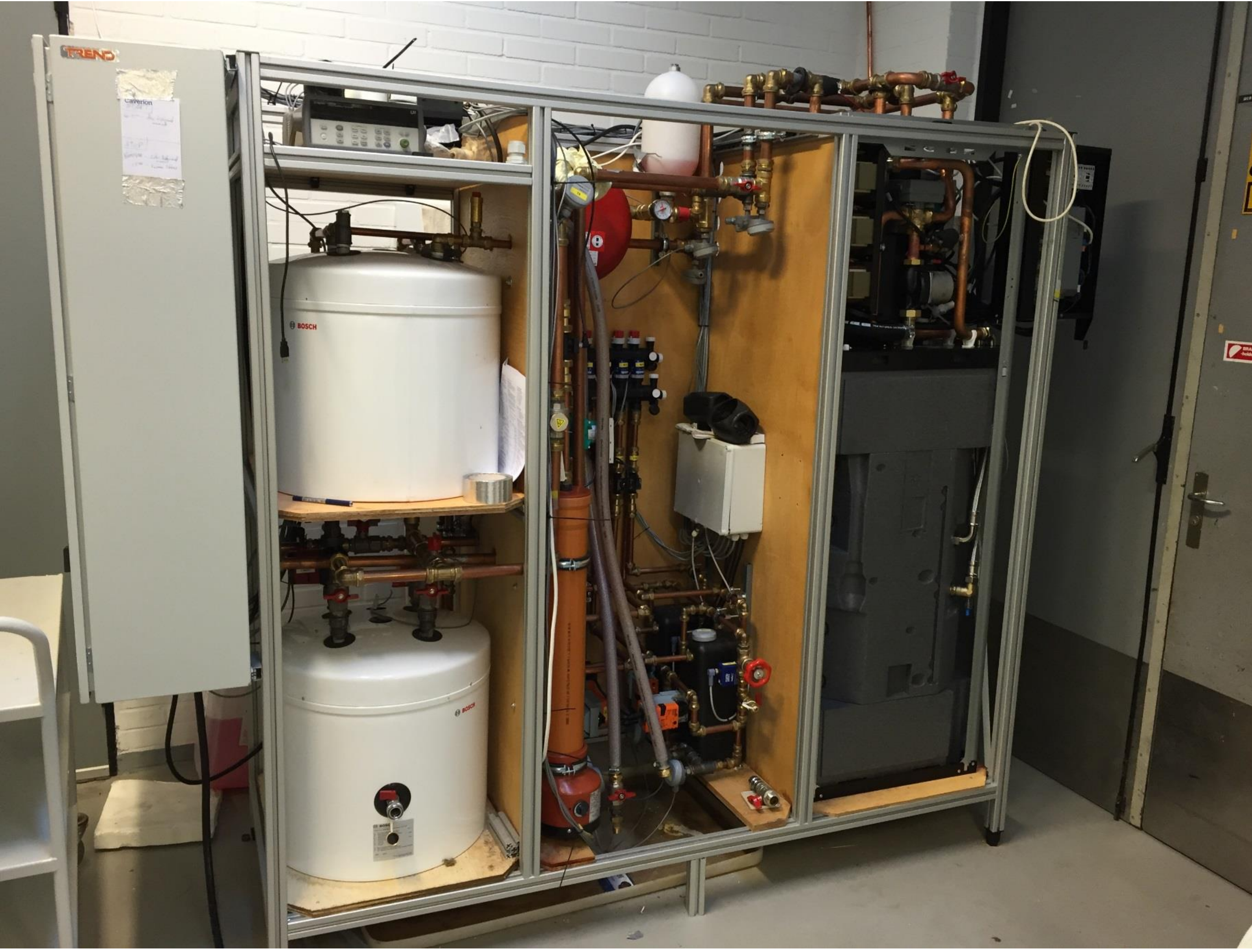

Combined optimization of heat pumps and heat emitting systems

Energy and Climate

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Title: Combined optimization of heat pumps and heat emitting systems

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Front page: the OPSYS test rig

Preface

The present report documents the results from the *Underfloor heating and heat pump optimization* project financed by the Danish Energy Agency through the EUDP project no. 64014-0548.

The purpose of the project was to investigate different possibilities for control of a heat pump and the heat emitting system of a house in order to increase the overall efficiency of the system.

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1 Introduction

The purpose of the project was to minimize the gap between the accredited efficiency of a domestic heat pump and the actual efficiency when installed in a house. Unfortunately, measurements on existing heat pump installations have shown Seasonal Performance Factors (SPF: mean annual COP (efficiency)) well below expectations as the heat pump and the heat emitting system are rarely properly adjusted at the installation of the heat pump (Poulsen et al, 2017). For example, the forward temperature (often also called supply temperature) from the heat pump is often set too high in order to guarantee sufficient space heating. A forward temperature higher than needed results in a lower COP.

