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Enhancing Energy Efficiency in Large-Scale Heat Pumps Using Digital Twins for Set Point Optimization

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Large-scale heat pumps can contribute towards the decarbonization of the heat supplied to buildings and industries, as long as such systems operate as expected. Modern digital technologies, such as digital twins, can enhance the energy efficiency of industrial equipment in real-time, but their use in heat pumps remains limited. This article evaluates the use of set point optimization using digital twins for commercial large-scale heat pumps. The results highlight the energy efficiency potential of digital twin-based frameworks for real-time set point optimization and fault-tolerant set point optimization.

The electrification of the heating supply in buildings and industries is essential for the decarbonization of these sectors. In this context, large-scale heat pumps are expected to play a relevant role in future energy systems, provided they operate under expected performance and reliability levels [1].

Achieving energy efficient large-scale heat pumps often requires identifying energy-optimal controller set points. Optimal set points are typically determined during the commissioning phase of a heat pump system. However, there is no guarantee that these set points will remain optimal over time, particularly under the presence of performance degradation and varying boundary conditions. Digital technologies offer the possibility to retrieve and process large volumes of data in real-time, enabling enhanced control and surveillance strategies [2]. In particular, digital twin technology, represented by virtual replicas of physical systems that can adapt to changes in their behavior, can be used for services such as real-time operation monitoring and optimization. However, the use of digital twin technology in the heat pump industry remains limited, with a few examples found in the literature, such as in [3][4][5].

This study aimed at evaluating the energy efficiency potential of digital twin-based set point optimization frameworks for large-scale heat pumps. These frameworks were developed for two commercial large-scale heat pumps used for district heating supply.

Demonstration cases

The demonstration cases, named Case I and Case II hereafter, are located in Denmark. Case I uses seawater as a heat source, whereas Case II uses industrial excess heat. The nominal heating capacities of Case I and Case II are 1 MW and 2 MW, respectively.

The layout of the demonstration cases is shown in Figure 1. Case I comprises a cascade heat pump system with a steam compression bottom cycle and an ammonia cycle at the top. The bottom cycle uses an axial turbo compressor, while a reciprocating compressor is used in the top cycle. Case II is a two-stage ammonia system with a reciprocating compressor in each stage.

Case II is prone to evaporator fouling. This is a common fault affecting large-scale heat pumps, which is difficult to characterize. The evaporator of Case II is cleaned through a cleaning-in-place (CIP) system, aiming to reduce the fouling-related performance degradation of the heat pump.

