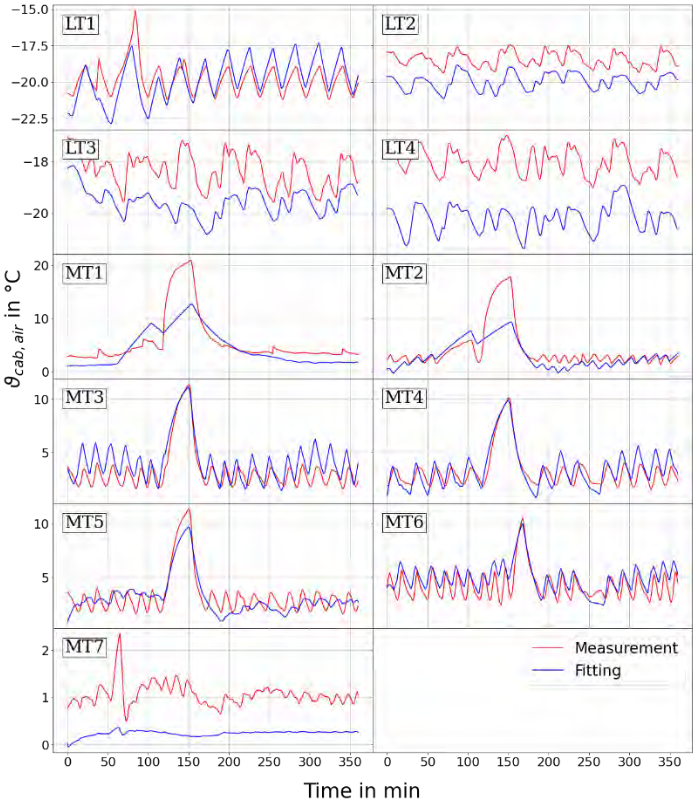
Example





Identification of parameters

- 7 MT evaporators and 4 LT evaporators
- Dynamic cabinet models fitted to monitoring data
- Physics-based compressor models
- Semi-Automated process for the cabinets (Python-Script)

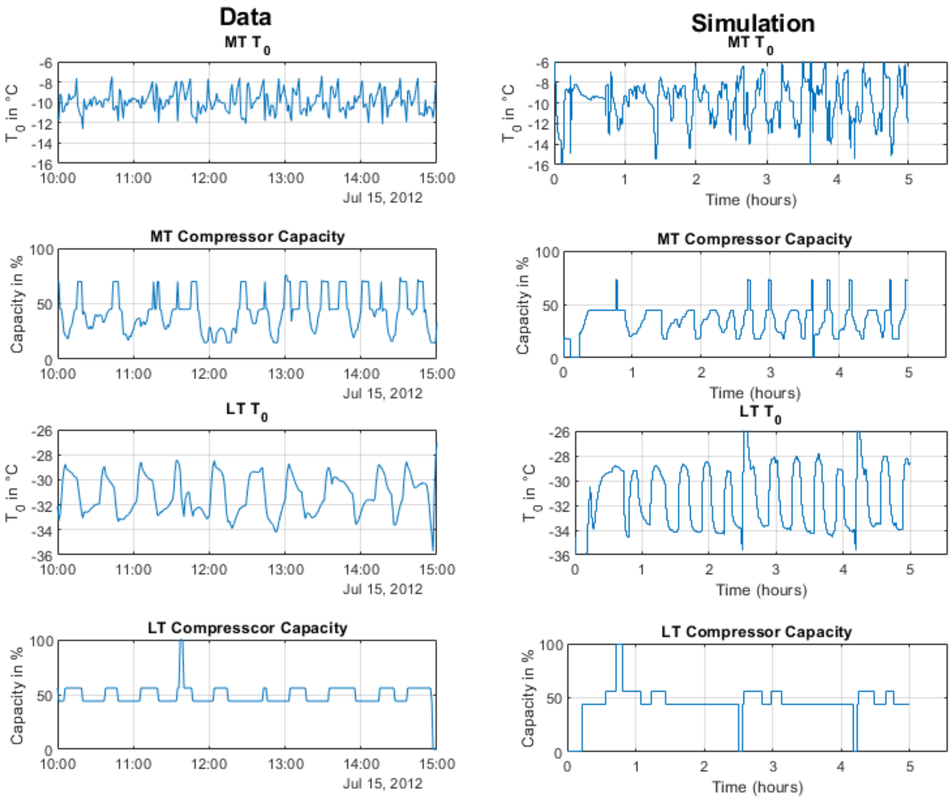


Results and Outlook

Technische
Universität
Braunschweig

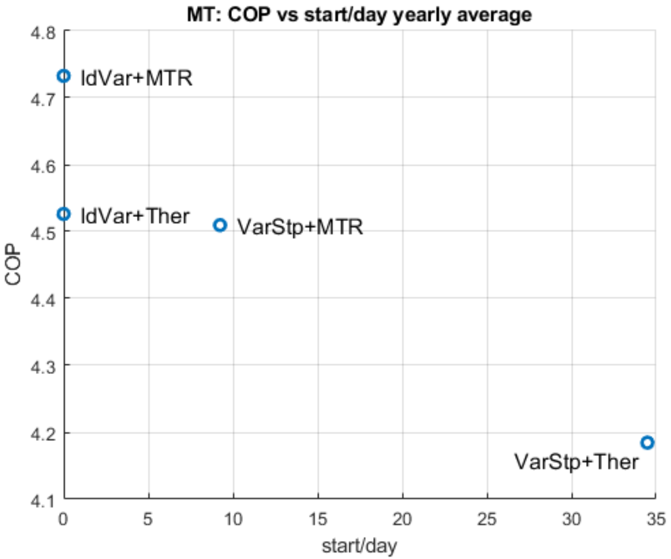
institut für
thermodynamik
ift

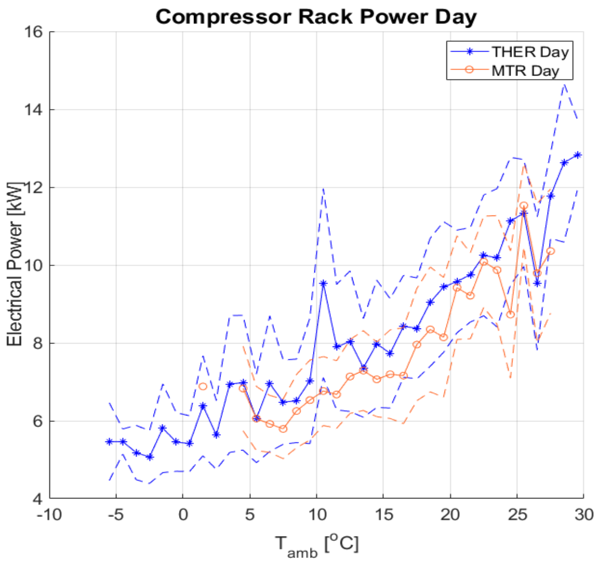
Daytime



Data
MT T0
T0 in °C
-6
-8
-10
-12
-14
-16
10:00
11:00
12:00
13:00
14:00
15:00
Jul 15, 2012
MT Compressor Capacity
Capacity in %
100
50
0
LT T0
-26
-28
-30
-32
-34
-36
LT Compresscor Capacity
Simulation
Time (hours)
0
1
2
3
4
5
LT Compressor Capacity

Results





Schulte, A., Försterling, S., Larsen, L., Heerup, C., Bacher, P., Gøtsch, R., Tegethoff, W., Zühlsdorf, B., Koehler, J.: The influence of evaporation pressure dynamics on energy consumption. The 26th International Congress of Refrigeration, Paris, 21.-25. August 2023

Schulte, A.; Larsen, L.; Försterling, S.; Heerup, C.; Tegethoff, W.; Zühlsdorf, B.; Koehler, J.: Energy efficient control strategies in supermarket refrigeration systems. 8th International Conference on Sustainability and the Cold Chain, Tokyo, 10.-11. Juni 2024.

Summary

- We were able to build a digital twin of a supermarket refrigeration system that includes the controllers and interactions within the system
- The digital twin shows similar dynamics than the real system
- A more stable operation leads to energy benefits
- Fluctuations of the evaporation pressure are mainly driven by dynamic interactions within the refrigeration system

Outlook

- More automatic generation of simulation models for supermarkets seems possible
- The usage of AI might improve automatic generation of digital twins
- A wider adoption of simulation models will improve utilization of the results
- Transfer of the knowledge to other system with multiple evaporators

  Initial work on a large air source heat pump has started as a master thesis

The End.

Farben der TU Braunschweig

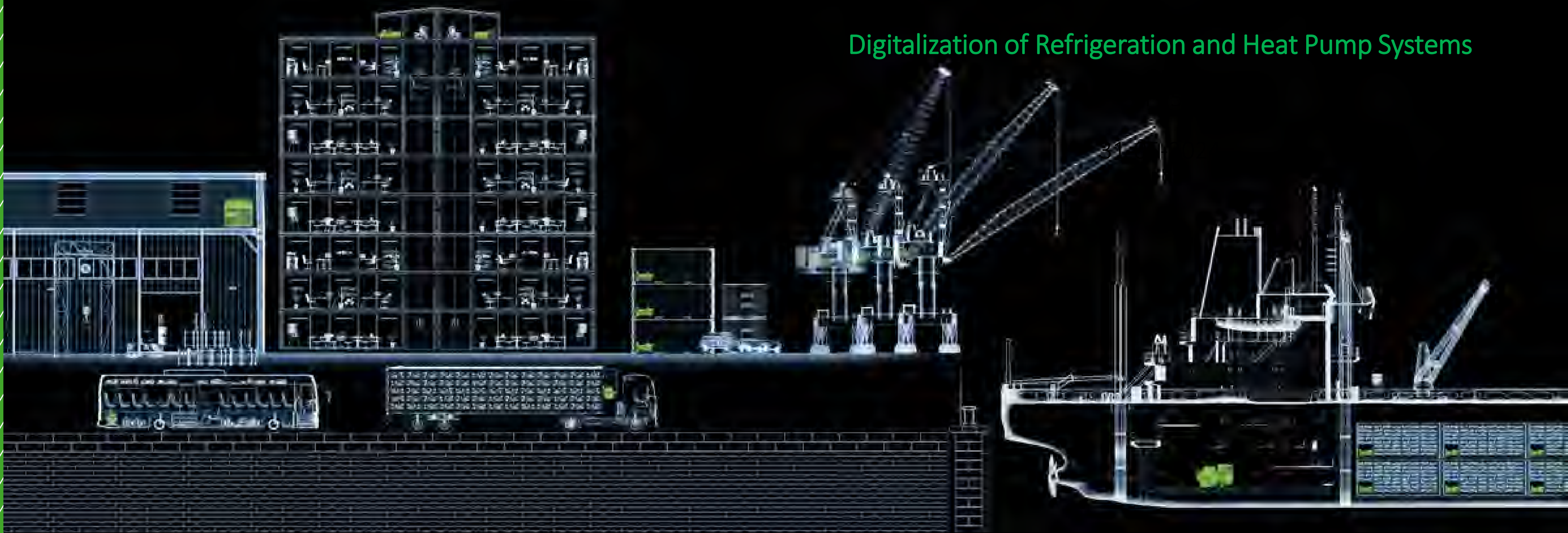
R 190 G 30 B 60					R 8 G 8 B 8	R 95 G 95 B 95	R 150 G 150 B 150	R 192 G 192 B 192	R 221 G 221 B 221
R 255 G 205 B 0	R 255 G 220 B 77	R 255 G 230 B 127	R 255 G 240 B 178	R 255 G 245 B 204	R 198 G 238 B 0	R 215 G 243 B 77	R 226 G 246 B 127	R 238 G 250 B 178	R 244 G 252 B 204
R 250 G 110 B 0	R 252 G 154 B 77	R 252 G 182 B 127	R 253 G 211 B 178	R 254 G 226 B 204	R 137 G 164 B 0	R 173 G 191 B 77	R 196 G 209 B 127	R 219 G 228 B 178	R 231 G 237 B 204
R 176 G 0 B 70	R 192 G 51 B 107	R 215 G 127 B 162	R 235 G 191 B 209	R 243 G 217 B 227	R 0 G 113 B 86	R 77 G 156 B 137	R 140 G 191 B 179	R 191 G 219 B 213	R 218 G 234 B 231
R 124 G 205 B 230	R 164 G 220 B 238	R 189 G 230 B 242	R 215 G 240 B 247	R 229 G 245 B 250	R 204 G 0 B 153	R 222 G 89 B 189	R 235 G 153 B 214	R 245 G 204 B 235	R 250 G 229 B 245
R 0 G 128 B 180	R 77 G 166 B 203	R 140 G 198 B 221	R 191 G 223 B 236	R 217 G 236 B 244	R 118 G 0 B 118	R 152 G 64 B 152	R 186 G 127 B 186	R 214 G 178 B 214	R 235 G 217 B 235
R 0 G 83 B 116	R 64 G 126 B 151	R 140 G 177 B 192	R 191 G 212 B 220	R 217 G 229 B 234	R 118 G 0 B 84	R 156 G 77 B 136	R 193 G 140 B 178	R 221 G 191 B 212	R 235 G 217 B 230

DANISH TECHNOLOGICAL INSTITUTE

AUTOMATIC FAULT DETECTION AND DIAGNOSIS IN REFRIGERATION SYSTEMS - A DATA-DRIVEN APPROACH

Zahra Soltani

BITZER Electronics A/S

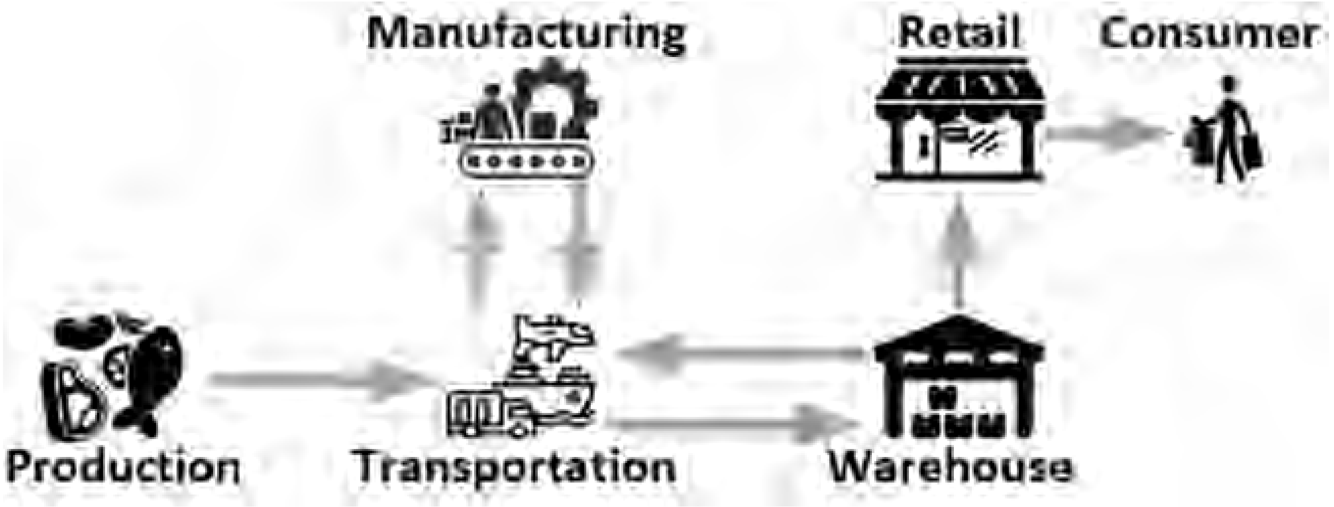


Automatic Fault Detection and Diagnosis in Refrigeration Systems
-A Data-driven Approach-

- BITZER Electronics A/S ,collaboration with Aalborg university
- **July, 04 - 2024**

DAS HERZ DER FRISCHE

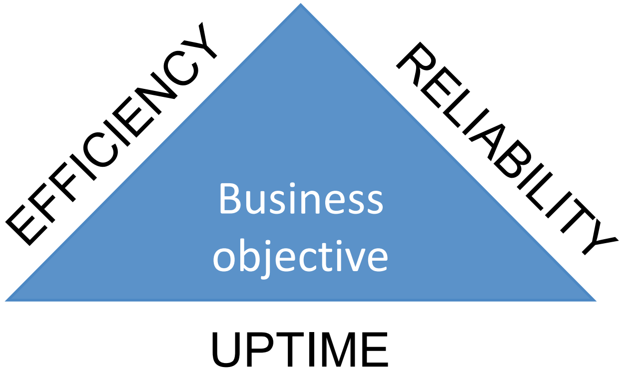
Refrigeration systems in cold chain



Refrigeration systems affect on:

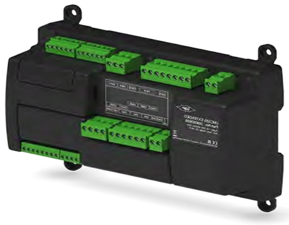
- Medicine and food
- Human health
- Economy
- Global warming

Bitzer, Green manufacturer



Important factors:

- Accuracy
- False positive rate
- Computation time
- Required amount of data and sample time
- Required variables (features)
- Ability to lower cost of human resources
- Robustness of the tool for distributed systems



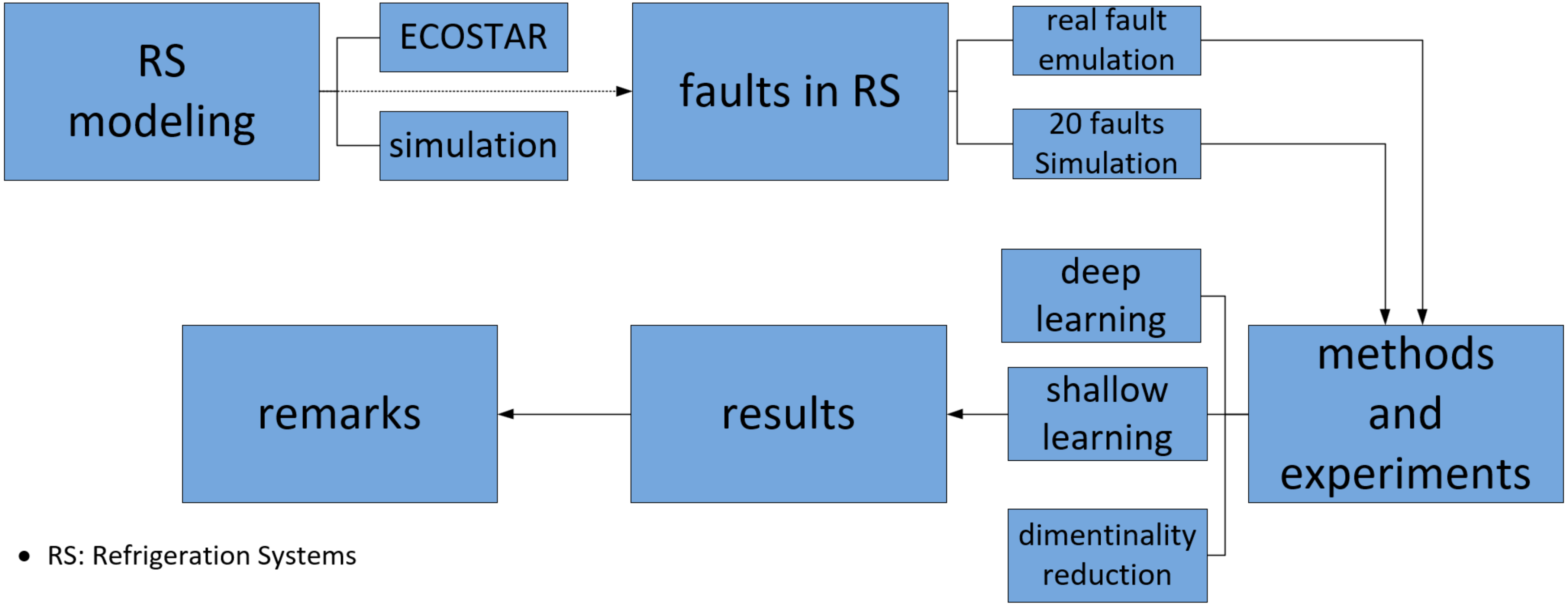
HVAC & R controllers

user panels
and
smart phone app

IQ
modules

and more products

Discussion points:



- RS: Refrigeration Systems

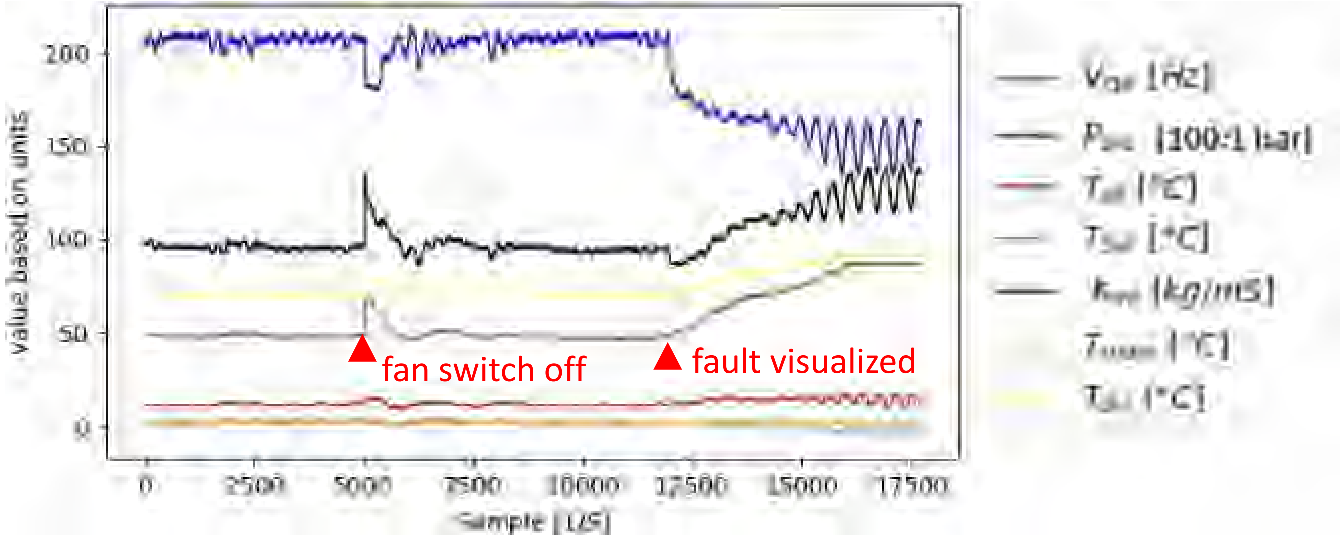
ECOSTAR Unit

Ecostar is a condensing unit for supermarket refrigeration systems

Evaporator fan fault

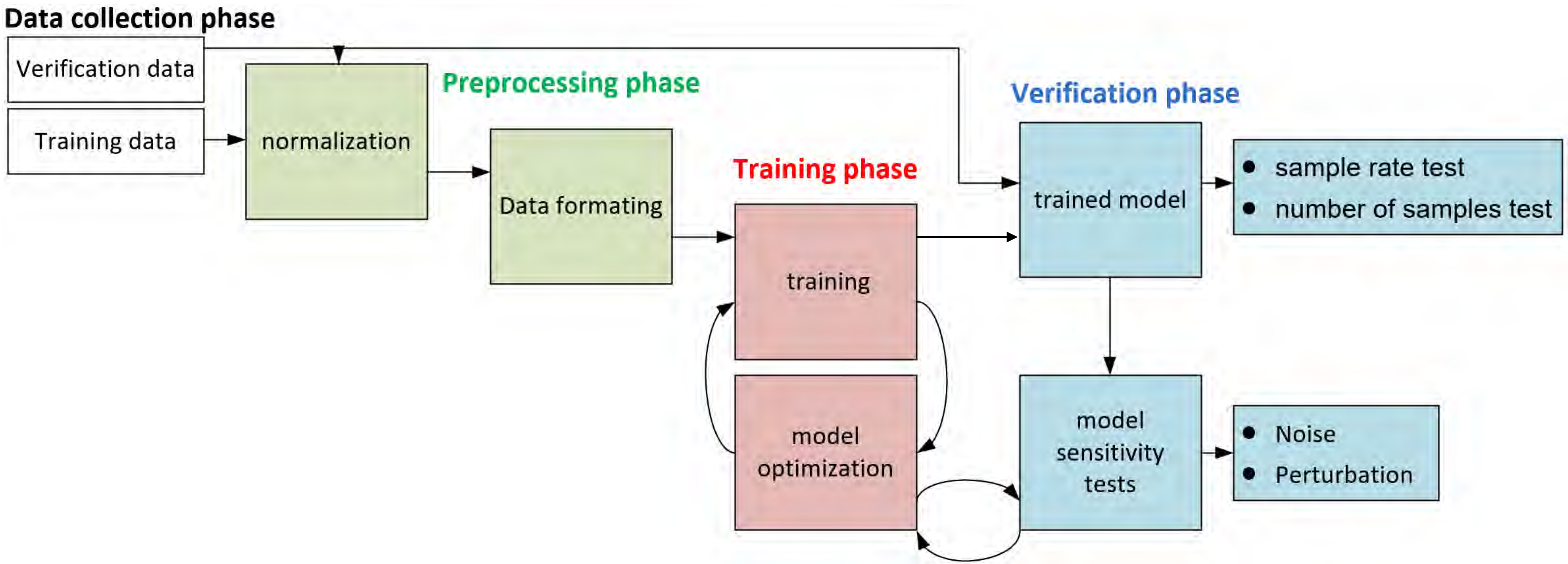
Switch off for one of the evaporator fans

Ice accumulation on evaporator when one of the fan was off
defrost mode : off



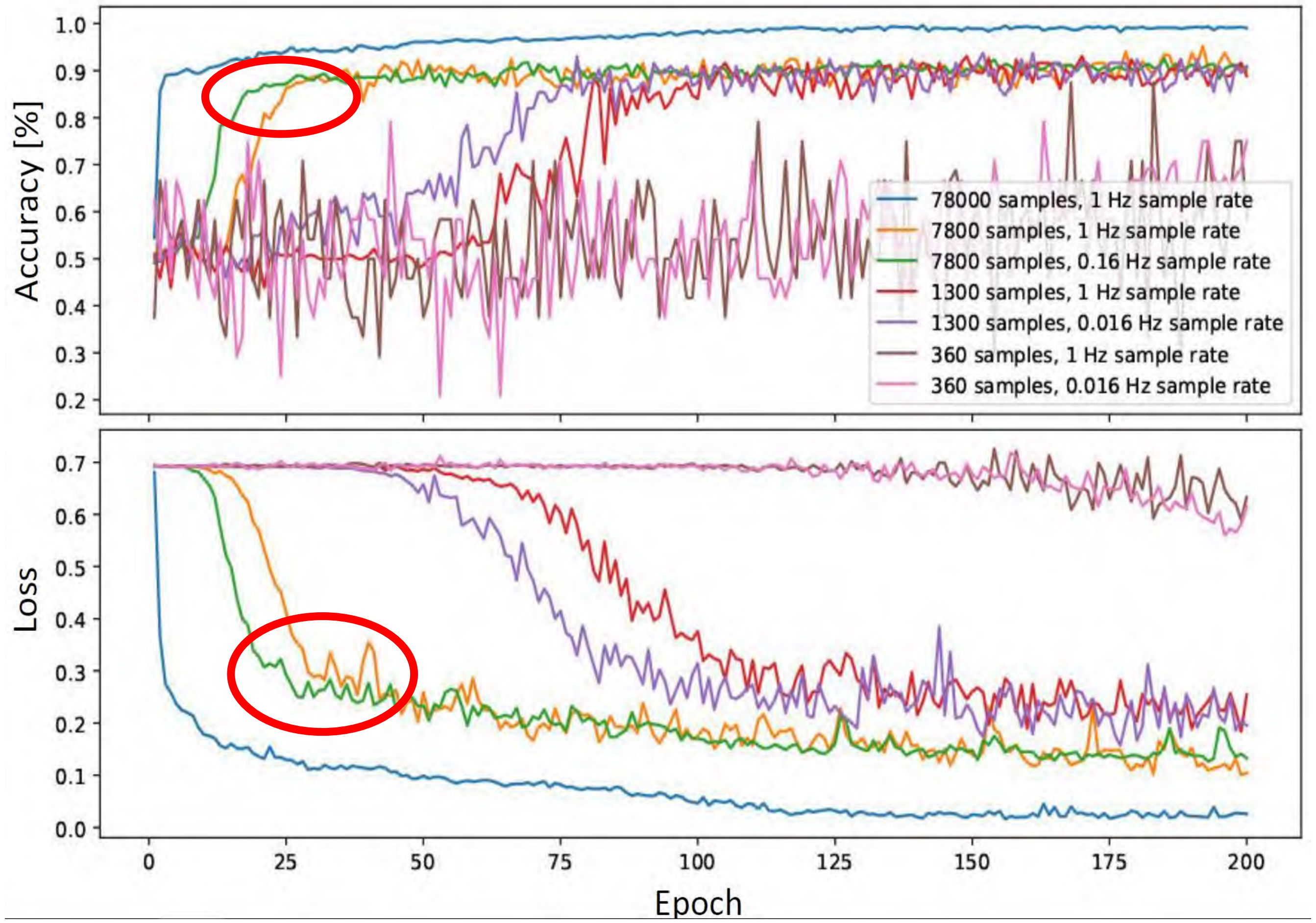
An example of datalog for fan fault detection. The fault happened in sample 5000 and it is obviously affected the data later.

CNN for Fan fault detection
Overview:



Lower resolution, faster convergence

- ✓ faster convergence
- ✓ same accuracy until 0.016 Hz



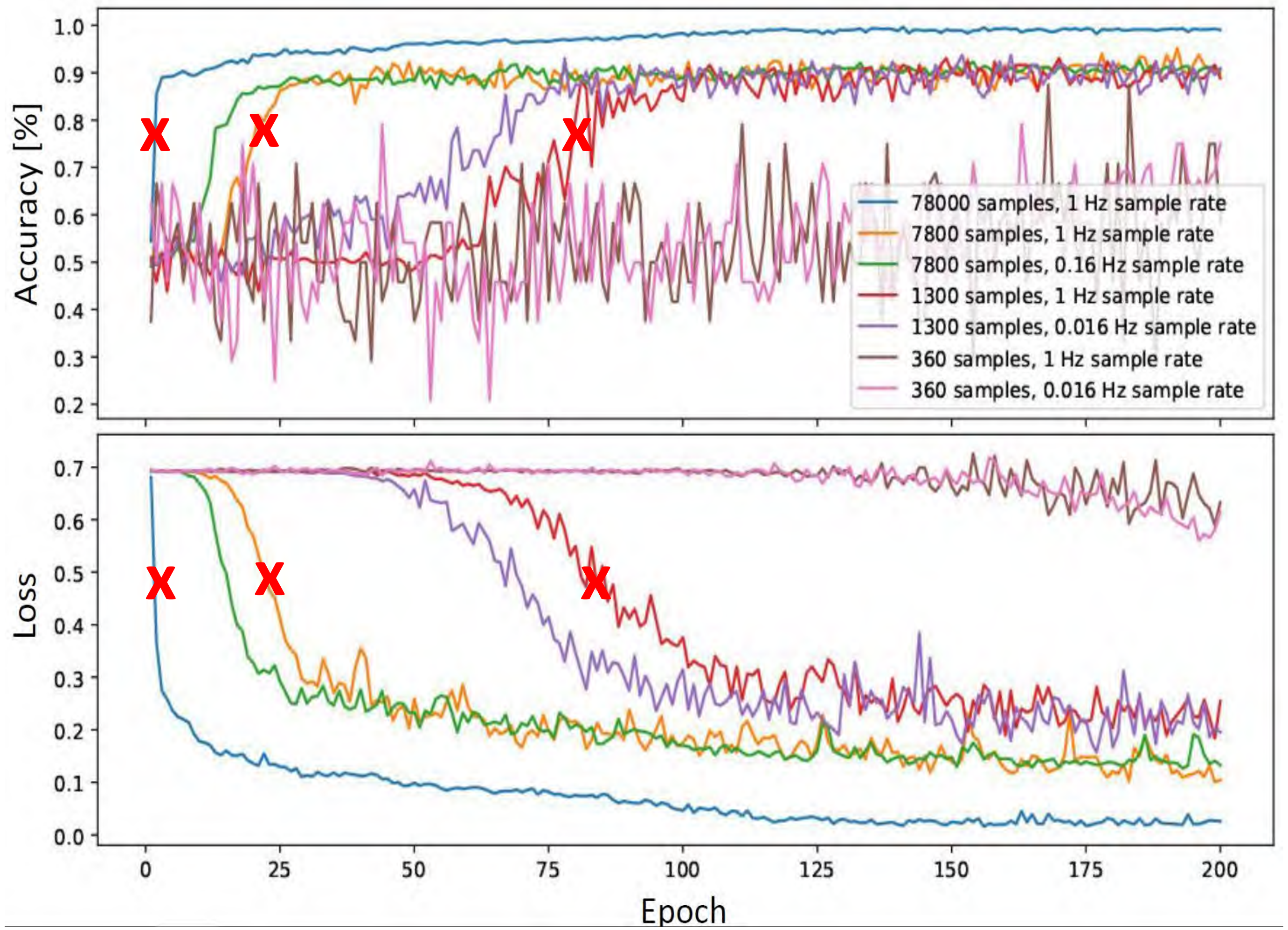
Evaluation of CNN training using data with different resolutions

Less number of samples, slower convergence

Less number of samples:

