Final report

1. Project details

Project title	Digital twins for large-scale heat pumps and refrigeration systems
File no.	64019-0570
Name of the funding scheme	EUDP (Energy Technology Development and Demonstration Program)
Project managing company / institution	Teknologisk Institut
CVR number (central business register)	56976116
Project partners	Danfoss, AK Centralen, TLK-Thermo GmbH, DTU Construct, DTU Compute, TU Braunschweig, Super Køl A/S, Kredsløb A/S
Submission date	02 May 2024

2. Summary

2.1 Project summary

2.1.1 Purpose of the project

Heat pumps and refrigeration systems aid in decarbonization by promoting electrification and sector coupling. The project focused on enhancing their efficiency and cost-effectiveness through digital twins, employing innovative reusable, modular, self-learning models, and advanced analytical methods for system analysis, diagnoses, and optimisation.

2.1.2 Results, conclusions, and perspective

Digital twins enhanced performance in heat pump and supermarket refrigeration systems by:

- Accurately reproducing their dynamic operating conditions.
- Enabling system optimisation, reducing energy consumption and costs.
- Providing a better understanding of system operation to system managers, designers, and manufacturers.
- Offering advanced system monitoring, optimisation, and fault detection and diagnosis capabilities.

Supermarket case highlights:

- A digital twin framework for the analysis and optimisation of supermarket refrigeration system successfully developed.

- Highlighted the importance of controllers' interaction for optimising operational performance.
- Cost and energy efficiency improved with variable speed compressors and modulated cabinet temperature control.
- Demonstrated the potential of grey-box models in effectively describing the dynamics of refrigerated cabinets and inferring their unknown thermophysical properties.

Large-scale heat pump case findings:

- An optimisation framework integrated with a graphical user interface (GUI) capable of enhancing operator decision-making.
- Underlined the use of online-calibrated simulation models as digital twins for effectively representing the operation of the heat pump over time, characterising the influence of fouling on performance degradation and describing effectiveness of fouling mitigation strategies.
- Demonstrated the potential of digital twin-based operation optimization services to enhance the energy efficiency and cost-effectiveness of a large-scale heat pump affected by performance degradation.

Conclusions and future directions:

- Digital twins offer a paradigm shift in system management and optimisation and enable additional services that open to new business opportunities.
- Incorporating digital twin insights into system design can further optimize performance and sustainability.
- The project paves the way for autonomous, self-regulating systems adapting to dynamic conditions, improving efficiency and sustainability.
- Future research to focus on automatic model generation and scalability.

2.2 Projektresumé

2.2.1 Formålet med projektet

Varmepumper og kølesystemer bidrager til dekarbonisering ved at fremme elektrificering og sektorkobling. Projektet fokuserede på at forbedre deres effektivitet og omkostningseffektivitet gennem digitale tvillinger, der anvender innovative genanvendelige, modulære, selvlærende modeller og avancerede analytiske metoder til systemanalyse og diagnose og optimering.

2.2.2 Resultater, konklusioner og perspektiv

Digitale tvillinger forbedret præstationerne i varmepumpe- og supermarkeds kølesystemer ved at:

- Nøjagtig gengivelse af deres dynamiske driftsforhold.
- Muliggøre systemoptimering, reducere energiforbrug og omkostninger.
- Giver systemadministratorer, designere og producenter en bedre forståelse af systemets drift.
- Tilbyder avanceret systemovervågning, optimering og fejlfinding og -diagnosticering.

Højdepunkter for supermarkedscasen:

- Et digitalt tvillinge-framework til analyse og optimering af supermarkedskølesystemer blev udviklet med succes.
- Fremhævede vigtigheden af controllernes interaktion for at optimere driftsydelsen.
- Omkostninger og energieffektivitet forbedret med kompressorer med variabel hastighed og moduleret kabinettemperaturstyring.
- Demonstrerede potentialet i grey-box-modeller til effektivt at beskrive dynamikken i køleskabe og udlede deres ukendte termofysiske egenskaber.

Nøgleresultater for stor-skala varmepumpecasen:

- Et optimeringsframework integreret med en graphical user interface (GUI) i stand til at forbedre beslutningstagning for operatører.
- Demonstreret potentiale for overvågning og optimering mod præstations-degradation på grund af tilsmudsning.

Konklusioner og fremtidige retninger:

- Digitale tvillinger tilbyder et paradigmeskifte i systemforvaltning og optimering og muliggør yderligere tjenester, der åbner op for nye forretningsmuligheder.
- At inkorporere indsigt fra digitale tvillinger i systemdesign kan yderligere optimere præstation og bæredygtighed.
- Projektet banebryder for autonome, selvregulerende systemer, der tilpasser sig til dynamiske betingelser, forbedrer effektivitet og bæredygtighed.
- Fremtidig forskning skal fokusere på automatisk modelgenerering.

3. Project objectives

3.1 Objective of the project

The objective of the project was to make the use of digital twins for large-scale heat pump and refrigeration systems more accessible to potential users, by reducing barriers to use and demonstrating the benefits on existing systems. To this end, the project harnessed the power of advanced mathematical modelling and digitalisation to develop adaptive, modular, and reusable digital twins that improve heat pump and supermarket refrigeration businesses by offering: advanced monitoring capabilities, efficient fault detection and diagnosis, and optimised operational performance. The main goals of the project can be summarised as follows:

- Reduce digital twins modelling effort by developing a general and modular framework for model development and validation.
- Improve long-term performance of heat pump and refrigeration systems using the developed digital-twin framework for advanced system monitoring, fault detection, control optimisation, and operation scheduling.
- Demonstrate how digital twin-based services can improve performance of existing systems and open to new business opportunities.

To summarise: the project was expected to provide additional knowledge on digital twins and their related services, thus leading to increased installations, optimised operation, improved coupling between heating/cooling and electricity sectors, and, in the long term, increased share of renewables.

3.2 Background on developed and demonstrated technology

Digital twins are virtual representations of physical objects, systems, or processes. They are designed to accurately reproduce the behaviour of the physical systems they mirror and therefore can serve as a simulation platform for product design, simulation, system integration, and operational optimisation. But a digital twin is much more than a simulation tool. Indeed, the integration of the digital model with real-time operational data enables further services, such as: advanced system monitoring, fault detection and diagnosis, and predictive analysis. Figure 1 shows how digital twins create value and open to new business opportunities.

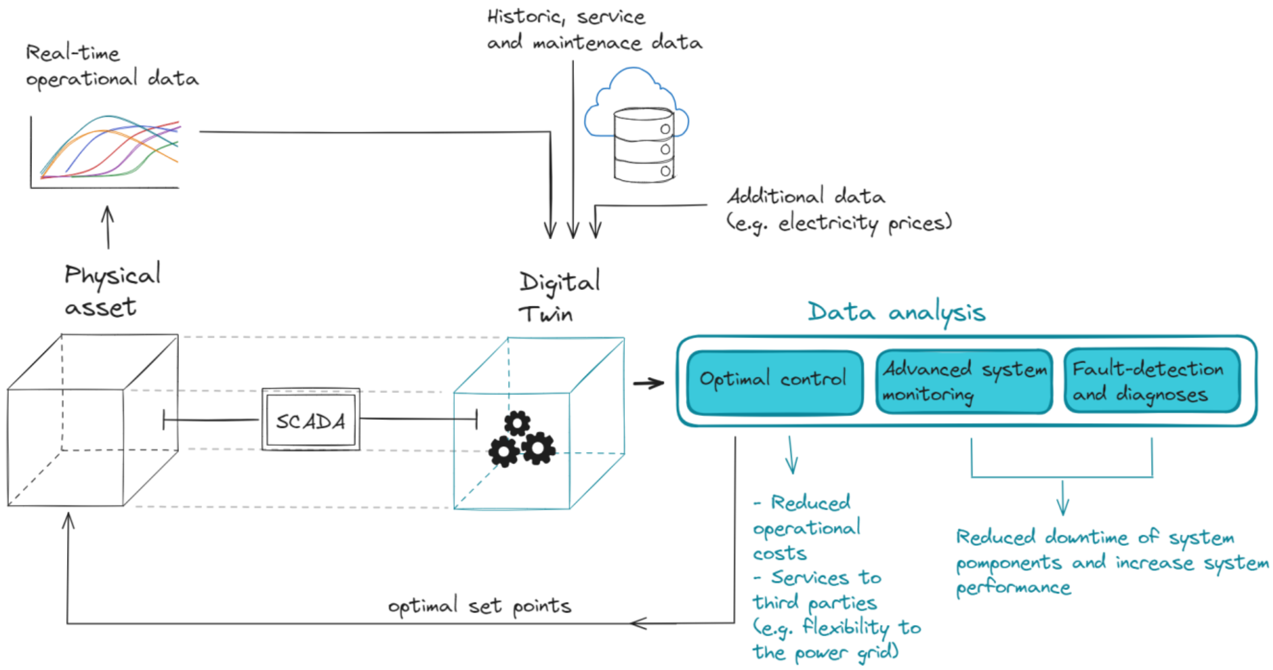

Figure 1: Digital twin value creation.

Digital twins are developed using advanced numerical models that can be grouped into two main types: detailed physics-based (or first principles) models and statistical (or data-driven) models. The former are fully based on the physical laws governing the system/process being modelled, i.e. continuity, momentum, and energy equations. Their parameters are fully interpretable and can be identified through expert knowledge and manufacturer datasheets. However, in practice, the parametrisation of these models can be complicated by partial or missing information, outdated documentation of the system and its components, or undocumented modifications. Furthermore, physic-based models require intensive work and are often numerically demanding. In contrast, data-driven models fully rely on measurement data and do not require any information about physical mechanisms, which limits their validity only to the operational range to which the training data refer. For these reasons, it appears promising to combine both modelling approaches using the so-called grey-box models. These models integrate the physical understanding with statistical methods and have demonstrated their effectiveness in modelling dynamic systems like heat pumps and supermarket refrigeration plants. They estimate the unknown parameters of a defined model structure (derived from prior physical knowledge) from data using statistical parameter estimation techniques. Moreover, unlike physics-based models, grey-box models can also include uncertainty effect into the model, e.g. the stochastic behaviour of customers in a supermarket, which, influencing the frequency of door opening in closed display cabinets, affects the cooling load. However, it is worth underlining that the choice of the modelling approach depends on the intended scope of use of the digital twin and that it can also result in a combination of two or more approaches.

The project investigated how to develop adaptive, modular, and reusable digital twins of large-scale heat pumps and supermarket refrigeration systems by developing a general modelling framework integrating grey-box and physical models. As for the grey-box models, two different modelling approaches were used. For refrigeration systems, grey-box models were derived from real operational data, while those used for heat pumps were derived from synthetic data generated from detailed physical models. As for the physic-based models, they were developed in Modelica [1] using TIL Suite [2], an external library of TLK-Thermo which contains a wide range of physics-based models for modelling thermodynamic systems.

4. Project implementation

4.1 How the project evolved

Overall, the project followed the planned schedule, and all milestones and objectives were reached (see Table 1). A two-months extension was necessary in order to finalise work packages 4 and 6, mainly due to paternity leave of key personal.

Table 1: Overview of the project milestones.

TMS	Description of Technical Milestones (TMS)	Status
TMS 1.1	Review finalized and recommendations for modelling frameworks and approaches for further work packages selected	Reached
TMS 2.1	Grey-box models for supermarkets generated and demonstrated using a detailed validated model.	Reached
TMS 3.1	Grey-box models for large-scale HP systems (case II and III) generated and demonstrated using a detailed validated model.	Reached
TMS 4.1	Report/publication about set point optimisation finalized/submitted for publication and potential for case studies determined.	Reached
TMS 4.2	Tool for indicating the potential for providing flexibility finalized and documented and potential for case studies determined.	Reached
TMS 4.3	Report/publication about predictive maintenance finalized/submitted for publication and potential for case studies determined.	Reached
TMS 5.1	Report/article about the methods for fault detection and diagnosis finalized/submitted for publication and potential for case studies determined	Reached
TMS 6.1	Establishment of the infrastructure for case I	Reached
TMS 6.2	Establishment of the infrastructure for case II	Reached
TMS 6.3	Establishment of the infrastructure for case III	Reached
TMS 7.1	Report with specifications of the digital twins finalized	Reached
TMS 8.1	Homepage published	Reached
TMS 8.2	First one-day event for technicians held	Reached
TMS 8.3	Second one-day event for technicians held	Reached
TMS 8.4	First article in magazine with focus on industry submitted	Reached
TMS 8.5	Second article in magazine with focus on industry submitted	Reached
TMS 8.6	Third article in magazine with focus on industry submitted	Reached
CMS	**Description of Commercial Milestones (CMS)**	
CMS 6.1	Online demonstration of the adapting models including monitoring services	Reached
CMS 6.2	Online demonstration of the set point optimisation including the tool to indicate the flexibility.	Reached
CMS 6.3	CMS 6.3: Online demonstration of the optimal production scheduling algorithms	Reached
CMS 7.1	CMS 7.1: Report about possible economic benefits and commercialization strategies finalized.	Reached
CMS 8.1	CMS 8.1: Guideline on digital twins published.	Reached

WP0: Project Management

The project was initiated with a two-day start-up meeting. Thereafter, there was continuous coordination of the project, with weekly meetings to plan and check the status of activities and reports.

WP 1: Definition of a framework for digital twins

A state-of-the-art review and analysis of possible data/communication infrastructures and software toolchains were conducted to define the framework within which to develop and deploy digital twin technologies. Results of the "state-of-the-art" review were documented in deliverable D1.1. As for the definition of the data/communication infrastructure and software toolchains, the task was initiated as planned, but formally finalized in 2021. The reason for this was the need to take into account the insights coming from work packages WP2 and WP3 concerning the modelling activities of digital twins. Results were finalised in deliverable D1.2.

WP 2: Development of grey-box models for supermarket refrigeration systems

This work package started with the implementation of the data infrastructure required to manage supermarket measurement data and access to the data by all partners. In parallel, an overview of failure mechanisms in supermarket refrigeration systems was carried out and results finalized in a report (i.e. deliverable D2.1). Different grey-box models were developed to model the display cabinets of supermarkets. These models consisted of a lumped-parameter description of the cabinets' dynamics derived from heat and mass balance equations, whose parameters were estimated directly from data using statistical techniques. Results of the modelling activity were presented at international conferences and disseminated through scientific publications. In parallel, a physic-based model of the remaining components of supermarket refrigeration systems was developed. Finally, the resulting grey-box models were integrated into the physics-based model, thus providing a functional digital twin of a supermarket refrigeration system, which was successfully validated against actual operational data.