Typically, an increase of 1°C of the forward temperature leads to a decrease of 2-3% in the COP. For most heat pumps, the only control and means of reducing the forward temperature is a simple ambient temperature correction, which, however, rarely leads to an optimal forward temperature. When the forward temperature is too high, it also has consequences for the heat emitting system. The volume flow through the system fluctuates due to uncoordinated opening and closing of the valves in the system, e.g. manifold valves for an underfloor heating system. The higher the forward temperature is above the minimum required forward temperature, the more the amplitude of the fluctuations increases. The fluctuating flow causes the heat pump to fluctuate in produced heating power resulting in a reduced COP compared to the optimal COP at the actual temperature level. The larger fluctuations, the higher decrease in efficiency (Jensen, Olesen and Paulsen, 2014).

The aim of the project was to minimize these problems, so that end users receive the expected efficiency from their heat pump installations. The goal was, therefore, to develop integrated controllers for the heat pumps and the heat emitting systems to reduce the forward temperature and the fluctuations of the flow rate in the system.

Preliminary results from a study financed by the Strategic Research Centre on Zero Emission Buildings (Jensen, Olesen and Paulsen, 2014) indicate a theoretical potential for improving the COP of a heat pump installation with a SPF around 3 by up to 15 % by optimizing the volume flow. The study shows an equally large improvement when keeping the forward temperature as low as possible.

A recent study on the performance of more than 160 Danish heat pumps (Poulsen et al, 2017) reveals that only around 15 % of the heat pumps perform as expected. The main reasons are, besides installation errors and too small heat emitters, that the flow rate through the differing heat emitters is wrongly adjusted and that the heating curve of the heat pump is set too high leading to potential combined savings of up to 25 %.

A too low pressure drop across one of the heat emitters will lead to a too high flow rate through this heat emitter. This will leave less flow rate for the other heat emitters, which then will require a higher forward temperature in order to be able to satisfy the heat demand of the rooms with a too low flow rate. A high forward temperature leads to a poorer COP for the heat pump.

An optimized controller, which controls both the forward temperature from the heat pump and the valves of the heat emitting system will, therefore, lead to a more efficient heat pump installation.

1.1 The report

The report is based on the following eight Appendixes:

Appendix A - The OPSYS test rig: contains a description of the test rig for testing different control strategies for a heat pump system consisting of both the heat pump and the heat emitting system. The heating system is exposed to a virtual heat demand of a typical Danish single-family house.

Appendix B – Description of the OPSYS test rig software – Focus on the control and simulation setup: contains a description of the software, which facilitates the interaction between the simulation program on a pc, the test rig (with the Trend BMS modules) and a data logger. The Appendix further describes how to process the measured data from the Trend BMS system.

Appendix C – House models for Dymola to be used in connection with the OPSYS test rig and annual simulations of the performance of heat pumps: contains descriptions including thermo-physical values of three typical Danish single-family houses: an 1970's house, a BR10 house and a BR15 house. The three houses form the basis for online simulation of the heat demand on the test rig and in the annual simulation program.

Appendix D – Simulation model: contains descriptions of the developed two simulation programs: one for the test rig and one fast annual simulation program. Both simulation programs contain a FMU (Functional Mock-up Unit) of the houses described in Appendix C. The simulation programs are developed in python and include the possibility to change the control of the heat pump and the heat emitting system in both the test rig and in the annual simulation program.

Appendix E – Control strategies, algorithms, and simulation results: contains descriptions and results from investigations of two control strategies: MPC (Model Predictive Control) and ANN (Artificial Neural Networks).

Appendix F – Evaluation of a baseline test on the OPSYS test rig: contains the results of a comparison of a) specified values from the simulation program vs measured data from the test rig, and b) specified/measured values from the test rig vs results from the annual simulation program for the same period.

Appendix G – Energy Flexibility: contains the results from an investigation on controlling the heat emitting system in order to obtain energy flexibility for providing stability services to the electricity grid.

Appendix H - Performance and other contributions: contains description of the work done to define and set up a pyFMI interface for communication between a real heat pump and a house model. Furthermore, the work on speeding up the simulation time for the heat pump model in Dymola is described.

A tremendous amount of work has been carried out in the OPSYS project leading to around 200 pages of documentation. The reader is invited to read all the documentation, however, the present main report only summarizes the overall results from the OPSYS project. It is indicated where further information may be found in the different Appendixes, if wanted.

2 The OPSYS project

As the title of the project was rather long, it was abbreviated to OPSYS (Combined **OP**timization of heat pumps and heat emitting **SYS**tems (translation of the Danish title)).