✓ lower accuracy

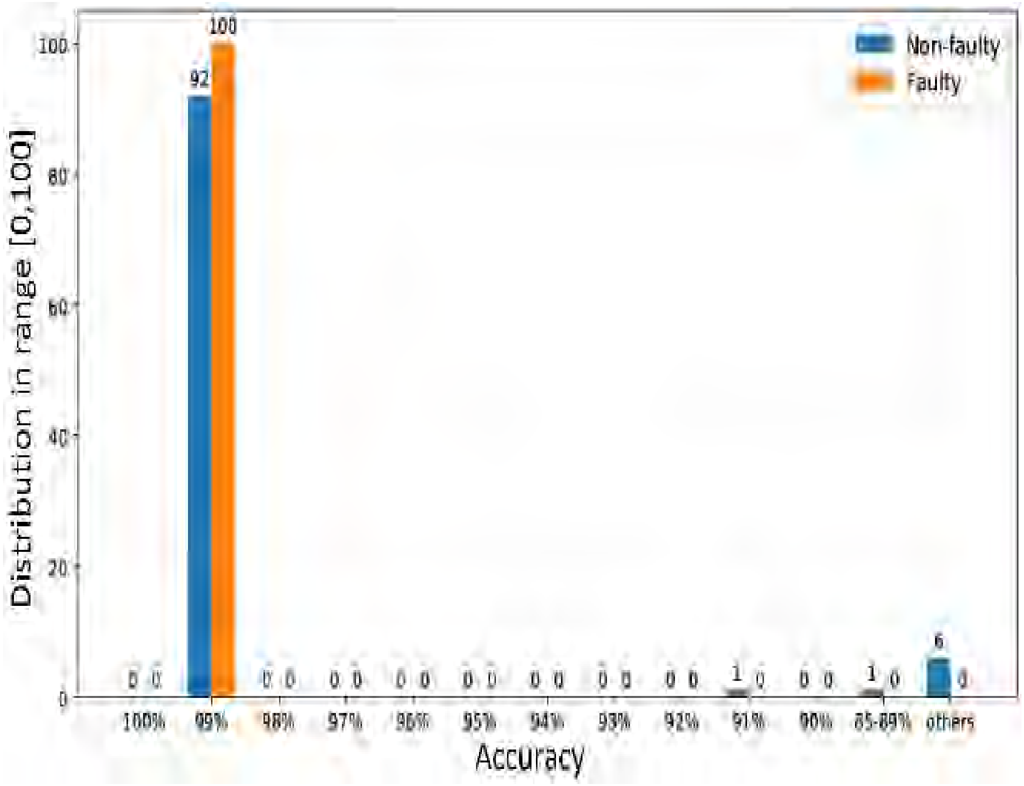
✓ Slower convergence



1. Evaluation of CNN training using data with different resolutions

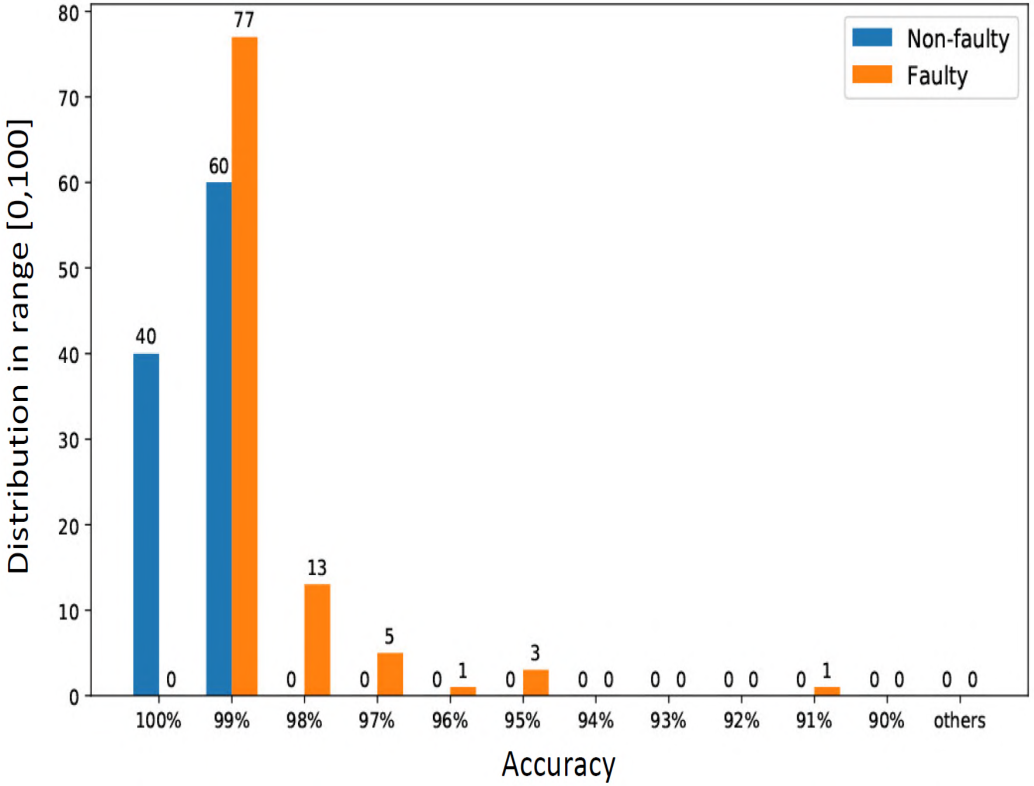
Effect of perturbation & noise – CNN

- ***Perturbation test:***
- 1% false positive rate, reliable for 92% of the time
- 99% classification accuracy for detecting faulty condition

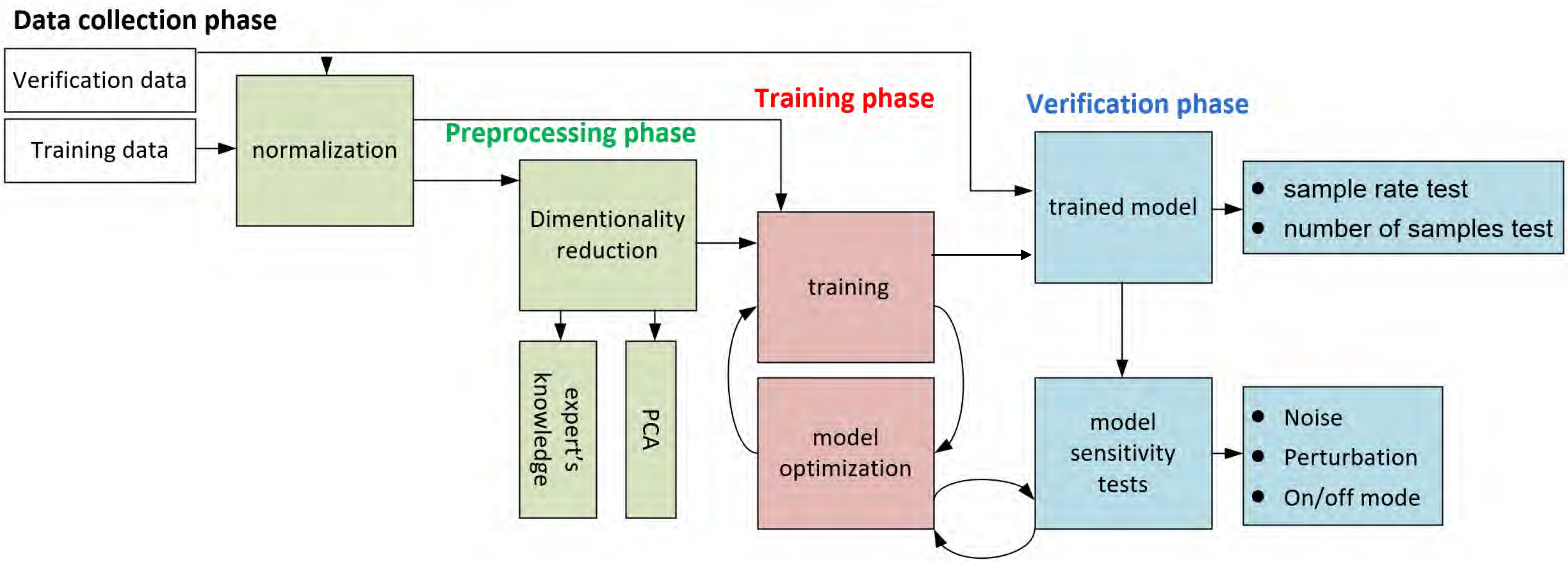


Noise test:

- < 1% false positive for all runs
- >95% fault classification accuracy for 99 runs out of 100



SVM for binary clssification: Overveiw



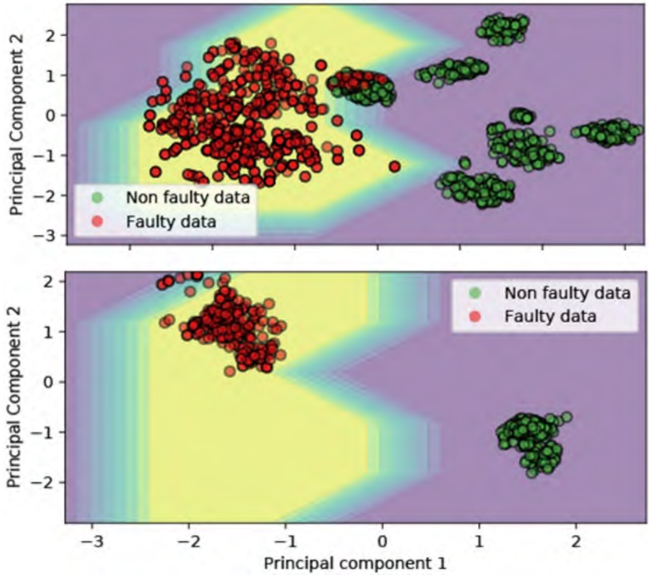
SVM sensitivity against data resolution and size

- Importance of data length selection for SVM training
- Result of the SVM training is independent to the sample rate, if data represents thermodynamical behavior of the systems

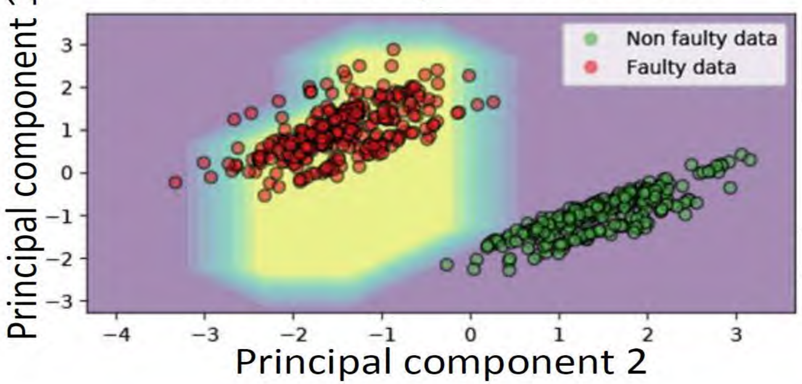
length	sample rate $[Hz]$	training time (s)	accuracy [%]
300	1	0.07	94
	0.1	0.08	94
	0.01	0.07	94
900	1	0.09	99
	0.1	0.09	99
	0.01	0.1	99
1800	1	0.57	93
	0.1	0.65	93
	0.01	0.63	93

PCA-SVM sensitivity tests

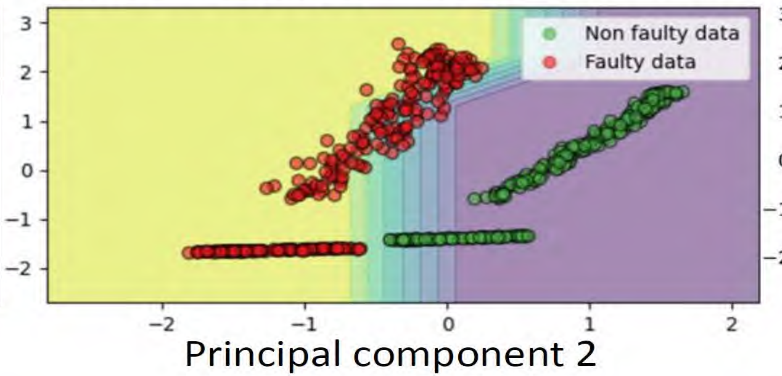
Training and test result for PCA-SVM



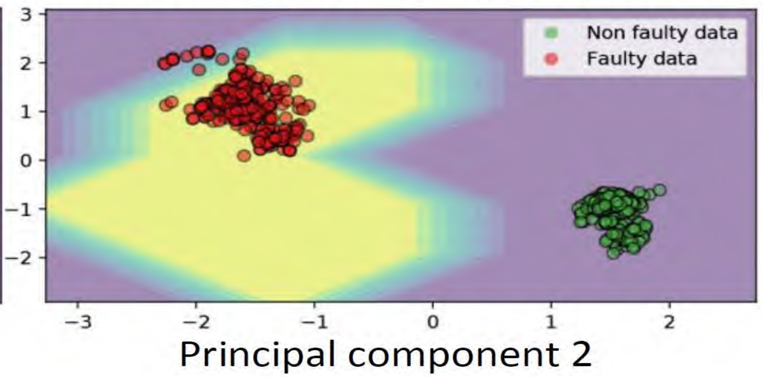
Result for noisy validation data



Result for validation data in On/OFF mode



Result for perturbed validation data



PCA-SVM better than the others

- **4D SVM** and **2D PCA-SVM** obtained very similar results
- PCA-SVM performs better in fault detection in On/Off experiment
- PCA-SVM is more robust and efficient as it automatically select the dimensions

	Algorithm	Non faulty[%]	Faulty[%]
Noisy	14D SVM	98.5 -99.6	98 -99.4
	4D SVM	98 -100	98 -99.4
	PCA-SVM	98 -100	98 -99.6
Perturbed	14D SVM	89-100	97-100
	4D SVM	99.2-100	99-100
	PCA-SVM	100	100
On/Off	14D SVM	50-60	53-60.5
	4D SVM	55-60	54-61
	PCA-SVM	85-86	95.5-96.4

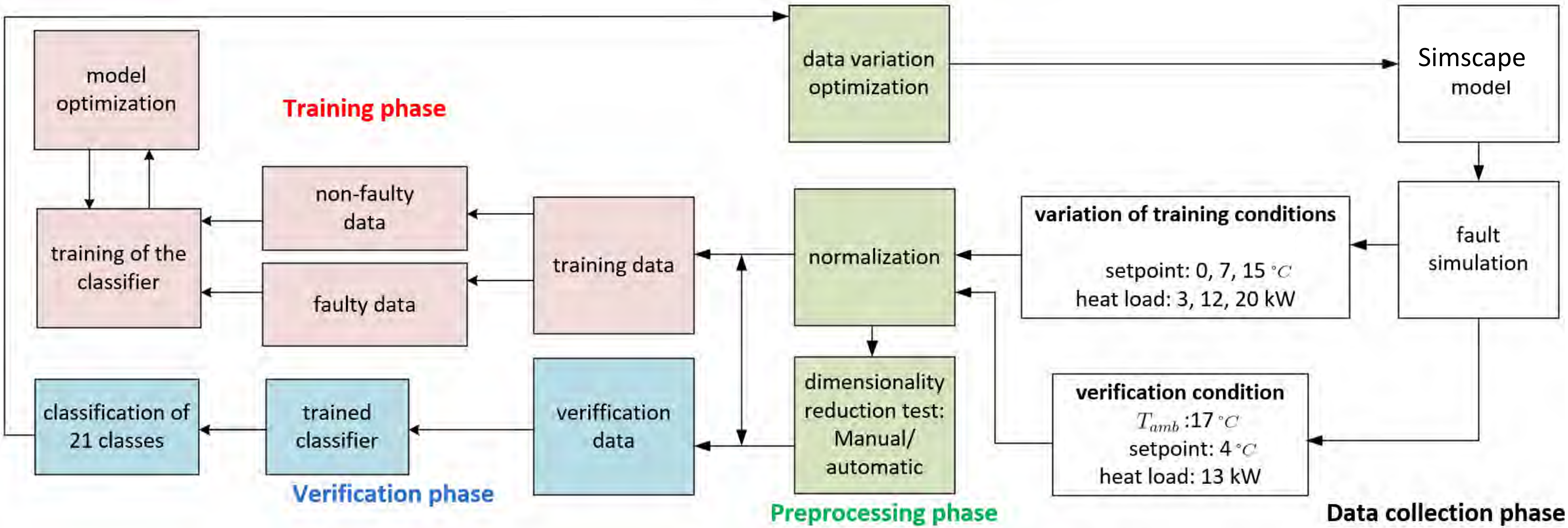
PCA-SVM obtained the best result for the experiments above

Faults description

- Temperature offset 2 0C
- Psuc offset 0.2 bar
- Pdis offset 1 bar

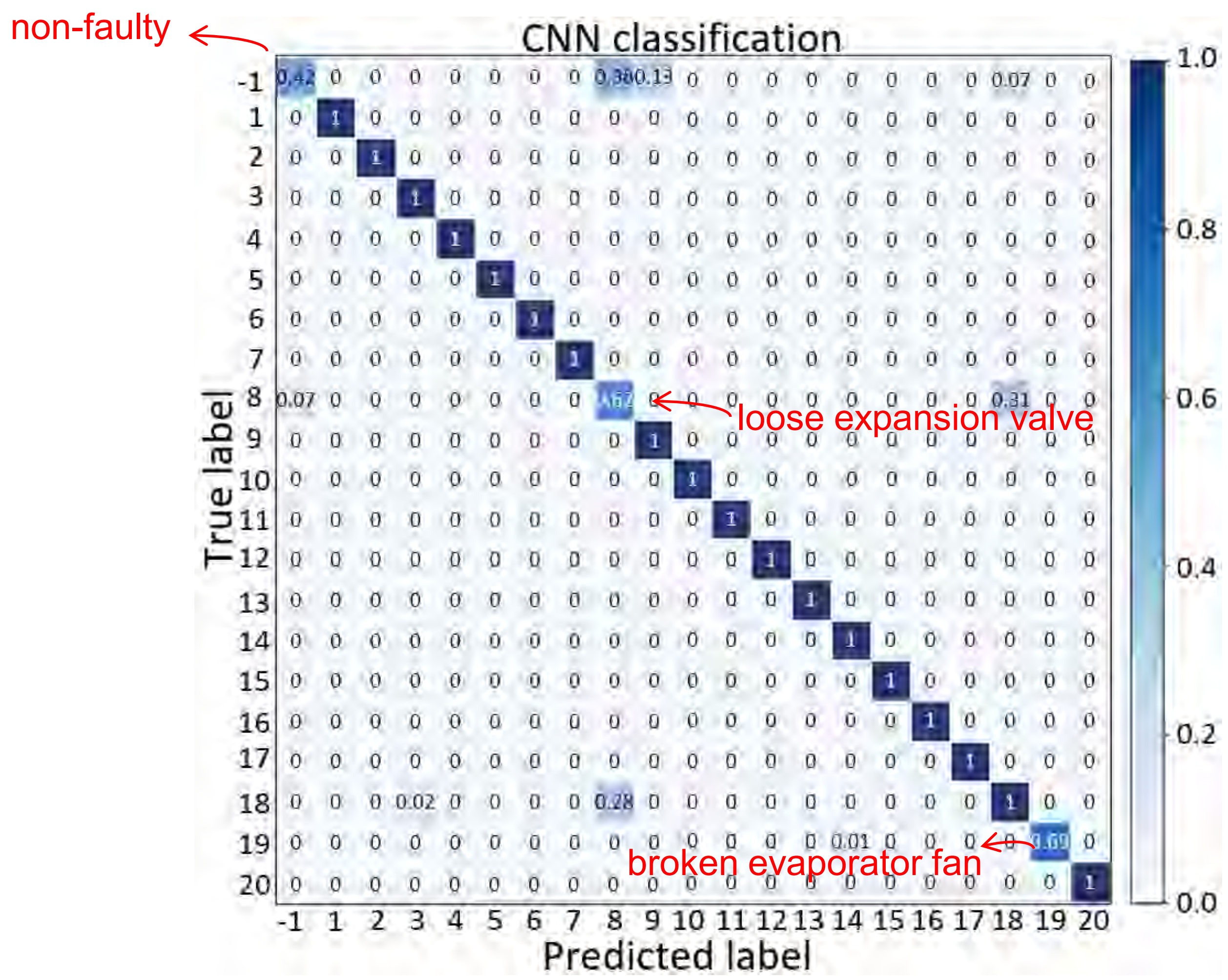
Label	Fault
1	T_{suc} sensors positive offset
2	T_{sup} sensors positive offset
3	T_{ret} sensors positive offset
4	T_{dis} sensors positive offset
5	P_{dis} sensor positive offset
6	P_{suc} sensor positive offset
7	Compressor poor performance
8	Losse expansion valve
9	Evaporator fan poor performance
10	Condenser fan poor performance
11	T_{suc} sensors negative offset
12	T_{sup} sensors negative offset
13	T_{ret} sensors negative offset
14	T_{dis} sensors negative offset
15	P_{dis} sensor negative offset
16	P_{suc} sensor negative offset
17	Broken compressor
18	Blocked expansion valve
19	Broken evaporator fan
20	Blocked condenser fan

Multi-class classification
Overview



CNN for multi-class classification

- Can classify most of the classes
- Total accuracy: 94%
- 58% false positive

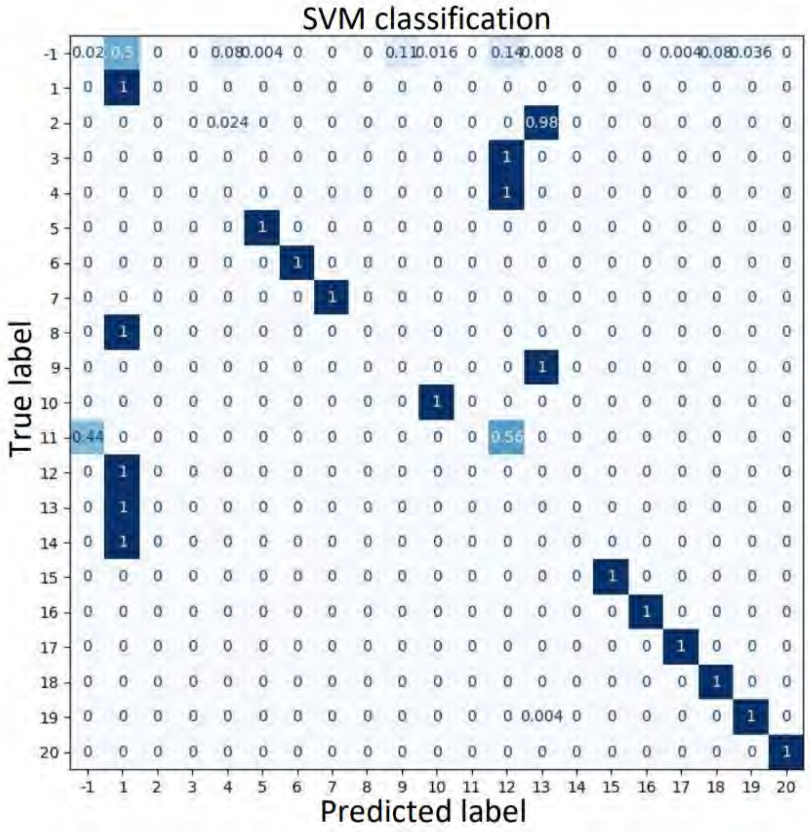


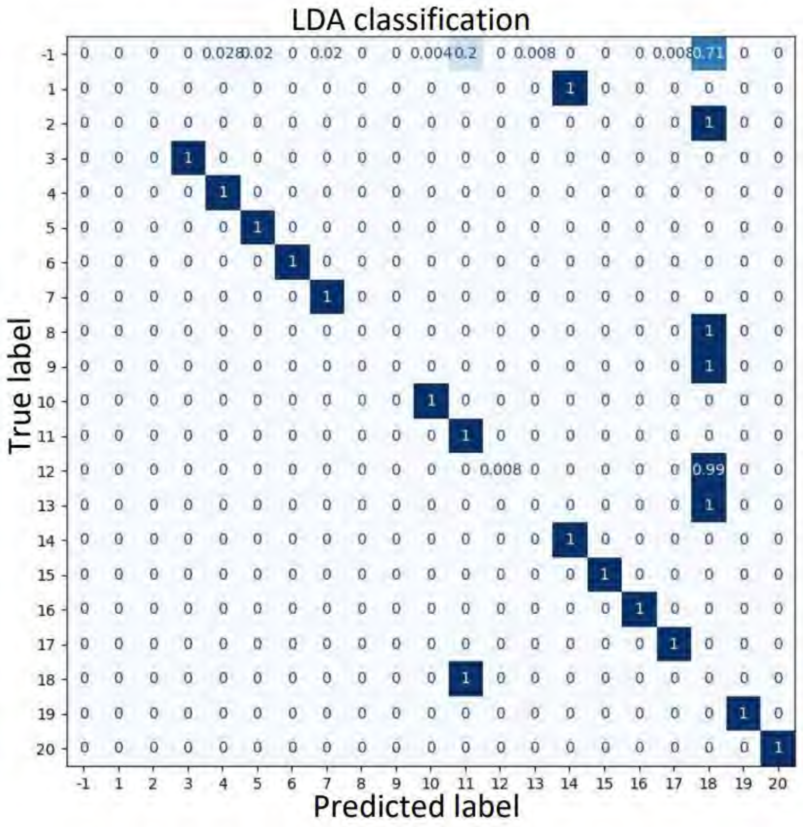
Models comparison: training/test results

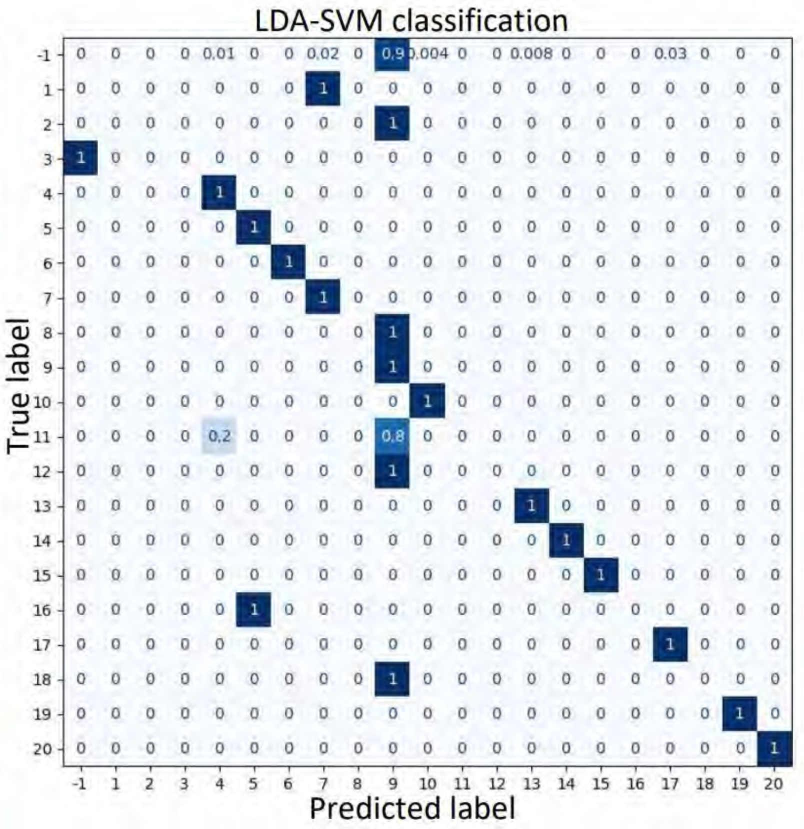
model	accuracy	false positive	training time	prediction time
SVM	99.6%	0%	1.1 s	1 s
LDA	99.8%	0%	3.2 s	0.3 s
CNN	94%	68%	112.5 s	0.1 s
PCA-SVM	55.4%	24%	7.2 s	5.6 s
LDA-SVM	96.6%	18%	1 s	1.1 s

- LDA, SVM, LDA-SVM obtained the most accuracy, respectivly
- False positive in LDA and SVM are perfect (training/test phase)
- Prediction time of LDA is comperatively lower than the others
- Training time is too slow in CNN and false positive is too high
- Total accuracy for PCA-SVM is too low

No satisfatory results





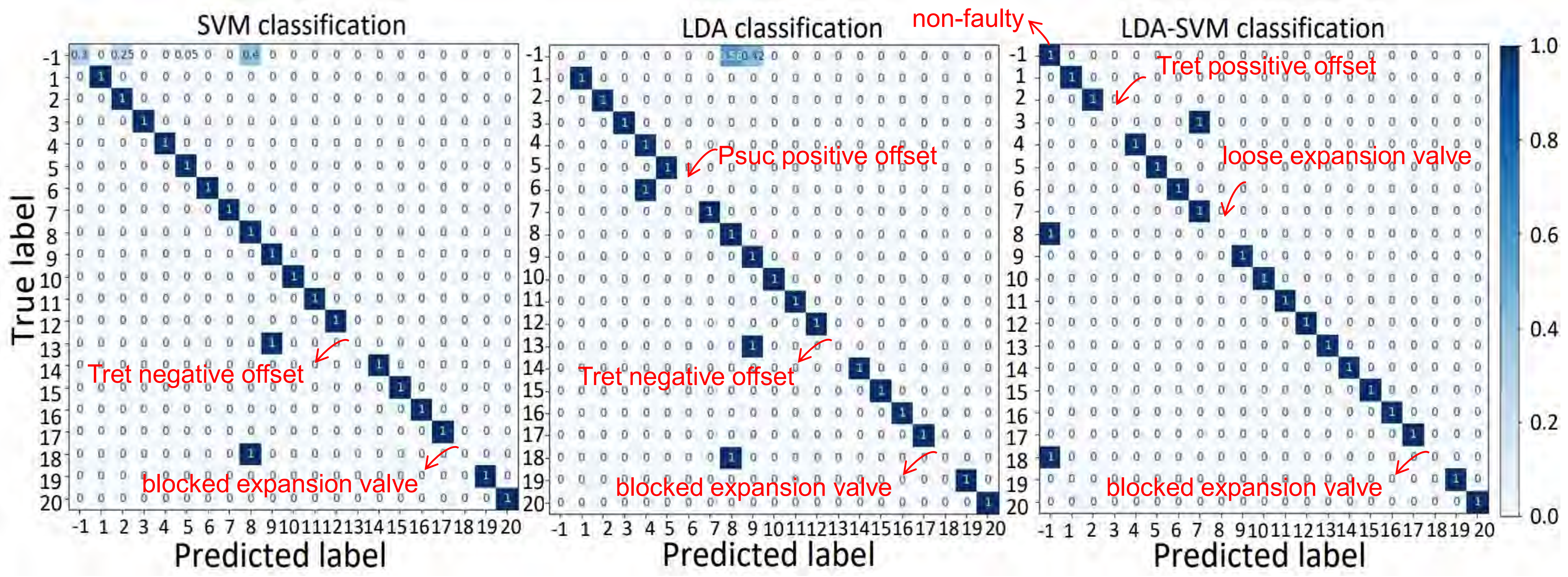


Verification data in different operation conditions than training

- Non-faulty data is **not** identified
- Faulty data are **not** classified satisfactorily

models with more data variation

Adding variation of ambient temperature and setpoint to the data features



- density, and power consumption of the compressor are removed.

LDA-SVM for fault detection

model	accuracy	false positive	prediction time
SVM	87%	70%	0.4 s
LDA	81%	100%	0.3 s
LDA-SVM	86%	0%	1.5 s

Reseach remarks

- PCA Vs LDA   (binary classification or multi-class classification)?

- Data resolution is not important when using SVM until it preserve dynamic of the systems
- Careful selection of data size when using SVM.

- Best model selection: a trade-off among a high accuracy, low computation, and low false positive

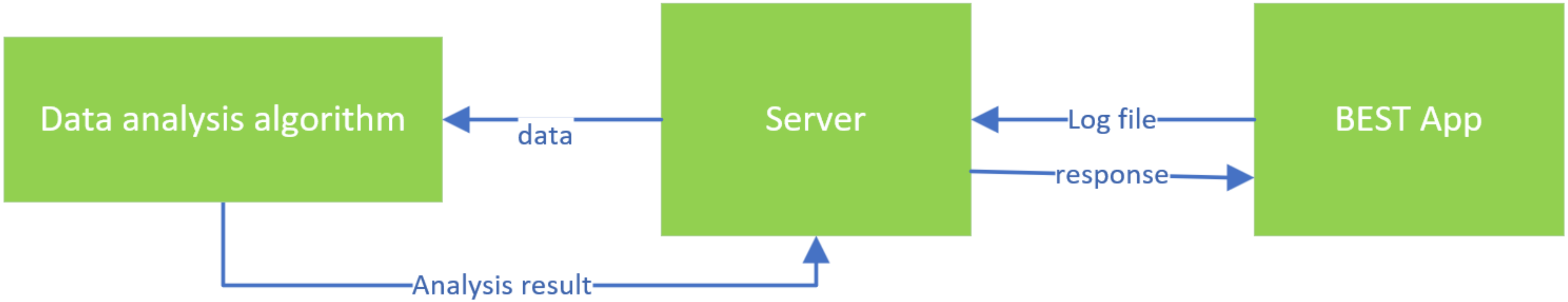
  LDA-SVM, a reliable model for fault detection with a 0% false positive

  SVM, the most accurate model for fault diagnosis

  LDA quick at prediction

- Careful selection of input data

Smart solution for performance monitoring



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FAULT DETECTION IN ULTRA-LOW TEMPERATURE FREEZERS

Francesco D’Ettorre

Danish Technological Institute

Fault detection in ultra-low temperature freezers

Seminar on Digitalisation of Refrigeration and Heat Pump Systems

July 04, 2024

Francesco D'Ettorre, PhD

Consultant, Danish Technological Institute

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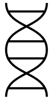
DANISH TECHNOLOGICAL INSTITUTE

Contents

- Background
- Digital Oracle Project
- Anomaly detection
- Case study
- Conclusions

Background

Ultra-low temperature freezers / Ultra-sensitive products

- Biological samples 
- Vaccine 

Temperature-sensitive products

- Maintaining temperatures between -60°C and -86°C is essential for sample integrity.
- Failure to detect faults can lead to sample loss and significant financial and scientific setbacks.