WP 3: Development of grey-box models for large-scale heat pump systems

WP 3 started with the definition of the demonstration cases through the collection of relevant information and identification of required measurement data. In parallel, an analysis of failure mechanisms in heat pump systems was initiated and finalized in a report (deliverable D3.1). In addition, the work package included the development of dynamic, detailed analytical models used as digital twins of large-scale heat pump systems. This modelling activity was successfully concluded with the development of digital twins for the analysed use cases, namely two large-scale heat pump systems for district heating supply: one utilizing seawater as a heat source and the other one cooling down an industrial water stream. The heat pump system for industrial cooling was prone to fouling, which was represented by the detailed dynamic model and a simpler simulation model named quasi-steady-state model. The numerical models have been compiled, parameterized, and validated for different operational scenarios and used for the development and testing of methods for monitoring and optimization. This concluded the work package.

WP 4: System control strategies and optimal scheduling of production periods

WP 4 started with the analysis of the operating conditions of supermarket refrigeration systems. Particular attention was given to the interactions between the dynamics of the display cabinets and the compressor packs. This was aimed at better understanding how these dynamic phenomena could be optimized to increase the system performance by using digital twins. Afterwards, the models developed in WP2 were coupled with an emulator of the pack controller to evaluate the impact of different control strategies on the performance of the refrigeration system, both at system and component level. Based on the simulation results, new optimized control settings were tested at COOP365 in Otterup (formerly Fakta). Heat recovery data from SuperBrugsen in Kerteminde was also analysed, and new control settings were recommended. However, technical issues with the heat recovery heat exchanger interrupted the ongoing analysis. For the heat pump systems, a framework for continuous set point optimisation was developed and used for the seawater source heat pump, while for the heat pump system for industrial cooling, a framework was developed for optimal planning of heat exchanger cleaning. Control strategies enabling flexible operation of the heat pump system for industrial cooling were also investigated. The results of this work package were finalised in several conference and journal papers.

WP 5: Development and application of methods for fault diagnosis

WP 5 started with the analysis of sensor data to be used for fault-detection. This was done to identify potential reading and installation errors. Then, historical data were used to develop and test different fault detection methods. Based on these methods, studies on refrigerant leakage detection, automatic fault detection on installed sensors and fault detection in ammonia plants were prepared and published. The fault detection algorithms developed for the supermarket case focused on refrigerant leak detection. These were first demonstrated in a supermarket installation in France and then continued with numerical studies. For the heat pump cases, the developed algorithms focused mainly on fouling detection and planning of the related cleaning processes.

WP 6: Demonstration of digital twins in case studies

For the supermarket facilities, refrigerant leak detection methods were demonstrated. Furthermore, optimized control settings based on simulation results from WP4 were tested for demonstration purposes. For the heat pump system for industrial cooling, methods for optimal cleaning planning of heat exchangers were developed and recommendations for implementation derived. For the seawater source heat pump, a digital twin framework for continuous monitoring and set point optimisation was built and integrated with a graphical user interface (GUI) to easily provide the plant operator with set point optimisation recommendations.

WP 7: Analysis of the potential of digital twins to create socioeconomic benefits

WP 7 began by forming an overview of possible services of digital twins for large-scale heat pumps and supermarket refrigeration systems. Based on the overview, various services were selected and prioritized during the modelling activities. Moreover, the socio-economic benefits of digital twin services for heat pump and supermarket refrigeration systems were documented in a final report.

WP 8: Dissemination

First, the project website was published: www.digitaltwins4hprs.dk. Thereafter, project results were continuously disseminated at workshops and conferences and on the website. Moreover, articles were published in both specialized magazines and scientific journals.

4.2 Risks associated with conducting the project

The main risks identified in the project and the strategies used for their mitigation are described in Table 2.

Table 2: Risks identified in the project and strategies used for their mitigation.

Risk	Mitigation strategy
Availability of operational data to develop, calibrate and validate numerical models.	Use of historical operational data or different systems when suitable data from a specific system was not available.
Cybersecurity concerns from data providers, including use cases.	Implementation of reliable data management and security procedures (firewalls, passwords, etc.), along with describing them to the companies operating the use cases.
Measured data with suitable quality levels (e.g. accuracy, completeness, timeliness).	Characterization of sensors and implementation of suitable data processing methods
Reliability of the data management infrastructure.	Employ mature data management technologies.
Operational challenges for the systems used as case studies.	Use of historical operational data or change of case systems when a specific system was not available.

5. Project results

5.1 Achievement of the project objectives

All the project objectives were successfully fulfilled, as documented by the project's reports and by the various publications in conference proceedings and scientific journals.

5.2 Technological results

The main technological result of the project is the modelling framework that facilitate the development and deployment of digital twins for large-scale heat pump and refrigeration systems. This framework consists of the numerical models developed in work packages 2 and 3, capable of closely reproduce the dynamic behaviour of heat pump and refrigeration systems, and of the digital infrastructure needed to build and connect such models with their physical counterpart. Figure 2 shows a schematic of the developed digital twin framework.

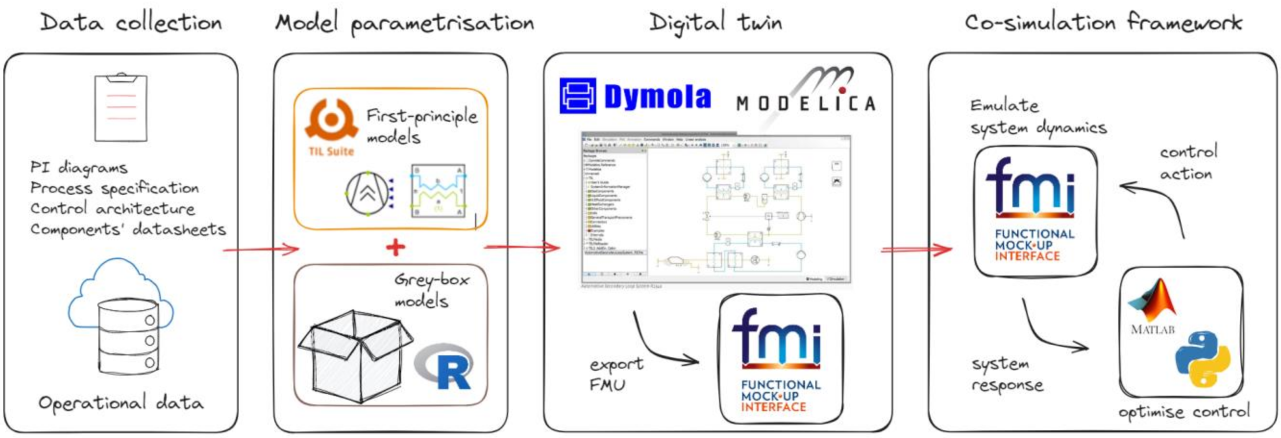

Figure 2: Modelling framework.

A further achievement of the project was the demonstration of how different modelling approaches can be combined to build a digital model that can be successfully used to improve the performance of its physical counterpart (i.e. real system). In particular, it was shown how to develop grey-box models from monitoring data and physical knowledge and how to integrate them with physical-based models to build an accurate and reliable digital twin. It was also shown how to use grey-box models to infer unknown physical parameters directly from data, thus facilitating the parametrisation of digital twins.

Hereinafter, the results on the three case studies investigated during the project are presented. A detailed description can be found in the related project deliverables (D6.1, D6.2, and D6.3), which are public available on the project website.

5.2.1 Case I: Supermarket refrigeration

Energy consumption of refrigeration systems is a major operational concern for supermarkets, along with ensuring the highest quality of goods and their preservation. Refrigeration accounts for about 50 % of the total energy use in a supermarket. The power input to compressor rack is the main responsible for this high energy usage. It is strongly influenced by the pressure levels between which the compression groups operate. Larsen et al. [3], showed that rising the suction pressure is one of the most effective ways to reduce this power consumption, while increasing energy and cost efficiency.

In modern refrigeration systems, the suction pressure is kept constant at its set point value by the pack controller, which adjusts the compressor capacities according to the actual cooling loads. However, operational data revealed that when the temperature of supermarket display cabinets is thermostatically controlled, this pressure fluctuates strongly due to the dynamic interaction between the control actions of the cabinet thermostats and the pack controller. This was suspected to lead to an increased energy consumption and an increased number of compressor starts and stops.

In light of this, the project set out to use a digital twin of a commercial refrigeration system to investigate further the mutual interactions between these two controllers, assess the impact of the pressure fluctuations on the energy consumption of the compressor groups and based on this, identify recommendations for better control solutions.

5.2.1.1 Case study description

The CO_2 refrigeration system of the supermarket Fakta in Otterup (DK) was taken as case study. This choice stemmed from the large amount of data available in this supermarket for model development and validation due to its participation in a previous research project [4].

The layout of the CO_2 refrigeration system (almost standard in Denmark) is shown in Figure 3. The medium-temperature (MT) group consists of one variable-speed and one fixed-speed compressor. The maximum capacity of the variable speed compressor is approximately 80 % of the capacity of the fixed speed compressor, which ensures an almost continuous capacity modulation. Conversely, the low-temperature (LT) suction group consists of two fixed speed compressors and can therefore provide stepped capacity control. However, despite the possibility of a smoother regulation, the MT group suffers from efficiency losses during part load operation and start/stop of the first compressor. As for the display cabinets, the MT and LT groups consist of seven and four evaporators, respectively, which are operated day and night at a fixed evaporation temperature reference of, respectively, -8 °C and -30 °C.

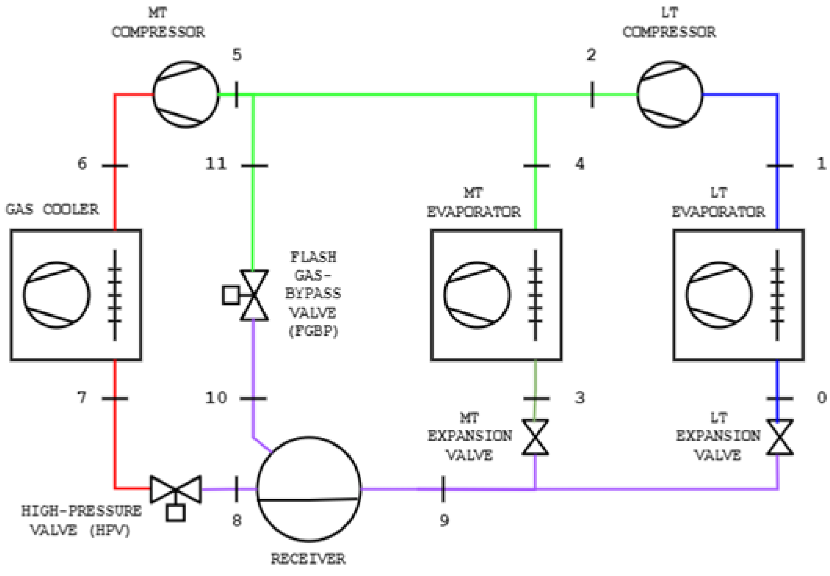

Figure 3: Layout of a typical CO_2 booster system.

5.2.1.2 Model-based framework

A detailed simulation model based on thermodynamic principles was used as a digital twin and developed in the language Modelica using the TIL Suite library. Parameters of the display cabinets were inferred from actual operational data using grey-box models. These models consisted of a lumped-parameter description of the cabinets' dynamics derived from heat and mass balance equations (see Equations 1 and 2, respectively), whose parameters were estimated directly from data using statistical techniques. For example, Equations 1-3 show one of the state-space models developed during the project to model a single display cabinet.

$$dT^c = \frac{1}{C_c} \cdot [UA_{load}(T^a - T^c) + M^r UA_m(T^e - T^c)]dt + \sigma_c d\omega_c \quad (1)$$

$$dM^r = (\dot{m}_{in} - \dot{m}_{out})dt + \sigma_r d\omega_r \quad (2)$$

$$\dot{m}_{out} = \frac{UA_m M^r}{\Delta h_e} \quad (3)$$

UA_{load}, UA_m, C_c, σ_r and σ_c were the parameter to be estimated. UA_{load} and UA_m are the overall heat transfer coefficients of the envelope and evaporator of the cabinet, respectively. Cc is the heat capacity of the air inside the cabinet, while σ_r and σ_c are the incremental standard deviation of the process. T^c and M^r are the variables of which we wanted to model the dynamic, i.e. the cabinet temperature and the mass of refrigerant inside the evaporator of the cabinet. In this respect, it is worth mentioning that the state representing the cabinet air temperatures also take into accounts the goods stored in the cabinet. More details about this modelling choice can be found in [5].

Figure 4 shows a representation of the modelled cabinets, where T^a, T^e, $\dot{m}_{in}$, and $\dot{m}_{out}$ are the ambient temperature, evaporation temperature, and mass flow of refrigerant entering and leaving the evaporator, respectively, and are inputs to the model. Δh_e is the enthalpy variation across the evaporator, and, as the previous parameters, is an input to the model. The last terms in Equations 1 and 2 are diffusion terms used to take into account the stochasticity of the dynamic process. The model parameters were estimated using the maximum likelihood estimation method with the CTSM-R package [6] in R [7]. For a rigorous mathematical description of the estimation process the reader can refer to [8,9].

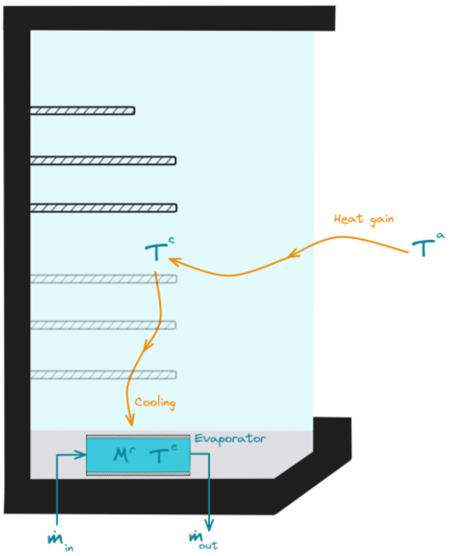

Figure 4: Schematic of the display cabinet and the simplified heat and mass balance described by Equations 1 and 2. In blue the model parameters.

The overall model was then exported as a Functional Mock-up Unit and integrated in MATLAB [10], where it was coupled with a Simulink model of the Danfoss pack controlled for CO_2 refrigeration systems, thus establishing a closed-loop connection between two systems.

With the aid of this co-simulation framework, comparisons were made between the original cabinets and pack control strategies (baseline) and improved strategies aimed at maintaining a higher and more stable evaporation pressure in order to assess the relative energy and cost-saving potential. Performances were assessed in terms of annual power consumption of the compressor pack, coefficient of performance (COP) and number of compressor start/stops. The investigated control settings were finally tested in the actual supermarket for demonstration. Table 3 gives an overview of the investigated control strategies.

Table 3: Overview of the investigated control strategies.