The aim of the project was to develop new and more advanced control strategies in order to increase the efficiency of heat pump installations. For the purpose of facilitating this, two tools have been developed during the OPSYS project: a test rig and a fast, annual simulation program. The rationale for this was:

1. demonstration in real houses is preferable, however, there are many non-controllable variables in a real house, which makes it difficult to draw reliable, significant conclusions - unless the control is demonstrated in several houses. Moreover, the demonstration in real houses is time consuming and very expensive
2. simulation is cheap and fast, but it lacks somewhat credibility since all inputs and the environment are fully specified and often in a very simple way, which may lead to conclusions that are not likely in real life
3. hardware in the loop (e.g. the OPSYS test rig) establishes a bridge between the two approaches described above. In the OPSYS test rig, some inputs are controllable, while the environment is realistic, but, different from real houses, repeatable

As combined control of both the heat pump and the heat emitting system is a new field, 1) demonstration in real houses was not within the scope of the project. However, it is believed that based on the obtained results from the OPSYS project, a follow-up project may include tests in real houses.

Tool 2) and 3) are both needed because tests in the test rig are conducted in real time – i.e. it takes a year to test a year. Therefore, only shorter and very precise tests should be carried out in the test rig. However, in order to facilitate the development of the combined controllers, there is a need for a very fast tool (i.e. tool 2)) for obtaining quick results and for performing various parametric analysis. In order to make tool 2) very fast, it is necessary to introduce several simplifications about the heat pump and heat emitting system. However, to gain confidence in the concept before moving the control strategies to real houses, there is a need for testing the concepts in a "hardware in the loop" system with a real heat pump and a semi-real heat emitting system – i.e. tool 3).

The two tools are briefly described in the following sections followed by an evaluation and a comparison.

2.1 The OPSYS test rig

A dynamic experimental setup has been constructed – see Appendix A and B. The system (test rig) emulates a house with an underfloor heating system to which a ground source heat pump can be connected. Figure 2.1 shows a principle sketch of the system. The system has two main elements denominated the hot side and the cold side, seen from the heat pumps point of view (cold side = evaporator side, hot side = condenser side).

The hot side emulates the underfloor heating system with the possibility of using a buffer tank. The underfloor heating system is emulated via a series of parallel-connected heat exchanges resembling each room in a house. In order to reduce the complexity of the test rig, the house is emulated by only four zones. The number of zones of the house may later be extended on the test rig. Hot water draw off may also be emulated, but this is currently not part of the test setup.

The control of the experimental setup is a simulation program that controls the heat consumption (via an embedded FMU of the considered house) and provides the BMS controller of the test rig with a return temperature and a valve position for each "room" (Appendixes C and D). In this way, it is, on one hand, possible to control an underfloor heating system like in an ordinary house, while it, on the other hand, makes it possible to test different, advanced control strategies. The size and function of the "rooms" can easily be changed by changing the load patterns and temperatures of the "rooms" in the simulation program – Appendix C and D.

The simulation program also controls the forward temperature of the heat pump. In the present set up, the ambient temperature sensor is replaced by a signal from the simulation program and utilizes the heating curve of the heat pump.

The cold side of the experimental setup (see figure 2.1) emulates a heat source, e.g. the ground. This is an electric heater, which is controlled by the simulation program in order to emulate the temperature of the brine to the cold side of the heat pump. With this method seasonal variations in the brine temperature (for both liquid to water and air to water heat pumps) and different lengths of tubes in the earth can be emulated.

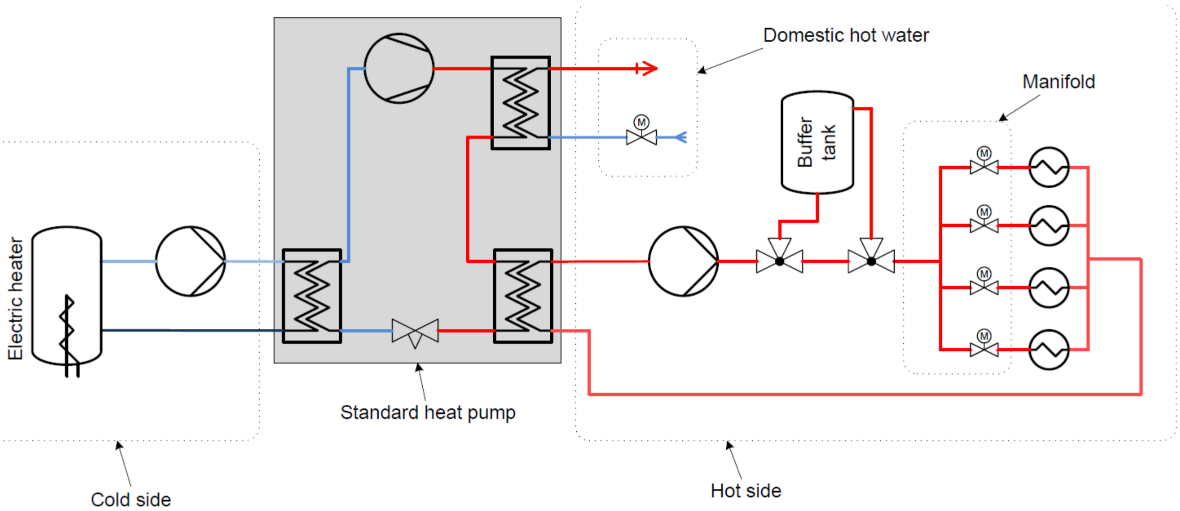

Figure 2.1. Principle sketch of experimental setup.