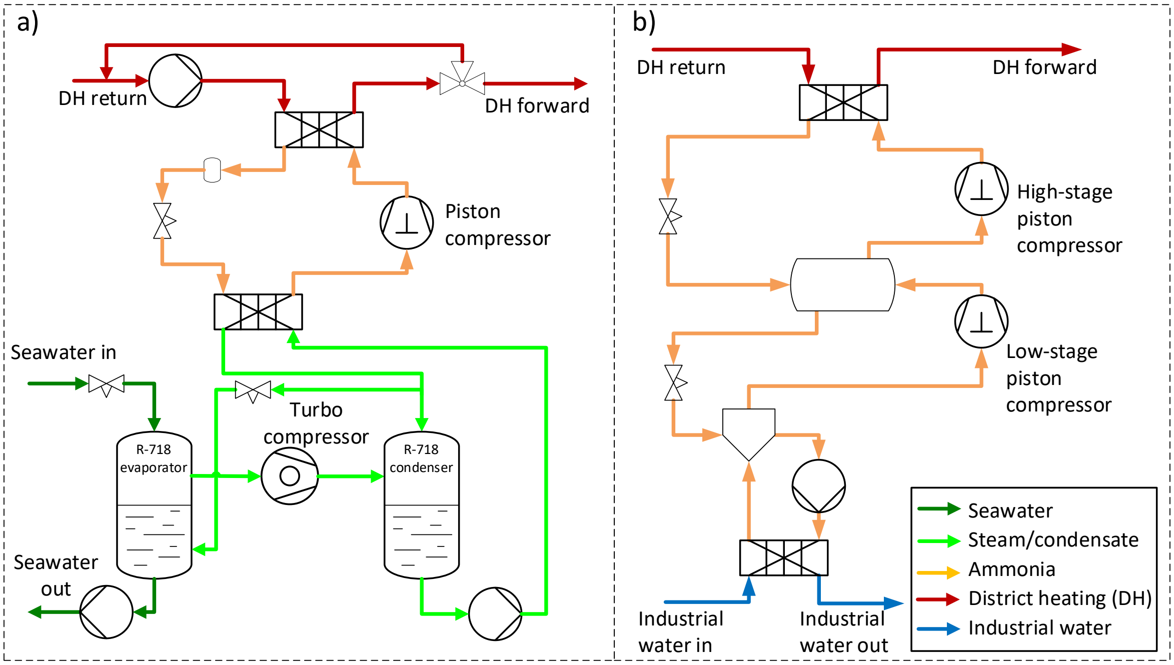

Figure 1: Layout of Case I (a) and Case II (b) of the demonstration cases.

Digital twin-based frameworks

The frameworks for set point optimization are presented in Figure 2. Operational data was retrieved through a cloud service connected to existing control and supervisory systems. The operation of Case I was represented through a dynamic simulation model developed in Modelica, using the software Dymola [6] and TIL Suite [7]. This model was simulated in Python using a Functional Mock-up Interface and was calibrated based on measurements, as described in [4]. Case II was simulated through a quasi-steady-state model developed in Python. In this model, parameters related to the heat transfer coefficients and fouling were repeatedly adjusted by means of an online calibration approach, explained in [5]. This online calibrated model was referred to as the adaptive model.

The set point optimization for both demonstration cases was implemented in Python using the module Scipy [8]. In Case I, the validated dynamic simulation model was applied to calculate the process out temperature set point in the top and bottom cycles that maximized the coefficient of performance (COP) of the system. This led to an adjustment of the compressor speed in each cycle. In Case II, the adaptive model was used to determine the intermediate pressure set point that led to the highest COP of the system. Through this optimization, the speed of the high-stage and low-stage compressors were modified.

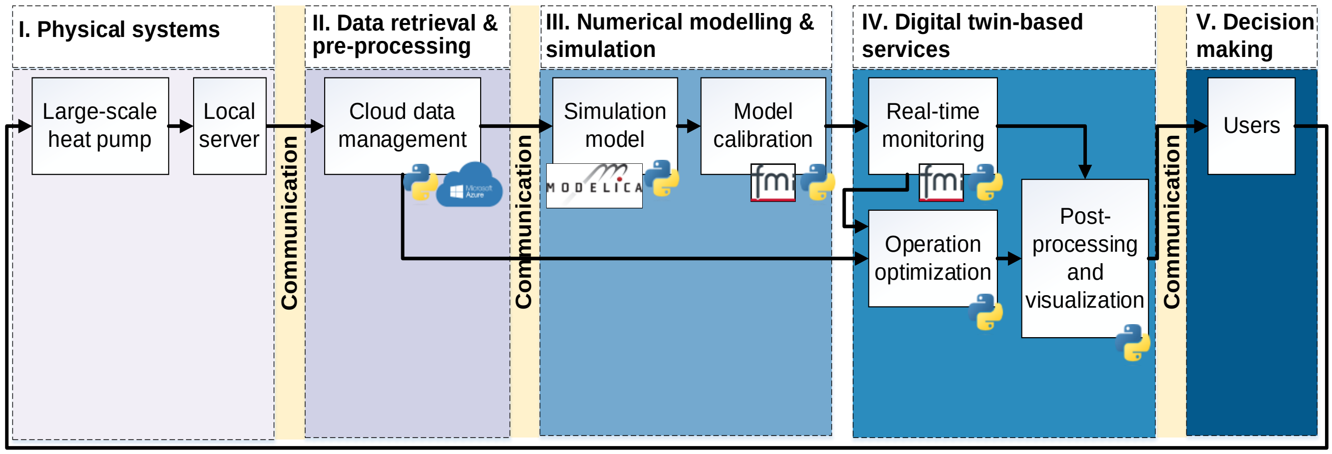

Figure 2: Diagram of the digital twin-based frameworks.

To reduce the time and computational resources required for the set point optimization in Case II, a surrogate polynomial regression model was derived from the adaptive model. The optimal set points obtained from the adaptive and surrogate models were compared with those from the simulation model without online calibration, referred to as fixed model. Additionally, these set points were compared with the geometric average value, a conventional approach for determining the intermediate pressure in two-stage vapour compression systems.

The comparison between the set points obtained from different approaches in Case II was done for six 2-hour periods of operation, extended over ten calendar months. In Case I, the set point optimization was performed every 3 hours over a period of 10 hours of operation data.