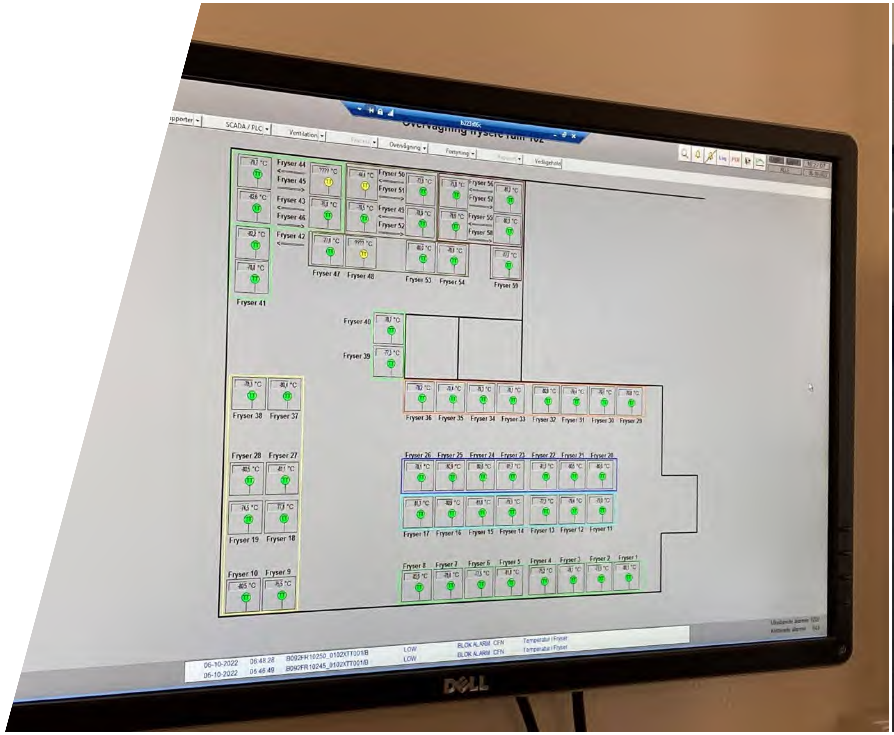
Background

Surveillance systems

- Monitor freezer temperature
- Flag alarms
- Visual inspection of temperature profiles

Untapped potential…

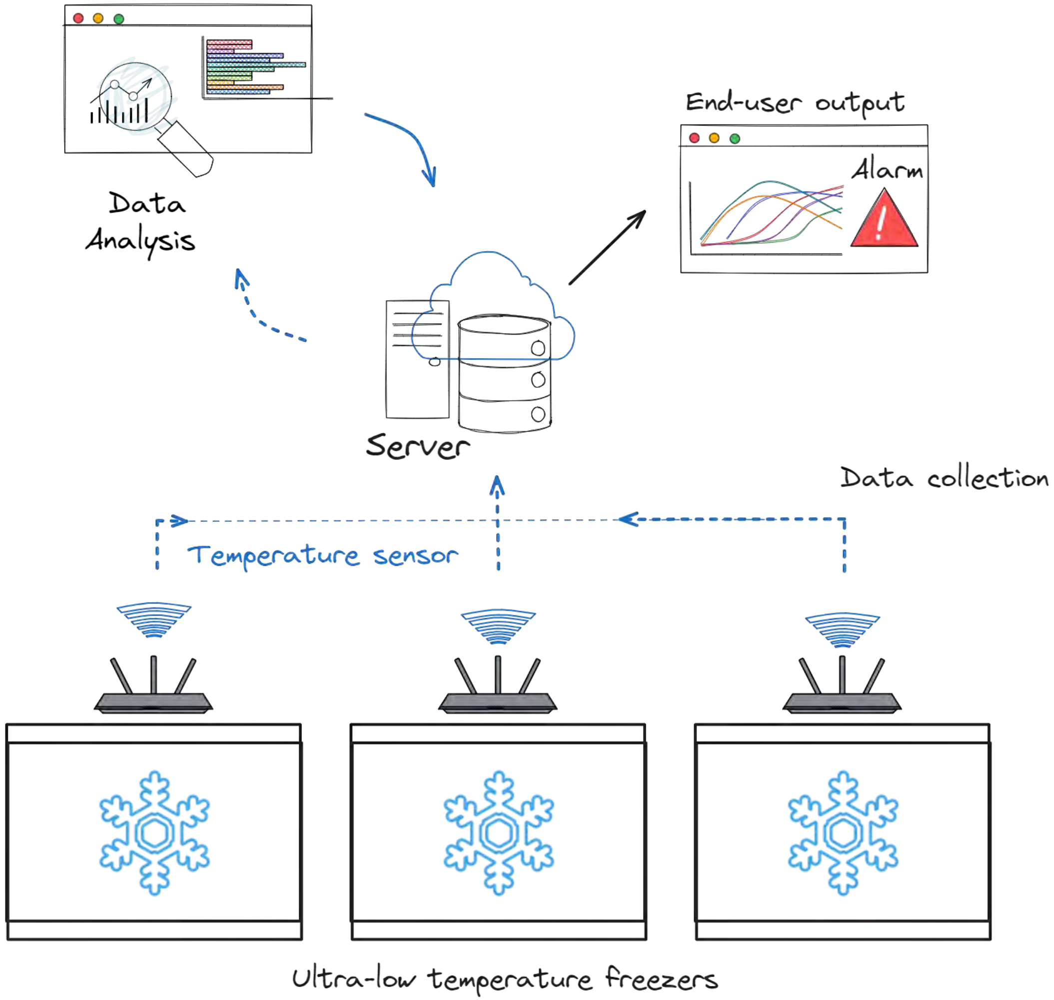
- Most data is not exploited
- Monitoring limited to internal temperatures
- Limited automation



Digital Oracle for ULT freezers- EUDP

Cloud-based surveillance system for ULT freezers (*Digital Oracle*) to transform large amounts of data into simple recommendations to:

- avoid inappropriate use of freezers
- detect the need for maintenance
- save energy



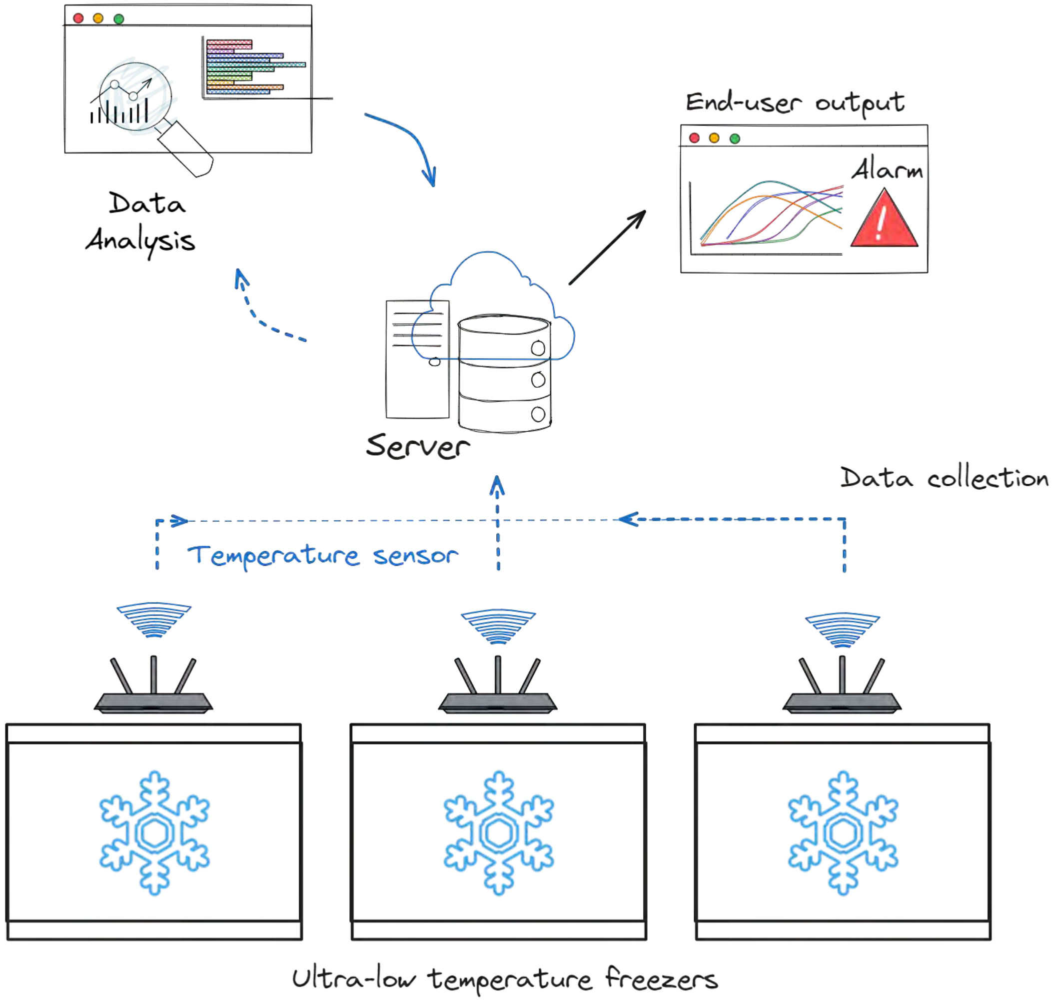
Digital Oracle for ULT freezers- EUDP

Data source
- *Region Sjælland Biobank*
- *Statens Serum Institut*
- *Elcold*

Data collection
Hardware for automatic data collection
- *LH Laboratorie Service*

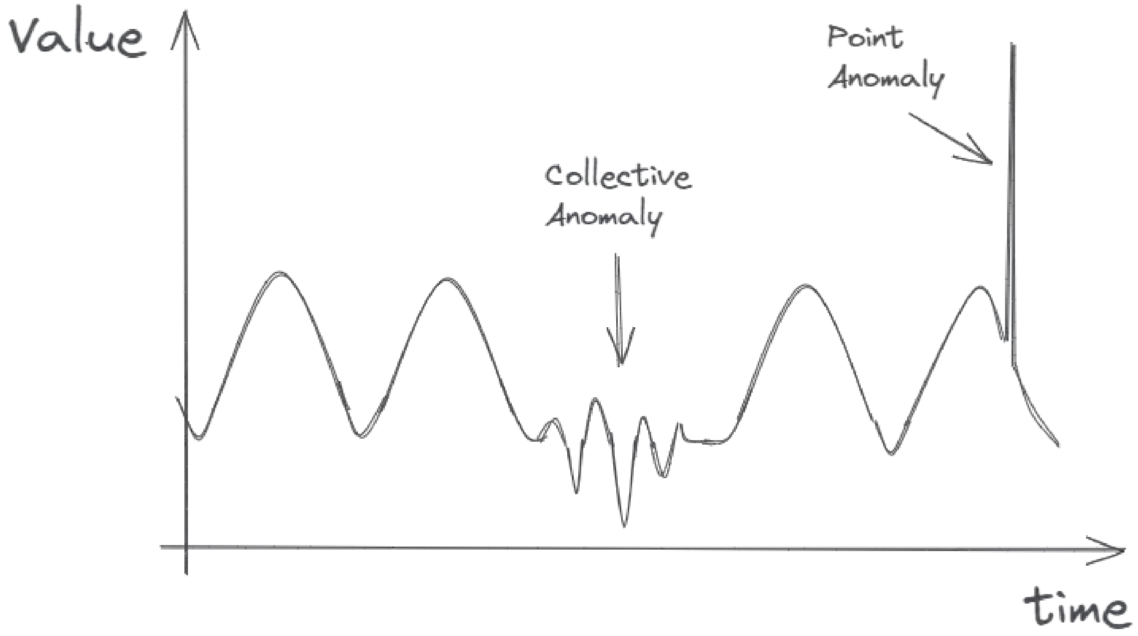
Data storage/sharing
Cloud-based solution for data storage/sharing
- *Schneider Electric*

Data analysis
Data analysis and algorithm development
- *DTU Compute*
- *Danish Technological Institute*



Anomaly detection

Identification of items, events or observations which do not conform to an expected pattern or other items in a dataset.

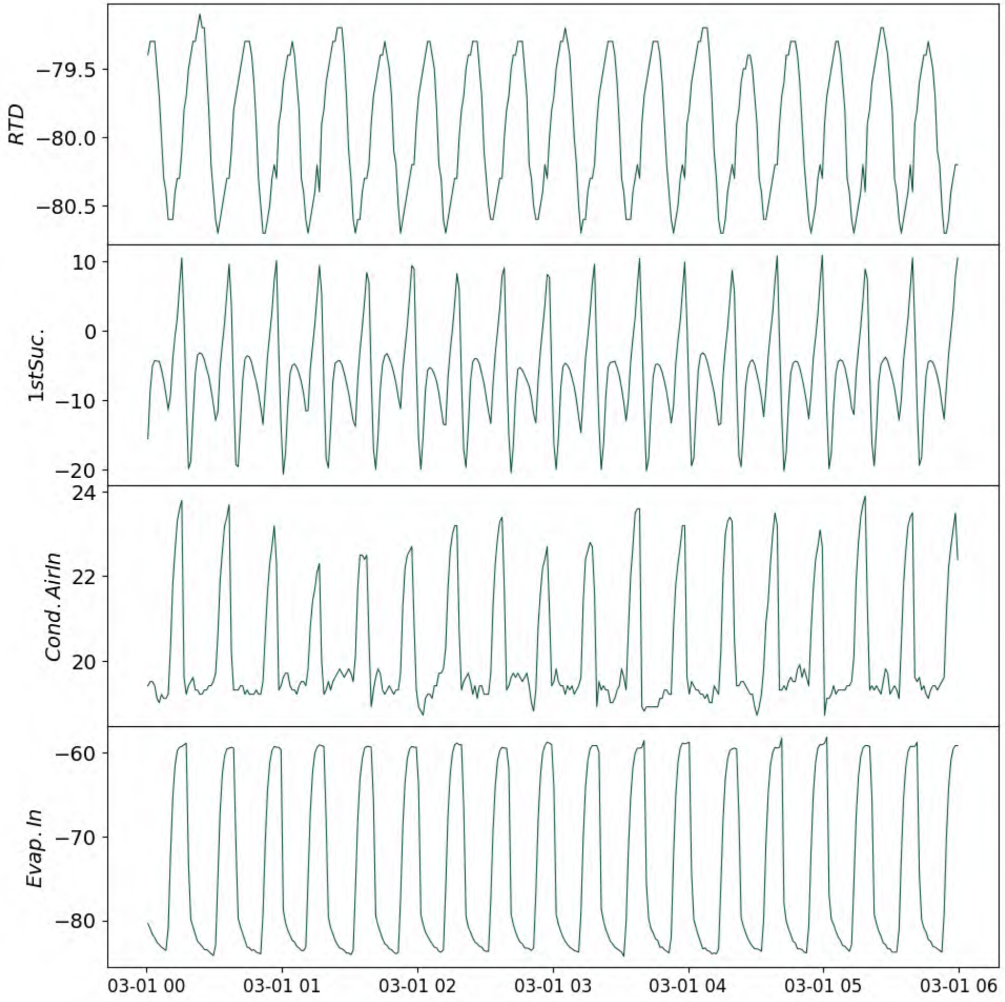


Anomaly detection

Identification of items, events or observations which do not conform to an expected pattern or other items in a dataset.

Repeated cyclic patterns under normal operating conditions.

Normal operation



Anomaly detection

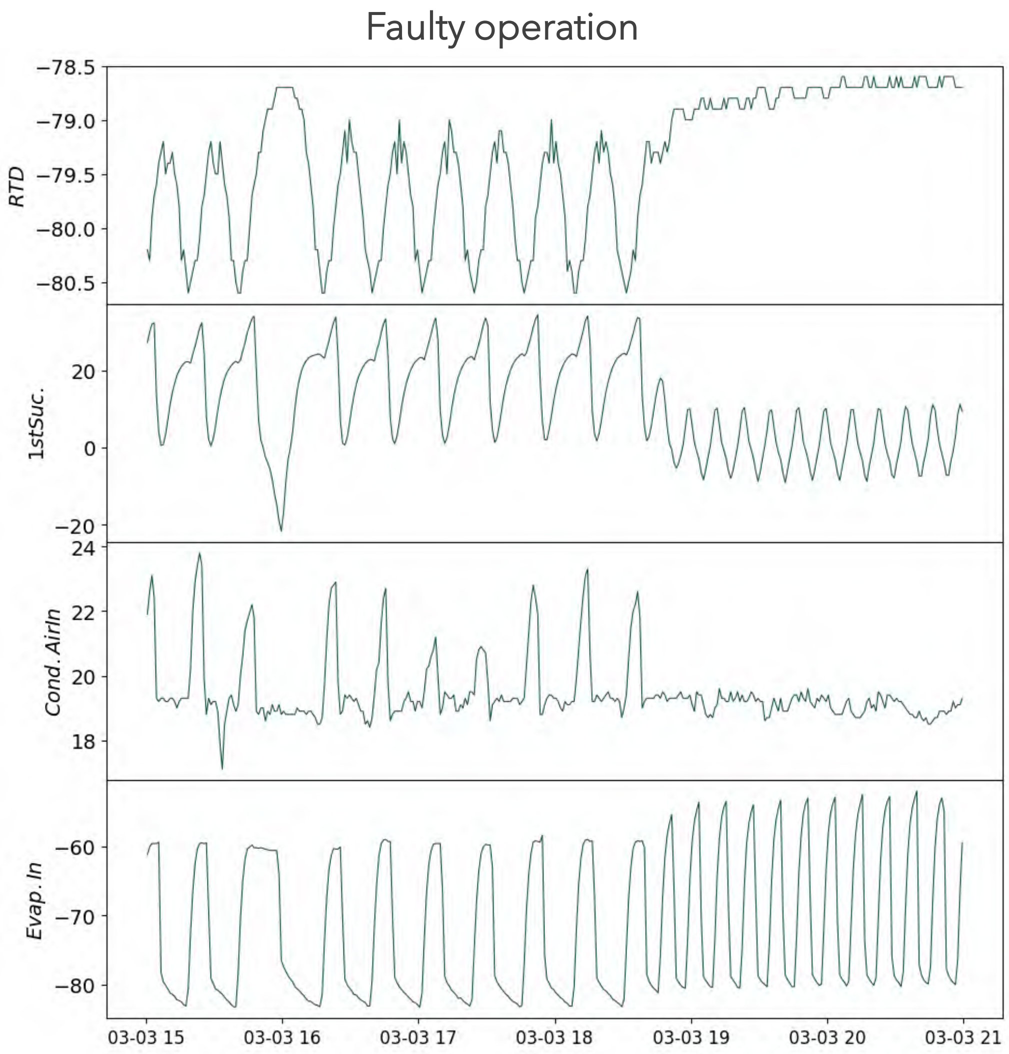
Identification of items, events or observations which do not conform to an expected pattern or other items in a dataset.

Repeated cyclic patterns under normal operating conditions.

Patterns disruption under faulty operating conditions.

Variation in both:

- Trend
- Cyclical component



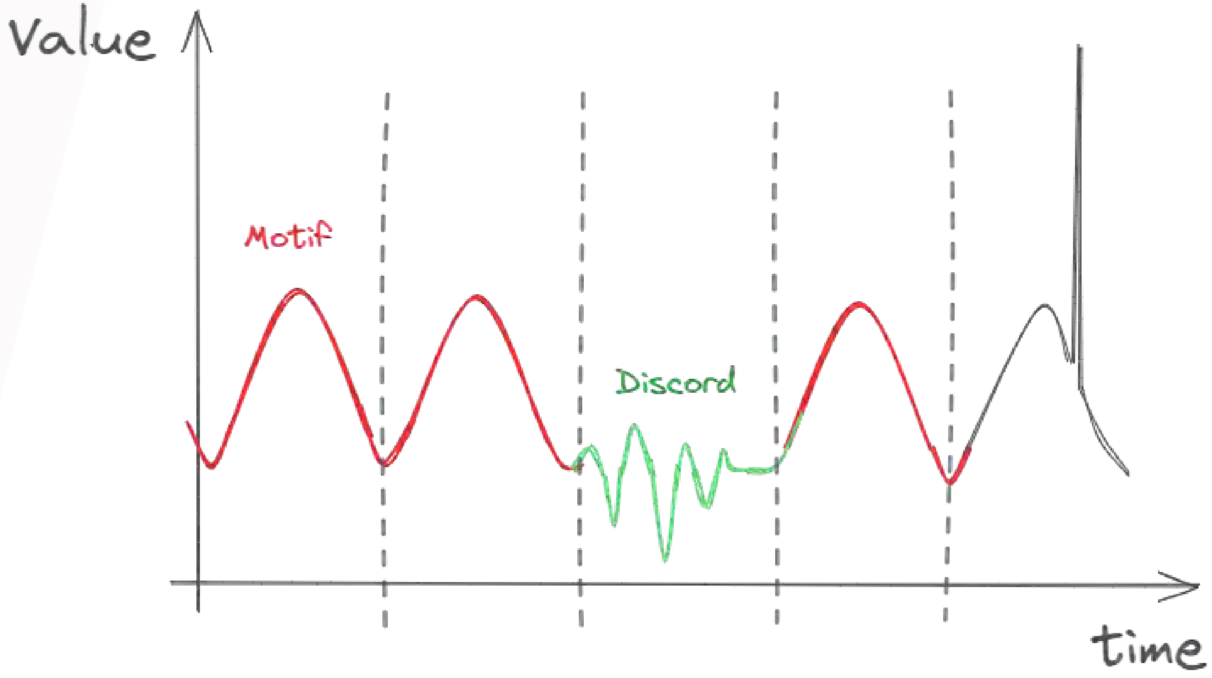
Anomaly detection

Contextual Matrix Profile (CMP)
Pattern recognition algorithm that performs all-similarity-join-search among timeseries.

CMP consists in scanning the entire time series to find:

Motifs: repeated (or very similar) patterns.

Discords: subsequences that differ from other subsequences in the time series (could be interpreted as a detected anomaly).



Anomaly detection

STEP 1

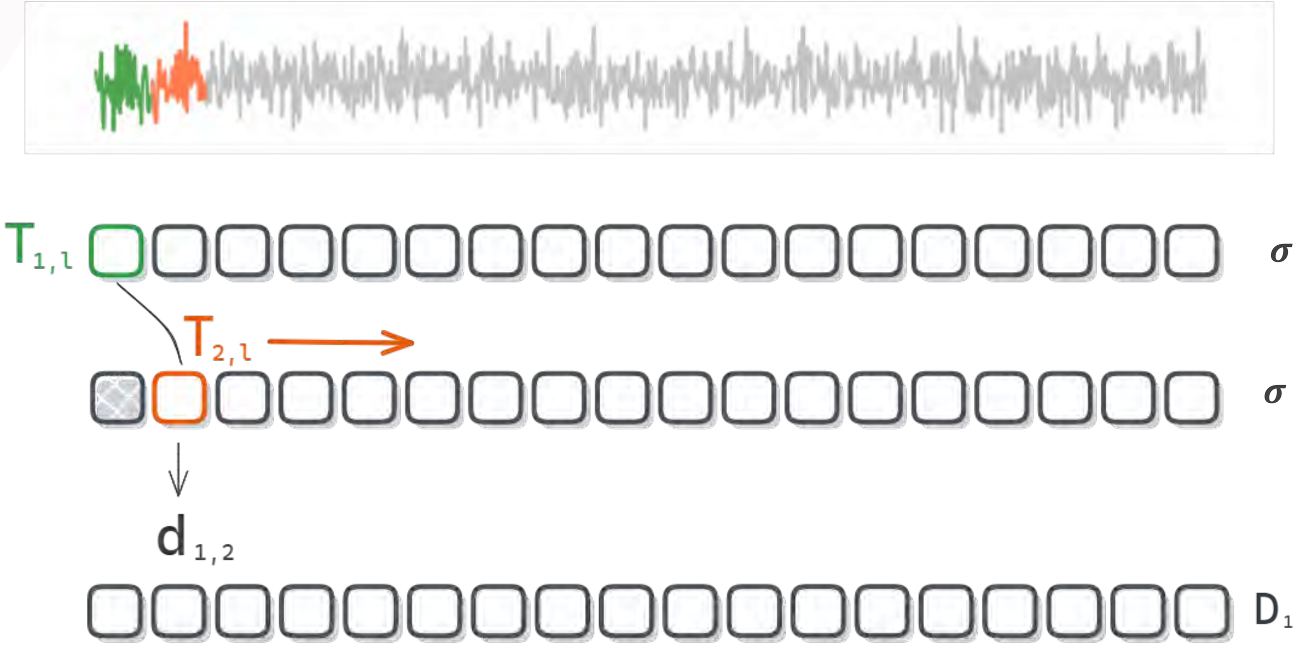
Given a query subsequence ($T_{1,l}$) and a distance metric (d), we can calculate the distance between the query and each subsequence in the subsequence set $\boldsymbol{\sigma}$.

$$d(i,j) = dist(T_{i,l}, T_{j,l}) = \sqrt{(T_{i,l} - T_{j,l})^2}$$

Anomaly detection

STEP 2

This results in a vector of distances D called Distance Profile.

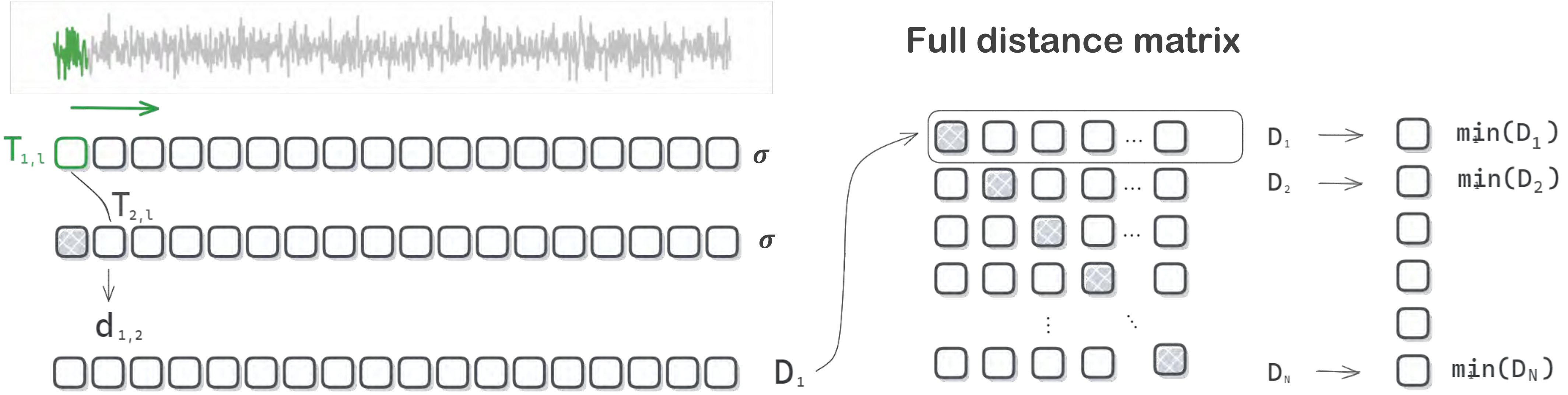


$$D_i = [d(i,1), \cdots, d(i,j), \cdots, d(i,N)]$$

Anomaly detection

STEP 3

Determining the distance profile for each subsequence in the subsequences-set σ results in the so-called full distance matrix (*DM*).



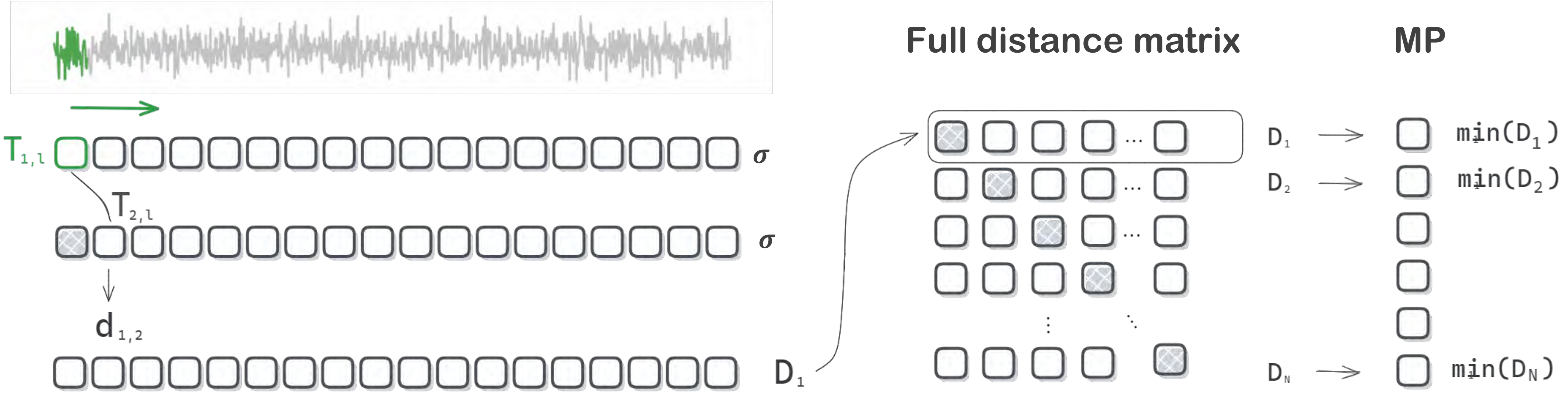
Anomaly detection

STEP 4

Define the matrix profile (MP) as the vector that stores the minimum distances between each subsequence and its nearest neighbour.

The matrix profile value gives a measure of subsequence similarity. If the value is:

- very low at some time index, then it means that somewhere else in the time series the subsequence is very similar.
- if the value is high, it means that the pattern is very atypical and represents a kind of anomaly in the data.



Case study: Biobank data

Statens Serum Institute

Data from 53 ultra-low temperature freezers

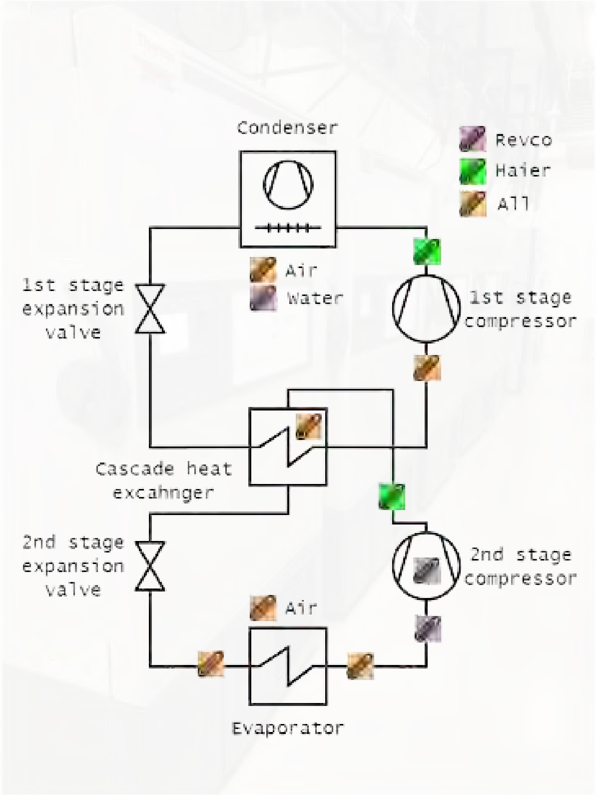
- 10 years 1 minute-wise data
- Temperature data
- Event data
- Service reports

Data publicly available on Nature scientific data:

GitHub

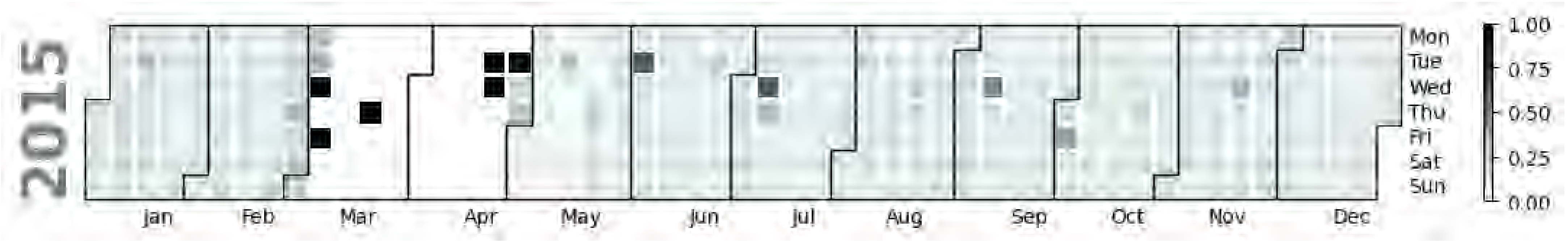
Huang, T. *et al*. *Labelled dataset for Ultra-Low Temperature Freezer to aid dynamic modelling & fault detection and diagnostics*. *Sci Data* **10**, 888 (2023). https://doi.org/10.1038/s41597-023-02808-6

Link to dataset



Case study: Biobank data

Matrix profile applied to internal temperature data (RTD sensor)



Daily-averaged values

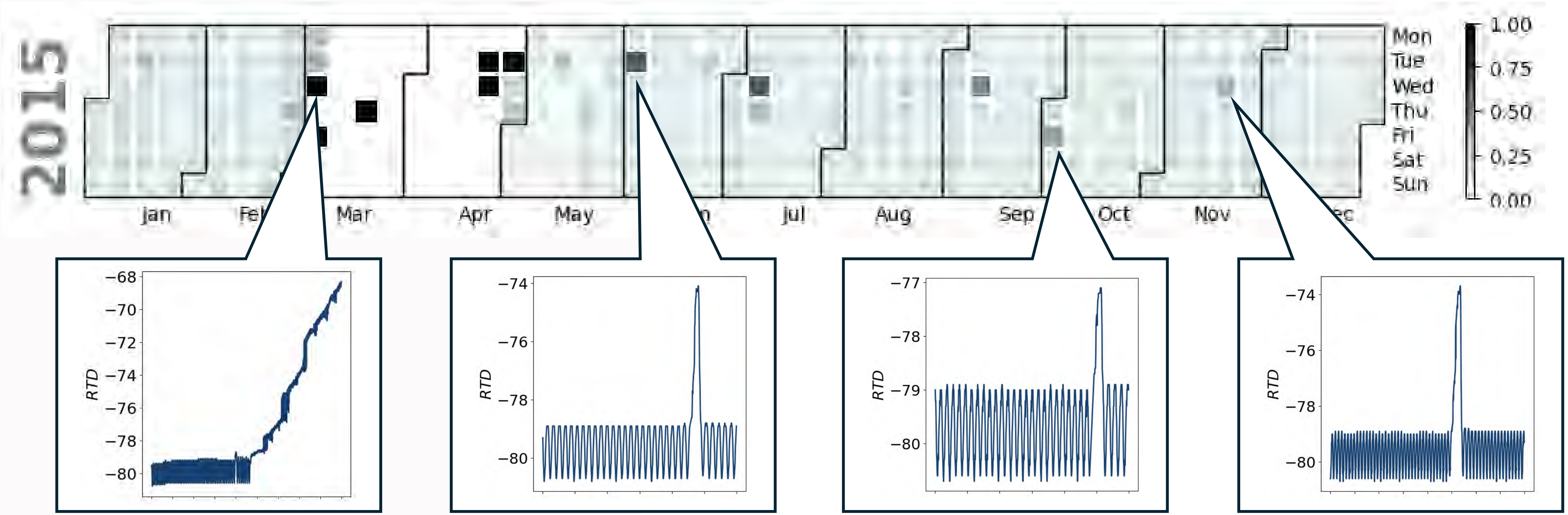
Batch processing of one year of historical data

*S*ub-sequence parameters:

- *Starting index: compressor turn-on*
- Length: duty cycle length

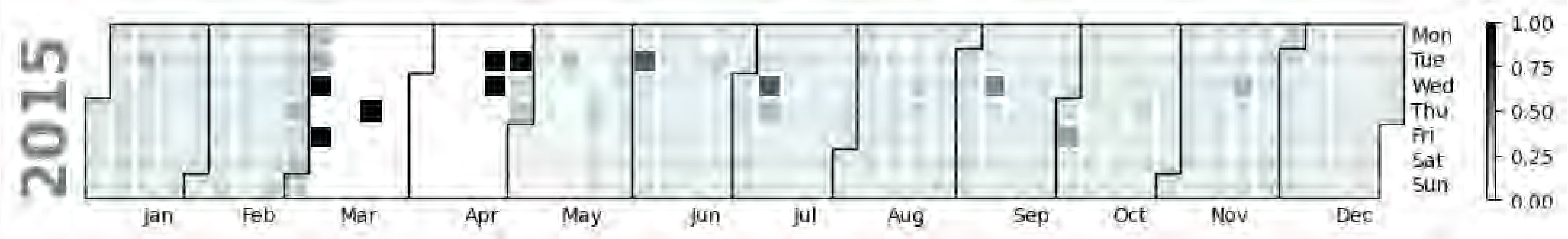
Case study: Biobank data

Matrix profile applied to internal temperature data (RTD sensor)



Case study: Biobank data

Matrix profile applied to internal temperature data (RTD sensor)



Inter quartile range analysis to define anomalous observations:

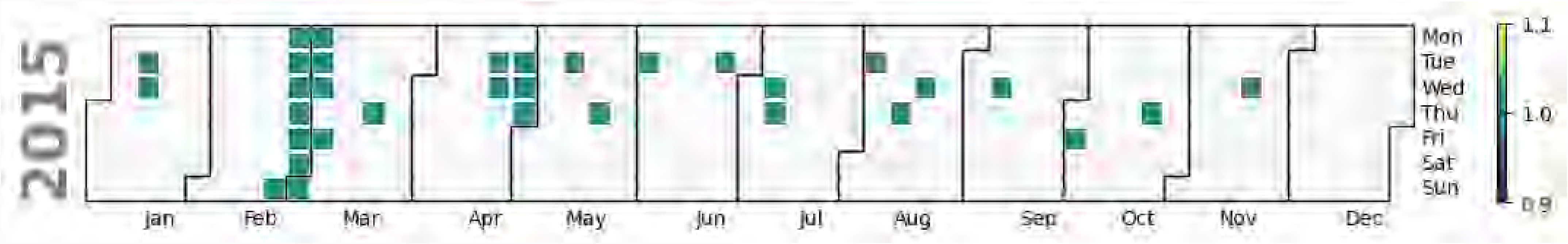
Any value that falls above Y is classified as an anomaly

Threshold = $Q_3 + 1.5IQR$

Q_1 = 1st quartile
Q_3 = 3rd quartile
$IQR = Q_3 - Q_1$

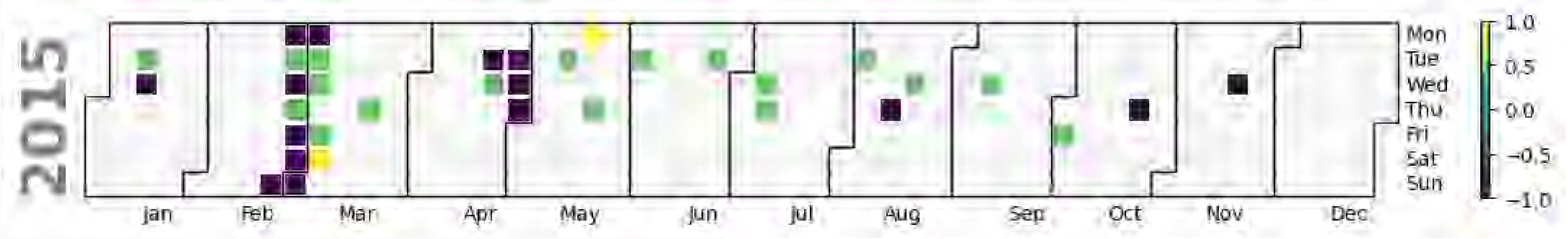
Case study: Biobank data

Anomalies filtered based on the inter quartile range analysis.