Appendix A describes the hardware of the test rig including the obtainable measurements and some control settings. Appendix B and D describe the software related to running the test rig. Appendix D describes the simulation model running on the pc of the test rig, while Appendix B describes the software for connecting the pc, the BMS (Building Management System from Trend) on the test rig and an external data logger. In order to facilitate the use of a Dymola FMU (Functional Mock-up Unit) in the python (programming language) scripts, a special pyFMI script was developed to facilitate communication via Modbus between the BMS at the test rig and the simulation pc – see Appendix H.

The Trend GUI running on the simulation pc for setting up a test, viewing the progress of a test and logging measured data from the BMS is called 963. The main screens of the 963 are shown in figures 2.2-4. Figure 2.2 shows the screen for viewing the four underfloor heating circuits. The main purpose of this part of the test rig is to emulate the heating system of the house, including securing the return temperature from the four heat exchanges as specified by the simulation program. Figure 2.3 shows the brine side of the test rig, while figure 2.4 shows the connection between the test rig and the central cooling system of the laboratory, where the OPSYS test rig is situated. The cooling system shown in figure 2.4 is responsible for providing the heat demand of the house, which the simulation specifies. For more information on the OPSYS test rig, please see Appendix A.

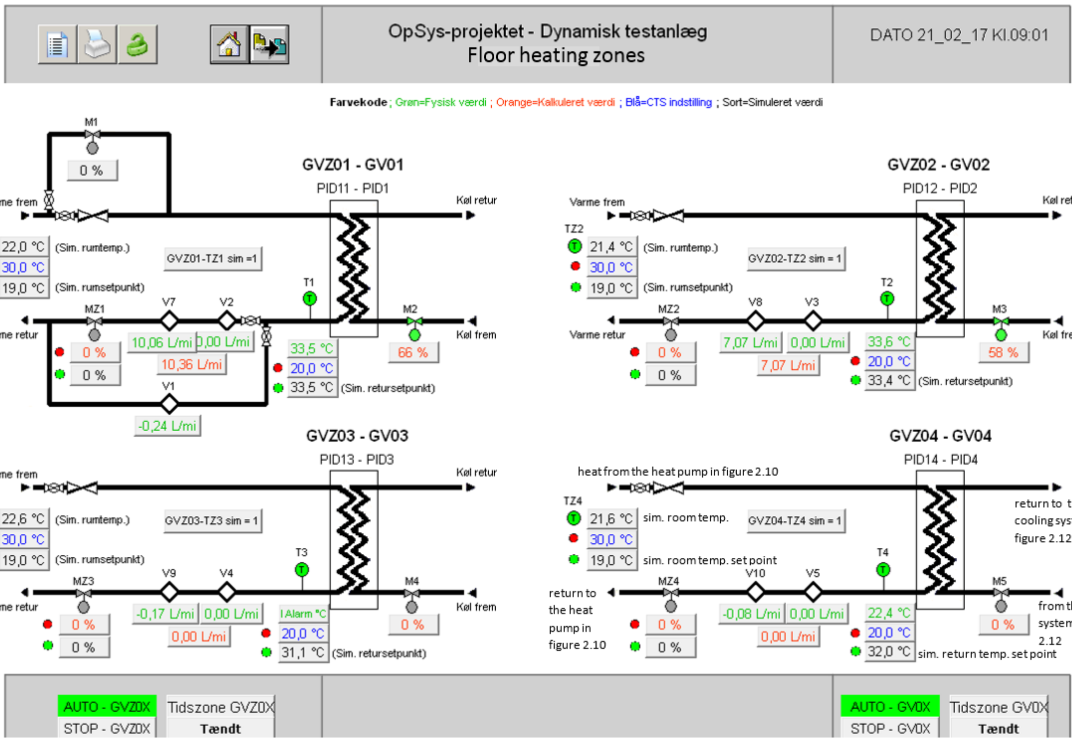

Figure 2.2. The BMS screen for viewing and controlling the four heating zones of the test rig.