Software interface for operators

A software tool (shown in Figure 3) was created to monitor and optimize the operation of Case I, and hence provide a graphical user interface (GUI) to the operator and owner of the heat pump. Its interface displays real-time operational variables alongside simulation model results. The tool also allows testing of hypothetical scenarios. This enables a simulation-based analysis of performance indicators resulting from different control parameters.

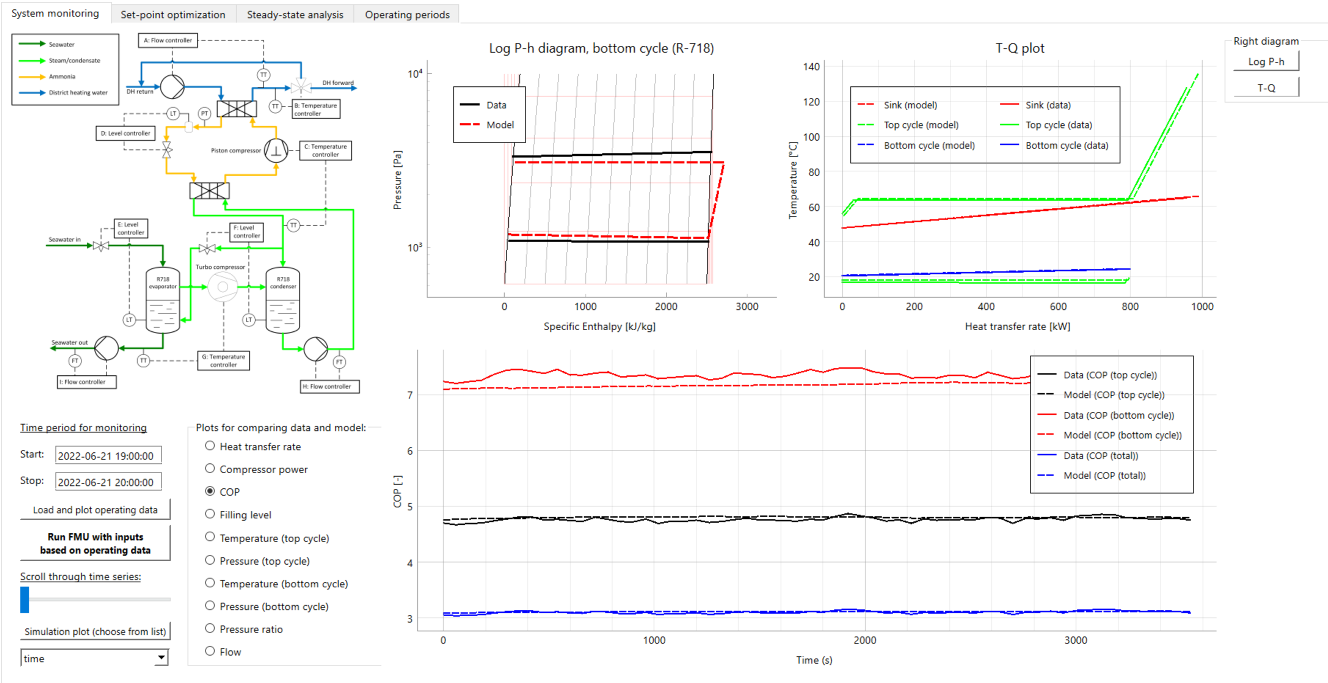

Figure 3: Screenshot of the GUI software interface with fans for various services.

Real-time set point optimization

An example of the set point optimization in Case I is shown in Figure 4, where the simulation model was used together with historical data to investigate the potential for performance increase.

Here, the simulation model initially showed a COP of approximately 3.35 (black curve) with a compressor speed of 87 % (blue curve) during the first three hours. This speed represented the conventional operation of the system during that period. After the first optimization (performed at 09:00), the compressor speed was adjusted to around 83 % of its nominal value. This resulted in a COP of approximately 3.40, i.e. an increase of 1.5 % compared to the value before the optimization. The second and third optimizations did not lead to changes in the compressor speed, given that the optimal values were already reached with the given boundary conditions after the first optimization.

In this study, the optimization was done using only the COP as a target variable, but it could also include other variables for the same function such as, for example, the heating capacity of the heat pump. This would require the use of multi-objective optimization or a weighted average of the different target variables.