Control	LT group	MT group	Cabinets
Baseline	Step control	Variable + Step control	ON/OFF
Stp+VarStp+MTR	Step control	Variable + Step control	Modulating
IdVar+Ther	Variable speed (Ideal)	Variable speed (Ideal)	ON/OFF
IdVar+MTR	Variable speed (Ideal)	Variable speed (Ideal)	Modulating

where IdVar, VarStp, and Stp refer to the compressor control mode and stand for “Ideal Variable”, “Variable + Step”, and “Step”, respectively. Ther and MTR refer to the control mode of the display cabinets and stand for “Thermostatic” (i.e. ON/OFF) and “Modulating temperature regulation”.

5.2.1.3 Simulation results

Table 4 summarises the simulation results in terms of annual coefficient of performance and daily-average start/stop of the first compressor for the LT and MT suction group, respectively.

Table 4: simulation results.

Medium-temp. compression group	Baseline	Stp+VarStp+MTR	IdVar+Ther	IdVar+MTR
COP	4	4.5	4.5	4.7
Number of average start/stops	34	8	0	0
Low temperature compression group	**Baseline**	**Stp+VarStp+MTR**	**IdVar+Ther**	**IdVar+MTR**
COP	1.74	1.78	1.92	1.96
Number of average start/stops	68	62	4	4

Results show that the most cost- and energy- efficient operation of a supermarket refrigeration system is achieved by equipping the suction group with a variable speed compressor and adopting a modulating regulation of the temperature of the display cabinets.

Indeed, switching from thermostatic to modulating control led to an improvement in the annual performance (COP) of about 2−2.5 % for the LT group, and of about 7 % for the MT group. This thanks a more stable load and, hence, a more stable and efficient operation of the compression group. It can also be noted a significant reduction in the average number of compressor start/stops. However, results also show that when only fixed-speed compressors are available, changing the operating mode of the thermostat of the display cabinets from thermostatic to modulating does not have a significant impact on the system performance.

5.2.1.4 On-site experimental results

On-site experiments were carried out to further validate the simulation results discussed above. In this respect, it is worth mentioning that the store underwent renovations during the project, leading to changes that made it impossible to conduct tests under the same conditions as the initial simulations. Specifically, modifications included the addition of cabinets, upgrading the compressor pack to a larger size, fitting the LT suction group with a variable speed drive, and equipping the MT lead compressor with modulating unloaders for improved capacity control. Notably, the control of evaporation pressure was enhanced by a feature that dynamically optimizes the reference pressure based on the most-loaded cabinet, rather than maintaining a constant value. This feature implemented by the Danfoss controllers is called Po-optimisation.

Figures 5 and 6 show the distribution of the evaporation pressure of the LT and MT suction groups before and after changes in the original control settings, which consisted in the switch of the cabinets' control mode from thermostatic to modulating temperature regulation:

- Before 8 August 2023: all cabinets in Thermostatic mode (baseline).
- 8 August 2023: all cabinets switched from Thermostatic to MTR mode (Maximum limit for Po-optimization equal to -5 ºC).
- 29 November 2023: Maximum limit for Po-optimisation changed from -5 ºC till -2 ºC.

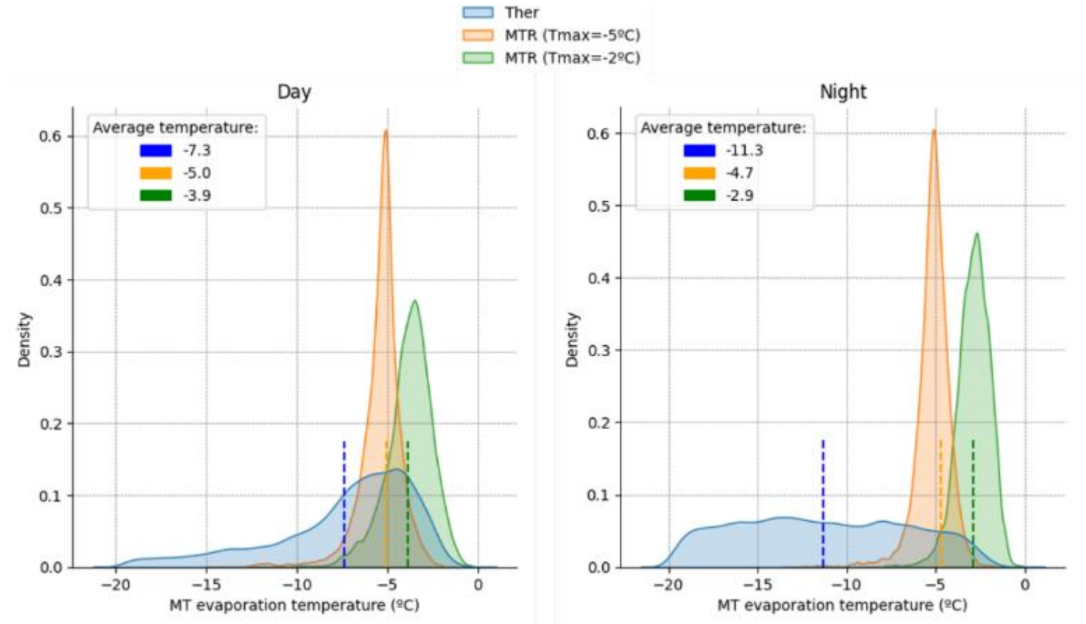

Figure 5: Medium-temperature (MT) evaporation pressure fluctuation for thermostatic (THER) and modulating (MTR) mode.

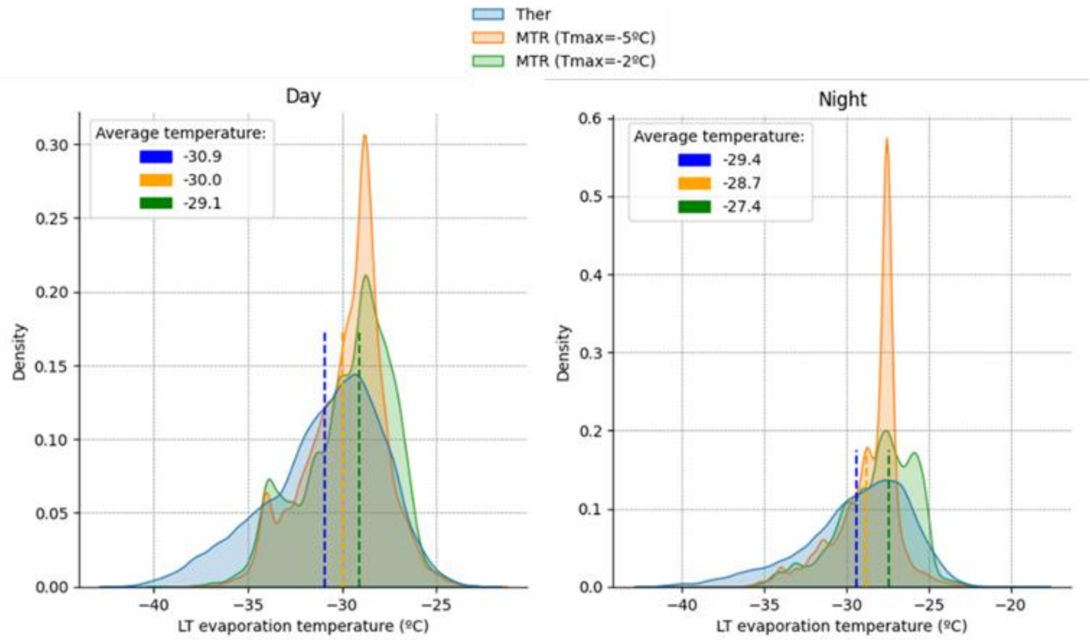

Figure 6: Low-temperature (LT) evaporation pressure fluctuation for thermostatic (THER) and modulating (MTR) mode.

Under MTR mode the evaporation pressure shows a more stable behaviour, with fluctuations of half the amplitude of the thermostatic mode during both day and night. Residual fluctuations are most likely due to the neutral zone of the compressor controller, which aims to avoid too frequent control actions. It can also be noticed how the changes from Thermostatic to MTR positively affected also the average evaporation pressure, which for the MT group increased from -7.3 °C to -3.9 °C during the day, and from -11.3 °C to -2.9 °C during the night. A similar behaviour can be noted for the LT group, although the increase in the average suction pressure was less pronounced changing from -30.9 °C to - 20.1 °C during the day, and from -29.4 °C to -27.4 °C during the night.

The transition from thermostatic to modulating temperature control has not only stabilised system operations but has also led to significant reductions in compressor power consumption. Indeed, as can be noted in Figure 7, the compressor power in MTR mode is on average 5-6 % lower than that required by thermostatic control across the whole operational range. Therefore, it can be argued that the annual energy consumption might be reduced by the same percentage.

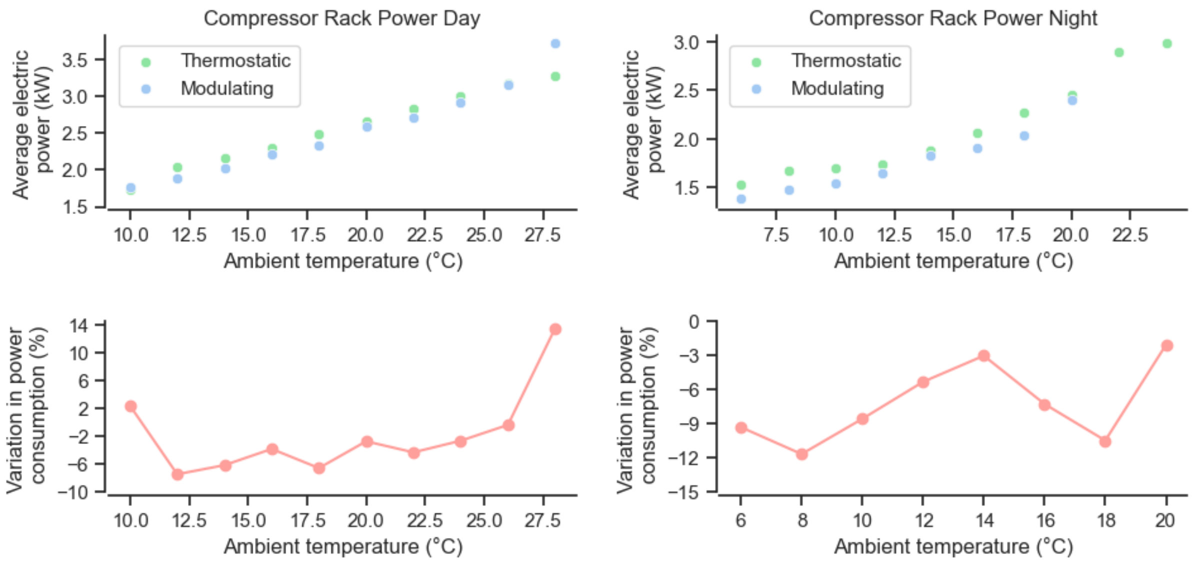

Figure 7: Compressor power consumption.

5.2.1.5 <u>Activities on fault detection and heat-recovery</u>

Alongside the previous activities, it has also been carried out research on fault-detection algorithms for low charge situation and assessment of heat recovery potential in supermarket refrigeration systems.

Detecting low-charge situations is crucial for ensuring optimal operation of supermarket refrigeration systems. Indeed, they can lead to energy inefficiency, failure to maintain temperature set points and system breakdown. In view of this, during the project a fault-detection algorithm based on static pressure changes and the so-called “waterfall effect” caused by refrigerant leakage was developed and tested on data from two different supermarkets, one in Denmark and the other in France. Results confirmed the effectiveness of the proposed methods in detecting low refrigerant charge and highlighted the early detection capabilities and potential for proper maintenance planning. Mathematical details on the detection algorithms can be found in the related project deliverable.

As for the heat recovery analysis, a field trials were conducted to investigate the impact of different high-pressure settings on the trade-off between amount of heat recovered and increase in the compressors power consumption. Indeed, higher pressures allow a greater heat recovery but at the price of greater electricity consumption. Therefore, to optimise the heat recovery strategy and optimally schedule when and how much to buy/sell from/to the district heating network or when to use the heat locally, it is important to identify the marginal price of the recovered heat. However, during the experimental campaign emerged technical issues related to a wrong commissioning of the heat recovery unit and to a leak in the heat recovery heat exchanger that had to be replaced. This was not possible to be fixed in time to allow for data analysis before the conclusion of the project.

5.2.1.6 Conclusions on Case I implementation

The case study implementation demonstrated how the use of digital twins for supermarket refrigeration systems enable a better understanding of the systems and the dynamic interactions among their components. These insights can be used by supermarket operators, service providers and system designers for the optimisation of the systems' operation and design. This can lead to increased efficiency and lower operational costs in supermarket refrigeration systems.

5.2.2 Case II: Heat pump system for industrial cooling and district heating supply

Large-scale heat pumps are an attractive technology for decarbonizing heat supplied in buildings and industries, provided their operation is within expected reliability levels. Fouling is the most common fault in large-scale heat pumps that can lead to excessive operation and maintenance costs, as well as a gradual degradation in their performance. Approaches outlined in the literature for optimizing the operation of large-scale heat pumps lack validation in real-world scenarios and do not address performance degradation caused by faults. To bridge this gap, a commercial large-scale heat pump system prone to fouling was used for demonstrating the potential of digital twin-based services in enhancing the conventional operation of this system. Here, services for operation optimization and predictive maintenance were complemented with an online monitoring framework. This enabled to adjust the services for the system in accordance with different levels of performance degradation due to fouling.

5.2.2.1 Case study description

The large-scale heat pump system selected as a case study is located in Copenhagen, Denmark. Figure 8 shows the layout of the system, which is used for district heating and industrial cooling supply. The system has a nominal heating capacity of 4 MW and is comprised of two identical two-stage heat pumps using ammonia as refrigerant, an open cooling tower and a water tank used as a thermal energy storage. The heat pumps increase the temperature of the sink stream from approximately 68 °C to 53 °C, whereas the temperature in the source stream is reduced from around 23 °C to 18 °C. The selection of the case study was because the heat pumps in the system are affected by fouling, which represents a common fault in large-scale heat pumps and thereby a relevant operational challenge to address in this project. The second reason was because the operational data from the system is stored and made available through a cloud computing solution, which is a suitable setup for the development of digital twin-based services. More details about the description of this case study can be found in Deliverable 6.2.