Case study: Biobank data

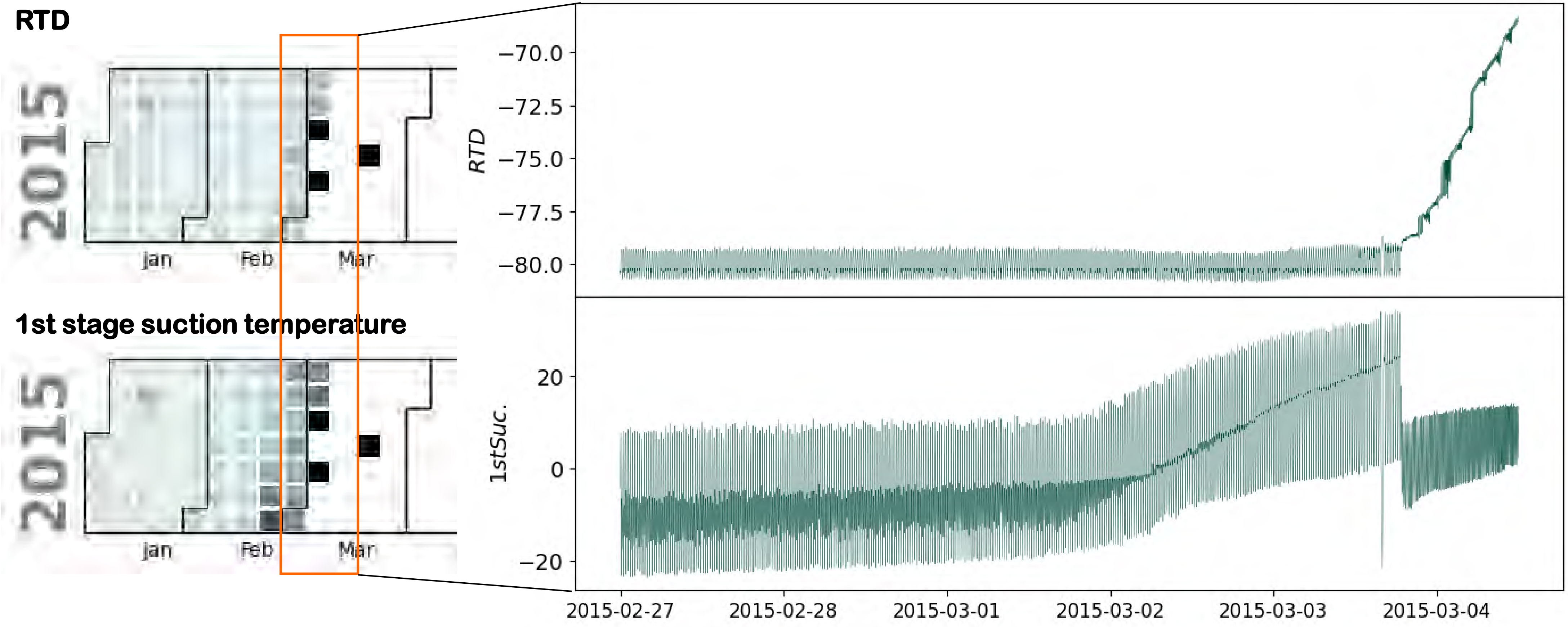
Comparison between predicted anomalies and actual alarm events (event log)´.



Accuracy: 0.95

Precision: 0.55

Case study: Biobank data



Conclusions

- Fault detection algorithm based on the application of the so-called Matrix Profile to identify abnormal patterns in freezer operation.
- MP is an unsupervised learning method that makes no assumption about the data: *simple, intuitive, highly scalable, transferable, and reduce the risk of overfitting ↔ physical interpretability*
- Successfully tested on offline temperature data from different ULT freezers.
- Provide guidelines for simple "rule-based" for system monitoring and predictive maintenance.

Fault detection in ultra-low temperature freezers

Seminar on Digitalisation of Refrigeration and Heat Pump Systems

July 04, 2024

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DANISH TECHNOLOGICAL INSTITUTE

Case study: Controlled failure tests

Elcold ULT freezers

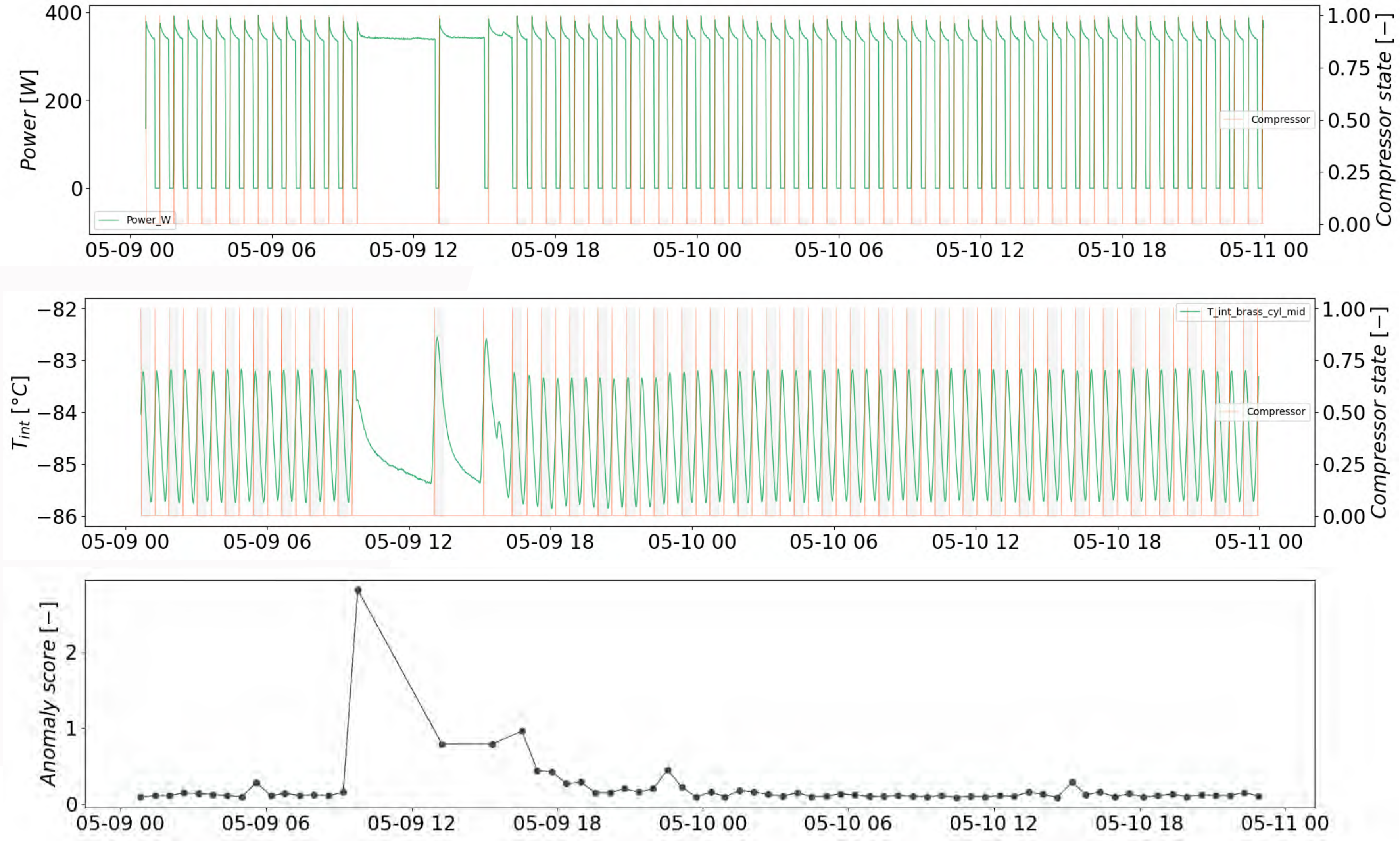
Experimental tests:

- Normal operation
- Loading
- Frequent lid openings
- Lid not properly closed
- Fan damaged/unplagged
- Dirty condenser




Case study: Controlled failure tests

Lid not properly closed



TOWARDS OPTIMAL PREDICTIVE MAINTENANCE IN LARGE-SCALE HEAT PUMPS THROUGH DIGITAL TWINS

José Joaquín Aguilera Prado

Danish Technological Institute

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

Danfoss

AK CENTRALEN

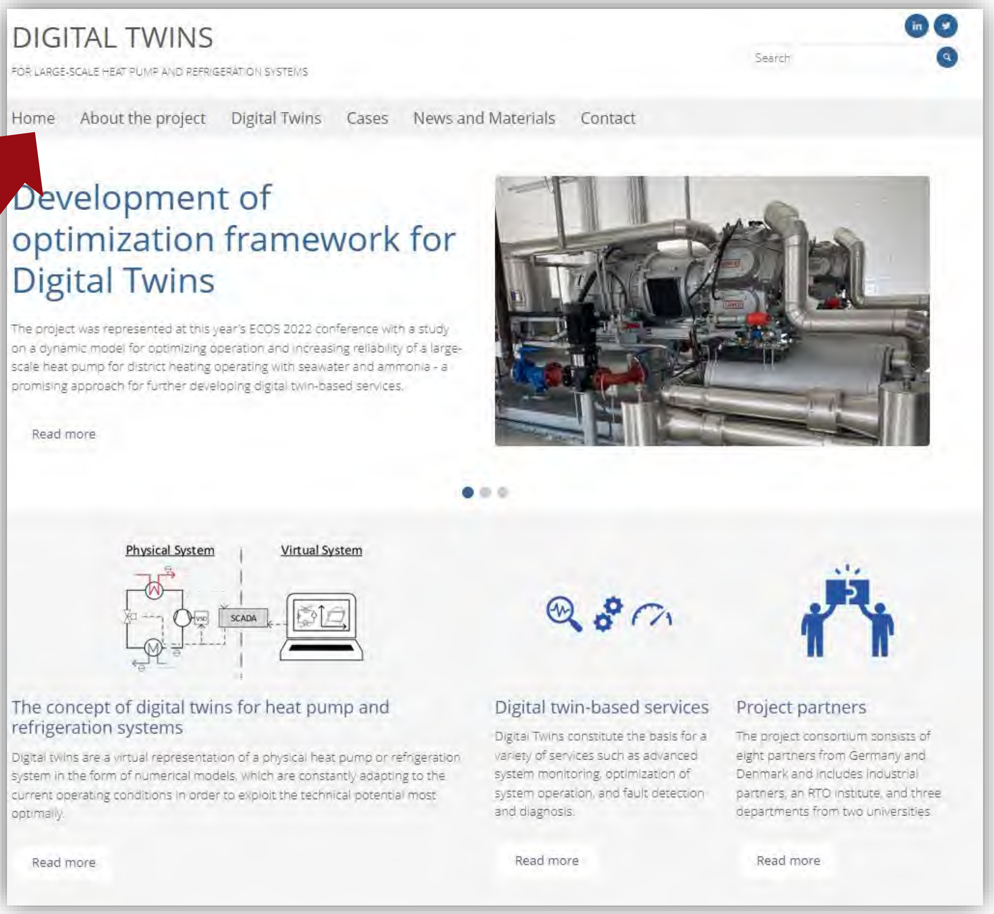
AFFALDVARME AARHUS

TLK-Thermo GmbH

DANISH TECHNOLOGICAL INSTITUTE

DTU

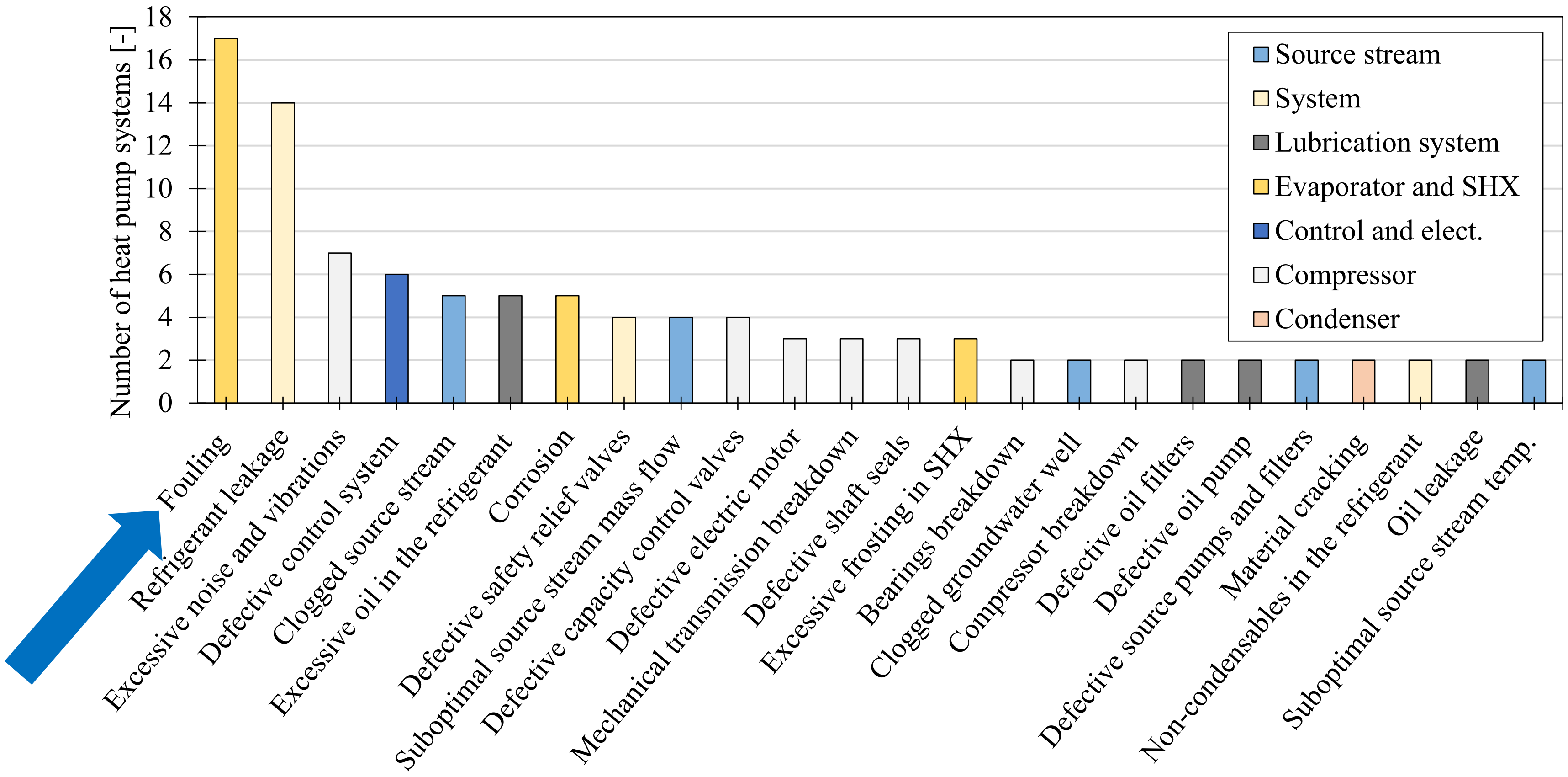
Technische Universität Braunschweig



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

Common faults in large-scale heat pump systems

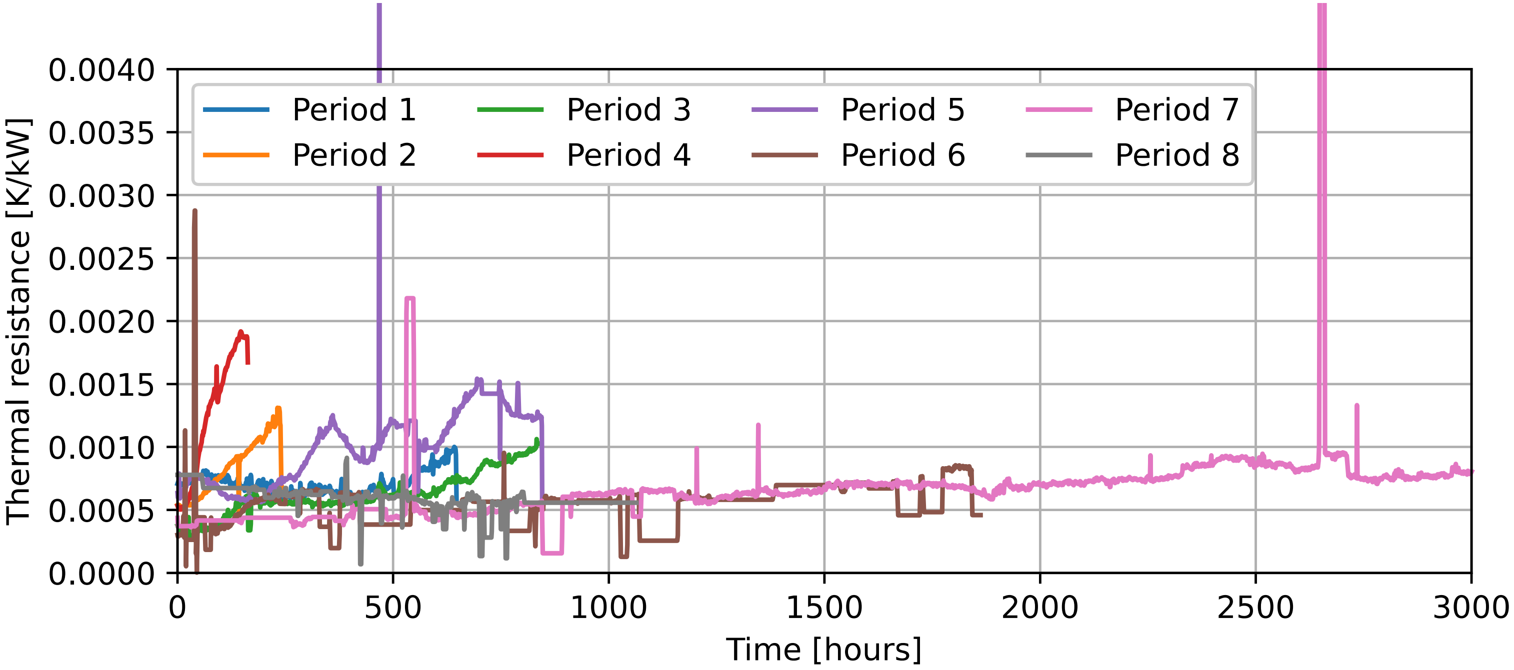
- Information from commercial systems described in the literature



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

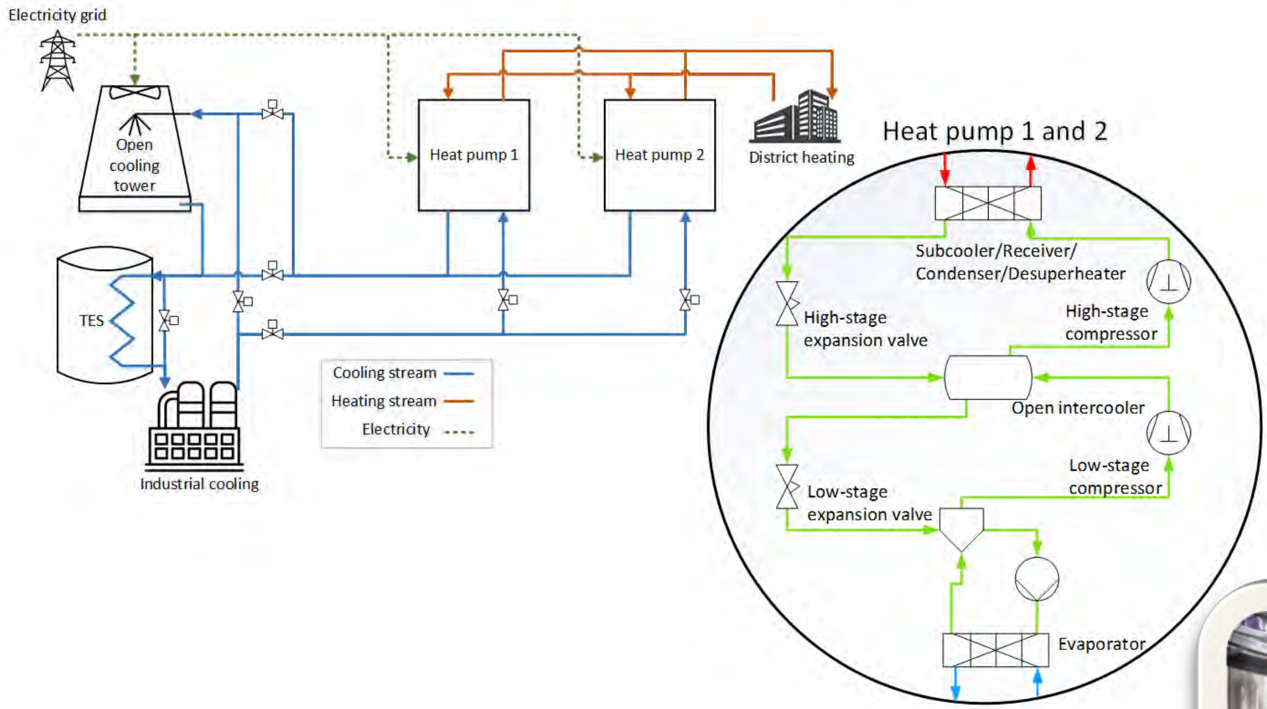
- Growth of fouling-related thermal resistance on the same system



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

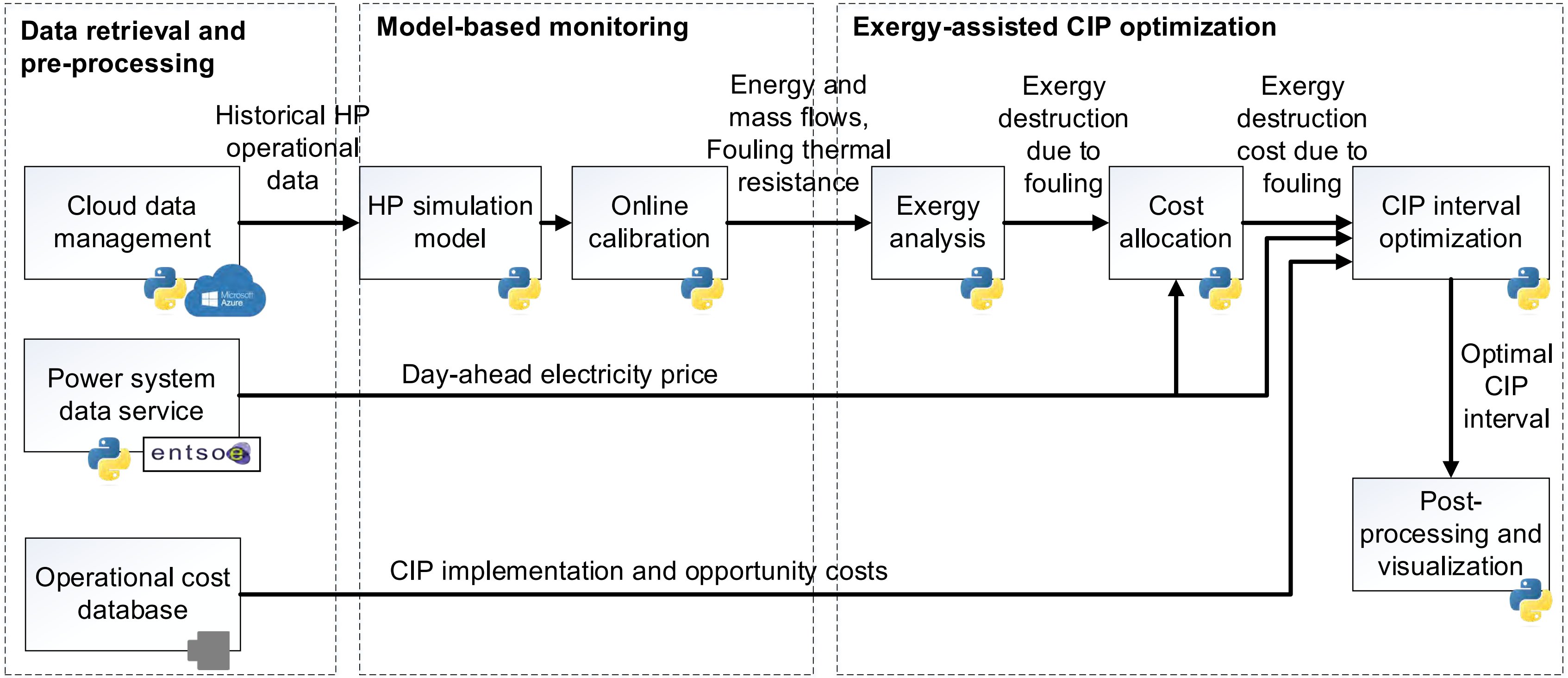


Heat pump characteristics:

- **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

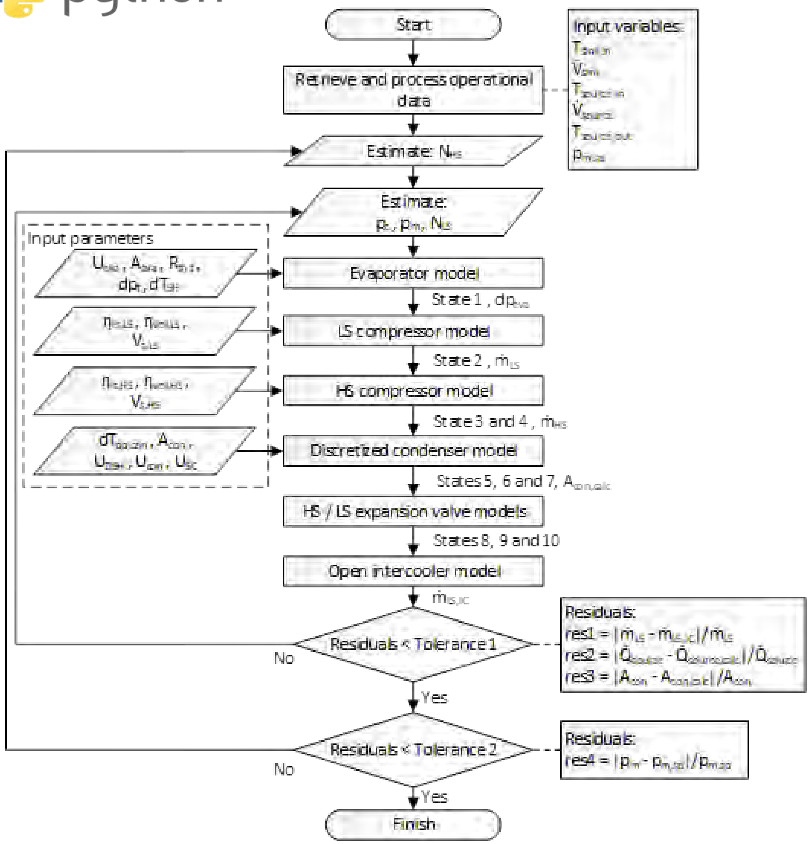
- Framework overview

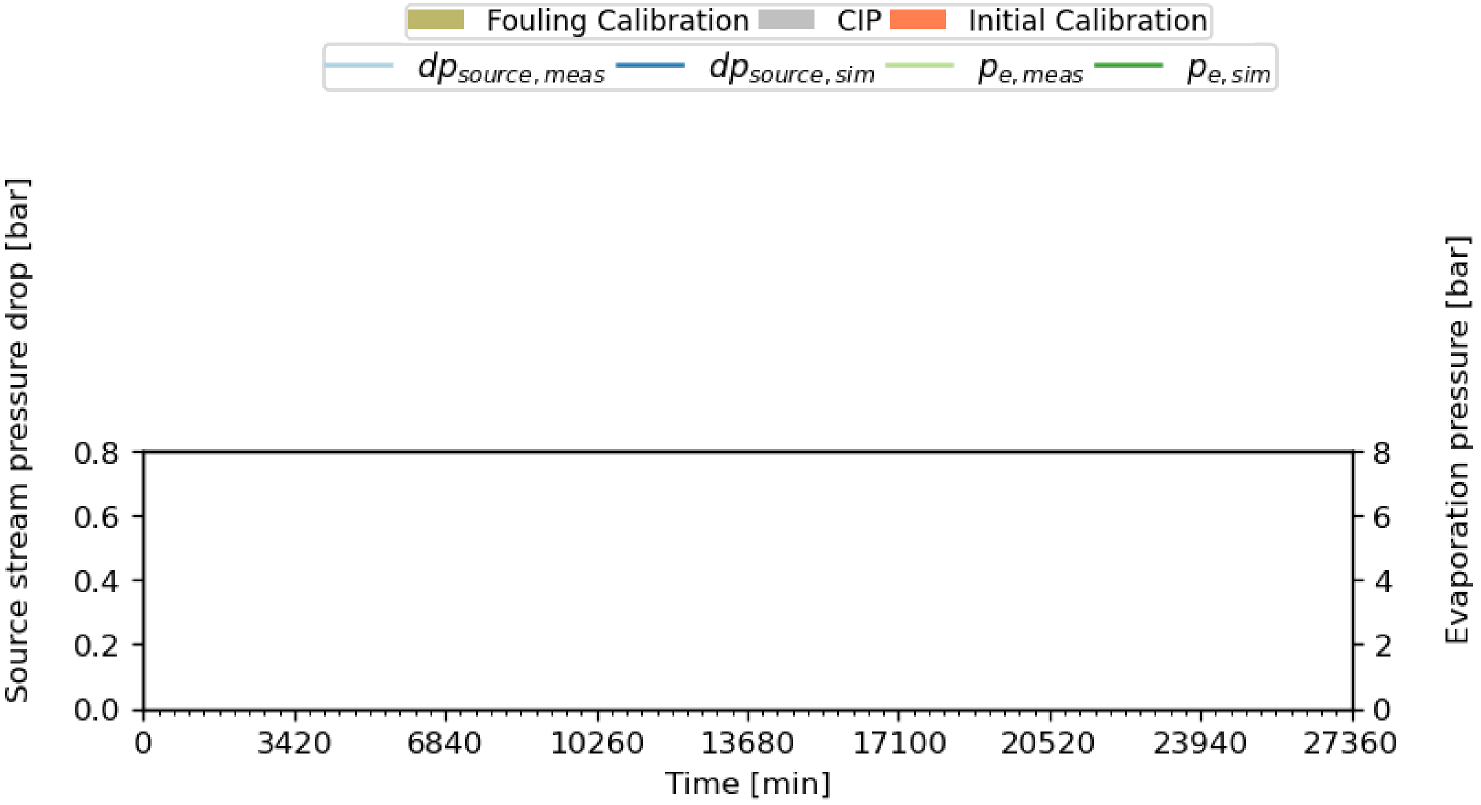


Source: J.J. Aguilera "**Digital twin-based services for large-scale heat pump systems**", Ph.D. thesis, Technical University of Denmark, 2024.

System monitoring

- Digital twin for online monitoring of performance and fouling effects

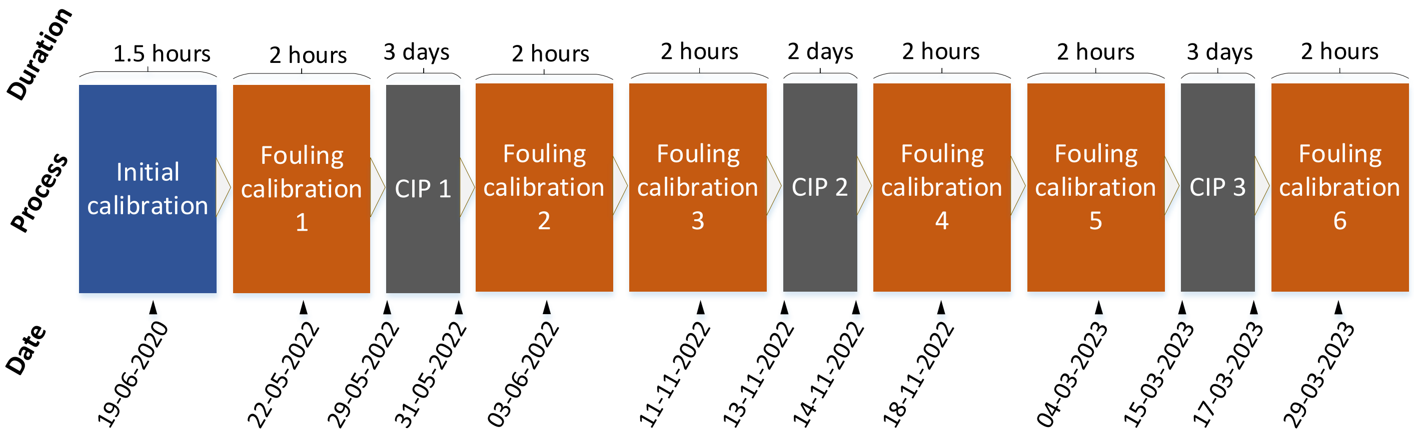




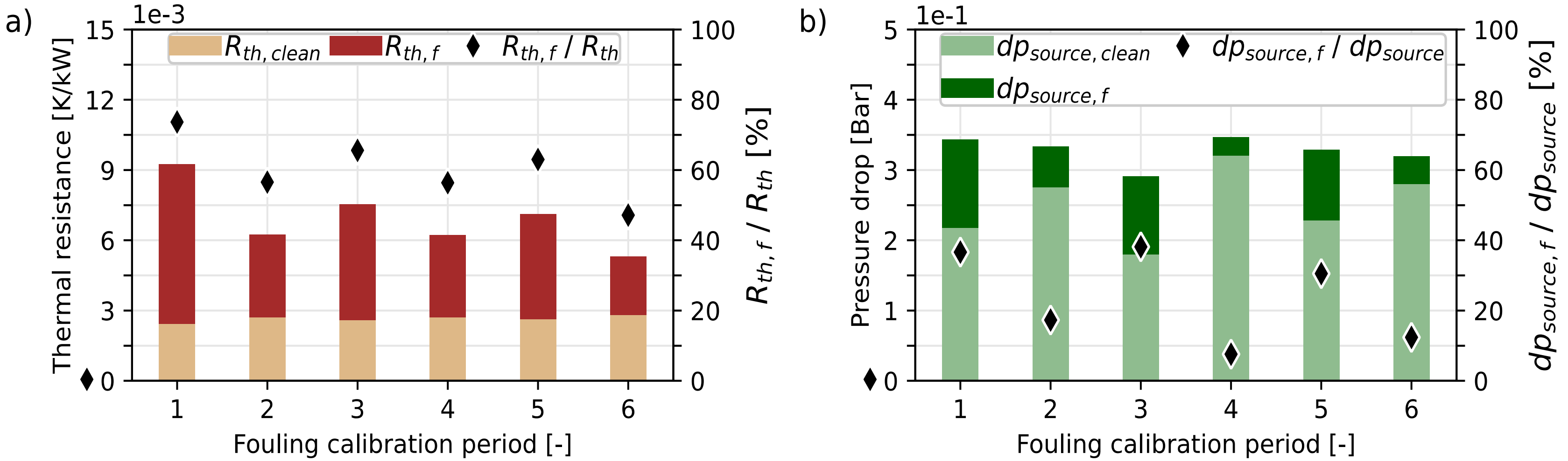
Source: J.J. Aguilera, W. Meesenburg, W. B. Markussen, B. Zühlsdorf and B. Elmegaard, "**Online model-based framework for operation and fouling monitoring in a large-scale heat pump**", Proceedings of ECOS 2023

System monitoring

- Characterization of fouling-related effects



Cleaning-in-place (CIP) system



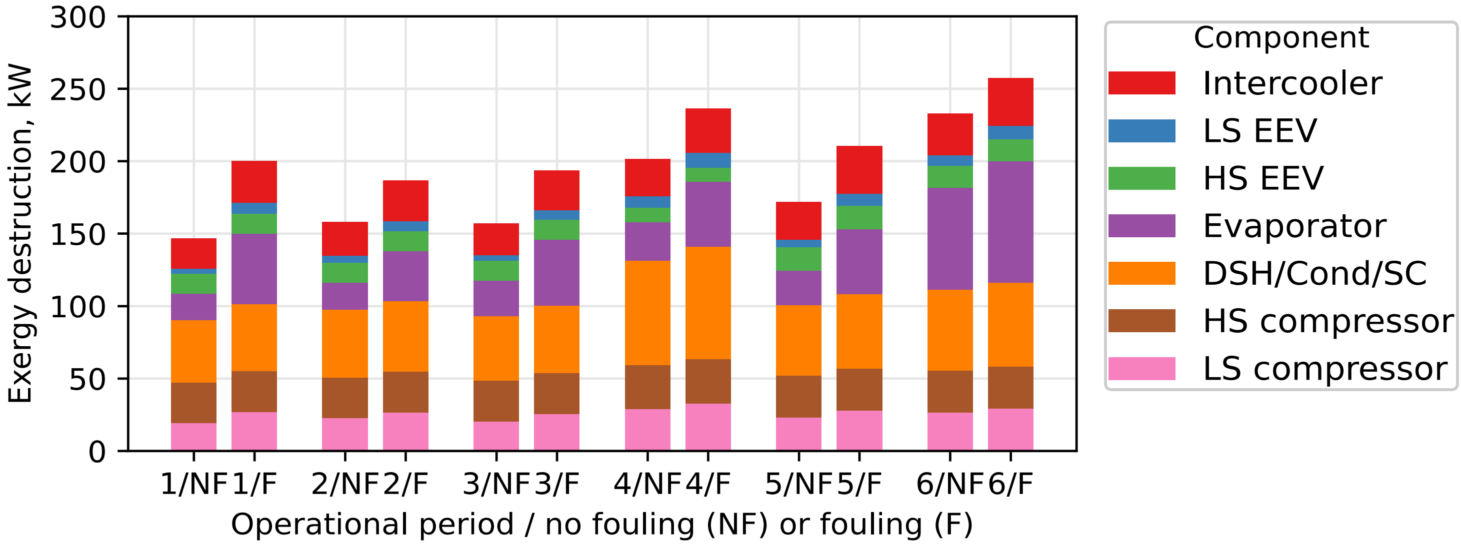
Source: J.J. Aguilera, W. Meesenburg, W. B. Markussen, B. Zühlsdorf and B. Elmegaard, "**Real-time monitoring and optimization of a large-scale heat pump prone to fouling - Towards a digital twin framework**", Applied Energy, 2024.