The use of the proposed digital twin-based framework has the potential to be extended for the assessment of hypothetical operational scenarios. The framework results can be used to represent trade-offs between conflicting variables of interest. This can enable heat pump operators to test different set points on a simulation model, providing accurate estimations of the performance of the system.

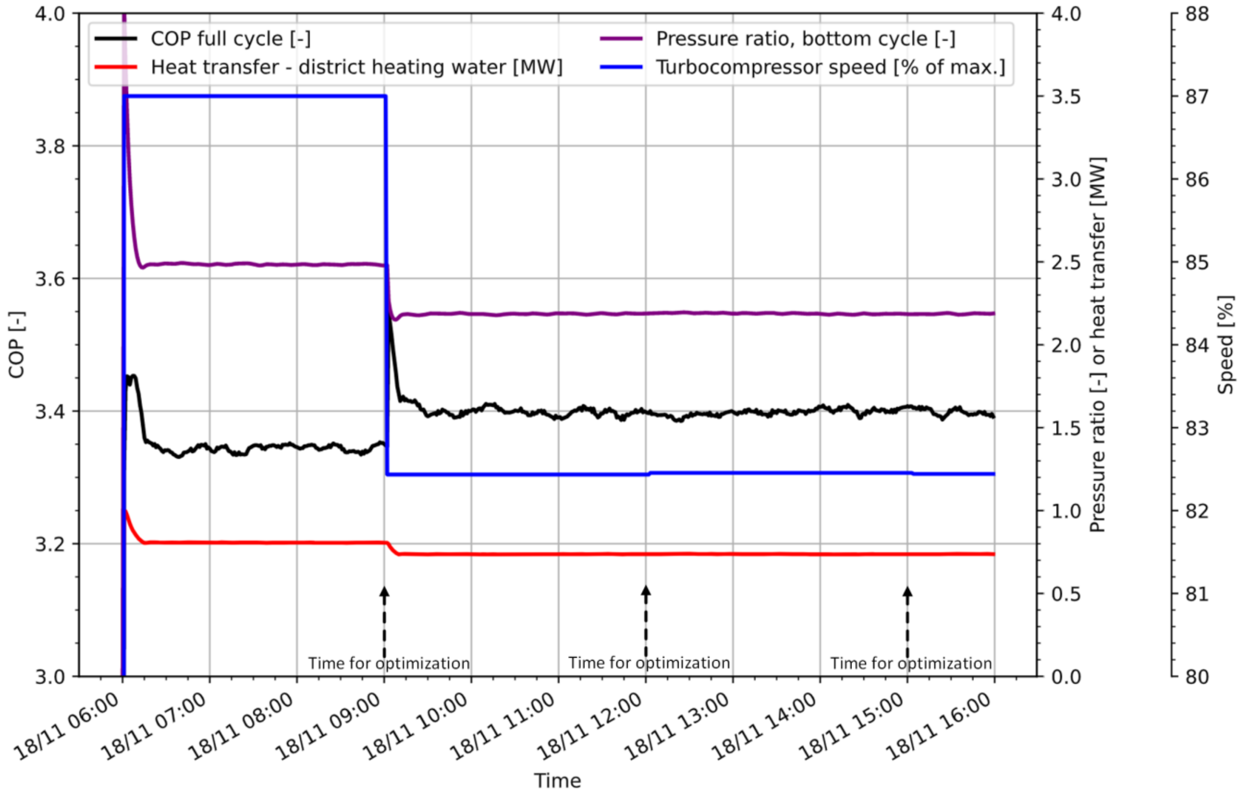

Figure 4: Real-time set point optimization in Case I, source [4].

Set point optimization under performance degradation

Figure 5 shows a comparison between the optimal intermediate pressure set points obtained from the geometric average, fixed model, adaptive model, and surrogate model, respectively. The optimal intermediate pressure set points resulted in a greater increase in COP compared to a decrease in heat capacity. This is applied across all the fouling levels and heat capacities analyzed. All model-based approaches in the study yielded similar estimations for the optimal intermediate pressure set point. These adjustments led to COP improvements within 0.2 % to 1.3 % above the geometric average value. Notably, the fixed model tended to overestimate COP improvement and heat capacity reduction due to the optimal set point, especially during periods when the heat pump operated at higher heat capacities (fouling calibration periods 4, 5, and 6). Comparing the surrogate model to the adaptive model, their estimations for optimal set points and related COP and heat capacity variations were similar. The most significant difference occurred during periods when the heat pump operated at the lowest heat capacities, specifically fouling calibration periods 1 and 3.