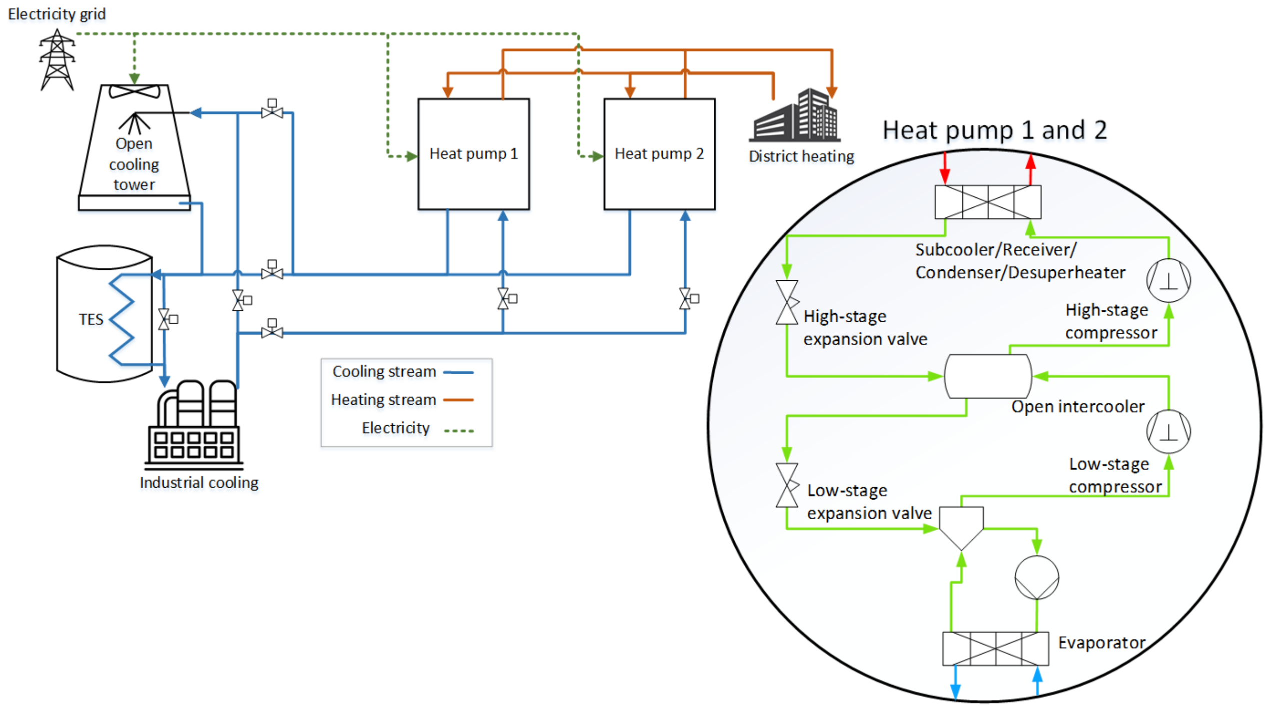

Figure 8: Layout of the large-scale heat pump system for industrial cooling and district heating supply.

5.2.2.2 Model-based frameworks

Online monitoring

The focus of online monitoring was to analyze the heat pump performance over time, assess the impact of fouling on the performance, and evaluate the effectiveness of Clean-in-Place (CIP) methods for fouling mitigation. Results from this monitoring framework were specifically obtained for heat pump 1, seen in Figure 8. The operation of the heat pump was represented by two thermodynamic simulation models developed in the programming languages Modelica and Python. A recursive calibration process, termed fouling calibration (FC), was employed to adjust model parameters related to fouling effects on the heat pump. This FC calibration was used after the initial calibration of the simulation model, which involved adjusting parameters associated with the design of the heat pump.

The influence of fouling on the operation of the heat pump was characterized by the effects on the thermal resistance and pressure drop of the evaporator. The total thermal resistance in the evaporator (R_{th}) was represented by the sum between the thermal resistance under clean conditions ($R_{\mathrm{th,clean}}$) and fouled conditions ($R_{\mathrm{th,f}}$). The total pressure drop in the source side of the evaporator ($\Delta p_{\mathrm{source}}$) resulted from the pressure drop under clean conditions ($\Delta p_{\mathrm{source,clean}}$) and a correction factor that increased the pressure drop under the presence of fouling ($\mathrm{CF}_{\Delta\mathrm{p,f}}$).

$$R_{\mathrm{th}} = R_{\mathrm{th,f}} + R_{\mathrm{th,clean}} \quad (4)$$

$$\Delta p_{\mathrm{source}} = \mathrm{CF}_{\Delta\mathrm{p,f}} \cdot \Delta p_{\mathrm{source,clean}} \quad (5)$$

The operational period of the heat pump assessed through online monitoring was extended throughout 10 calendar months. This operational period was analyzed through the simulation of six intervals of operation. The intervals were selected before and after three CIP processes were applied in the system, as shown in Figure 9.

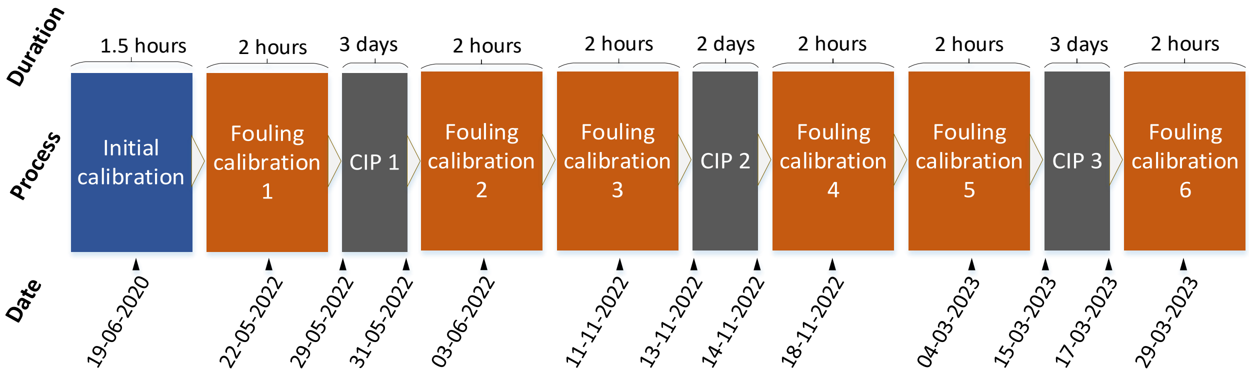

Figure 9: Monitored operational periods of the case study that were spread over 10 calendar months.

Operation optimization

The objective of the operation optimization service was to enhance the energy efficiency and cost-effectiveness of the heat pump system. This was performed by optimizing set points in the heat pumps and scheduling the operation of the entire system in accordance to different levels of fouling.

The set point optimization framework calculated the optimal intermediate pressure set point ($p_{\mathrm{m,sp}}$) in heat pump 1, which is related to the control of the high-stage compressor in the heat pump. This set point was defined as a constant value in the conventional operation of the heat pump, which was implemented during the commissioning of the system. The value of $p_{\mathrm{m,sp}}$ was determined from an exhaustive search approach, where the objective was to determine the intermediate pressure set point that maximized the COP of the heat pump, as shown in Equation 6. Here, the COP was calculated as the division between the heat output of the heat pump ($\dot{Q}_{sink}$) and the power intake from the compressors ($\dot{W}_{total}$). As seen in Equation 6, $p_{\mathrm{m,sp}}$ was constrained by the condensation pressure (p_{c}), the evaporation pressure (p_{e}) and a differential pressure (dp). The COP was obtained from the online-calibrated model developed for online monitoring. This enabled determined optimal set points for varying levels of fouling over time. Moreover, a simpler polynomial regression model for set point optimization was derived from the online-calibrated simulation model.

$$\max \mathrm{COP}(p_{\mathrm{m,sp}}) = \max\left(\frac{\sum_{i=1}^{n} \dot{Q}_{sink,i}}{\sum_{i=1}^{n} \dot{W}_{total,i}}\right) \qquad (6)$$
$$s.t. \quad p_{\mathrm{e}} + dp \leq p_{\mathrm{m,sp}} \leq p_{\mathrm{c}} - dp$$

The operation scheduling framework aimed at determining a cost-effective schedule for the heat pump system while meeting the heating and cooling requirements of the system. The optimization of the schedule was performed through a mixed integer linear programming (MILP) model. The framework also included forecasting methods for the prediction of unseen cooling and heating demands. The online-calibrated model defined for operation monitoring was also used for identifying the optimal operation schedule of the system under different levels of fouling.

The optimal schedule of the system corresponded to the operation that had the lowest operational cost over an interval of operation. As seen in Equation 7, the total operational cost over an interval k depended on the power consumption from the heat pumps ($\dot{W}_{\mathrm{t}}^{\mathrm{HP1}} + \dot{W}_{\mathrm{t}}^{\mathrm{HP2}}$) and from the fans present in the open cooling tower ($\dot{W}_{\mathrm{t}}^{\mathrm{CT}}$), as well as the hourly electricity price ($\mathrm{C_{el,t}}$). The optimal schedule was compared with the business-as-usual (BAU) operation of the system over two different intervals of operation extended over five calendar days each, named operational periods A and B.

$$\min \mathrm{C_{op}} = \min\left(\sum_{\mathrm{t}=1}^{\mathrm{k}} (\dot{W}_{\mathrm{t}}^{\mathrm{HP1}} + \dot{W}_{\mathrm{t}}^{\mathrm{HP2}} + \dot{W}_{\mathrm{t}}^{\mathrm{CT}}) \cdot \mathrm{C_{el,t}}\right) \qquad (7)$$

Predictive maintenance

The predictive maintenance framework aimed at enhancing the availability of heat pump 1 in the system while also minimizing its operation and maintenance costs. This was achieved by determining an optimal interval between CIP processes. The framework integrated exergoeconomic analysis as well as the online-calibrated model for online monitoring. The CIP processes addressed through the predictive maintenance framework were CIP 2 and CIP 3, shown in Figure 9.

The total operation and maintenance cost related to the CIP ($C_{CIP,total}$) was calculated based on cumulated fouling-related cost between CIP intervals ($C_{D,f,cum}$), along with the cost of implementing a CIP (C_{CIP}) and the opportunity cost incurred by not operating the heat pump during the CIP implementation ($C_{CIP,OC}$). The value of $C_{D,f,cum}$ was determined through the online-calibrated model, whereas $C_{CIP,OC}$ was calculated based on information from the operator of the heat pump system. As seen in Equation 8, the optimal interval between CIP processes was obtained by minimizing $C_{CIP,total}$ as a function of the interval between CIP processes (Δt_{CIP}) over one year of operation.

$$\min C_{CIP,total}(\Delta t_{CIP}) = \min (C_{CIP} + C_{CIP,OC} + C_{D,f,cum}) \quad (8)$$

5.2.2.3 Simulation results

Online monitoring

Figure 10 presents the results from the online-calibrated model related to the effects of fouling on the thermal resistance and pressure drop in the evaporator. Under clean conditions, as depicted by lighter colors, the thermal resistance remained constant across all the monitored periods. Conversely, the source pressure drop exhibited fluctuations due to the changing mass flow rates in the source stream during these periods. Under the presence of fouling, represented by darker colors, the thermal resistance and source pressure drop varied throughout the monitored periods of operation. This impact was quantified through ratios: the fouling-induced thermal resistance to the total thermal resistance ($R_{th,f}/R_{th}$) and a comparable ratio for the source pressure drop ($\Delta p_{source,f}/\Delta p_{source}$). These ratios showed that fouling had a larger influence on the thermal resistance compared to the pressure drop. Moreover, $R_{th,f}/R_{th}$ indicated that the effect of fouling on the thermal resistance of the evaporator did not decrease below 40 %. Therefore, the CIPs performed during the monitored operation of the heat pump where not able to completely mitigate the effects of fouling.

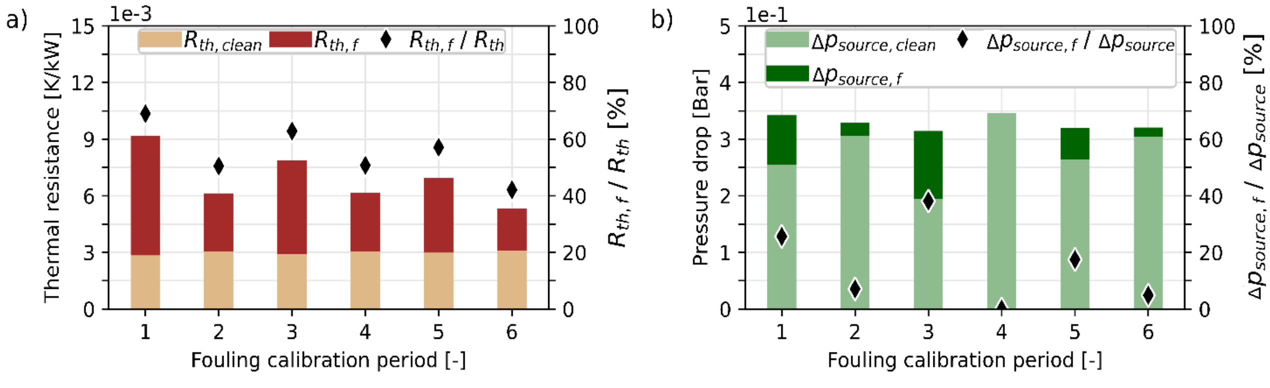

Figure 10: Effects of fouling on the evaporator thermal resistance a) and pressure drop b) resulting from the fouling calibration process.

The effect of implementing online calibration to improve the correspondence between measurements and simulated data is shown in Figure 11. This correspondence is assessed using residuals, which indicate the relative difference between measurements and simulation results for each minute of operation. The minute-by-minute residuals for each period are illustrated as box plots, where the box represents the interquartile range, and the whiskers extend to the minimum and maximum residual values. The findings indicated that the online calibrated model, also referred to as adaptive model, had lower discrepancies between simulated and measured evaporation pressure and COP in contrast to the same model calibrated only once, also named fixed model. There were no notable variances between the two models concerning the heat output and the source pressure drop. The most significant difference between the adaptive and fixed models emerged during the initial fouling calibration phase, where it was observed the highest thermal resistance attributed to fouling between the analysed periods.