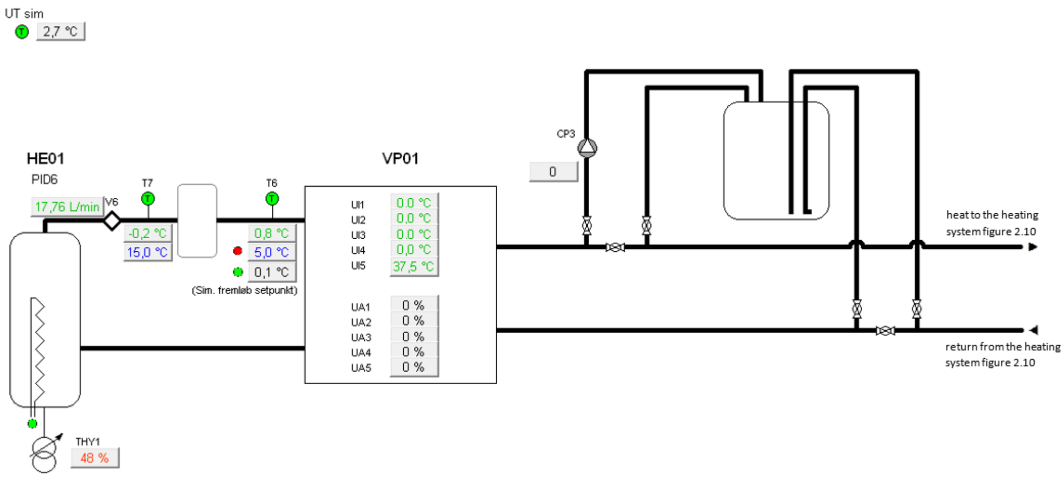

Figure 2.3. The BMS screen for viewing and controlling the heat pump and the brine side of the test rig.

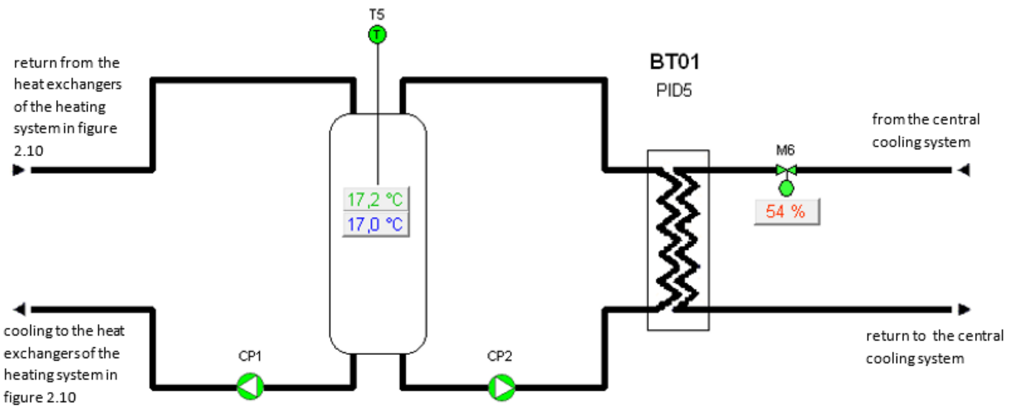

Figure 2.4. The BMS screen for viewing the controlling of the cooling system of the test rig.

In the simulation program running on the test rig pc, it is possible to introduce and investigate different control strategies of the forward temperature from the heat pump and the position of the valves of the four heat exchangers emulating the heat emitters of the house – see Appendix D. The control strategies developed by using the annual simulation program may, therefore, directly be implemented in the control of the test rig.

2.2 The annual simulation program

The core of the annual simulation program is a model of a typical Danish house. The same model is used in the simulation program running on the test rig pc. The house model is developed in Dymola (Modelica) and imbedded in a python script as a FMU (Functional Mock-up Unit). The house model includes all constructions of the house (walls, windows, ceiling, etc.), the underfloor heating system of the four rooms, internal gains (people and appliances), external gains (solar radiation through windows), and the ambient temperature. All input data to the house model for three typical Danish houses is given in Appendix C.

Appendix D describes the developed house model. Figure 2.5 shows a top layer view of the house model with constructions, while figure 2.6 shows the elements of the heating system including the four underfloor heating circuits in details.