The results shown in Figure 5 highlighted the relevance of accounting for fouling on the set point optimization. Not including fouling in the model led to overestimated changes in the COP and heat capacity derived from the optimal set points.

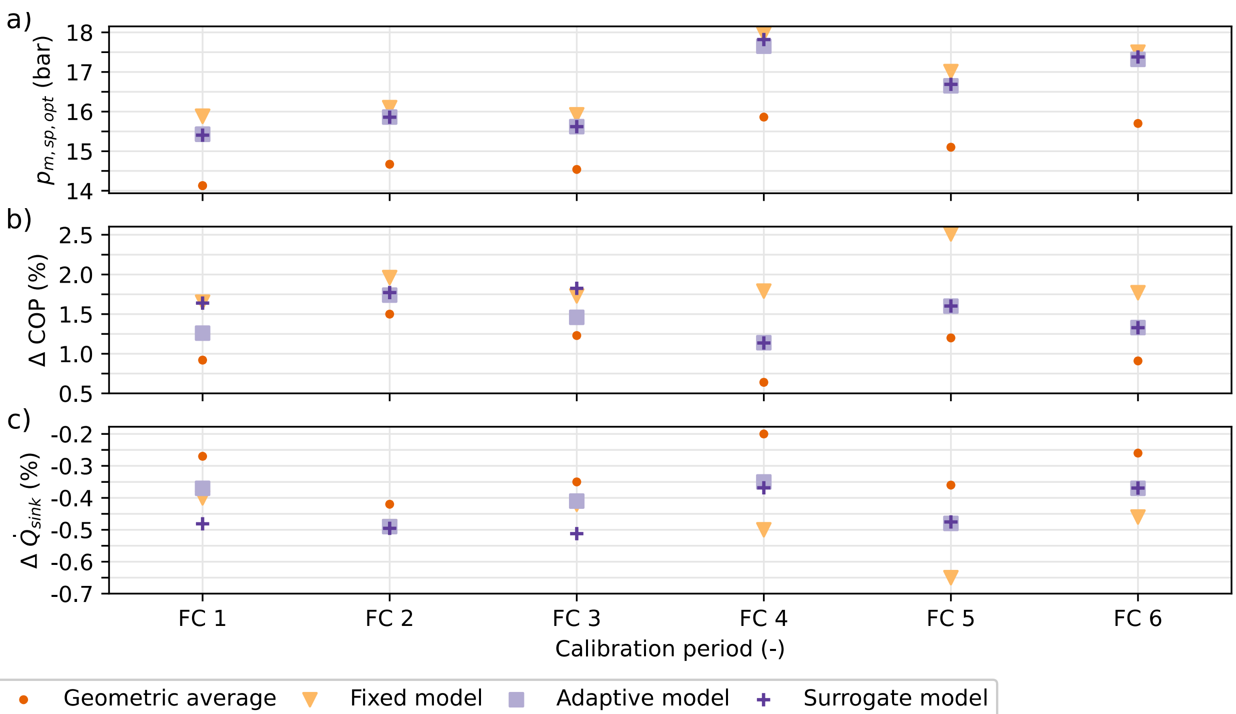

Figure 5: Set point optimization in Case II. Different approaches were used for determining the optimal intermediate pressure set point for six periods of operation (FC 1 to 6). Baseline (not optimized) set point equal to 10 bar, source [5].

The development and implementation of the fixed model are expected to require less time compared to the adaptive and surrogate models. The adaptive model relies on a data infrastructure that enables the retrieval of real-time operational data. The development of the surrogate model will take longer due to its dependence on results from online calibration of the adaptive model using retrieved operational data. Once developed, the surrogate model is expected to provide similar estimations to the adaptive model for optimal intermediate pressure set points, but more rapidly, as it does not require an optimization routine. This can enable the use of the surrogate model in component or system controllers.

Conclusions

This study addresses frameworks based on digital twins for optimizing the operation of large-scale heat pumps in district heating systems. The first framework optimized real-time process outlet temperature set points in a cascade heat pump system. The second framework defined optimal intermediate pressure set points for a two-stage heat pump system, considering varying levels of fouling. The results demonstrated the potential to enhance energy efficiency in large-scale heat pumps by extending the proposed frameworks using digital twin technology. It is essential to define suitable model complexity levels and multiple optimization targets for an optimal integration of these frameworks in existing heat pump control systems.

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