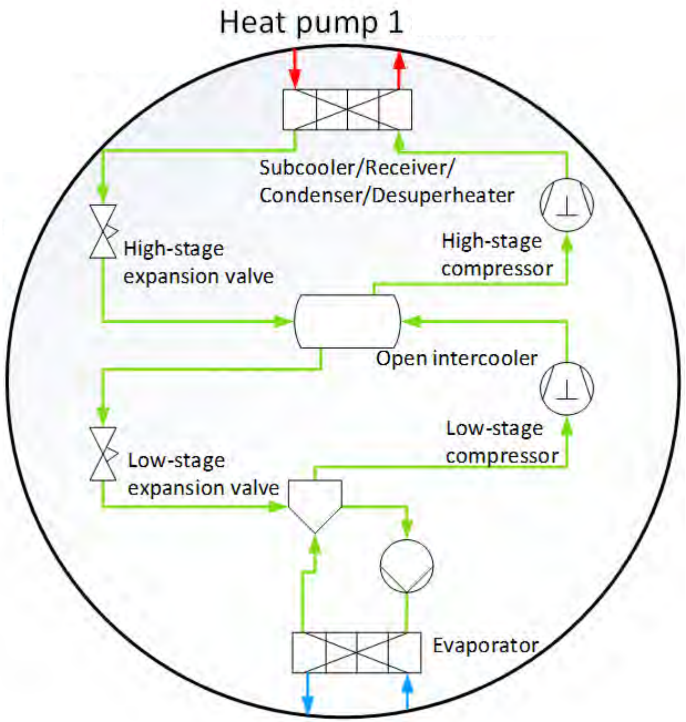
Exergy analysis derived from monitoring results

- 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.

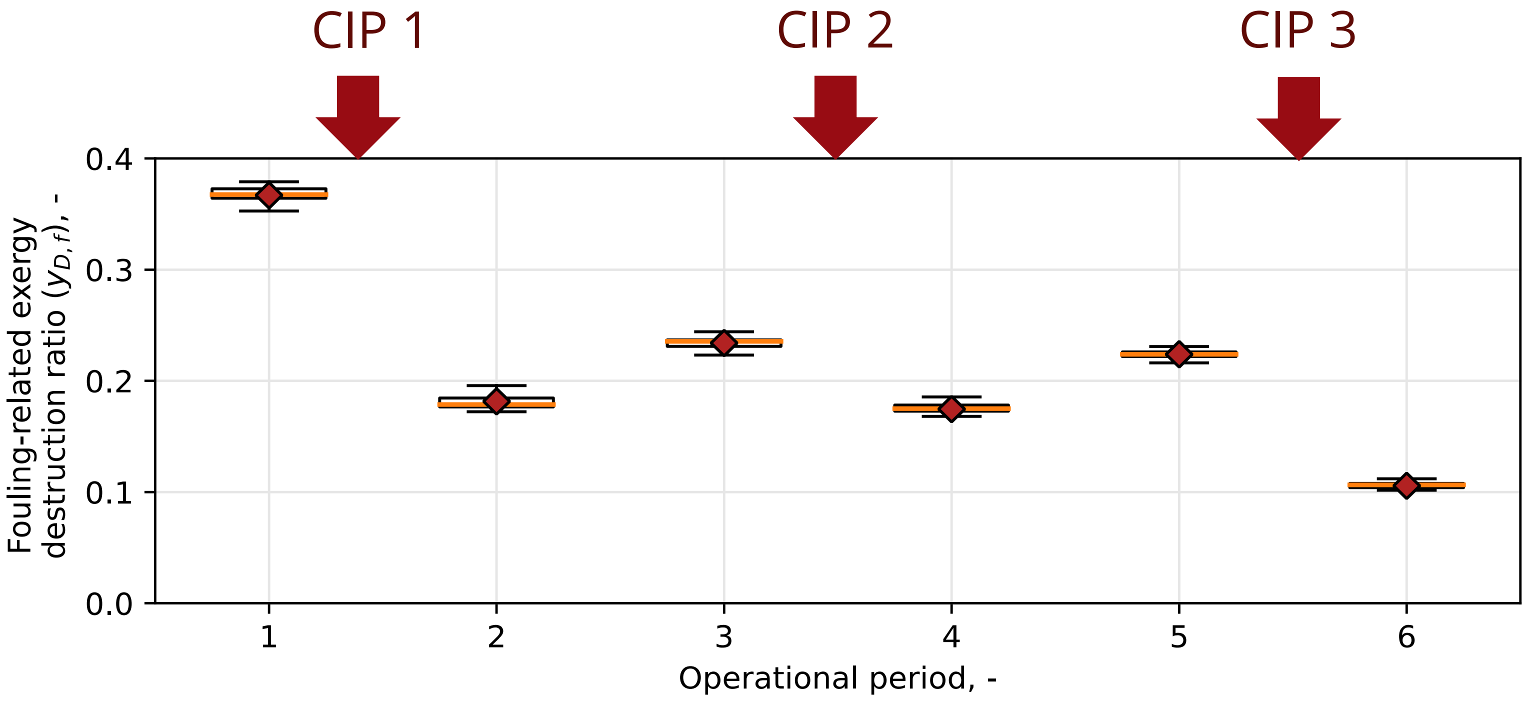
Fouling contribution to exergy destruction

- 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**

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

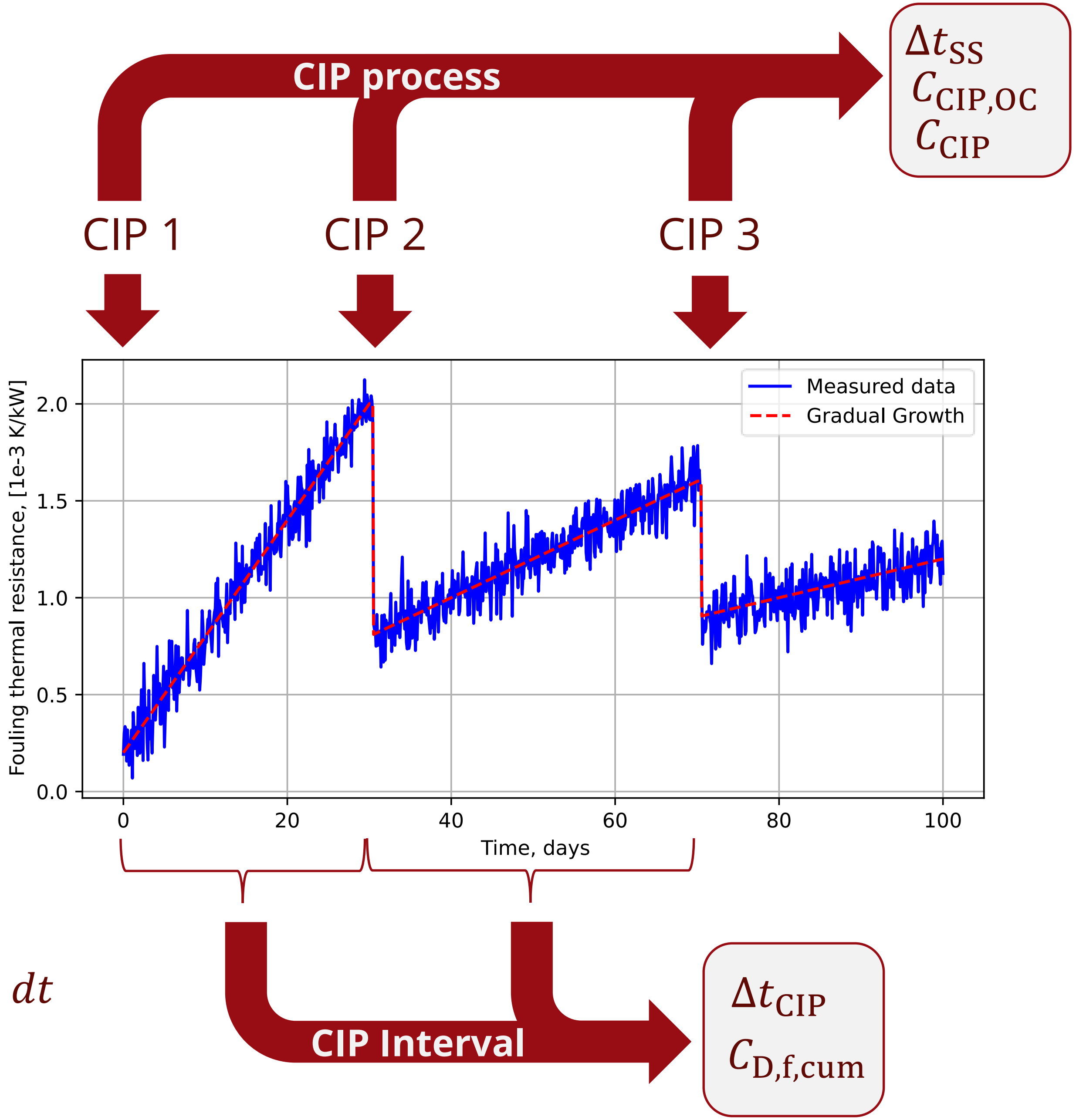
- **Cumulative cost of fouling**

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

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

- **Opportunity cost of CIP**

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



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

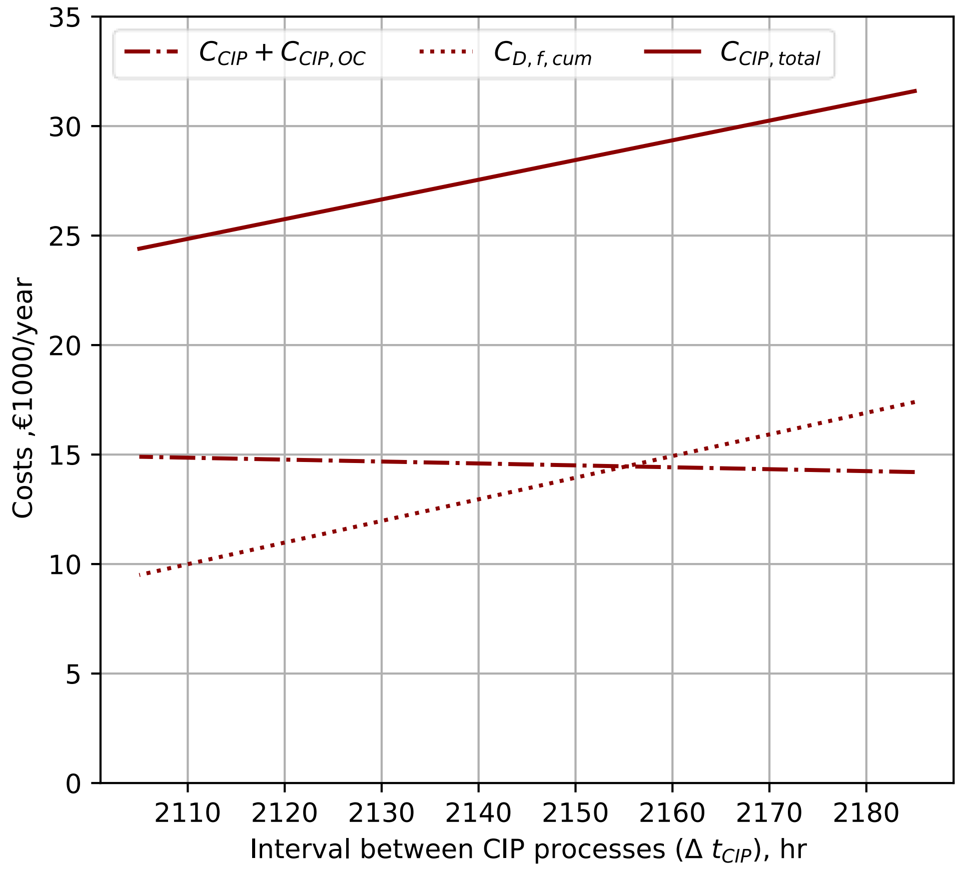
Definition of optimal CIP interval

- **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)	$C_{\mathrm{CIP}} + C_{\mathrm{CIP,OC}}$ (€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



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

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

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FLEXIBLE STEADY STATE HP MODEL

Emil Navntoft Pedersen

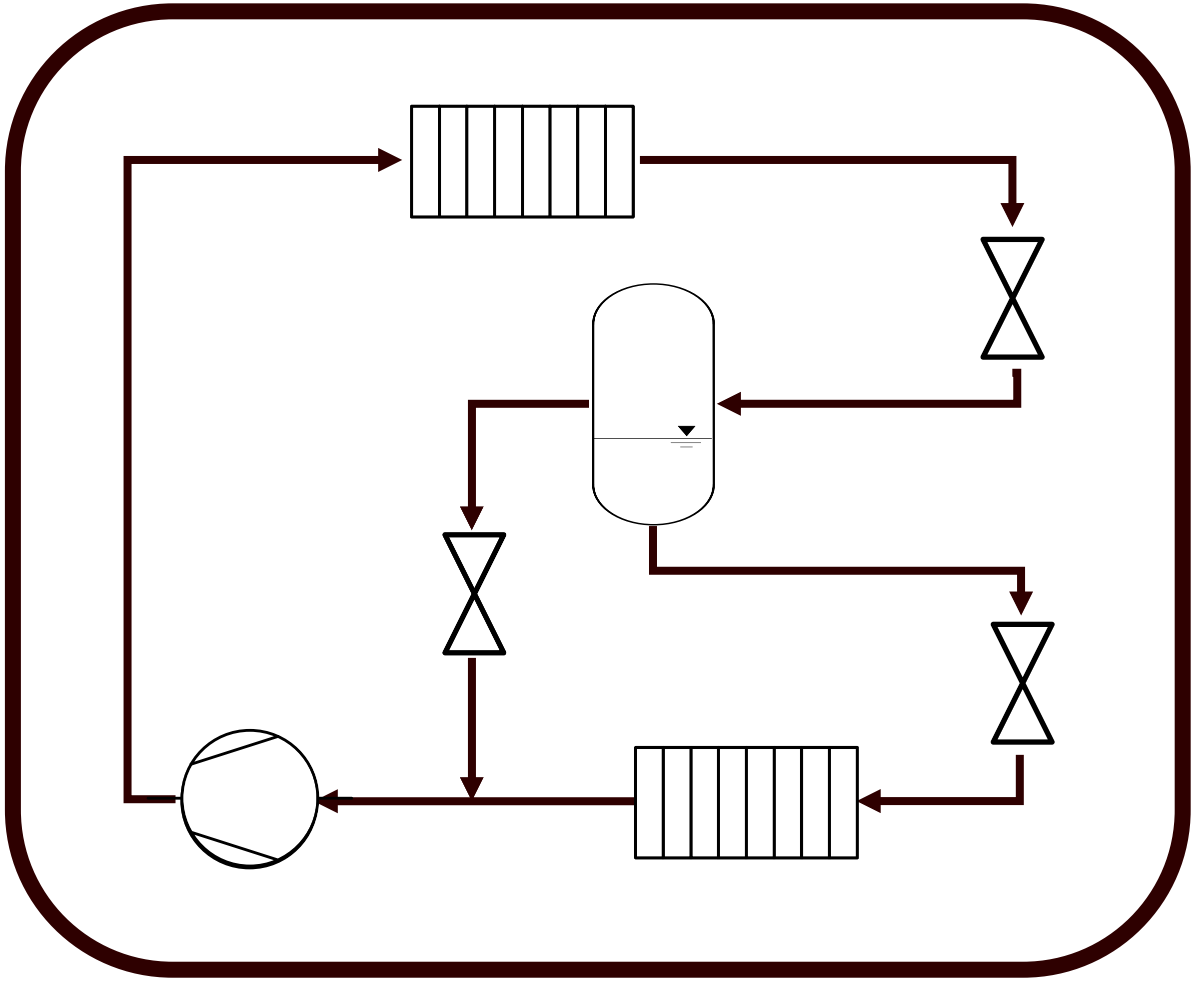
Danish Technological Institute

TEKNOLOGISK INSTITUT

Flexible steady state HP model

What is it?

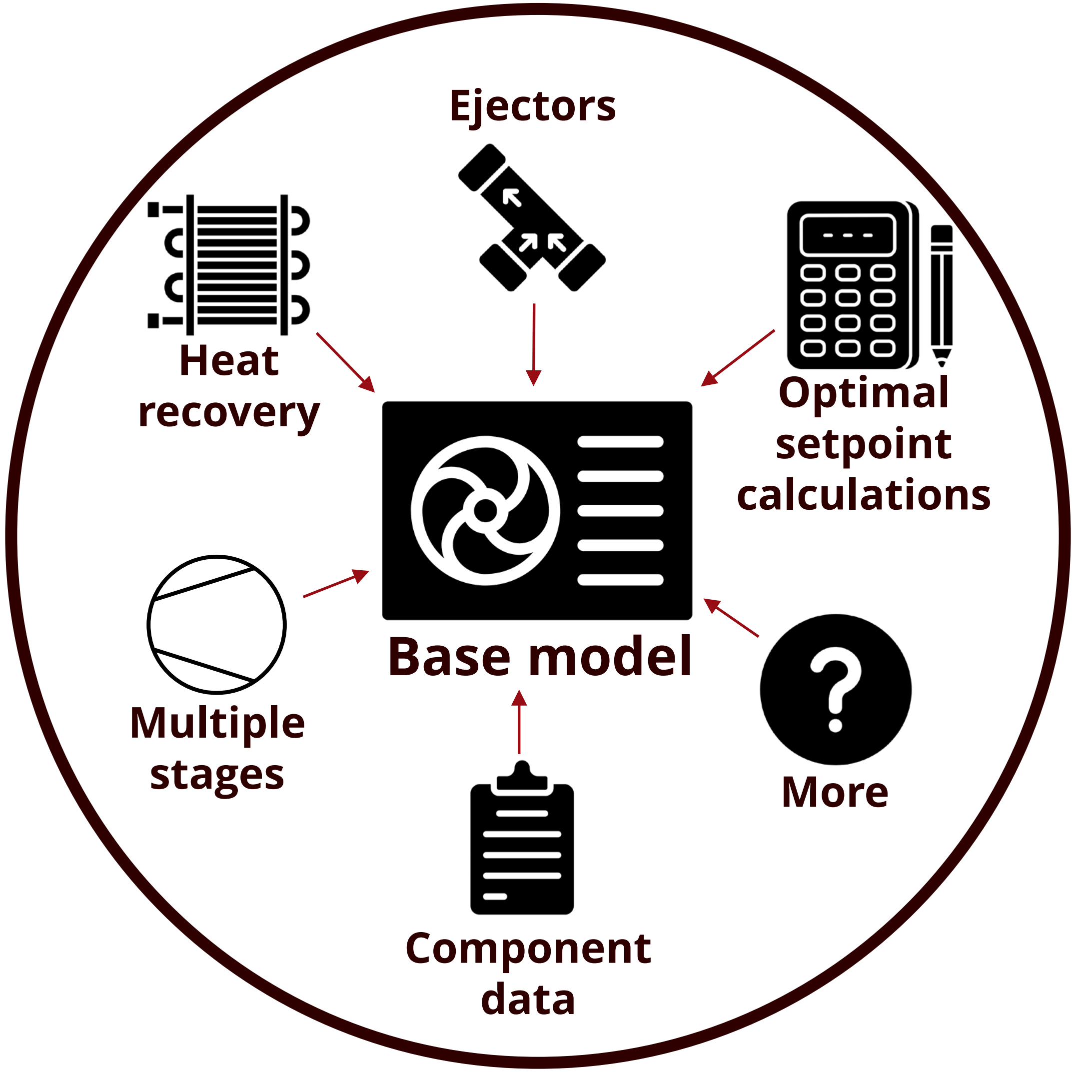
- At the base level is a simple heat pump model
  - Built for CO2 systems, but can be modified to model other refrigerants
  - Steady state
  - Subcritical and transcritical operation
- Written in C#
- Object oriented
  - Based on individual independent components that can be 'dragged and dropped' together



Base CO2 HP model

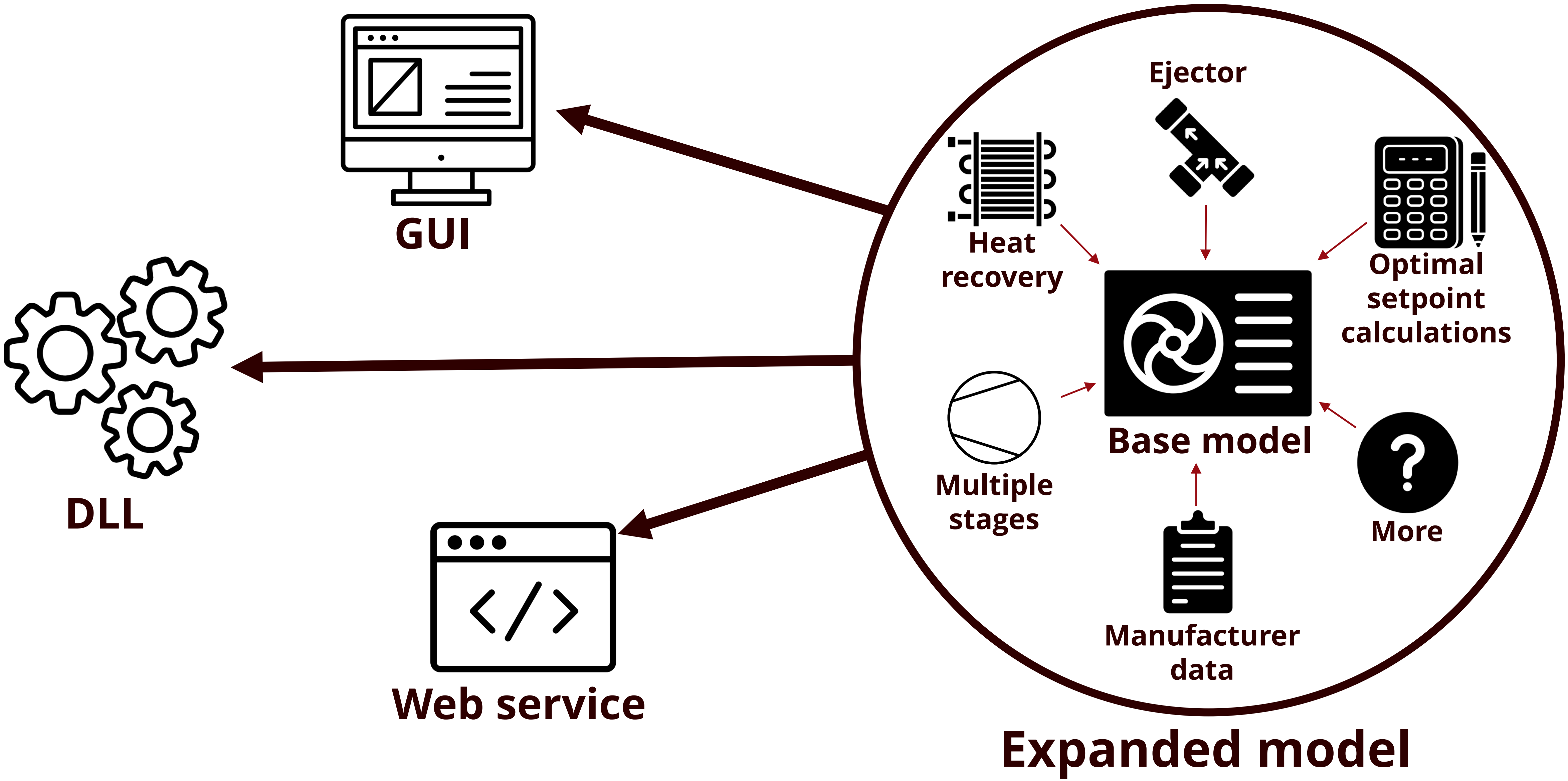
What is it?

- Model can be expanded with advanced features
- Examples
  - Heat recovery
  - Internal heat exchangers
  - HP/LP ejectors
  - Multiple suction stages
  - Integrate external calculation software from component manufacturers (compressors, heat exchangers, ejectors)
  - Calculation of optimal gascooler and receiver pressure setpoints

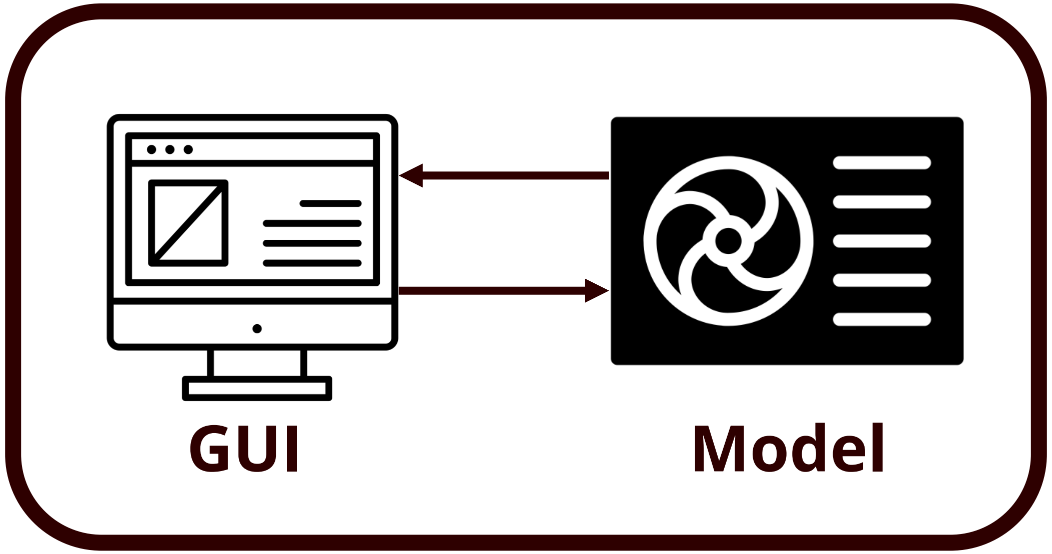


Expanded model

What is it?


GUI
DLL
Web service
Ejector
Heat recovery
Optimal setpoint calculations
Base model
Multiple stages
More
Manufacturer data
Expanded model

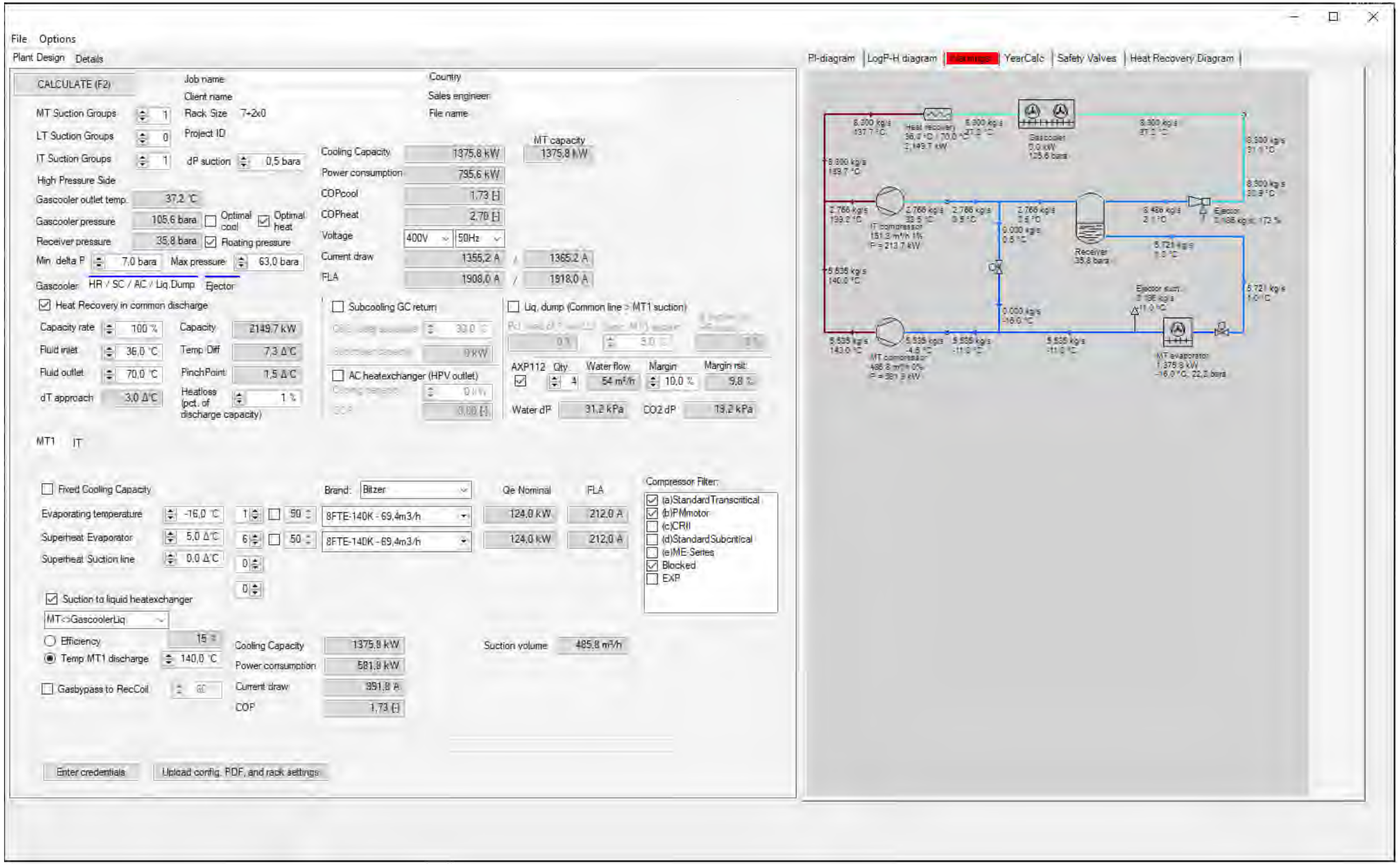
Implementations – Custom UI



C# desktop application

Implementations – Custom UI

- Can be tailored to exactly what is needed
- Includes
  - Report generation
  - Integration with an external system
  - Seasonal calculation
  - Safety valve(s) selection
- Could be extended into a true selection tool



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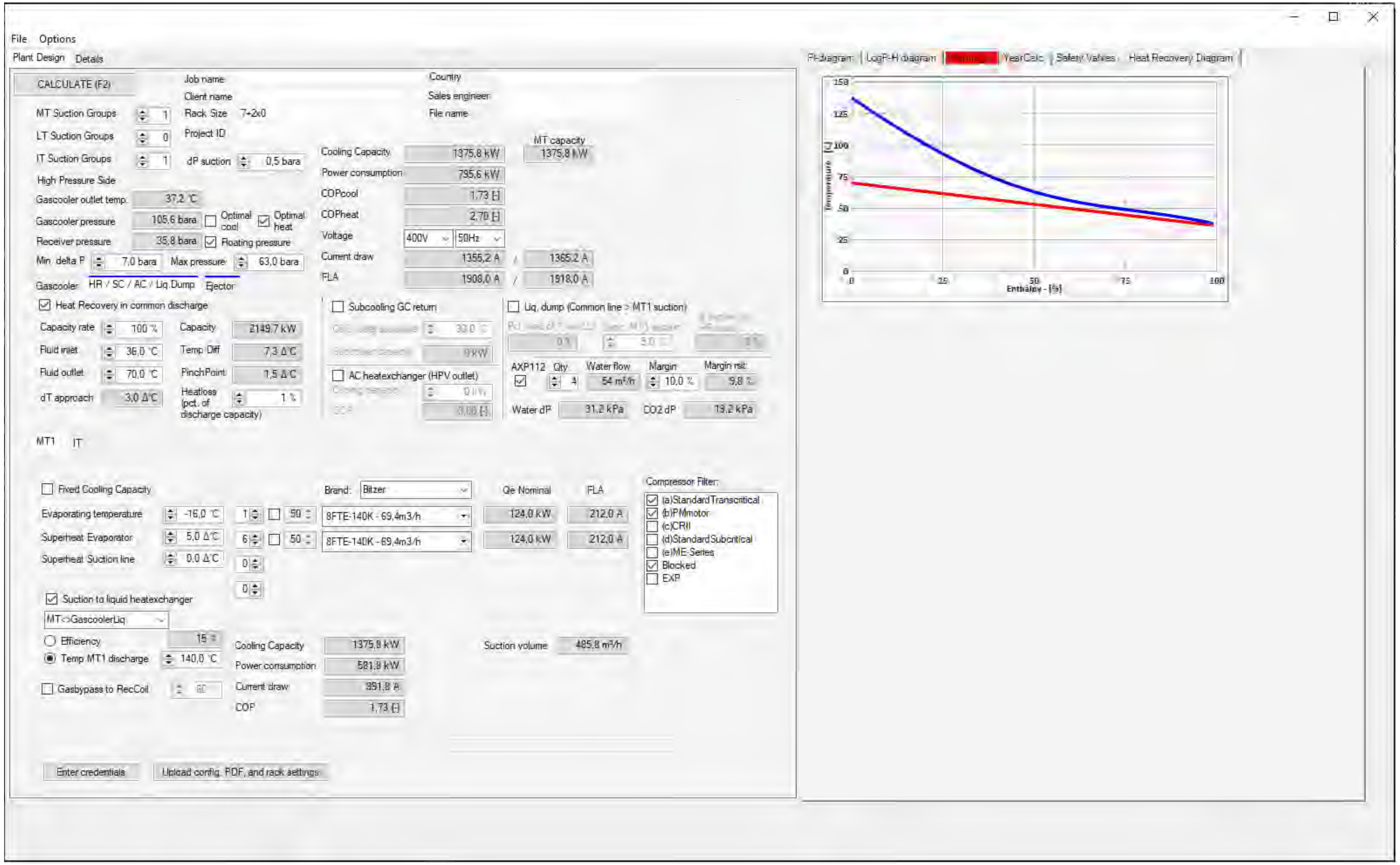