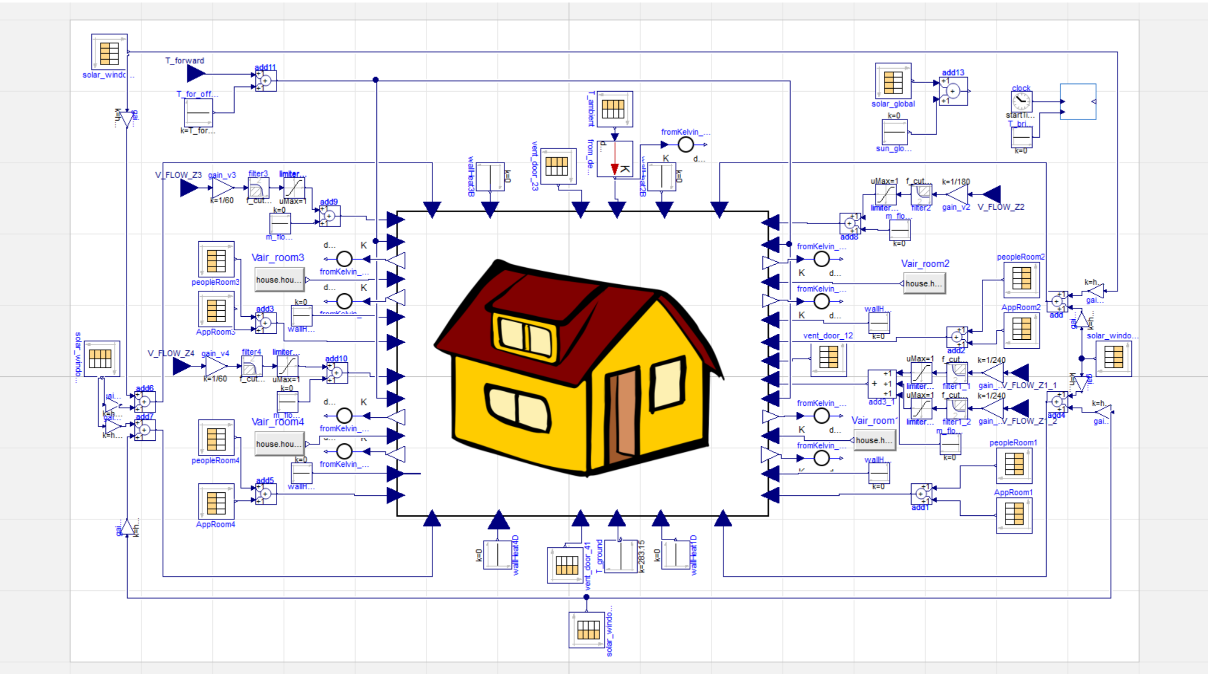

Figure 2.5. Top layer view of house simulation model.

The main differences between the simulation program on the test rig and the annual simulation program are:

- the simulation program on the test rig runs in real time. The annual simulation program is much faster.
- the simulation program on the test rig controls a real heat pump, while the heat pump in the annual simulation program is virtual

Originally, the idea of the virtual heat pump in the annual simulation program was to utilize the detailed heat pump model from Dymola. However, the computation time of this was too long to facilitate a fast, annual simulation. A simpler model was, therefore, chosen for the annual simulation program. However, work has, as part of OPSYS, been carried out to accelerate the speed of the heat pump model in Dymola. For further information on this please see Appendix H.

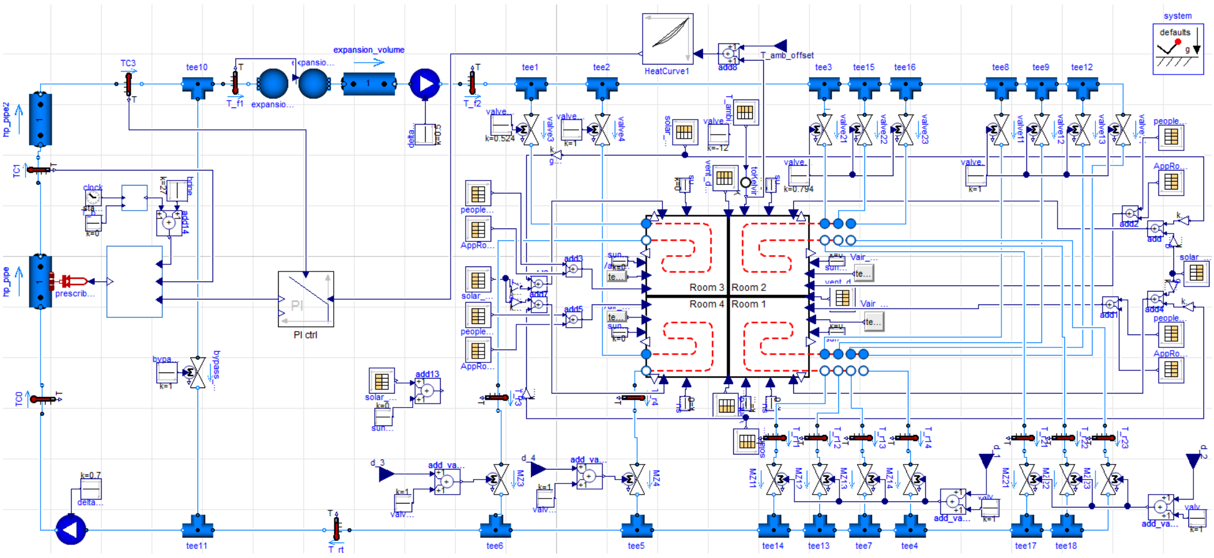

Figure 2.6. Overview of the heating system in the house model.