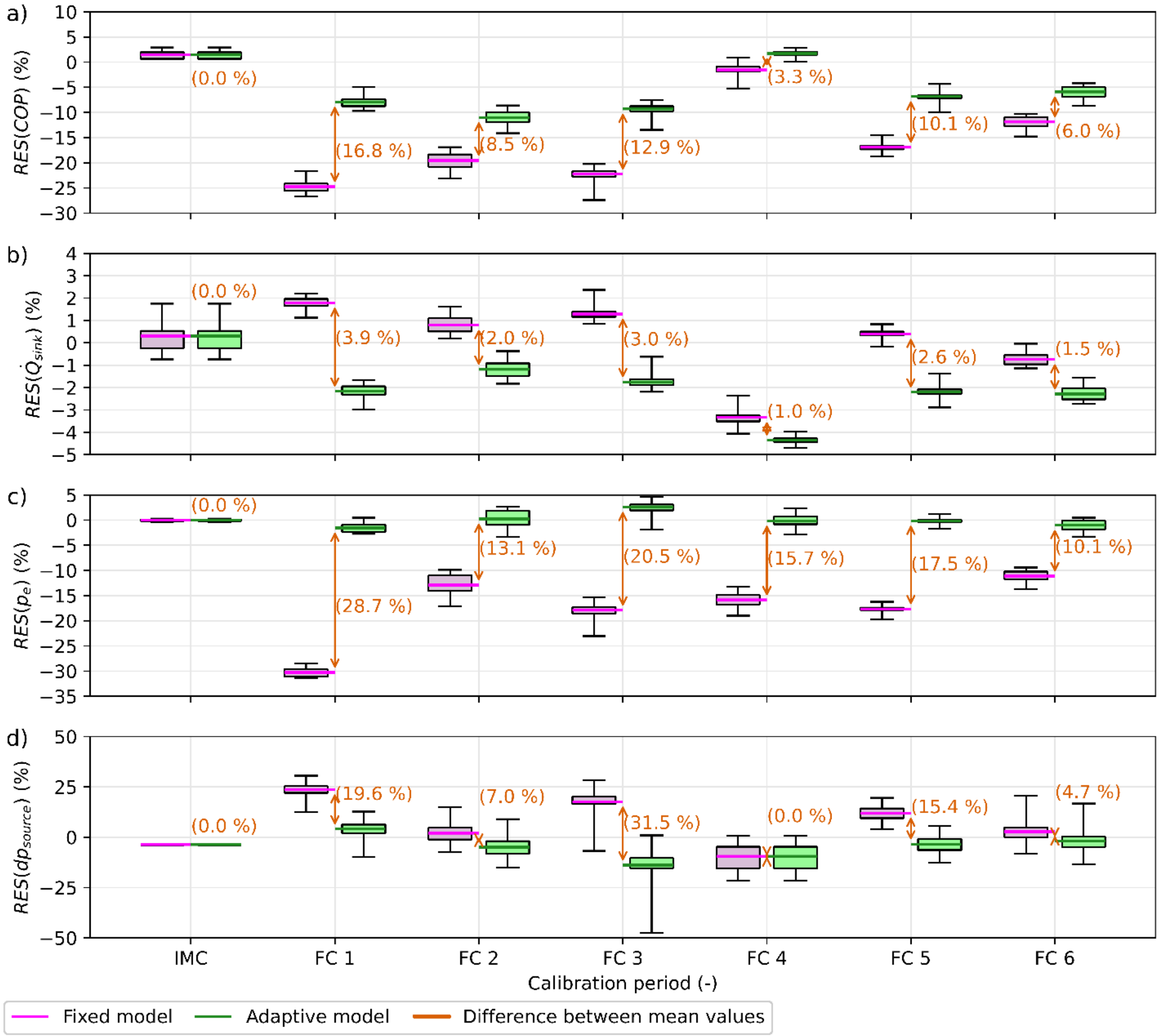

Figure 11: Simulation residuals obtained from the quasi-steady-state model adjusted only with the initial calibration (IMC) and further adjusted with the fouling calibration (FC), named fixed and adaptive models, respectively. This includes the relative difference between both models in ().

Operation optimization

Figure 12 shows the results from the set point optimization framework. Here, the online-calibrated model was used to characterize the relationship between the intermediate pressure set point, the thermal resistance attributed to fouling, and both the COP and heat output of the heat pump. These observations were conducted while the heat pump operated at heating capacities approximately around 1.5 MW, 1.8 MW, and 1.6 MW, corresponding to normalized heat loads of 0.75, 0.9, and 0.8, respectively. The results showed that increased fouling levels diminished the ideal intermediate pressure set point. This led to a reduction in the performance improvements and heating capacity reduction related to that set point. The optimal intermediate pressure set point consistently resulted in a COP increase (up to 3 %) and a decrease in heating capacity (up to 0.7 %) across all the analysed levels of fouling and heat capacities.

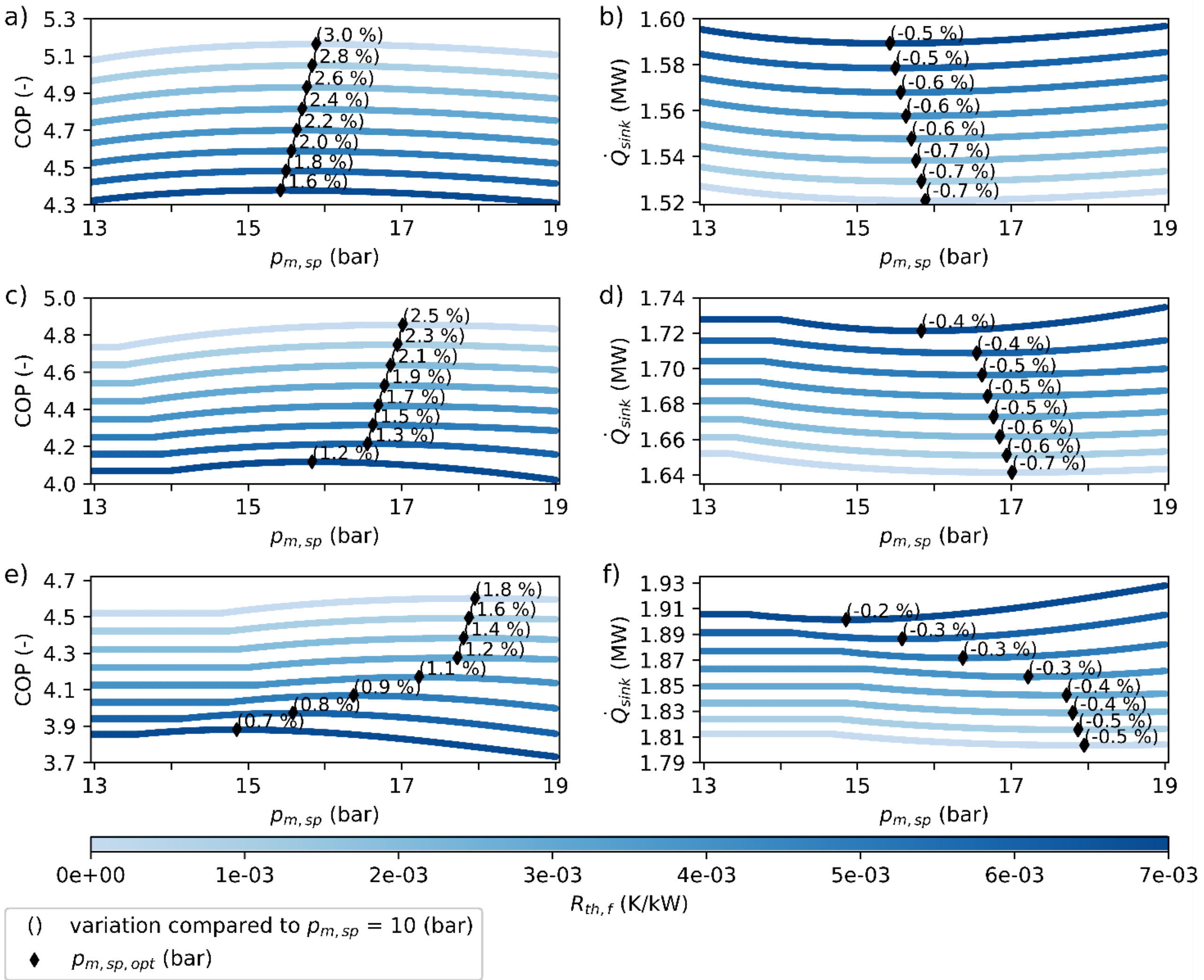

Figure 12: Influence of fouling-related thermal resistance on the optimal intermediate pressure set point, along with the resulting changes in COP and heat capacity. This analysis covers fouling calibration periods 1 (shown in a) and b)), 5 (shown in c) and d)), and 4 (shown in e) and f)), each corresponding to different heat capacities provided by the heat pump during operation.

Figure 13 shows how the fouling thermal resistance influences operational costs and savings within the operation scheduling framework. The results were obtained with and without the use of forecasting methods for the heating and cooling demands driving the operation of the system. The "relative cost difference" in the figure highlights the gap between total operational costs at zero fouling and those at various non-zero fouling levels. The findings indicated that neglecting fouling leads to an overestimation of the savings attained through operational scheduling compared to BAU operation. Within the range of observed fouling thermal resistance ($2 \cdot 10^{-3}$ K/kW to $2.5 \cdot 10^{-3}$ K/kW), the optimization resulted in savings ranging from 1.5 % to 5 % with forecasting and 1 % to 3.5 % without forecasting. However, beyond this range, the operational costs increased, reaching approximately 7 % to 8 % for a thermal resistance of $4 \cdot 10^{-3}$ K/kW, thereby diminishing savings by 2 percentage points in comparison to the observed fouling levels.

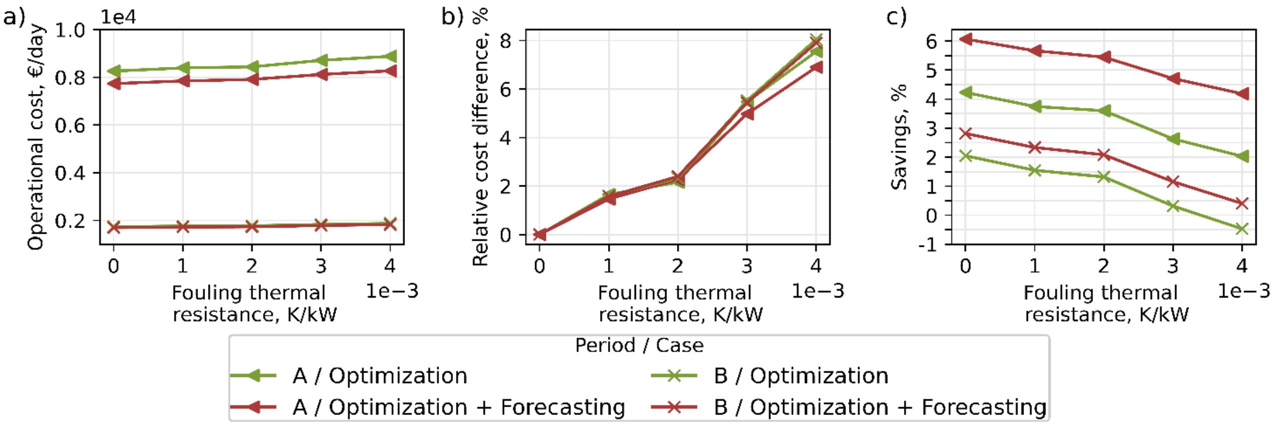

Figure 13: Operational costs and savings associated with employing schedule optimization instead of BAU operation for varying levels of fouling thermal resistance.

Predictive maintenance

Table 5 shows a comparison between the time intervals leading up to CIP 2 and CIP 3, alongside the corresponding annual costs related to those processes. The longer interval before CIP 2 resulted in decreased CIP implementation costs (represented by C_{CIP} + $C_{CIP,OC}$) and increased operational costs related to fouling growth (represented by $C_{D,f,cum}$) compared to CIP 3. Nevertheless, it was not possible to identify an optimal CIP interval given that only two CIP processes where included in the analysis. The results shown in Table 5 showed potential to be complemented with results from additional CIP processes for determining a CIP interval that effectively reduces the operation and maintenance costs of the heat pump.

Table 5: Operational period prior the two evaluated CIP processes, along with their costs over a year.

CIP process	(h)	C_{CIP} (€1000/year)	$C_{CIP,OC}$ (€1000/year)	C_{CIP} + $C_{CIP,OC}$ (€1000/year)	$C_{D,f,cum}$ (€1000/year)	$C_{CIP,total}$ (€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

5.2.2.4 Conclusions on Case II implementation

Three services were introduced in a large-scale heat pump system used for district heating and industrial cooling supply, namely online monitoring, operation optimization, and predictive maintenance. The services were developed from operational data retrieved online from the system. These services aimed to enhance the energy efficiency and cost-effectiveness of the system. Despite limitations in applying these services directly, simulation results showed efficiency improvements of up to 3 %, with potential cost reductions of up to 5 %. This case study implementation showed potential for extending the proposed services using digital twin technology for enhancing the operation of large-scale heat pump systems.

5.2.3 Case III: Seawater source heat pump system for district heating supply

The widespread adoption of natural refrigerants in heat pumps is crucial for reducing the environmental impact related to their operation. Ammonia and water are attractive natural refrigerants for heat pump systems used for district heating and industrial heating supply due to their high energy performance and low production costs. However, these systems can be exposed to a number of operational challenges. For instance, ammonia leakages can pose a risk to human health due to the toxicity of this refrigerant, whereas systems with water as refrigerant require the reliable operation of compressors exposed to high compression ratios and high mass flow rates. Digital technologies such as digital twins have the potential to outperform conventional control and monitoring services for heat pump systems, but their use in the heat pump industry remains limited. In this study, a large-scale heat pump for district heating supply using ammonia and water as refrigerants was selected for the development and implementation of a digital twin-assisted framework for operation optimization.

5.2.3.1 Case study description

The large-scale heat pump system selected as a case study is managed by the Danish energy company Kredsløb and located in “Maskinrummet” at Aarhus, Ø Denmark, see Figure 14.

Figure 14: Machine room at Århus Ø where the heat pumps are located [Kollision, 2020].

Two parallel systems were installed by Johnson Controls Denmark. Each of the system has a nominal heating capacity of 1 MW and a two-stage cascade layout, shown in Figure 15. The lower stage is a novel unit that uses seawater as a heat source and steam as refrigerant. In this stage, a fraction of the seawater enters in the evaporator and evaporates under low pressure. The resulting steam undergoes compression in an axial multi-stage turbo compressor, which is then condensed in a separate vessel and transfers heat to an upper stage using ammonia as refrigerant. Further information about the case study can be found in the deliverable 6.3.