Teknologisk Institut

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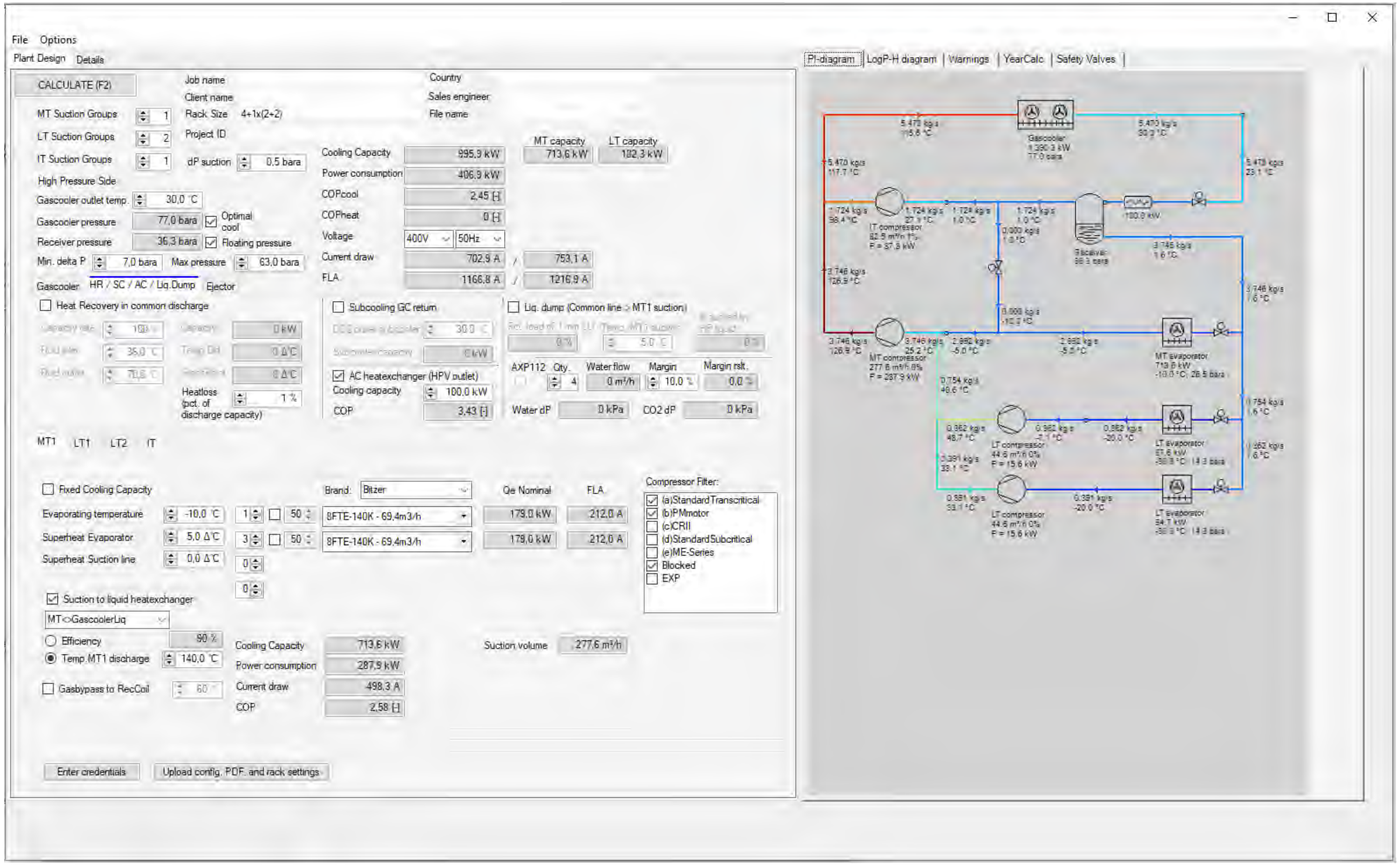

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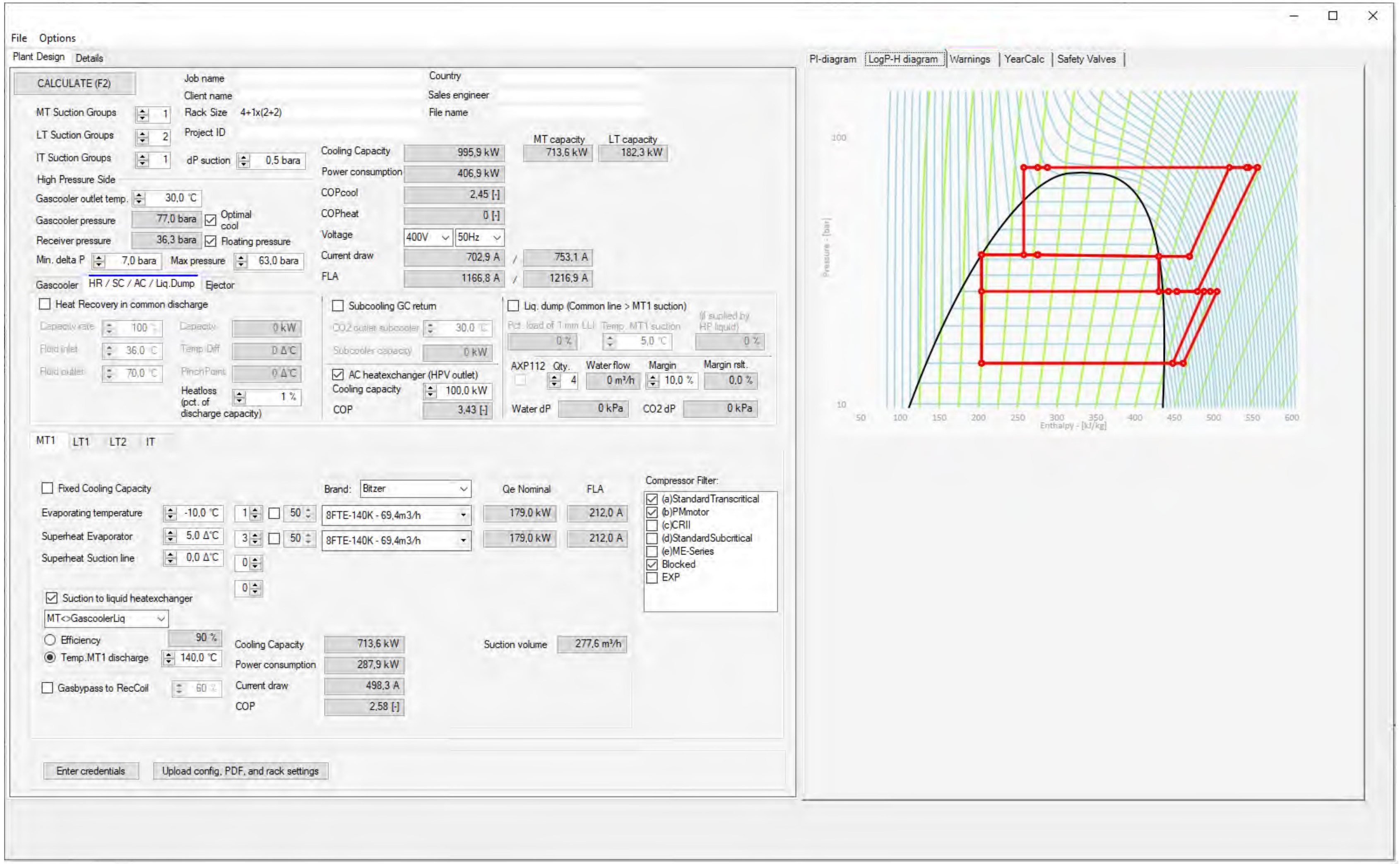
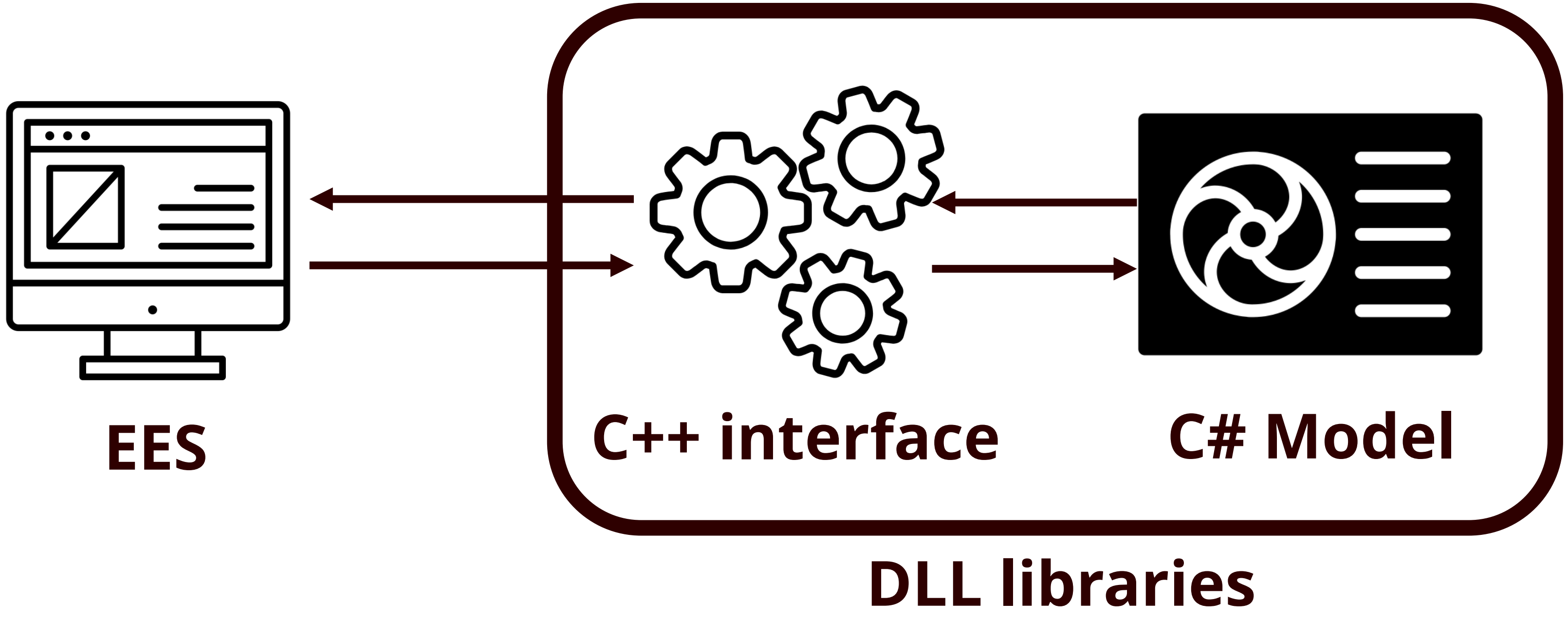
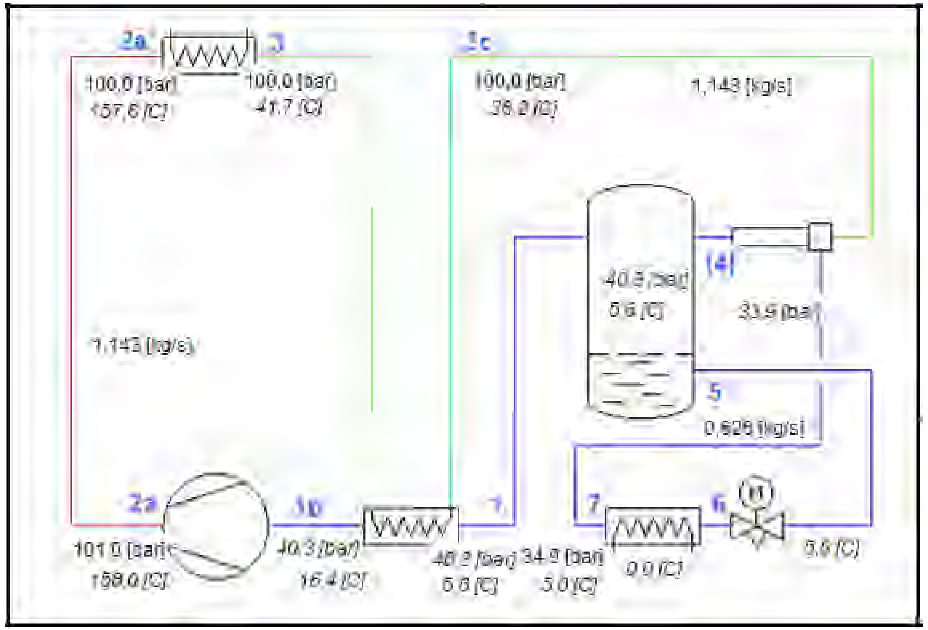


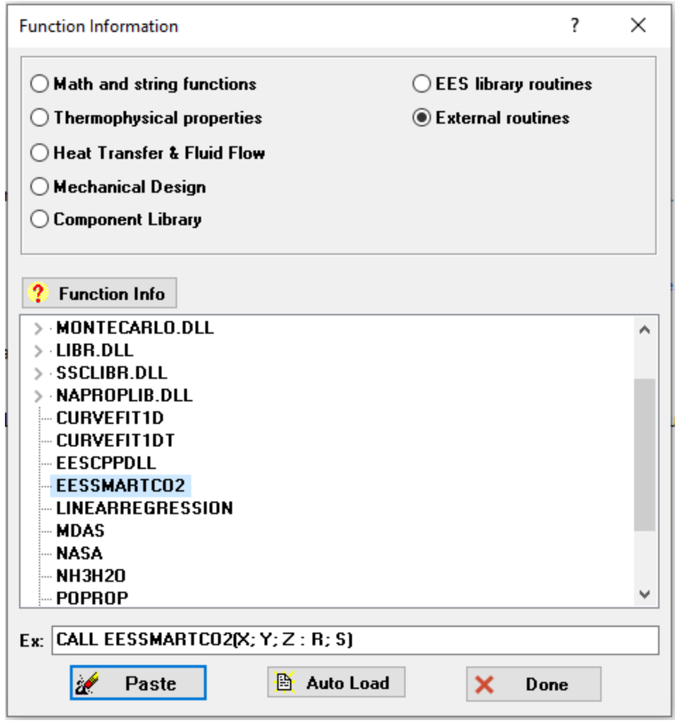
Implementations – EES function



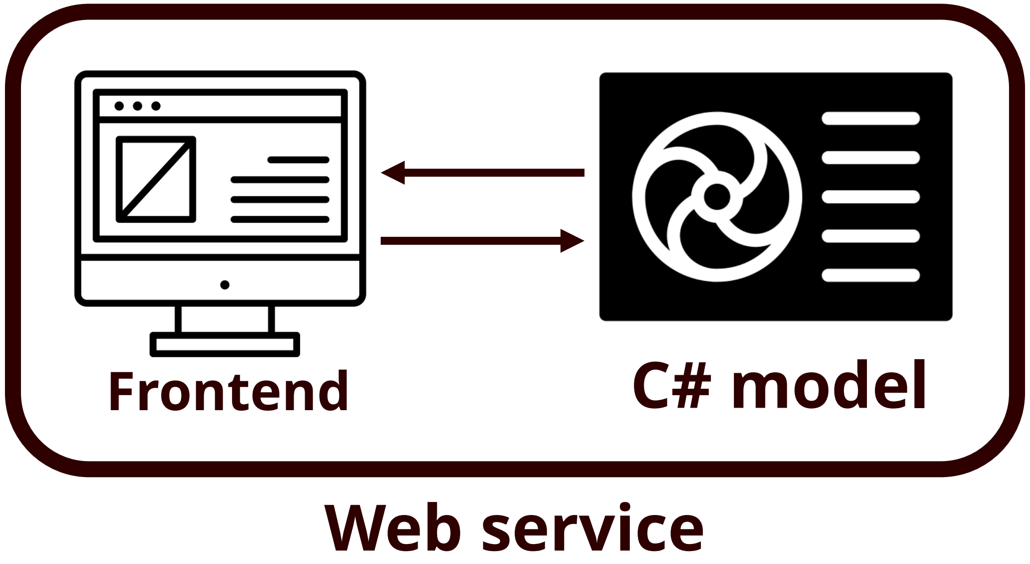
Implementations – EES function

- Callable via EES as an external routine
- Debugging of DLL via EES is possible
- With a similar setup, it is also possible to call the model from other code languages





Implementations – Web service



Implementations – Educational web tool

- Accessed via a browser
- Intuitive graphical user interface suitable for non-experts
- Backend consists of our model

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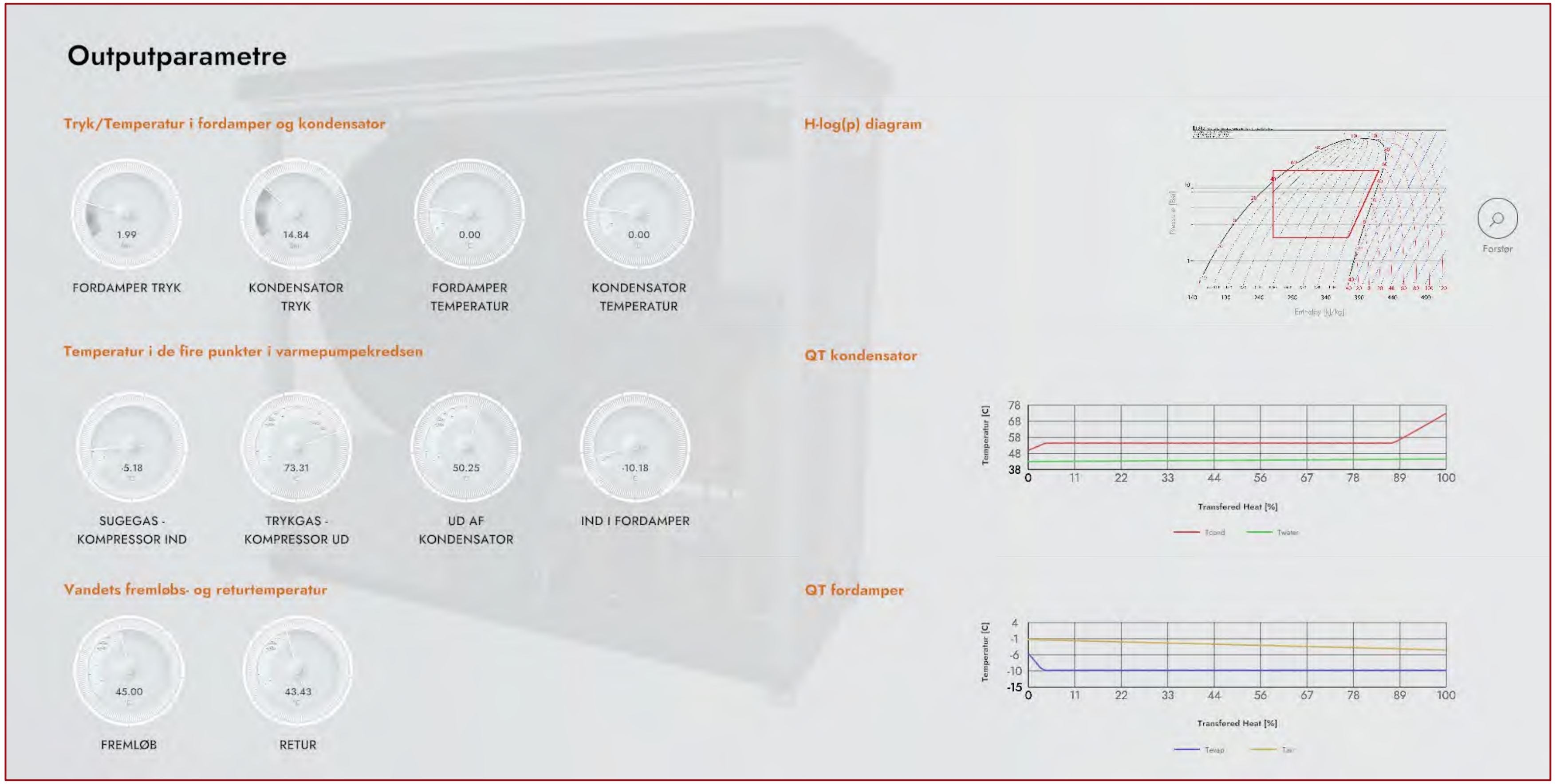

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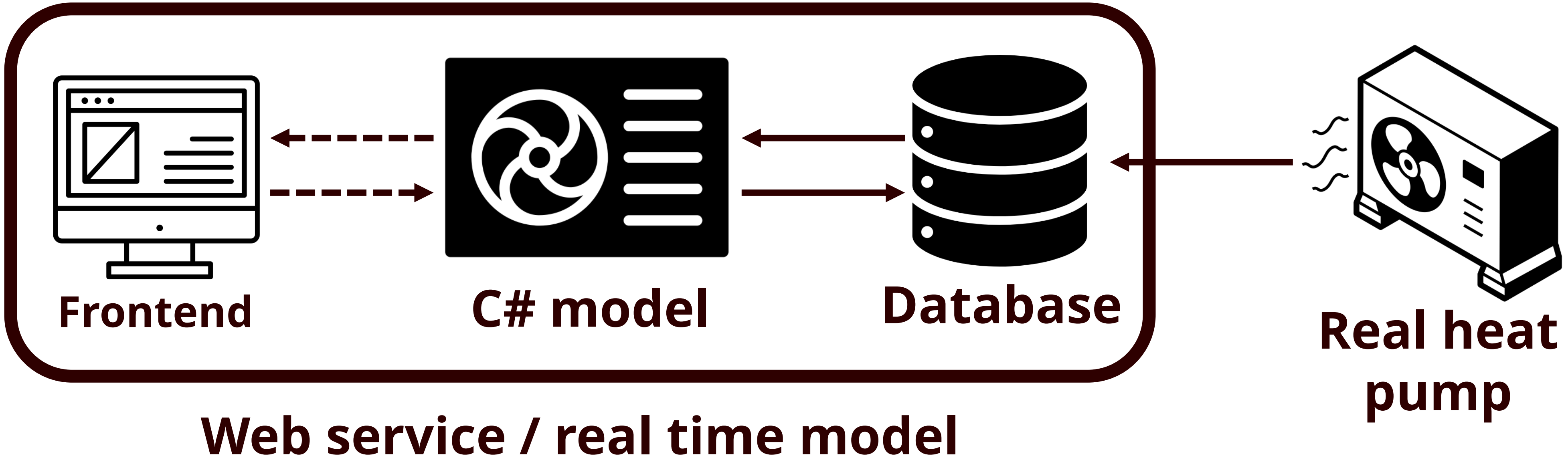


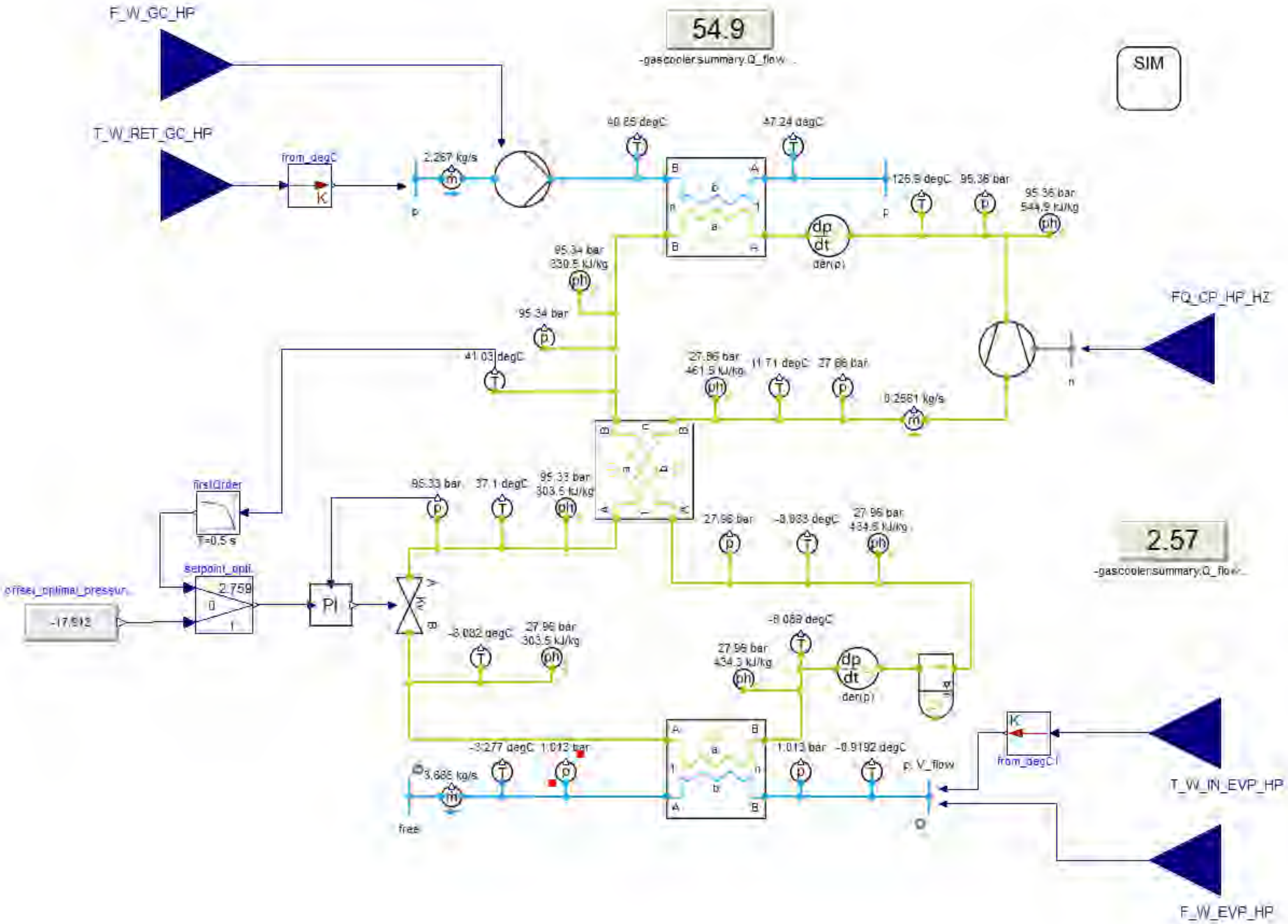
DANISH TECHNOLOGICAL INSTITUTE

VERSATILE SIMULATION MODELS OF HEAT PUMP AND REFRIGERATION SYSTEMS WITH DYMOLA

Pierre Jean Deletre

Danish Technological Institute

TEKNOLOGISK INSTITUT



Versatile simulation models of heat pump and refrigeration systems with Dymola

Pierre-Jean Delêtre

Danish Technological Institute

Why to use a numerical model?

Cost

- Building a test prototype is expensive
- Time saving by running simulations over few seconds

Flexibility and control

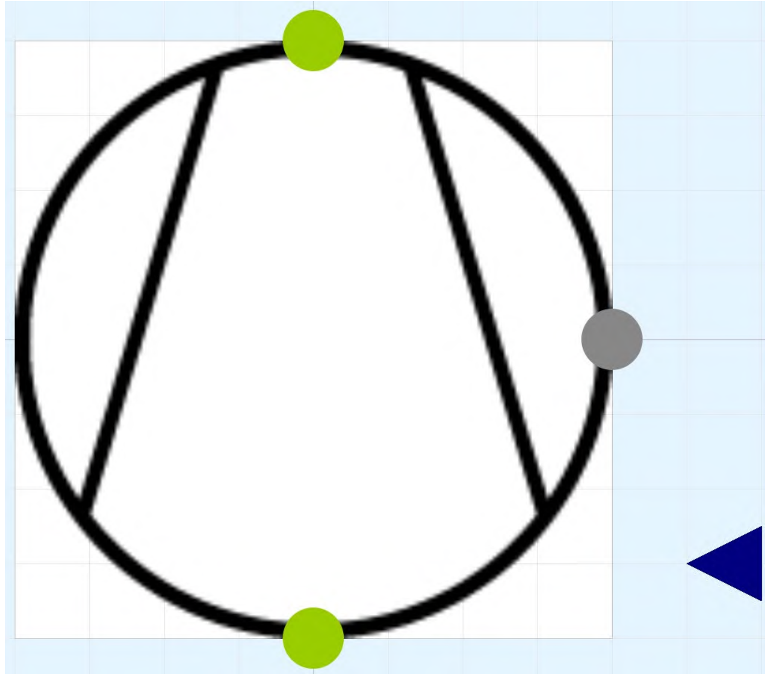
- Parameter variation: possible to “map” the whole spectrum of application
- Simulate complex and/or numerous scenarios
- Reusability of the models: easy scaling and change of subcomponents

Insight and analysis

- Detailed data, which are not always available during tests
- Fault detection/simulation

Versatile language: Modelica

- Multi-domain modelling language
- Object oriented with component approach
- Non-causal
- Open source
- Dynamic modelling
- Graphical and text views

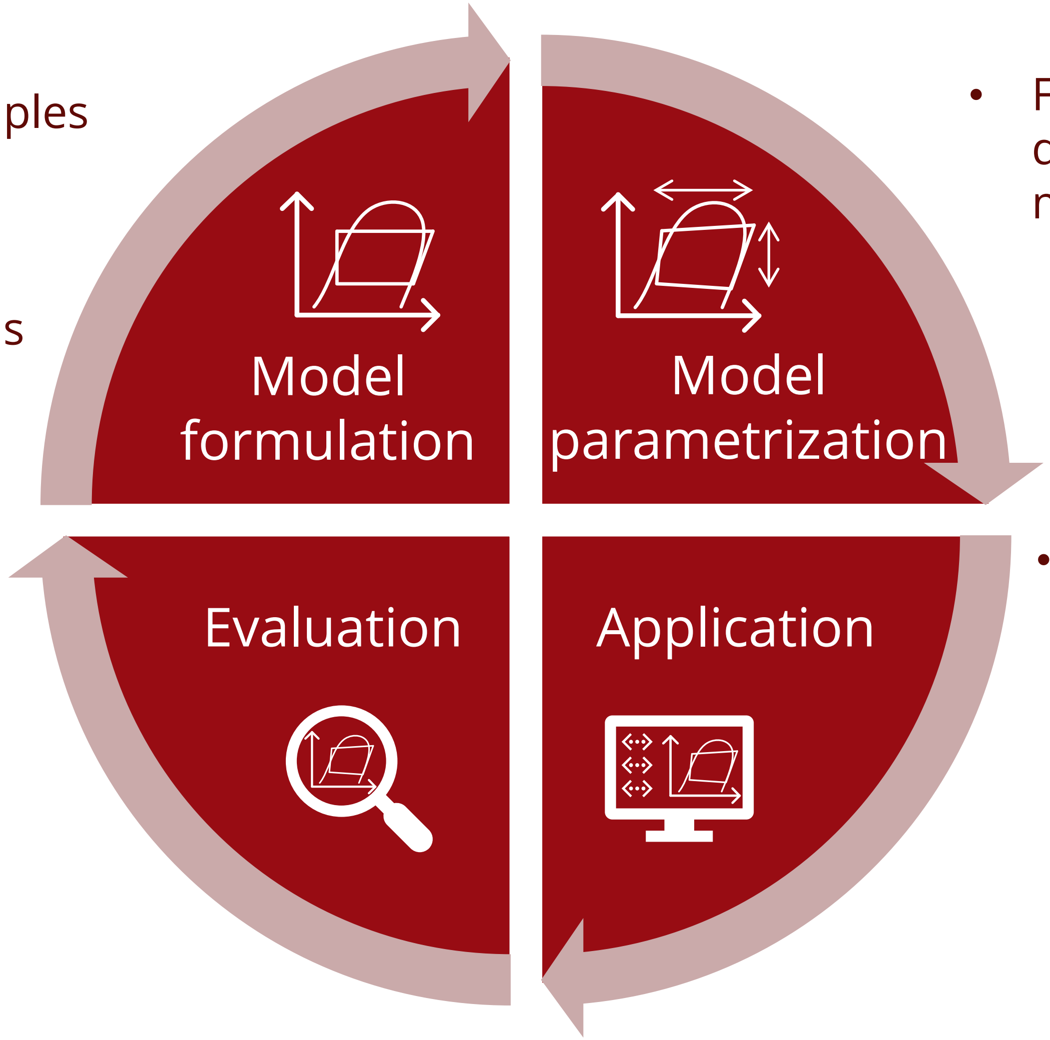


```
model PolynomialCompressor
  "Compressor for which the efficiencies are defined with manufacturers polynomials."
  extends TIL.VLEFluidComponents.Compressors.BaseClasses.PartialEffCompressor;

  import Modelica.Units.Conversions.{to_degC,to_bar};

public
  inner replaceable parameter SmartCO2HP.Components.Compressors.Polynomials
    polynomials constrainedby SmartCO2HP.Components.Compressors.Polynomials
    "Polynomials";

  SI.Temperature To "Saturated suction temperature";
  SI.Temperature Tc "Saturated discharge temperature";
  SI.VolumeFlowRate volumeFlow "Volume flow rate in the compressor";
  SI.MassFlowRate massFlow "Mass flow rate in the compressor";
  SI.VolumeFlowRate sweptVolume "Swept volume";
  SI.Power power "Electrical power consumed by the compressor";
  Real capacity(
    quantity="percentage",
    min=0,
    unit="1",
    displayUnit="%") "Compressor capacity";

equation

  To = to_degC(suctionVLEFluid.VLE.T_v);
  Tc = if polynomials.useDischargePressureForPolynom then to_bar(portB.p) else
    to_degC(dischargeVLEFluid.VLE.T_v);
  capacity = n/50;
  //assuming 100% capacity at 50Hz

  massFlow = 1/3600*capacity*(polynomials.massFlowCoefficients[1] + polynomials.massFlowCoefficients[
    2]*To + polynomials.massFlowCoefficients[3]*Tc + polynomials.massFlowCoefficients[
    4]*To^2 + polynomials.massFlowCoefficients[5]*To*Tc + polynomials.massFlowCoefficients[
    6]*Tc^2 + polynomials.massFlowCoefficients[7]*To^3 + polynomials.massFlowCoefficients[
    8]*Tc*To^2 + polynomials.massFlowCoefficients[9]*To*Tc^2 + polynomials.massFlowCoefficients[
    10]*Tc^3);

  power = capacity*(polynomials.powerCoefficients[1] + polynomials.powerCoefficients[
    2]*To + polynomials.powerCoefficients[3]*Tc + polynomials.powerCoefficients[
    4]*To^2 + polynomials.powerCoefficients[5]*To*Tc + polynomials.powerCoefficients[
    6]*Tc^2 + polynomials.powerCoefficients[7]*To^3 + polynomials.powerCoefficients[
    8]*Tc*To^2 + polynomials.powerCoefficients[9]*To*Tc^2 + polynomials.powerCoefficients[
    10]*Tc^3);

  //Isentropic efficiency
  effIsEff = (isentropicDischargeVLEFluid.h - suctionVLEFluid.h)*massFlow/power;
  isEff = effIsEff;

  //Volumetric efficiency
  volumeFlow = massFlow/suctionVLEFluid.d;
  sweptVolume = displacement*n;
  volEff = volumeFlow/sweptVolume;

end PolynomialCompressor;
```