A very simple representation of the heat pump was taken from another project (Jensen, Christensen, Jørgensen and Huet, 2016) based on a regression of test results for a specific heat pump not identical to the heat pump in the test rig:

$$\Delta T = (T_h - T_c) \quad [1]$$
$$COP_{carnot} = T_h / \Delta T \quad [2]$$
$$COP_{HP} = eta * COP_{carnot} \quad [3]$$
$$eta = -0.02623*P + 0.0010993*\Delta T + 0.4016 \quad [4]$$
$$Q_H = P * COP_{HP} \quad [5]$$

where: COP_{carnot} is the system Carnot COP based on the forward temperature from the heat pump and the brine temperature to the heat pump

- T_h: is the forward temperature from the heat pump [K]
- T_c: is the brine inlet temperature to the heat pump [K]
- COP_{HP}: is the "real" COP of the heat pump at the actual operating conditions
- eta: is the system Carnot efficiency of the heat pump
- P: is the electrical power to the heat pump [kW]
- Q_H: is the calculated heat produced by the heat pump [kW]

For further information on the simple heat pump representation, please see Appendix D and F.

The performance of the simple representation of the heat pump in the annual simulation program is dealt with in the following section.

The python script of the simulation program on the test rig and the annual simulation program include control options for controlling the performance of the heat pump and the heat emitting system. Two control options have been tested in the test rig: a typical uncoordinated on/off control of the valves (telestats) of an underfloor heating system (Appendix F) and an on/off control for obtaining energy flexibility from a house with a heat pump (Appendix G). Furthermore, it is possible to implement highly advanced controls in both simulation environments (Appendix D and E).

2.3 Evaluation of the two OPSYS tools

For the two developed tools to fulfil their purpose, it is necessary that the test rig gives realistic measurements and that the two tools give comparable results. Therefore, the purpose of not only Appendix F, but also Appendix G was to investigate if:

- the test rig realistically represents the conditions in a real house
- the two tools giver comparable results

The investigations in Appendix F for a baseline case show that the test rig operates as intended and as specified by the simulation program on the test rig pc. The test rig emulates a realistic pattern of the flow rates in the four heat exchangers (the four underfloor heating circuits). More importantly, the measured return temperatures from the four heat exchangers are almost identical to the values specified by the house model when there is a flow in the heat exchangers as shown in figure 2.7. The return temperature from the underfloor heating circuits is of course different in the test rig compared to the house model when there is no flow in the underfloor circuits. This is due to different thermal inertia of the heating systems in the two cases. However, as the measured temperature quickly gets identical to the simulated return temperature, as seen in figure 2.7, when the flow starts again, this deviation is of no importance.

The ability of the test rig to closely follow the return temperature specified by the simulation program on the test rig pc is surprisingly good. PID control (as used here) of this temperature is very tricky to tune properly.

Due to the inertia of system, the forward temperature of the test rig is not possible to fit exactly to a temperature given by a heating curve with the ambient temperature as input. However, this is also the case in real life due to the inertia of the system, which means that the test rig performs as expected. It was shown that the "virtual" ambient temperature (instead of an ambient temperature sensor) given to the heat pump functioned as expected. This means that the forward temperature can be manipulated by a more advanced control system, which also controls the telestats of the heating system.

The temperature of the brine has been a challenge. A buffer tank and a lot of speculations were needed to obtain the not perfect, but quite good fit with the temperature of the brine specified in Appendix C – a sinus curve over the year without daily fluctuations. However, the very stable brine temperature given in Appendix C is not really seen in real life, where the brine temperature also slightly fluctuates depending on the actual running of the heat pump. Therefore, it is assessed that the test rig gives a realistic picture of this value.

The patterns of the flow rates and the air temperature of the rooms are judged to be very realistic – see figures 2.7 and 2.8. The flow rates influence each other as in real life. The decay and increase of the air temperatures in the rooms due to the night set back seems realistic when considering that it is a not well-insulated 1970's house. In addition, the influence of solar radiation, people, and appliances seems to be correctly modelled. For further information please see Appendix G and F.

Although there are many simplifications in the annual simulation program regarding the heat pump model, the flow rates, the forward temperature and the brine temperatures, the comparison showed good compliance between the results from the two tools – see figure 2.8 for an example. As an example, the calculated electricity demand of the heat pump was only 8 % lower than the electricity demand measured at the test rig for the 21 days long baseline test. The main reason for the difference was that the simple model of the annual simulation program did not correctly consider the entire amount og electricity to the pumps and the control in the test rig.