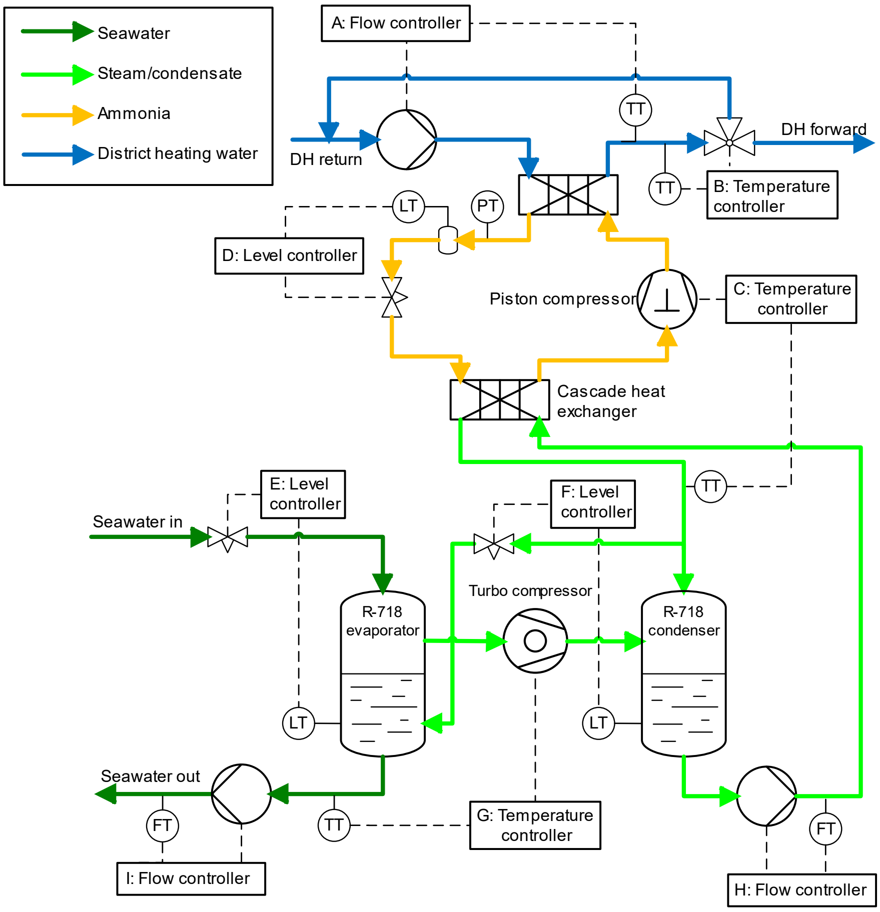

Figure 15: Layout of the seawater source large-scale heat pump system used as a case study.

5.2.3.2 Model-based framework

The operation optimization framework aimed at enhancing the energy performance of the case study by characterizing and adjusting its operation through digital twins. This framework was comprised of a data management setup, a detailed dynamic simulation model of the system, and a control optimization routine. The framework was developed based on operational data from the system. Due to security reasons, it was not possible at this stage to directly modify the conventional operation of the system, instead a “human-in-the-loop” approach were planned, where the Digital Twin continuously collected data which in turn could provide insights and suggestions to the operation of the heat pump.

The operational data from the system was retrieved from programmable logic controllers (PLCs) used for the operation of the ammonia and water cycles, along with the secondary streams. The retrieval and collection of such operational data required the installation of new hardware, namely a new local server and a data logging equipment. The data processing and analysis tasks were performed through at SQL database and the programming language Python.

The detailed simulation model was built in the programming language Modelica by using the software Dymola and the TIL Suite library. All the heat exchangers in the system were represented by modified plate heat exchanger models available in the TIL Suite library. The exception to this was the evaporator, which was modelled by a vessel that separated the seawater in the heat source stream into gas and liquid. The ammonia compressor was represented through polynomial regression models derived from experimental data provided by the compressor manufacturer. The model for the turbo compressor used in the water cycle was a table-based interpolation map derived from experimental data provided by the compressor manufacturer. All the controllers in the system (seen in Figure 15) were modelled by proportional integer (PI) controllers available in the TIL Suite library. The simulation model of the entire system was converted to a Functional Mock-up Unit (FMU), which is a standard that allows the exchange of simulation models between different software and programming languages.

The optimization process was performed in Python using the Scipy module and the simulation model converted into a FMU. One of the possible optimization procedures was to calculate the set points for the process out temperature which influences the evaporation source temperature ($T_{\text{source,sp}}$) in the water and ammonia cycles and maximized the COP of the system, as shown in Equation 9. This process was performed for single-time steps of operation, maintaining the boundary conditions of the system fixed during the optimization. As a result of the optimization, the speed of the compressor in the water cycles was reduced, decreasing the total power intake of the system.

$$\max \text{COP}(T_{\text{source,sp}}) = \max\left(\frac{\sum_{i=1}^{n} \dot{Q}_{sink,i}}{\sum_{i=1}^{n} \dot{W}_{total,i}}\right) \tag{9}$$

A software tool was developed for monitoring and optimizing the operation of the large-scale heat pump system, which is shown in Figure 16. The development of this tool was directed to Kredsløb responsible for the operation of the system. The tool was made with QT designer and Python, and uses a setup with an interface, which shows the layout of the system, along with operational variables of the system in real-time and their comparison with the results from the simulation model. Moreover, the tool enables to test different hypothetical scenarios. In this context, control set points as well as other relevant system parameters can be modified, and the resulting performance of the system is estimated through the simulation model.

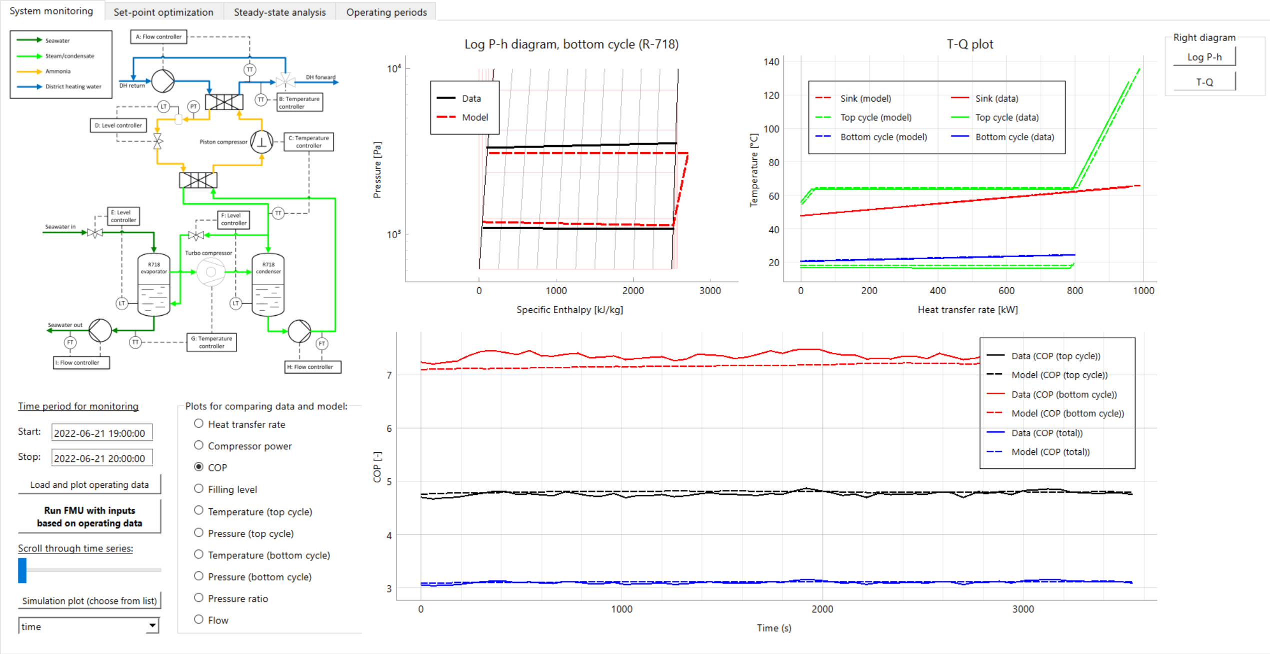

Figure 16: Interface of the software developed for monitoring and optimizing the operation of the large-scale heat pump system used as case study.

5.2.3.3 Results

After setup of the dataflow and the validation of the model some operation issues with the heat pump system occurred, causing some parts of the novel heat pump system to be out for overhaul in a longer period, which caused the demonstration and investigation of the potential of the digital twin to be made on the basis of historical data, and hence not with live data in a continuous loop.

Figure 17**Error! Reference source not found.** shows a comparison between simulation results and measurements over a period of operation of the system of approximately two hours, where there is a change in the set point of the turbo compressor with an increase of 150 RPM after 3200 seconds. These results**Error! Reference source not found.** compare various temperatures in the bottom cycle with the turbo compressor speed.

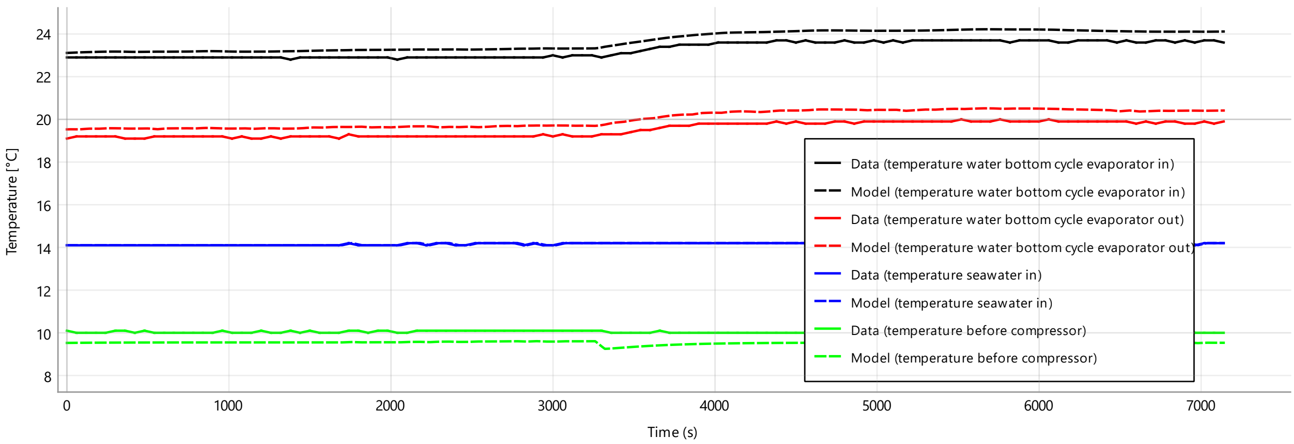

Figure 17: Measured and simulated temperatures in the bottom cycle.

Figure 18 presents a comparison between the simulated and measured heat transfer rates for the district heating water and the cascade HEX. In general the comparison between measurements and simulation results indicated that the simulation model provides a suitable description of the operation of the system, both in steady-state mode (off-sets) and during dynamic changes of the system.

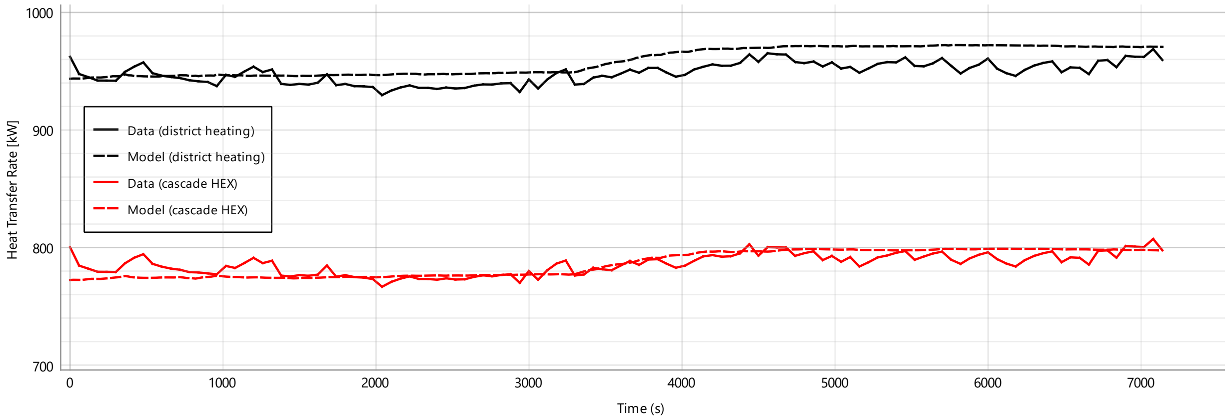

Figure 18: Measured and simulated heat transfer rate delivered by the water cycle (red) and the ammonia cycle (black).

Once the model was validated, it was utilized to determine the set points for controlling the speed of the compressors in the system, aiming to maximize its energy efficiency. This is illustrated in Figure 19 and Figure 20. Figure 19 shows the relation between the speed of the turbo compressor in the water cycle and the COP as well as the heat output of the system, whereas Figure 20 presents the same relation for the ammonia cycle. These findings facilitated the identification of optimal controller set points, represented by specific compressor speeds for each cycle, which maximized the COP of the system. In the water cycle, the optimal compressor speed resulted in a reduction in heat output compared to higher speeds, while for the ammonia cycle, the optimal (and maximal) compressor speed did not lead to a reduction in heat output compared to higher speeds. In this context, the detailed simulation model enabled the characterization of the trade-off between energy performance and the net output of the system resulting from set point variations. Although the focus of this study was on defining energy-optimal set points, the proposed framework could also be applied to adjust the balance between the heat output of a system and its energy performance.

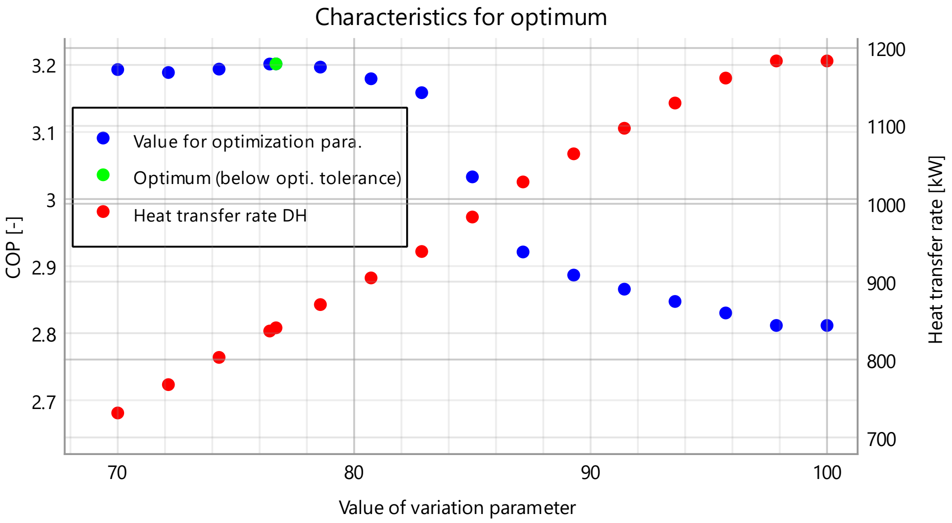

Figure 19: COP and heat output of the system as a result of a variation of the water compressor speed, where the energy-optimal value for this speed is shown in green.