General Modelling Procedure

- Formulation of physical principles
- Implementation as numerical model
- Structured libraries available
- Generic and adaptable models

- Fitting models to historical data, detailed simulations or online measurements



- Evaluation if simulation results are satisfying
- Derivation of adjustments in formulation, parametrization, application

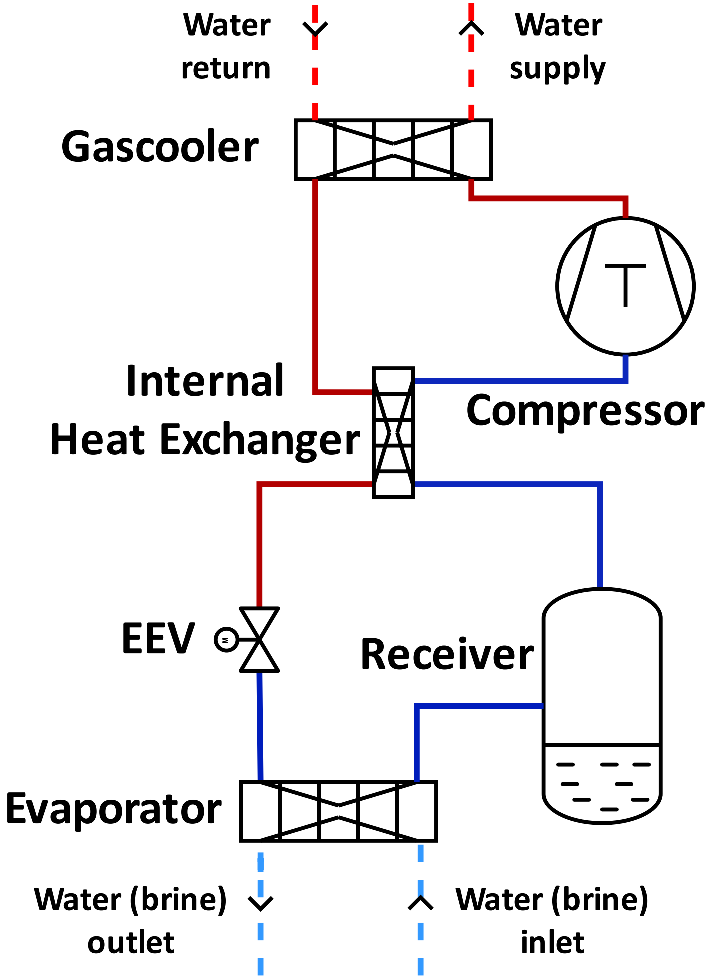
- Simulation of models for different purposes
    - What-if-analysis
    - System & component design
    - Benchmarking
    - Fault detection & diagnosis
    - System control

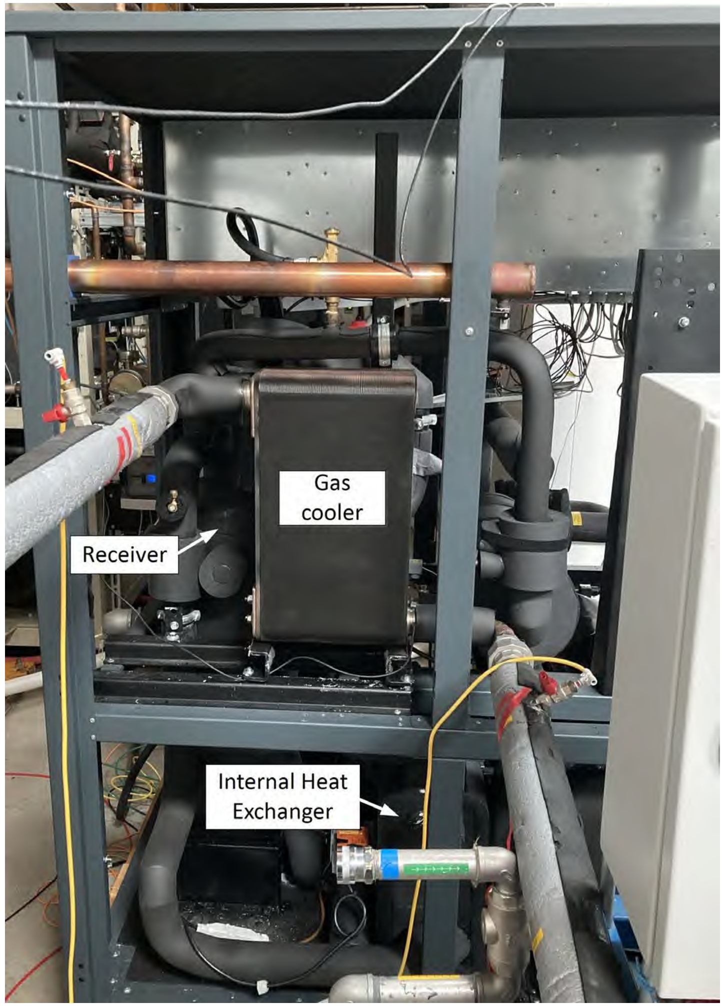
The SmartCO2HP project

- Develop a CO2 heat pump in the range 20 kW to 200 kW
- Online monitoring of the heat pump
- Water-to-water and air-to-water
- Receives funding from EUDP

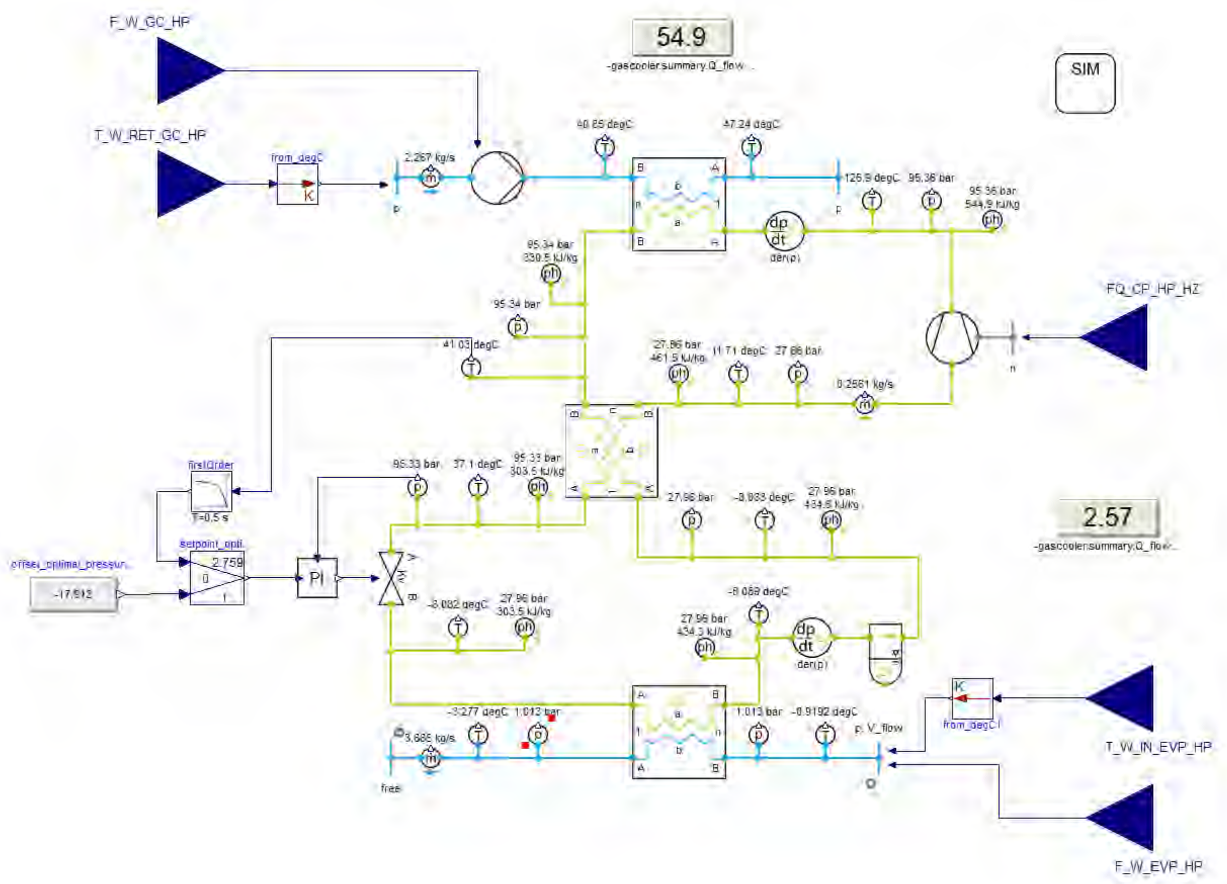
SMART CO_2 HEAT PUMP

Water-to-water heat pump





Model



Yang L, Li H, Cai SW, Shao LL, Zhang CL. Minimizing COP loss from optimal high pressure correlation for transcritical CO2 cycle. Applied Thermal Engineering.

Components

- Plate heat exchangers from TIL Suite, calibrated with measurements data
- Compressor adapted from TIL Suite, but using polynomials following EN12900
- Simple correlation for optimal pressure

  → potential for more realistic control

Inputs

- Temperature and flow in the gas cooler
- Temperature and flow in the evaporator
- Speed at compressor

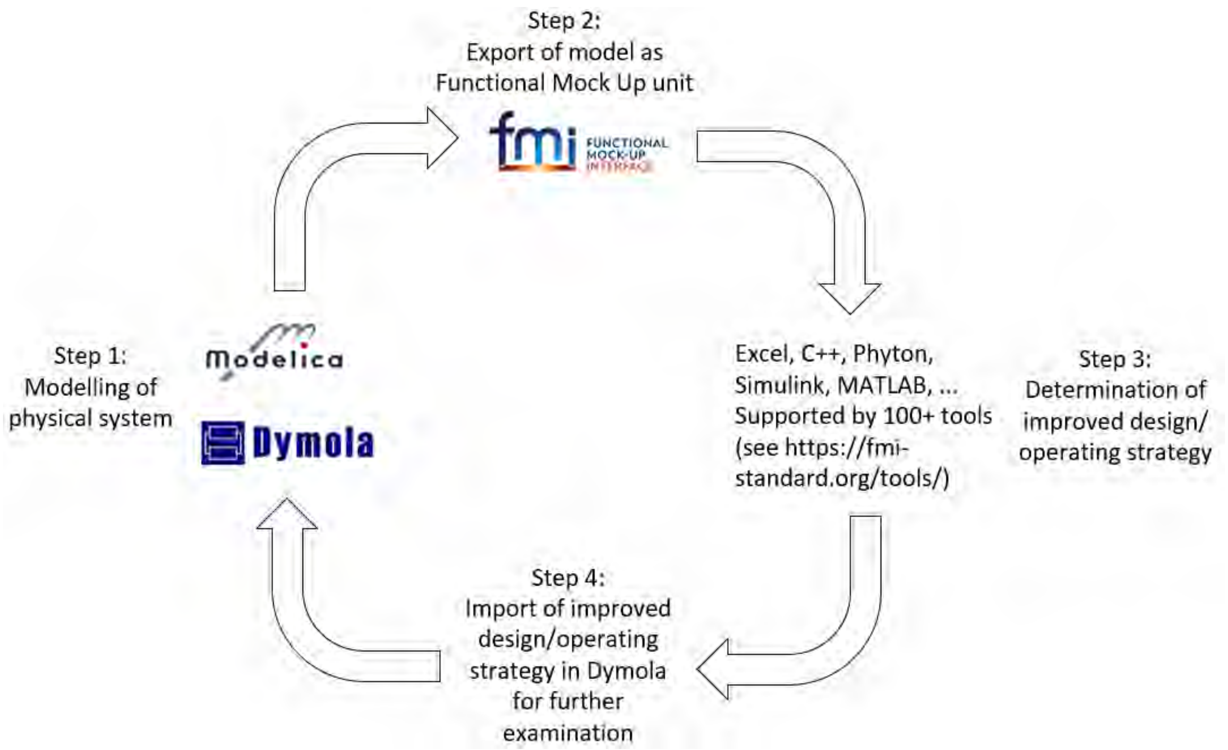
  → Can also run after setpoint on supply temperature

From model to results

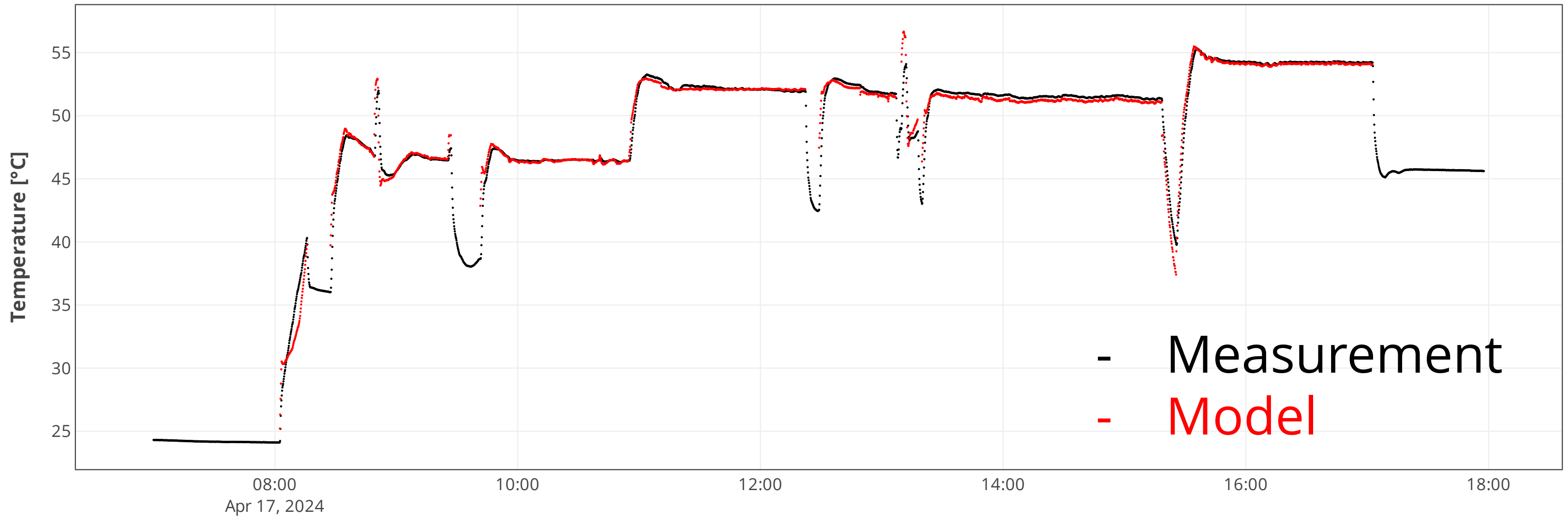
1. The model is built in Dymola
2. The model is exported as an FMU (Functional Mockup-Unit)

   FMU is a single zipped file (*.fmu) containing a description of interface data, functionality (code), calculation algorithm, and eventually additional information (documentation, tables/etc.)

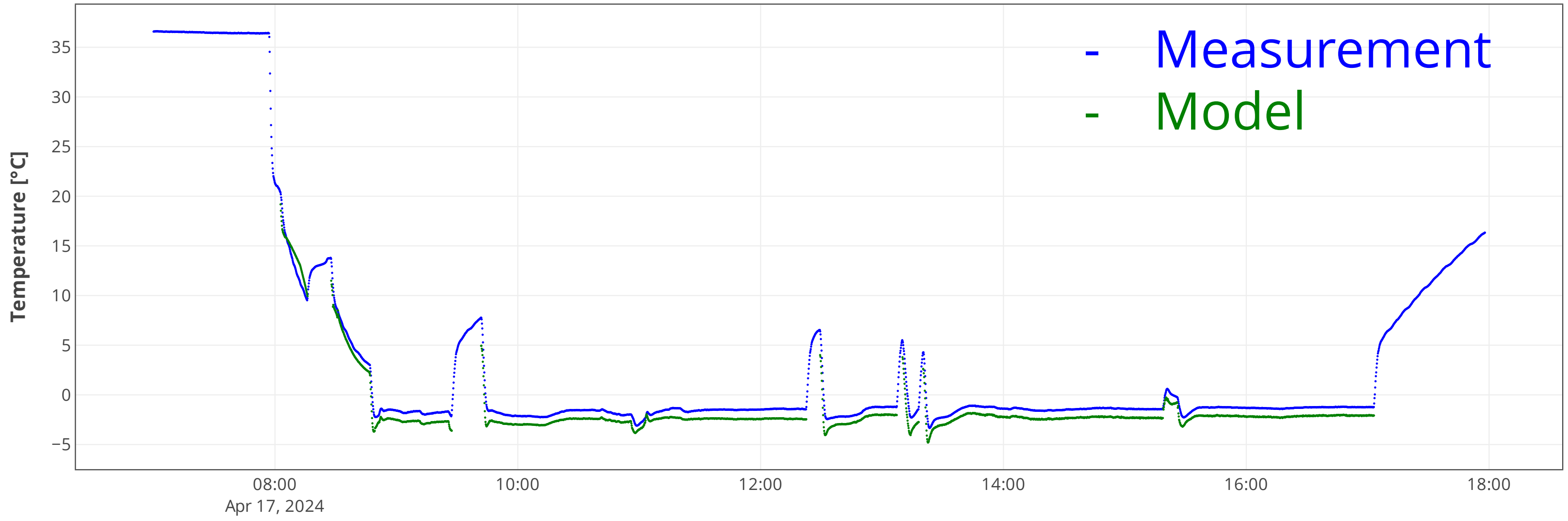
3. The FMU is run in Python with measured data (inputs of the model)
4. The measurements and calculations are compared and the model is improved



Results

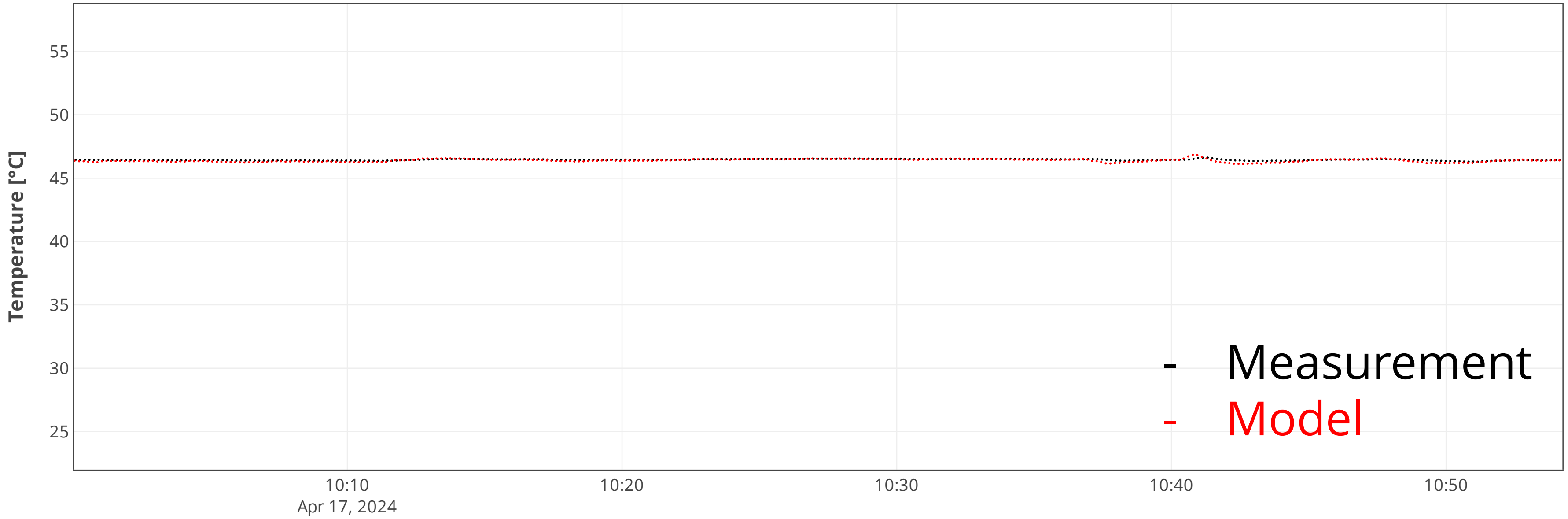


Water temperature out of the gas cooler

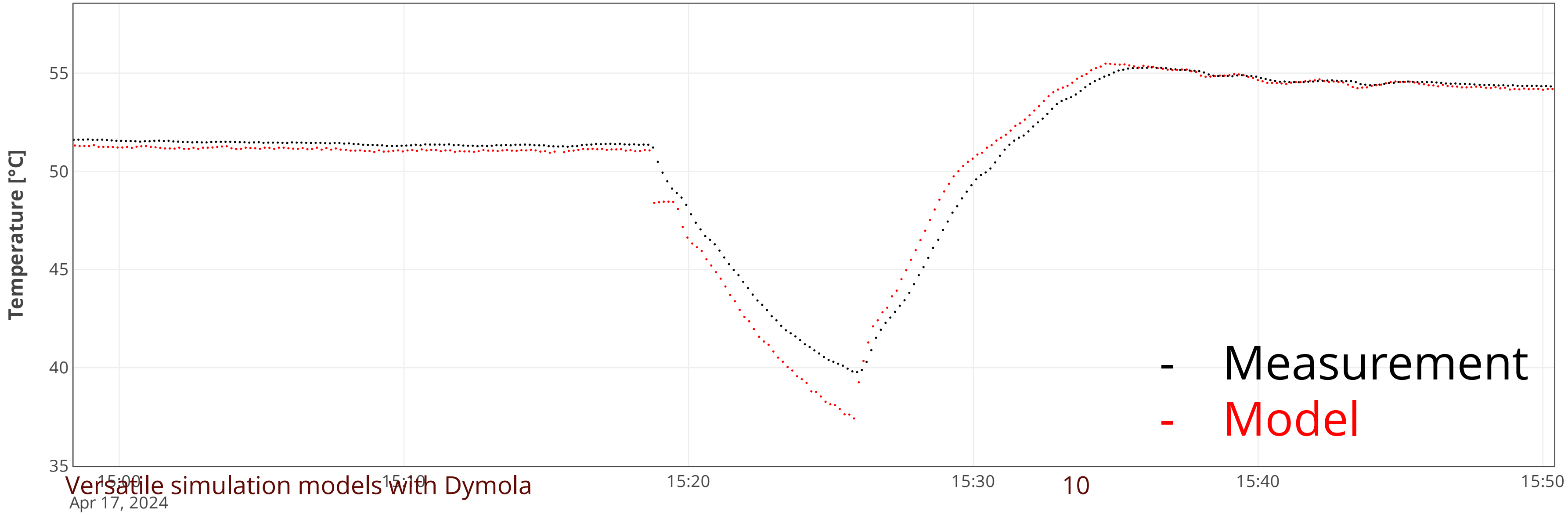


Brine temperature out of the evaporator

Results

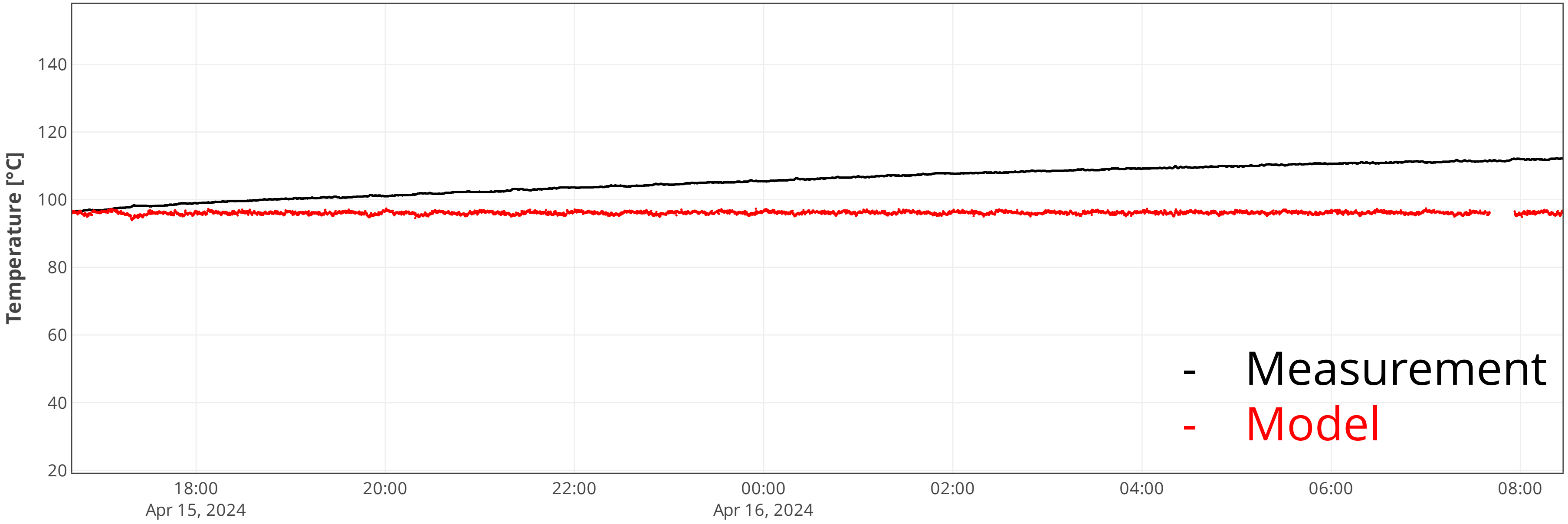


Steady state operation

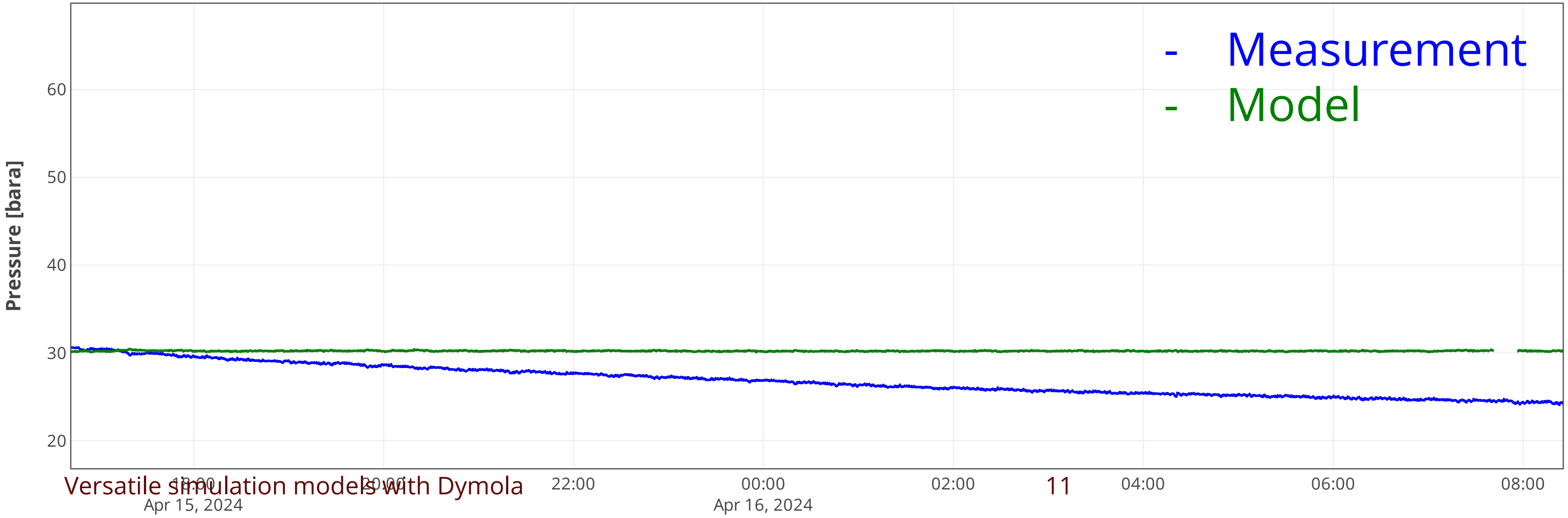


Change of the compressor speed from 66 Hz to 40 Hz, then to 66 Hz again

Results

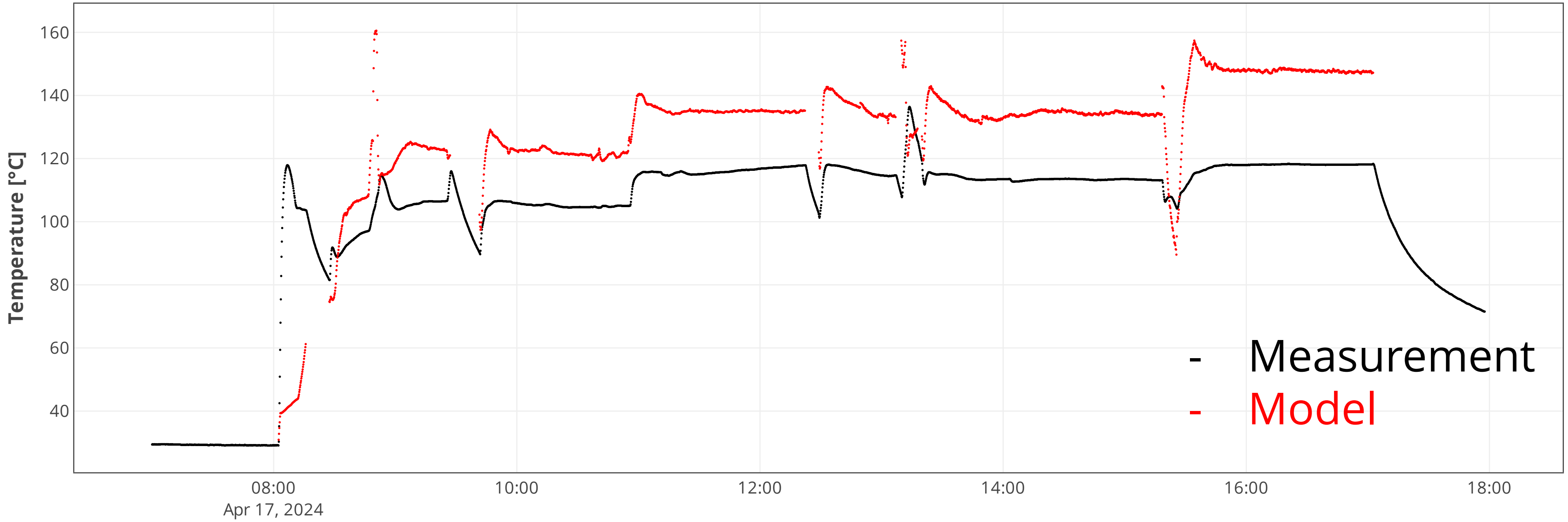


Discharge temperature



Suction pressure

Improvements to the model



Discharge temperature

- The model gives a much higher discharge temperature than measured
- Hypotheses:
  - Heat losses at the compressor not considered
  - Oil management is not present in the model

Future work

- Connect the model and run it parallel to the measurements

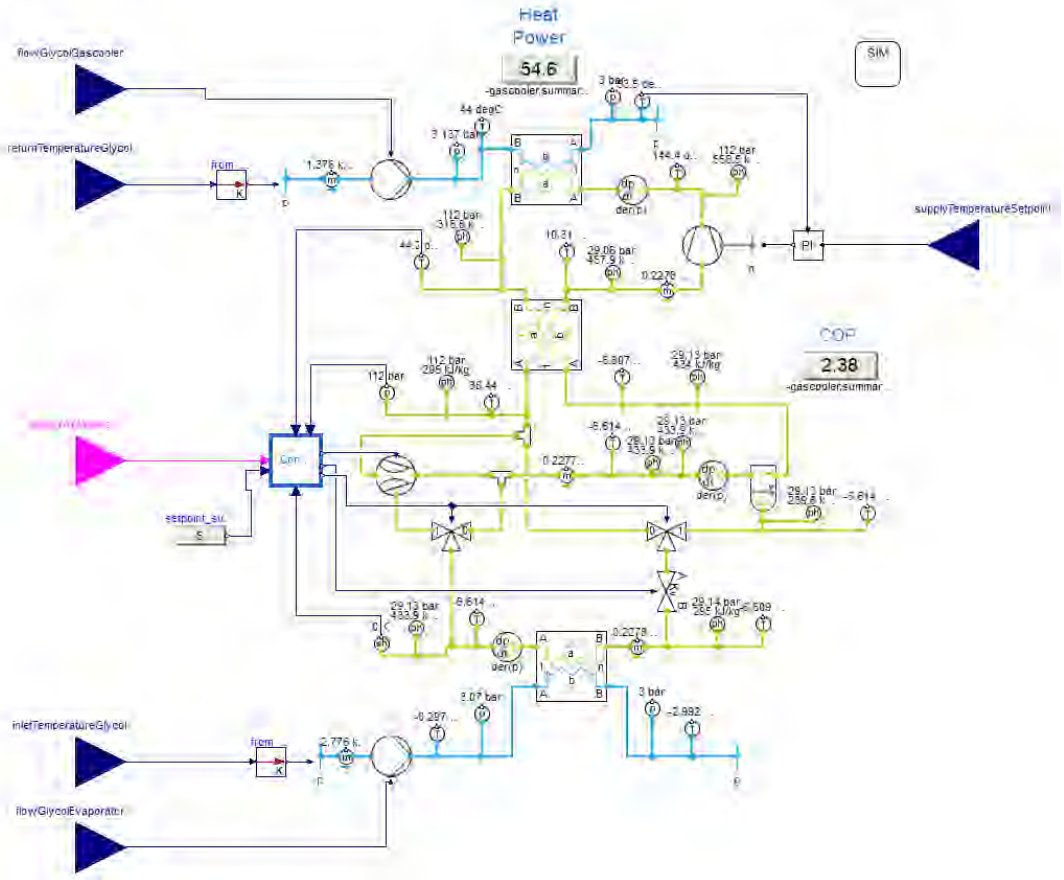
  → has already been done with a non calibrated model for trial

- Add the possibility to run with ejector

  → model ready but controls need to be finetuned

- Adapt the model for air-to-water unit

  → integrate and model the defrost strategies



Conclusion

Modelling of heat pumps and refrigeration systems with Dymola is a fast and efficient way to:

- Accurately estimate the performance of a system
- Conduct tests with limited test resources (test used for calibration)
- Better understand the system and detect faults
- Optimize the operation of the system by adapting the control strategies on a "virtual test bench"