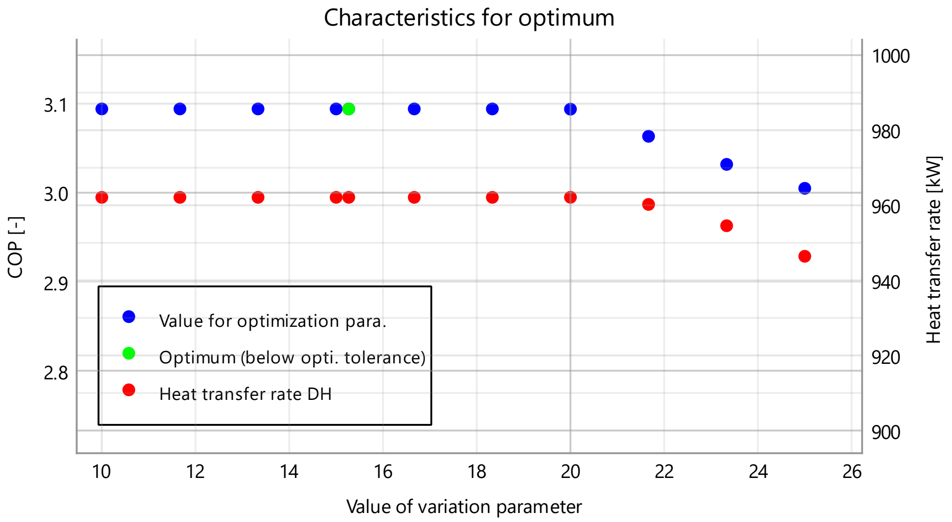

Figure 20: COP and heat output of the system as a result of a variation of the ammonia compressor speed (which is a function and the process out temperature shown here as the “value of variation parameter”, where the energy-optimal value for this speed is shown in green.

The energy-optimal set point for the turbo compressor in the water cycle was calculated online through the simulation model and the results were compared with the measurements from the system if no optimization has been made, as presented in Figure 21. The detailed simulation model here provided a description of the dynamics related to the implementation of the energy-optimal set point, which was implemented after one hour of operation (at time = 3600 seconds). This information could be used for adjusting the operation of other components supplying or storing heat in the same network as the heat pump system. The results showed that the optimal set point increased the COP of the system by around 3 % compared to how the system was running before. These findings underscored the potential of using the proposed set point optimization framework for enhancing the energy performance of the system used as a case study.

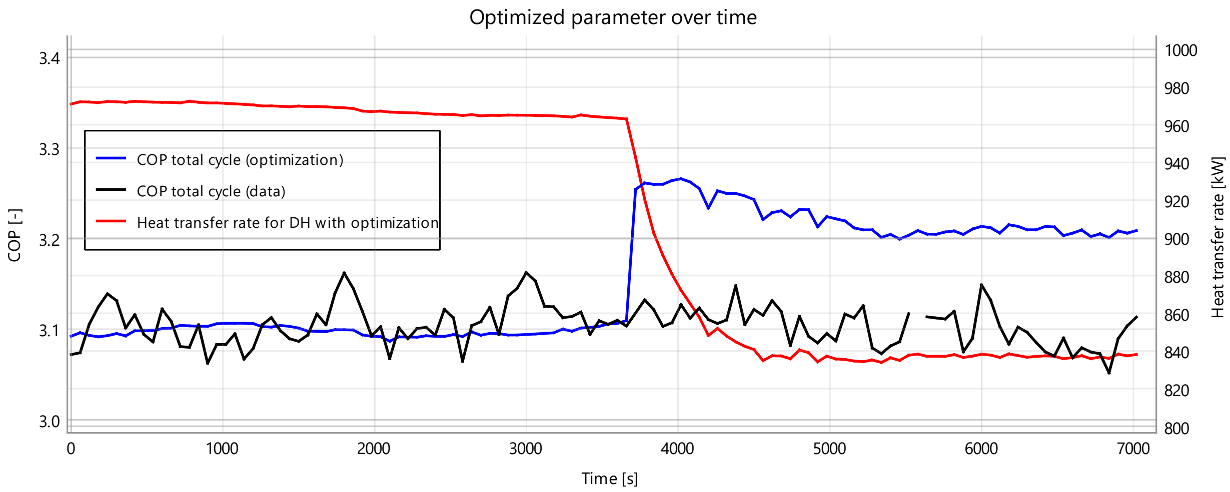

Figure 21: COP and heat output of the system resulting from the implementation of the energy-optimal speed of the water compressor.

5.2.3.4 Conclusions on Case III implementation

A model-based framework was proposed for optimizing the energy efficiency of a large-scale heat pump system using seawater as a heat source. The framework comprised a data management system, a detailed heat pump simulation model, a data-driven optimization method, and an GUI for the operator. The optimization aimed at determining energy-optimal set points for controlling the speed of the compressors in the system. The simulation results showed that the simulation model used was able to provide a suitable representation of the operation of the system. This showed the potential for using the simulation model as a performance benchmark for the physical heat pump system, where the expected COP of the system is obtained through simulations. The model complemented with the optimization enabled to characterize the trade-off between enhancing the energy efficiency and heat production of the system derived from adjusting the speed of the compressors. Overall, the findings from the implementation of the framework in the case study highlighted its potential for optimizing the operation of the system in real time.

5.3 Commercial results

The digital twin solutions developed during the project are expected to benefit all the stakeholders in the heat pump and refrigeration industry, from component manufacturers to end-users, including system designers and service providers. Furthermore, the continuous interaction between this industry and the project established a solid foundation for the commercial deployment of the project outcomes.

Operation optimisation and maintenance services: AK-Centralen currently offers control and operational services to approximately 1,500 supermarkets in Denmark. By analysing data gathered from these supermarkets, they can optimize system operation by adjusting controller set points remotely. The outcome of the project can enable AK-Centralen and other companies that provide services to large-scale heat pump and refrigeration systems to enhance the energy efficiency and cost-effectiveness of the systems they service. These services include optimized operation and predictive maintenance. These services will be offered as additional features to both existing and new service agreements with supermarket clients. Consequently, clients will benefit from reduced operational expenses and decreased downtime of their system components.

Control systems: Danfoss specializes in manufacturing control systems for heat pumps and refrigeration systems. By utilizing the digital twin technology developed within the project, Danfoss will enhance intelligence of its control equipment. This holds relevance across various product categories, presenting Danfoss with a substantial market opportunity.

Grid flexibility services: In the coming years, the use of heat pump and refrigeration systems for supplying ancillary services to the electricity grid is expected to become technically and economically feasible. The outcome of this project can contribute towards delivering flexibility services through large-scale heat pump and refrigeration systems without compromising their operational integrity and equipment safety. This is expected to provide economic benefits to district heating companies and supermarkets, along with contributing to the stability of the electricity grid.

5.4 Target group and added value for users

The target group of this project includes manufacturers of heat pump and refrigeration systems, service providers, and third parties with an interest in these technologies and in their new business potentials. Moreover, the project incorporates a significant research component, making it highly relevant for researchers as well.

As for the added value that digital twins can create for the different users, these vary depending on the considered target group as shown in Table 6.

Table 6: Value creation of digital twins for the different target group.

Digital twin service	Description	Beneficiary user		
		Manufacturers	Service providers / asset owners	Energy grid
Real-time monitoring and analysis	Continuous collection and analysis of operational data that enables the identification of potential inefficiencies, such as anomalous consumption patterns, and offers the possibility to implement corrective measures, thus enhancing the overall system performance.		✓	
Operational (set-points) optimisation	Use of simulations and scenario testing to analyse and fine-tune operational parameters, e.g. controllers' set points, to enhance efficiency, minimize energy consumption, and optimize overall performance. Manufacturers of control systems like Danfoss can also use this knowledge to develop new control algorithms that can increase the smartness level of their controllers.	✓	✓	
Predictive analytics	By closely mirroring the dynamics of their physical counterparts, digital twins enable the deployment of predictive control methods, such as model predictive control (MPC). These methods determine the optimal control action by not only considering the current state of the system but also taking into consideration future boundary conditions, such as varying electricity prices, weather forecasts, and load forecasts. This enables the refinement of set-point optimisation strategies over time.		✓	
Condition monitoring	Digital twins can improve fault detection and diagnosis (FDD) by integrating real-time monitoring with simulation and predictive analysis. This allows to detect and diagnose fault mechanisms before or at an early stage of their occurrence, helps reduce unexpected failures and equipment downtime and extend the overall life of systems and components.		✓	
Increased knowledge on operating conditions	Digital twins will enable an enhanced understanding of heat pump and refrigeration systems during operation. This will lead to an improved operating performance by set point tuning and may enable deriving and improved design of future systems.	✓	✓	

Flexibility services	Digital twins can enable flexibility services, which represent an additional commercial product that can be offered by supermarkets and large-scale heat pump to the grid.		✓	✓

5.5 Dissemination of results

During the project, results were constantly disseminated through the project websites and through a variety of activities aimed at the different target groups. These activities included presentations at conferences, articles in academic journals, articles in magazines with a focus on end-users and manufacturers, and dedicated workshops. In this latter regard, an event for industry experts was organised, which involved the entire sector from manufacturers to end users, via consultants and service providers, and another one is planned in June 2024. In addition, to facilitate the dissemination of the results, continuous communications with interested companies and institutions were held throughout the project. Finally, the main findings of the project were summarized and condensed into guidelines aimed at boosting a further development and application of digital twins.

Below a complete overview of the dissemination activity carried out during the project. Overall, the project has led to 5 peer reviewed scientific journal articles, 15 conference papers, 3 articles in magazines, and 2 workshops. All the public deliverables and results have been made available on the project website.

Journal articles

- Leerbeck K., Bacher P., Heerup C., and Madsen H., "Estimation of evaporator valve sizes in supermarket refrigeration cabinets", Journal of Process Control, 124, 2023, 179-186.
- Leerbeck K., Bacher P., Heerup C., and Madsen H., "Grey box modeling of supermarket refrigeration cabinets", Energy and AI, 11, 2023, 100211.
- Aguilera, J. J., Meesenburg, W., Ommen, T., Markussen, W. B., Poulsen, J. L., Zühlsdorf, B. & Elmegaard, B., "A review of common faults in large-scale heat pumps", Renewable and Sustainable Energy Reviews, Volume 168, 2022, 112826, https://doi.org/10.1016/j.rser.2022.112826.
- Aguilera, J.J., Meesenburg, W., Markussen, W.B, Zühlsdorf, B., and Elmegaard, B., "Real-time monitoring and optimization of a large-scale heat pump prone to fouling - Towards a digital twin framework ", Applied Energy, Accepted for publication.
- Aguilera, J.J., Padullés, R., Meesenburg, W., Markussen, W.B., Zühlsdorf, B. and Elmegaard, B., "Digital twin-assisted online operation scheduling of a large-scale heat pump system", submitted to Applied Energy.

Conference papers and presentations

- Schulte, A.; Försterling, S.; Tegethoff, W.; and Köhler, J., "Ein physikbasiertes dynamisches Simulationsmodel für Kühlmöbel", Deutsche Kälte-Klima-Tagung, DKV-Tagungsberichte, Magdeburg, 16.-18. November 2022.
- Leerbeck K., Bacher P., and Heerup C., "Grey Box Modelling of Supermarket Refrigeration Room", International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town, South Africa, 2021, pp. 1-6.
- Aguilera, J.J., Meesenburg, W., Ommen, T., Poulsen, J.L.; Rugholm Kramer, K.; Markussen, W.B, Zühlsdorf, B., and Elmegaard, B., "Operational challenges in large-scale ammonia heat pump systems", In Proceedings of the 34th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems 2021 — 2021, pp. 1842-1853.
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ammonia as working fluids. In Proceedings of ECOS 2022 - The 35th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems 2022 ECOS.
- Aguilera, J.J., Meesenburg, W., Markussen, W. B., Zühlsdorf, B. & Elmegaard, B., “Online model-based framework for operation and fouling monitoring in a large-scale heat pump”, Proceedings of ECOS 2023 - The 36th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems 2023. ECOS, p. 3296-3306.
- Aguilera, J.J., Meesenburg, W., Markussen, W.B, Poulsen, J.L., Zühlsdorf, B., and Elmegaard, B., “Adaptive model-based monitoring of large-scale heat pump prone to evaporator fouling”, Proceedings of the 26th IIR International Congress of Refrigeration: Paris, France, August 21-25, 2023.
- Schulte A., Försterling S., Larsen L., Heerup C., Bacher P., Gøttsch R., Tegethoff W., Zühlsdorf B., Koehler J., “The influence of evaporation pressure dynamics on energy consumption”, Proceedings of the 26th IIR International Congress of Refrigeration: Paris, France, August 21-25, 2023.
- Schulte A., Larsen L., Försterling S., Heerup C., Tegethoff W., Zühlsdorf B., Koehler J., “Energy efficient control strategies in supermarket refrigeration systems”, 8th IIR International Conference on Sustainability and the Cold Chain | June 9-11 2024 | Tokyo, Japan.
- Heerup C., “Gascooler optimal pressure revisited”, 15th IIR-Gustav Lorentzen conference on Natural Refrigerants | June 13-15 | Trondheim, Norway.
- Poulsen, J.L. and Aguilera, J.J., “Digital twins for large-scale heat pumps and refrigeration systems”, 8th International Symposium on Advances in Refrigeration and Heat Pump Technology, 23 March 2023.
- Meesenburg, W., Aguilera, J.J., Kofler, R., Markussen, W. B., & Elmegaard, B. (2022). Prediction of fouling in sewage water heat pump for predictive maintenance. In Proceedings of ECOS 2022 - The 35th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems 2022 ECOS.
- Aguilera, J.J., Meesenburg, W., Schulte A., Markussen, W.B, Ommen, T.S., Zühlsdorf, B., Poulsen, J.L., Försterling S., and Elmegaard, B., “Integration of dynamic model and classification methods for fault detection and diagnosis in a chiller”, 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2022): Proceedings. Trondheim, Norway, June 13-15th 2022.
- Schulte A., Tegethoff W., and Koehler J., “Correlation Analysis of evaporation pressure readings in CO2 supermarket refrigeration systems.”, 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2022). Proceedings. Trondheim, Norway, June 13-15th 2022.
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- Schulte A., Bacher, P., Heerup, C., Tegethoff W., Zühlsdorf, B., and Koehler J., “Identification of refrigeration load parameters for display cabinets from monitoring data”, 16th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2024). Proceedings. Maryland, USA, August 11-14th 2024.

Articles in magazines

- Meesenburg, W., “Digital twins to improve heat pump operation”, 2020, published online on the news section of the DTU website (link to article).
- D´Ettorre, F., Heerup, C., Larsen, L., “The role of digital twins in boosting energy efficiency and sustainability of supermarket refrigeration systems”, to be submitted to refrigeration magazine, 2024
- Poulsen, J.L., Aguilera, J.J. “Set point optimization for large-scale heat pumps through digital twins”. To be submitted to IEA HPT Magazine, 2024.

Table 7: Overview of dissemination activities.

Dissemination type	Name	Year	Number of works

Conferences	German Refrigeration and Air Conditioning Conference	2022	1
	International Conference on Electrical, Computer and Energy Technologies (ICECET)	2021	1
	International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS)	2021/ 2023	4
	IIR International Congress of Refrigeration	2023	2
	IIR International Conference on Sustainability and the Cold Chain	2024	1
	15th IIR-Gustav Lorentzen conference on Natural Refrigerants	2022	4
	8th International Symposium on Advances in Refrigeration and Heat Pump Technology	2023	1
Scientific journals	Journal of Process Control	2023	1
	Renewable and Sustainable Energy Reviews	2022	1
	Energy and AI	2023	1
	Applied Energy	2024 /Under review	2
PhD Thesis	Digital twin-based services for large-scale heat pump systems – Technical University of Denmark, Department of Civil and Mechanical Engineering	2024	1
Magazine/ Online articles	• Digital twins to improve heat pump operation • IEA HPT Magazine • Refrigeration magazine. To be determined.	2020 2024 2024	3
Workshops	• 8th International Symposium on Advances in Refrigeration and Heat Pump Technology • Seminar on Digitalization of Refrigeration and Heat Pump Systems	2023 2024	2

6. Utilisation of project results

6.1 Future use of the technological results

As mentioned above, the digital tools developed during the project will be used by all the potential customers working with large-scale heat pump and refrigeration technologies.

The project successfully proved the effectiveness of digital twins in supporting the analysis and fine-tune of operational parameters for both heat pumps and refrigeration systems. These adjustments, e.g. controller set points, were shown to enhance efficiency, minimise energy consumption, and optimise overall performance. This knowledge will integrate the Danfoss know-how and assist them in developing more intelligent control algorithms for heating and cooling applications, while supporting their customers in optimising their energy systems based on the use of Danfoss' components. Furthermore, this digital twin framework will be used and further developed by Danfoss with the aim of modelling the Danfoss Smart Store located in Nordborg. Service providers like AK Centralen will also exploit this know-how to improve the set point optimisation services to their customers, which in turn can benefit from lower operational costs.

The fault detection and diagnosis capabilities developed in the project integrated with heat recovery and thermal energy storage systems can provide additional services at both local and grid scale. Waste heat from the cooling system can be used locally to meet the local heating demand or can be sold to district heating networks. At the same time, smart control algorithms can made cooling and heating system grid responsive. This can result in lower operational costs, and in positive cash flows from the provision of flexibility services and the sale of heat to district heating networks.

6.2 Future use of the commercial results

The developed technology will enable advanced digital twin-based services that could be sold as an add-on to the existing services and that could open new business opportunities.

The case implementation results showed that digital twins enable advanced system monitoring, operational optimisation and fault-detection and diagnosis for large-scale heat pump and refrigeration systems. In this context, the digital tools developed in the project will play a key role to achieve cost-effective and efficient heating and cooling production, as well as in developing smart control algorithms enabling flexibility services and advanced algorithms for condition monitoring. All these services will be used by AK-Centralen to expand their portfolio of activities and by Danfoss to yield a market advantage for the systems they sell, which could be sold already with these advanced functionalities included.

The digital twin-based services developed in this project can provide cost reductions for companies that own and maintain large-scale heat pump systems. This includes Kredsløb as well as other district heating supply companies and services providers. The use of the proposed set point optimization and schedule optimization services can reduce operational cost reductions, whereas the service for scheduling of cleaning processes can be used for reducing maintenance cost and increasing the availability of large-scale heat pumps used for district heating supply.

The services developed for data handling and operational optimisation are expected to be the first one to be implemented within a period of 4 years. The implementation of advanced services in control product and heat pump and refrigeration systems will require a longer time (up to six years) mainly due to the additional work needed before market entry/commercialisation to standardise and automate the model parametrisation and development.

The TRL increased as planned from 3-4 to 6-7 having tested the use of digital twin technologies in relevant use cases and demonstrated their potential in improving operating conditions.

6.3 Competition analysis

The market for digital twins is rapidly growing and increasingly competitive. Several players are competing for market share in this sector, including:

- Companies: Siemens used its expertise to develop digital twinning solutions for industrial customers to facilitate supply chain collaboration in the design, construction, maintenance and decommissioning of critical energy and utility assets. Energy Machines™ offers the development of digital twins of buildings to simulate their energy performance and gather crucial insights into optimal energy management. In particular, they offer a combined hardware/software solution that enables the provision of online/live transparent performance monitoring of heat pumps as well as the provision of early warning systems for predictive maintenance.
- Start-ups: CEDAR (Cost Efficient heat pumps using DigitAl twins and Reinforcement learning) develops next-generation technology for optimal control of heat pump systems. They provide an "install-and-forget" type of system for retrofitting residential heat-pump systems that exploit monitoring data to develop an AI-driven digital twin of the heat pump based on which the heat pump performance is then optimised.

None of the potential competitor offer solutions in the field of large-scale heat pump and commercial refrigeration. However, as the demand for energy-efficient and sustainable refrigeration and heating solutions grows, the competition in the digital twin market is expected to intensify. Key differentiators among competitors include the depth of domain expertise, the breadth of integrated capabilities (e.g., simulation, optimization, predictive maintenance), ease of integration with existing systems, and the ability to deliver tangible cost savings and sustainability benefits.

Successful players in this market will need to continuously innovate and adapt their offerings to meet the evolving needs of supermarket operators, while also addressing concerns around data security, interoperability, and scalability.

6.4 Commercialisation barriers

One of the main challenges related to the commercialisation of the project results is the general lack of awareness and practical experience with digital twin technology among potential users. Many of those who could benefit from digital twins are not fully familiar with how these technologies work or their effective application in their business area. This project overcomes this barrier by demonstrating the various applications and economic benefits that the digital twin technology can offer. It was aimed to engage all stakeholders who might have an interest in exploiting these technologies, highlighting not only the technical advantages, but also the business opportunities they present.

Another commercialization barrier identified in the project was the potential inability to obtain design information and relevant operational data required for developing simulation models. Component and system manufacturers, along with service providers may be constrained in sharing detailed information about the systems they operate, design or maintain. This barrier was overcome in the project by including manufacturing companies and service providers in the development of digital twin-based solutions. For third-party companies, the approach involved describing the benefits that the outcome of the project could offer them (e.g. faster and fewer maintenance services, improved design). A similar approach to this can be applied when commercializing the outcomes of the project.

6.5 Project outcome related to energy policy objectives

a) **Security of supply:** electrifying the heating and cooling sector, heat pump and refrigeration systems enable the exploitation of renewable electricity, sector in which Denmark is at the forefront, thus reducing the dependence from external energy sources. This increase security and competitiveness and reduce vulnerability to price shocks and supply difficulties. In this respect, the project supported the electrification of the Danish energy system, by contributing to the development of more efficient and reliable heat pump and refrigeration systems.

b) **Independence of fossil fuel:** besides increasing the security of supply, the electrification of the heating sector through heat pumps contributes to the reduction of the use of fossil fuels. This decarbonisation potential became particularly evident in countries like Denmark where a significant share of the heating demand is covered by district heating. Indeed, using heat pumps to supply hot water to the network it is possible to further increase the share of renewable electricity in the heating sector. Furthermore, heat pump and refrigeration systems are sector-coupling technologies that if operated in a flexible manner can support the grid balance and avoid the curtailment of renewable generation. The project proven that the use of digital twins is crucial to achieve these goals while make these technologies more competitive compared to others, by increasing their efficiency and reliability, and to unlock their cost-, energy-saving- and flexibility potentials through the development of optimised control algorithms.

c) **Climate and environmental concerns:** the project aimed to promote a larger deployment of large-scale heat pumps for district heating. Heat pumps are characterised by higher efficiencies compared to traditional technologies like boilers. Indeed, unlike the latter, which convert only a fraction of the energy input into useful energy output, the useful effect of heat pumps, i.e. the heat supplied to the user, is greater than the amount of work introduced into the system. This is because it consists of the sum of the energy drawn

from the heat source, which in the case of heat pumps is often ambient air, and the work supplied. Therefore, replacing a boiler with a heat pump reduces energy consumption for heating and allows renewable electricity to be used, contributing significantly to the reduction of greenhouse gas emissions. In this framework, digital twins for large-scale heat pumps can further improve energy efficiency and fault detection and facilitate the roll out of the technology.
As for supermarket refrigeration systems, where energy consumption is a major operational concern, digital twins can play a key role in increasing energy efficiency, which in turn lead to lower CO_2 emission related to the electricity usage. Moreover, enabling advanced fault-detection services digital twins can also contribute to the reduction of direct CO_2 emissions, by early detecting CO_2 (or other refrigerants) leakages from the refrigeration system.

d) **Cost efficiency:** The project aimed to minimise the operational and maintenance costs of large-scale heat pump and refrigeration systems through the use of digital twins that enable advanced functionalities in terms of system monitoring, optimised operation and fault detection and diagnosis.

6.6 PhD's activities

One PhD student was involved in the project, who was part of the Department of Civil and Mechanical Engineering at the Technical University of Denmark, DTU. The focus of this PhD was on digital twin-based services for large-scale heat pumps. This work resulted in three publications in scientific journals, six conference contributions, and a PhD Thesis. Moreover, the learnings from the project were included in teaching activities at DTU. In particular, the findings of the project were shared in the courses "Refrigeration and Heat Pump Technology" and "Digitalization of Thermal Energy Technologies".

7. Project conclusion and perspective

The research and demonstration activities conducted during the project successfully proved the potential of digital twins in enhancing the performance of large-scale heat pump and supermarket refrigeration systems. The project showed that digital twins:

- provide a suitable representation of the complex dynamics present in the operation of heat pumps and refrigeration systems through simulation models with different levels of complexity.
- describe the real-world operating conditions of heat pump and refrigeration systems, along with the interactions among their components.
- enable the optimisation of control settings leading to lower energy consumption as well as lower operational costs.
- enable predictive maintenance functionalities that have the potential for reducing maintenance costs.
- provide valuable and intelligible insights for system managers, designers, and component manufacturers related to the behaviour and enhancement potential of heat pump and refrigeration technologies.

As for the supermarket case, it has been shown that:

- the mutual interaction between the controllers of the display cabinets and the compressor pack strongly influences the stability of the evaporation pressure, hence the system performance. Therefore, to optimise the latter, it is necessary that the control action minimises fluctuations in the evaporation pressure.

- the most cost- and energy- efficient operations of a supermarket refrigeration system can be achieved by equipping the suction group with a variable speed compressor and adopting a modulating regulation of the temperature of the display cabinets. This would ensure a more stable evaporation pressure and load and, hence, a more stable and efficient operation of the compression group.
- grey-box models can successfully describe the temperature dynamics of refrigerated display cabinets. Moreover, it was shown the capability of grey-box models to infer the actual parameters of the modelled physical system, which can thus be used as inputs in physic-based modelling approaches, classification problems, and fault detection applications.

As for the large-scale heat pump cases, it can be concluded that:

Large-scale district heating heat pump operating with seawater as heat source

- the operating conditions of a large-scale heat pump for district heating operating with seawater and ammonia was successfully reproduced by its digital counterpart, and advanced monitoring possibilities were demonstrated.
- the developed digital twin framework allowed a steady state analysis of the thermodynamic cycle, hence a parametric study of the impact of the main operational variables on the cycle performance. This aids the monitoring of the operating conditions and the implementation of corrective measures when needed. To this end and to facilitate plant operators in identifying the optimal measures, an optimisation framework integrated with a graphical user interface (GUI) was developed.
- the use of the optimisation framework for continuous set point optimisation, aiming to maximize the COP of the heat pump system, led to a 3 % increase in COP through the adjustment of the turbo compressor speed, thus showcasing the potential for digital twin-based services in optimizing the operation of large-scale heat pump systems.
- the optimisation framework would especially be suitable for heat pump systems with a high degree of changing boundary conditions, which increases the potential for this service further.
- the optimisation framework can be used in an open-feedback loop between the physical and virtual entity via a human operator, to perform continuous set-point optimisation of a large-scale district heating heat pump system.

Large-scale district heating heat pump operating with industrial excess heat as heat source

- the digital twin framework demonstrated potential for monitoring and optimizing large-scale heat pumps under time-dependent performance degradation due to fouling, suggesting broader applicability for other operational challenges and system types.
- a quasi-steady-state model was derived from a dynamic model of a two-stage ammonia heat pump and successfully used to simulate its operation.
- an online calibration method for the quasi-steady-state model that adjusted for fouling-related parameters based on real-time data was proposed. This approach reduced simulation errors for the COP between 3 % and 17 % compared to using only the initial calibration. It also enabled estimating the influence of fouling on evaporator thermal resistance and source pressure drop and assessing cleaning-in-place effects on fouling mitigation.
- the resulting adaptive model demonstrated that fouling had a more significant impact on the evaporator's thermal resistance than on the source pressure drop. The model helped evaluate the effectiveness of different Cleaning-In-Place (CIP) procedures, showing that none completely removed fouled material from the evaporator.
- It was found that fouling levels influenced the optimal intermediate pressure set point, which in turn affected the COP by up to 3 %. In view of this, the adaptive model and a derived surrogate polynomial model were used to determine the optimal set point for the intermediate pressure, which varied with the level of fouling.

- The surrogate model, based on the adaptive model, offered rapid estimations similar to the adaptive model for the optimal intermediate pressure set point but required less computational resources.

The project was a crucial step in lowering the entry barriers for the use of digital twin technologies, making them accessible to a broader range of users. However, it also highlighted areas that require further investigation to fully leverage the potential of this technology. Future steps might include exploring automatic model generation to facilitate the development of digital twins from existing monitoring data. Building on the insights gained from this project, future efforts will focus on standardizing and automating model parametrization in a way that minimizes the time required for model development. Additionally, it would be beneficial to explore how digital twins can also enhance the design of heat pump and refrigeration systems.

The project effectively demonstrated how digital twins can enhance efficiency, minimize energy consumption, and optimize system performance. The next step could involve incorporating this knowledge into system design. This feedback loop would support the decision-making process during the design stage, allowing for the consideration of not only the impacts of individual components but also the dynamic operation of the system and its interaction with dynamic boundary conditions. Such an approach would provide insights into system-wide operational strategies and integration possibilities.

The knowledge gained through this process could, for example, integrate Danfoss' expertise and support their efforts to assist customers in developing efficient and optimally designed integrated energy systems using Danfoss' components.

In conclusion, the project showed that the adoption of digital twin technology represents a paradigm shift in the management and optimisation of large-scale heat pump and supermarket refrigeration systems. Digital twins, coupled with advanced analytics, machine learning algorithms, and IoT sensors, enabled these systems to adapt to real-world boundary conditions. This adaptation has the potential to outperform conventional operational strategies for large-scale heat pump and refrigeration systems, thereby enhancing their energy efficiency and reducing their operational and maintenance costs.

8. Appendices

Further results of the project can be found here:

https://digitaltwins4hprs.dk/

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