Questions and answers

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Consultant, Danish Technological Institute

pde@teknologisk.dk

DANISH TECHNOLOGICAL INSTITUTE

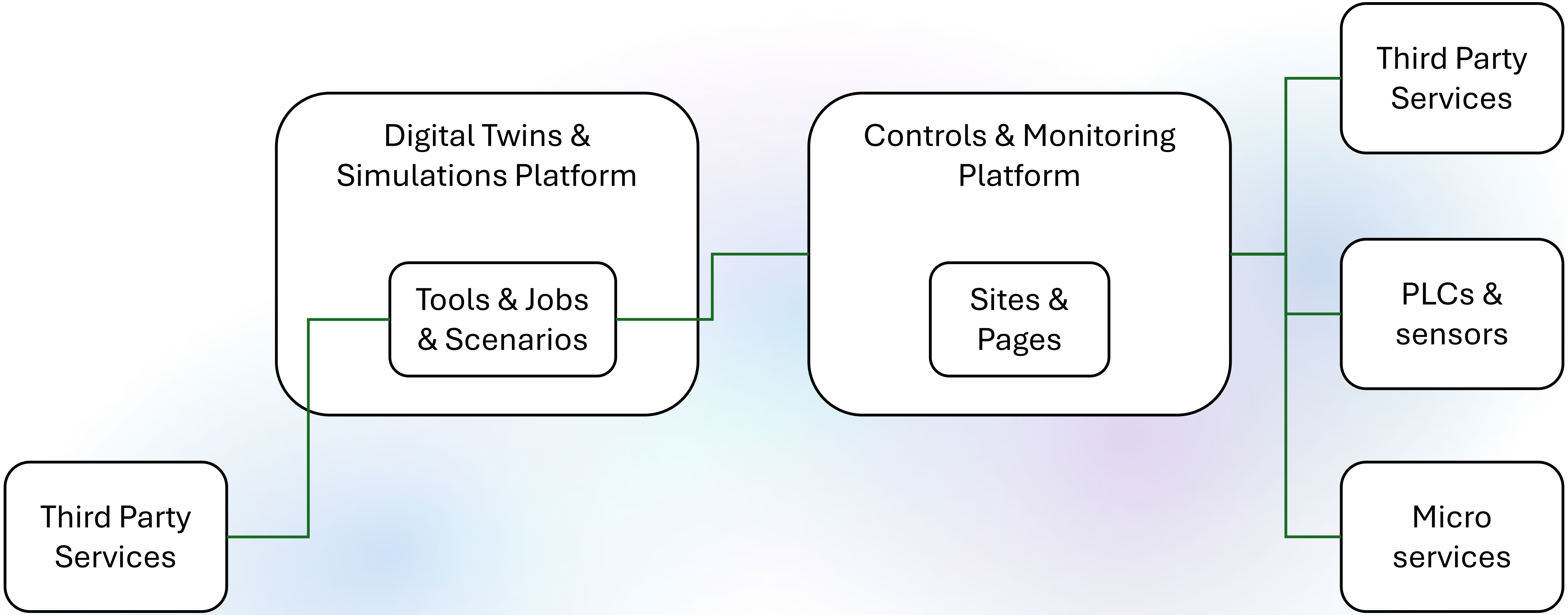
SCALING DIGITAL SERVICES FOR HEAT PUMP SYSTEMS

Lasse Nyberg Thomsen

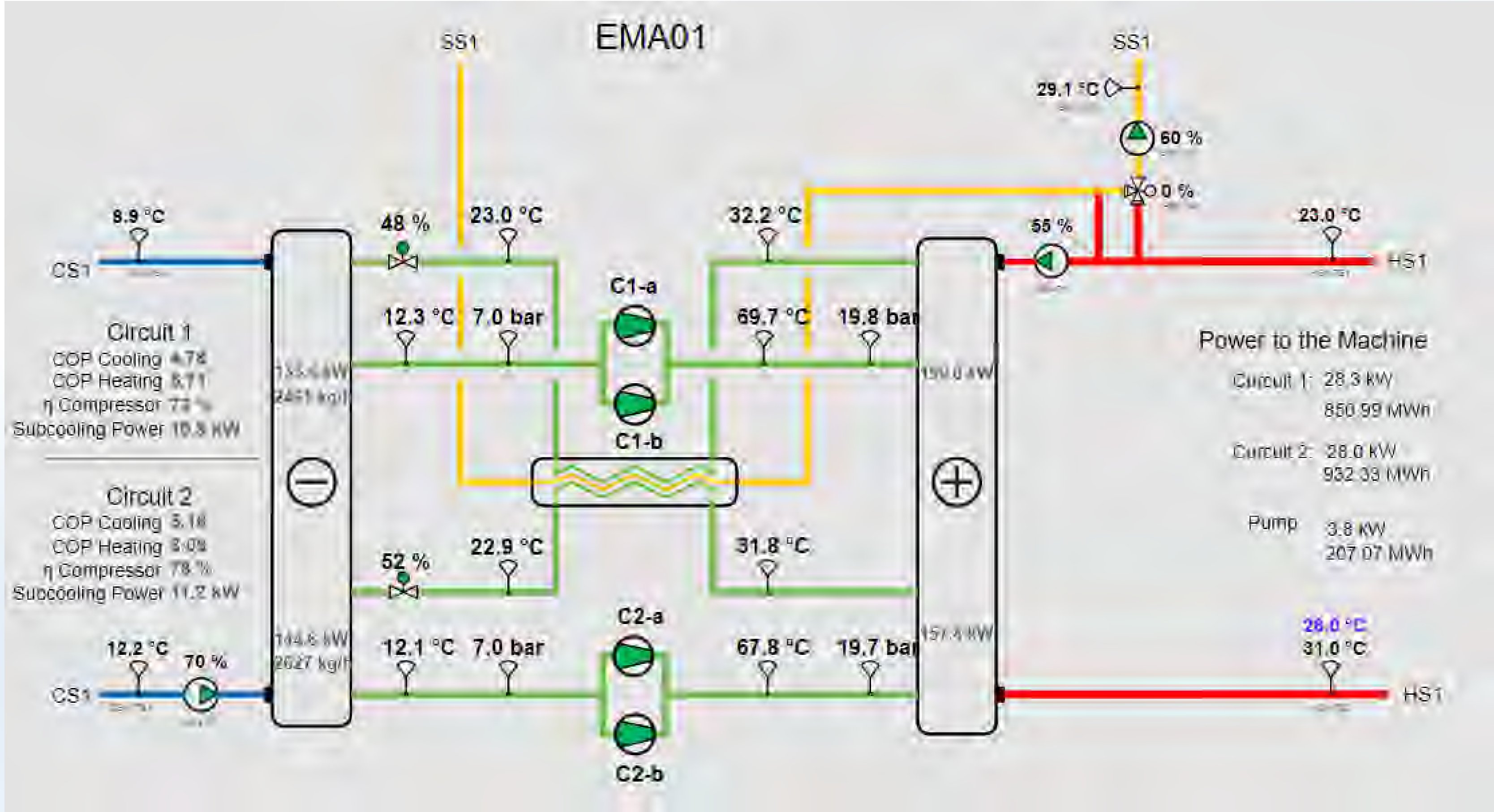
Numerous

Scaling Digital Services for Heat Pump Systems

Lasse Thomsen, 04072024


Digital Twins & Simulations Platform
Tools & Jobs & Scenarios
Controls & Monitoring Platform
Sites & Pages
Third Party Services
PLCs & sensors
Micro services
Third Party Services
Numerous

Example 1: Energy Machines Verification (EMV) Micro Service

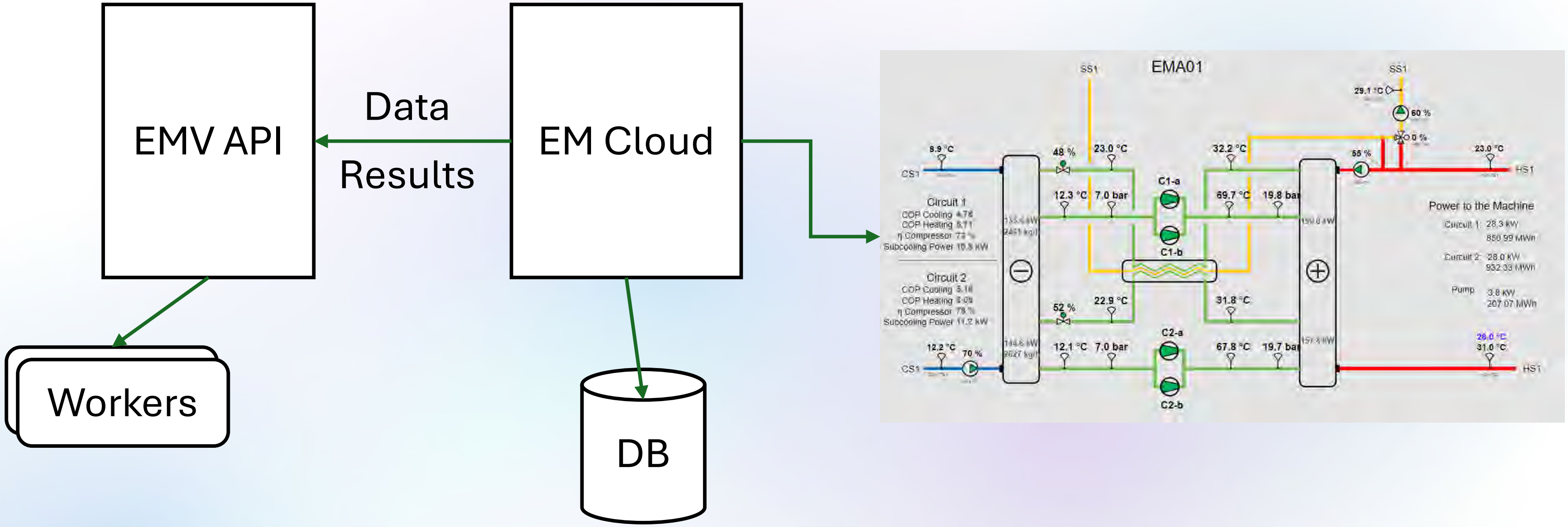


80 circuits online

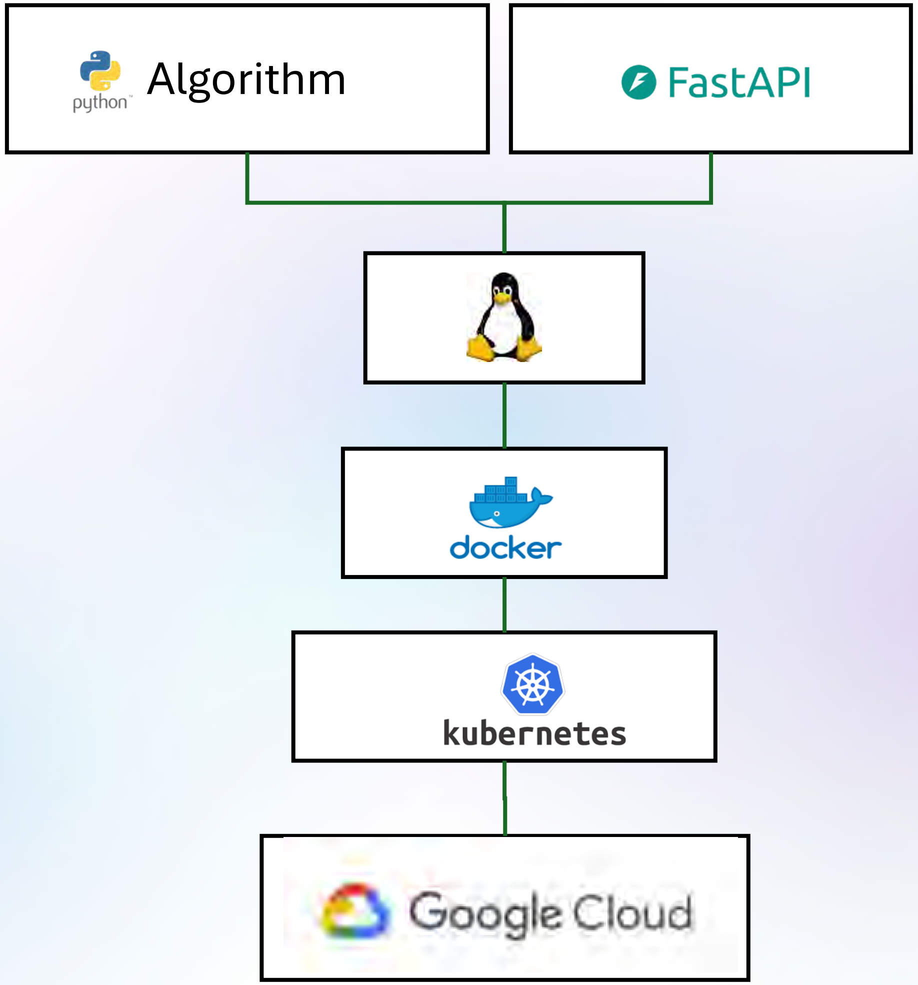
6 refrigerants

6 circuit types

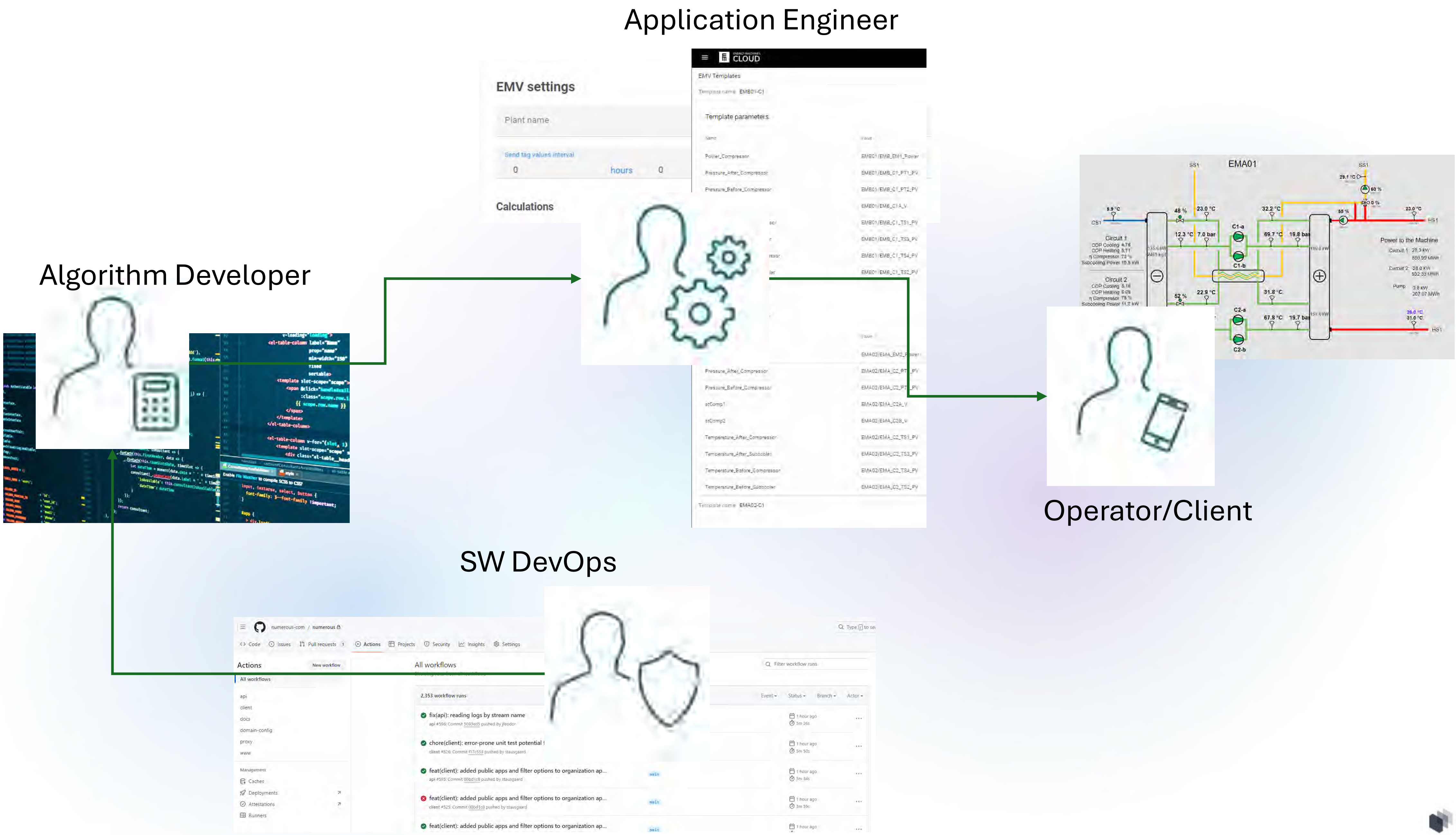
Numerous


EMV API
Data
Results
EM Cloud
Workers
DB
EMA01
Circuit 1
Circuit 2
Power to the Machine
C1-a
C1-b
C2-a
C2-b

Numerous



Numerous

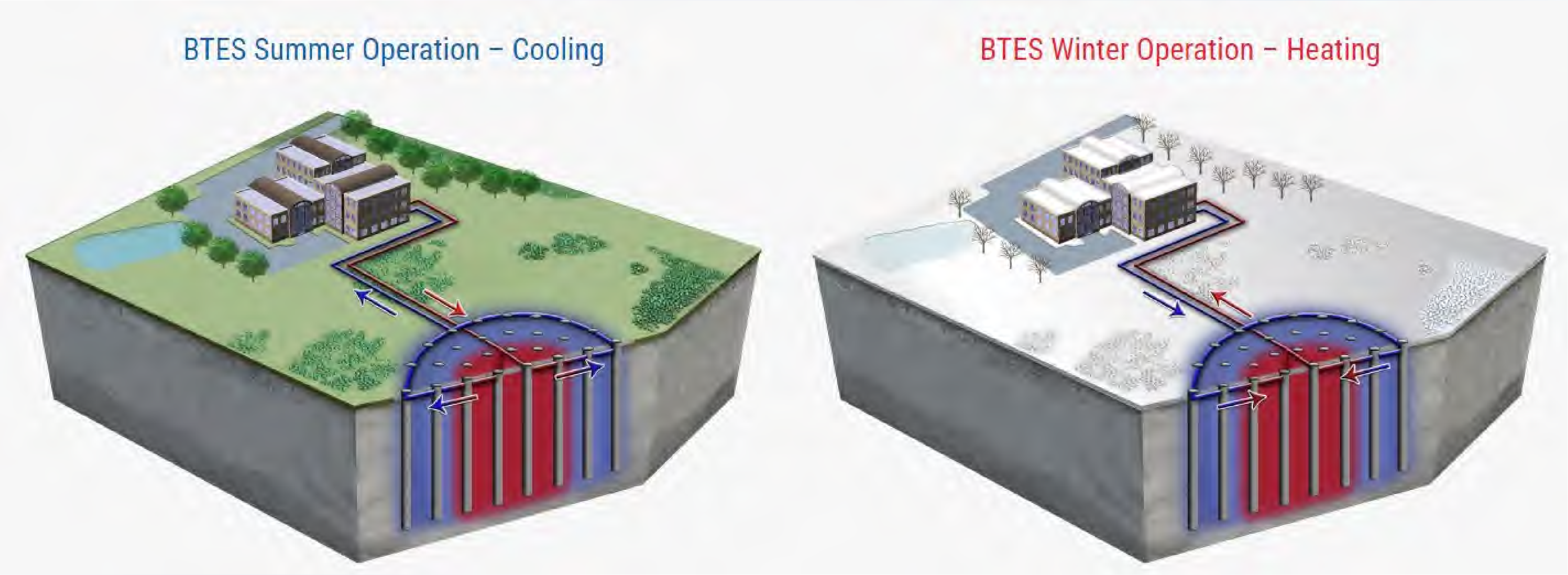

Application Engineer
Algorithm Developer
Operator/Client
SW DevOps
EMV settings
Plant name
Send tag values interval
hours
Calculations
CLOUD
EMV Templates
Template parameters
EMA01
Power to the Machine
Circuit 1
Circuit 2
Actions
All workflows
2,353 workflow runs
fix(api): reading logs by stream name
feat(client): added public apps and filter options to organization ap...

Numerous

Modularity

- The API can be used for offline processing, testing and validation
- The code base of EMV and the Controls Systems are separated
- The service is simple to integrate for third parties

Example 2: Monitoring Thermal Storage Performance



From underground-energy.com

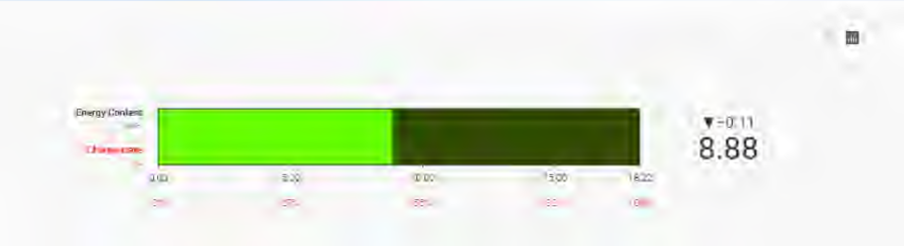
Numerous

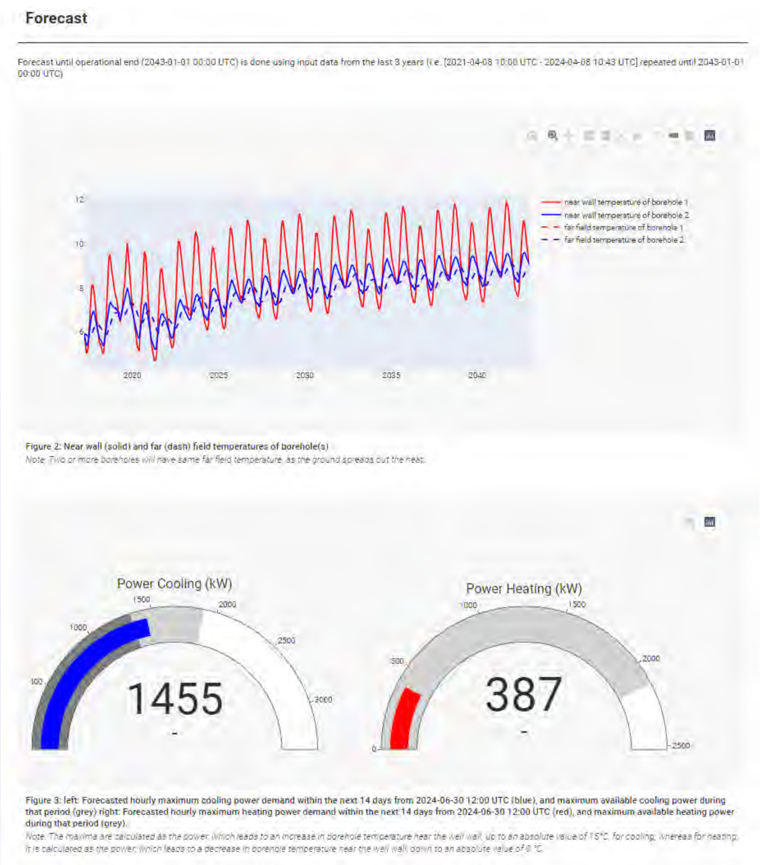
Value

- Monitoring operations and performance
- Ensuring sustainable operations for many years
- Analyzing potential in the storage
  - Possible cooling and heating loads

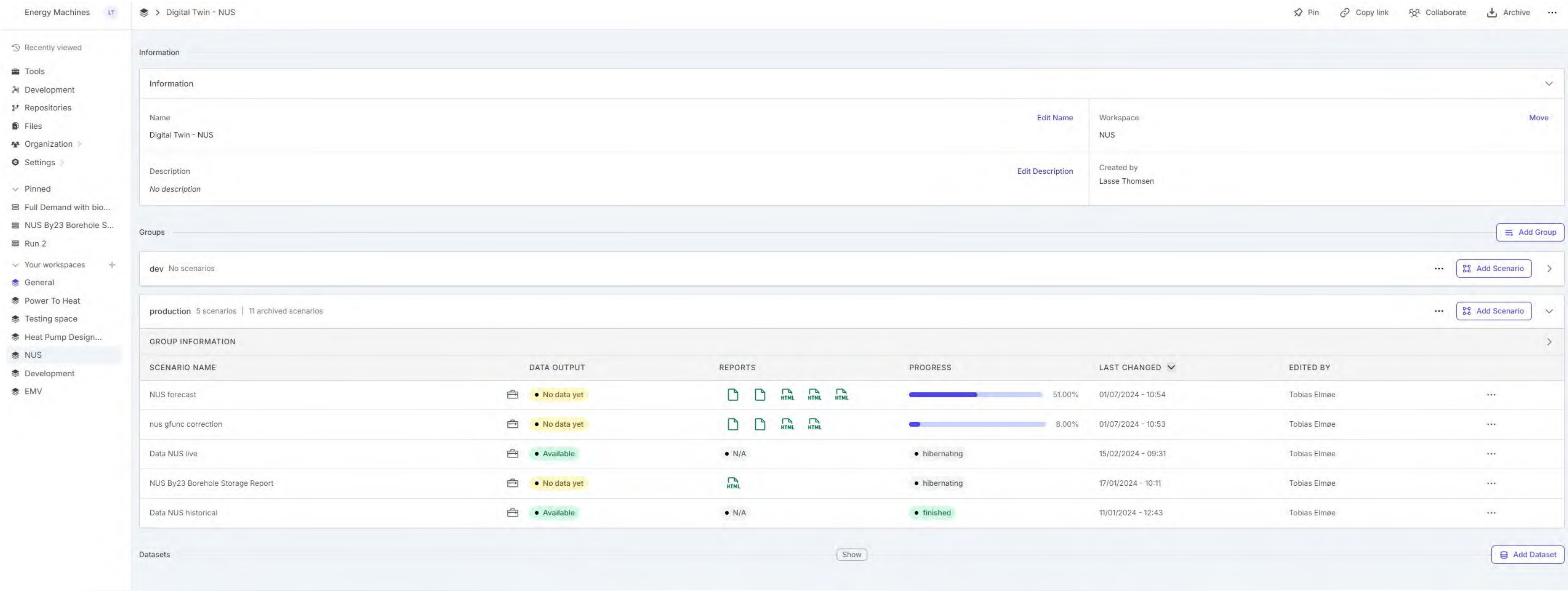
Service

Interactive HTML Report in Controls System updated Daily

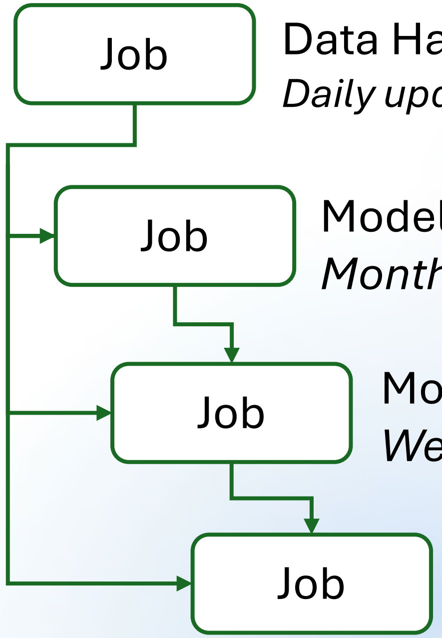




Numerous


Energy Machines
LT
Digital Twin - NUS
Pin
Copy link
Collaborate
Archive
Recently viewed
Tools
Development
Repositories
Files
Organization
Settings
Pinned
Full Demand with bio...
NUS By23 Borehole S...
Run 2
Your workspaces
General
Power To Heat
Testing space
Heat Pump Design...
NUS
Development
EMV
Information
Information
Name
Edit Name
Digital Twin - NUS
Workspace
Move
NUS
Description
Edit Description
No description
Created by
Lasse Thomsen
Groups
Add Group
dev No scenarios
Add Scenario
production 5 scenarios | 11 archived scenarios
Add Scenario
GROUP INFORMATION
SCENARIO NAME
DATA OUTPUT
REPORTS
PROGRESS
LAST CHANGED
EDITED BY
NUS forecast
No data yet
51.00%
01/07/2024 - 10:54
Tobias Elmøe
nus gfunc correction
No data yet
8.00%
01/07/2024 - 10:53
Tobias Elmøe
Data NUS live
Available
N/A
hibernating
15/02/2024 - 09:31
Tobias Elmøe
NUS By23 Borehole Storage Report
No data yet
hibernating
17/01/2024 - 10:11
Tobias Elmøe
Data NUS historical
Available
N/A
finished
11/01/2024 - 12:43
Tobias Elmøe
Datasets
Show
Add Dataset

BTES Monitoring Service



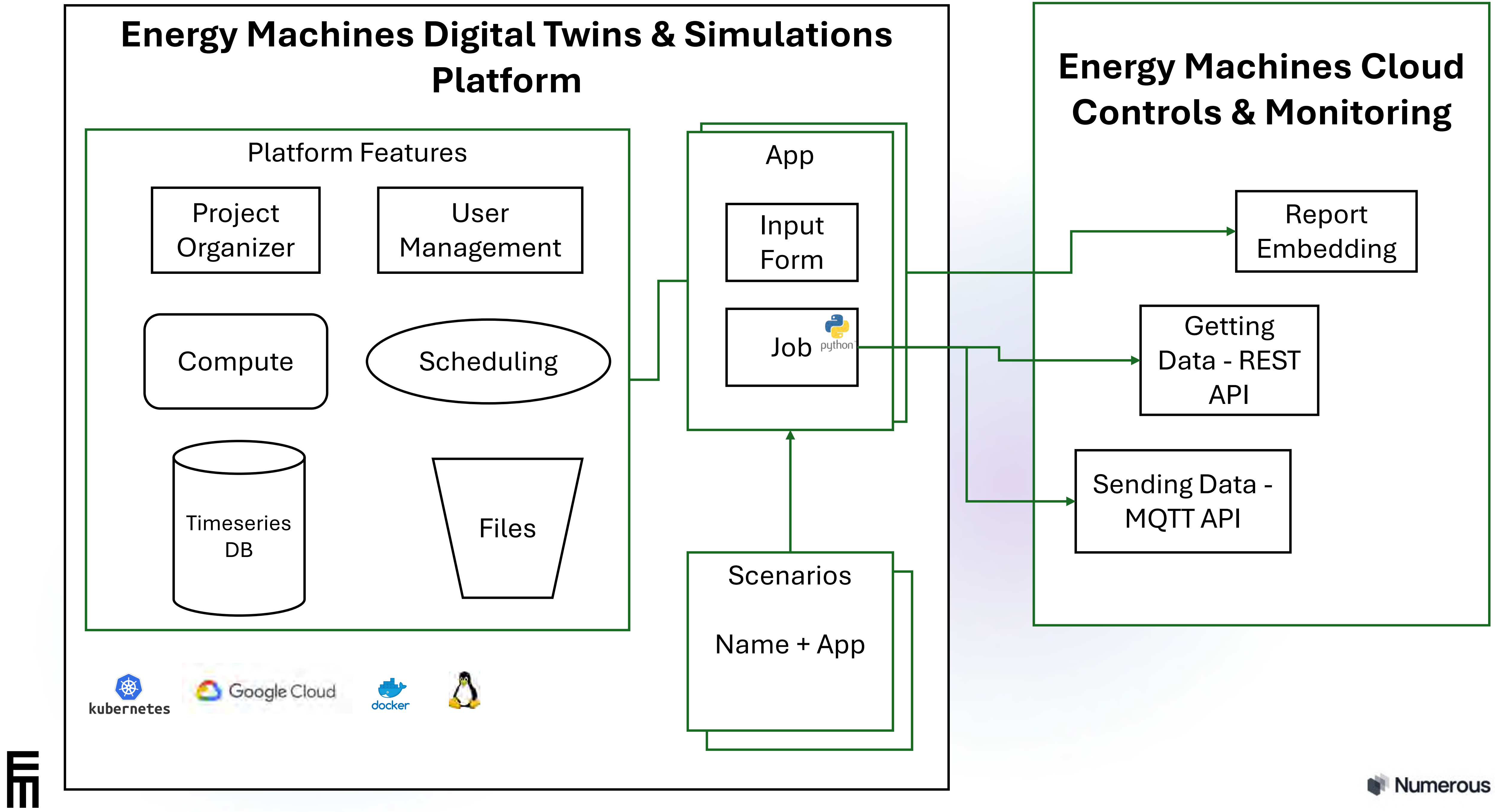
Data Harvester: Reading measurement data to timeseries storage
Daily update (5 min run time)

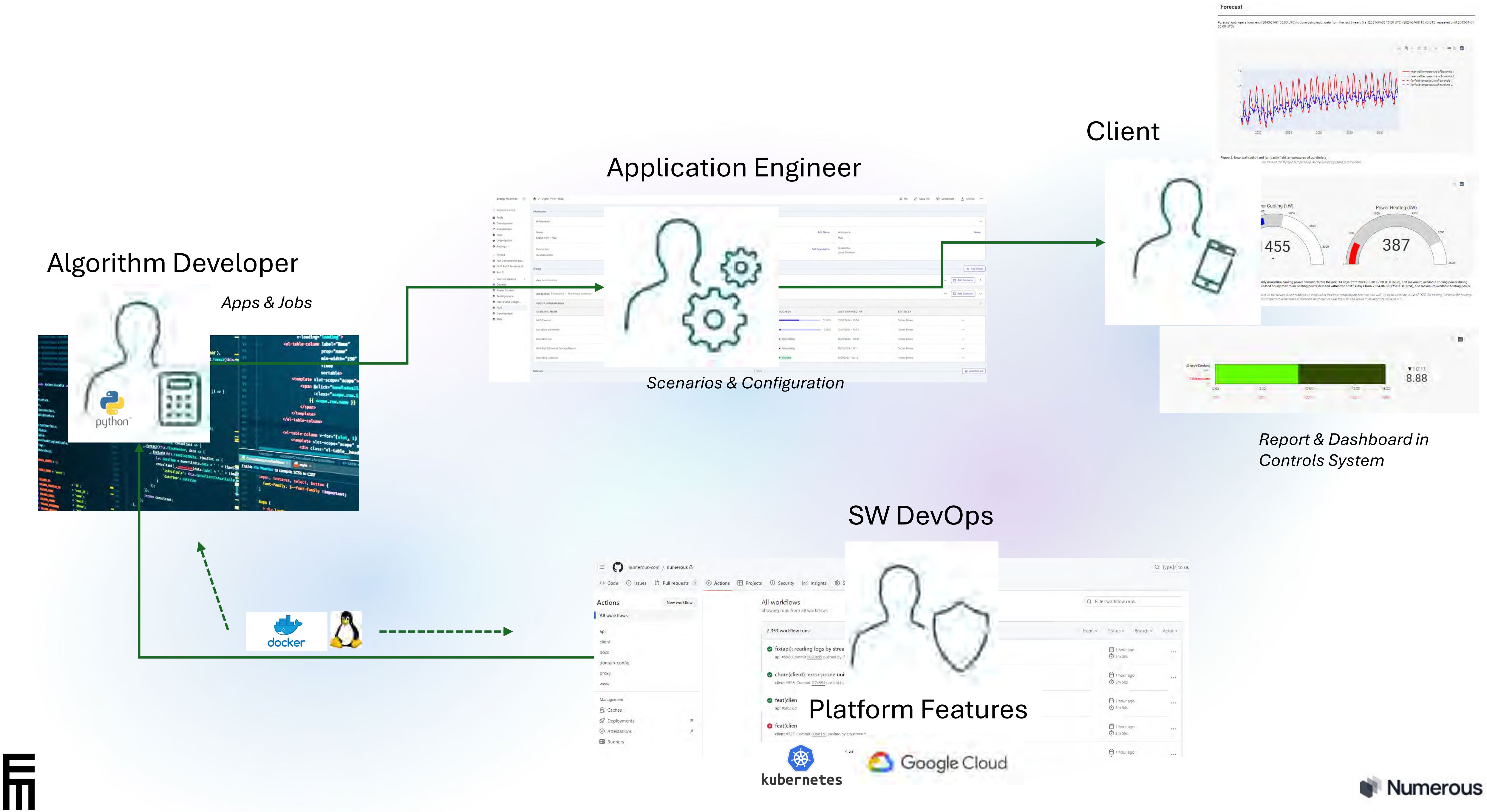
Model Correction: Updates model parameters based on data
Monthly update (10-12 hour run time) – report of coefficients and fitting

Model Forecast: Main simulation to forecast storage performance
Weekly update (1 hour run time) – report of simulation results

Analysis and Report: Performing data analysis on measured data and simulations
Daily update (5 min run time) – report for plant operators with high level analytics

Numerous


Energy Machines Digital Twins & Simulations Platform
Platform Features
Project Organizer
User Management
Compute
Scheduling
Timeseries DB
Files
kubernetes
Google Cloud
docker
App
Input Form
Job
python
Scenarios
Name + App
Energy Machines Cloud Controls & Monitoring
Report Embedding
Getting Data - REST API
Sending Data - MQTT API
Numerous


Algorithm Developer
Apps & Jobs
python
Application Engineer
Scenarios & Configuration
Client
Report & Dashboard in Controls System
SW DevOps
docker
Platform Features
kubernetes
Google Cloud
Numerous

Thank you for your attention!

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