Summing up, the performed investigations lead to the conclusion that the two tools seems to perform as intended.

Figure 2.7. Simulated and measured return temperatures and measured mass flow rates for one day.

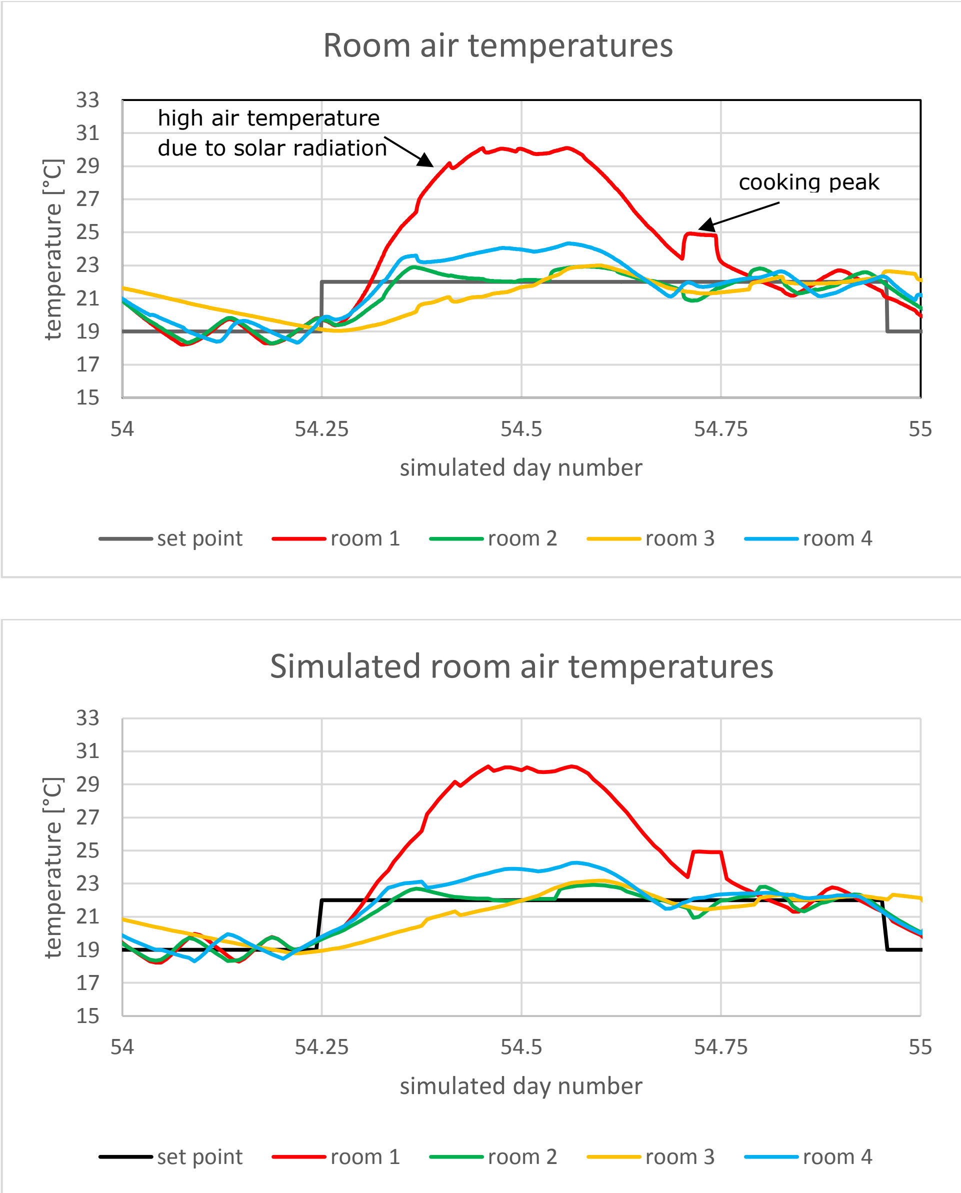

Figure 2.8. Comparison of air temperatures in the four rooms between the test rig (top) and the annual simulation program (bottom) for one day with clear sky conditions during the baseline test.

3 Control strategies

The purpose of the OPSYS project was to develop and test combined control strategies for heat pump installations in order to increase the efficiency of these heating systems. The development of the two OPSYS tools took, however, more time than anticipated leaving less time to develop and test new control strategies. The following control strategies has, however, been investigated:

Both annual simulation and in the test rig:

a) typical uncoordinated on/off control of the telestats – Appendix F

b) preheating and setback of the set points in order to obtain energy flexibility – Appendix G

Only simulation:

c) MPC (Model Predictive Control) optimization of both forward temperature and valve positions – Appendix E

d) ANN (Artificial Neural Network) optimization of the forward temperature from the heat pump – Appendix E

3.1 Traditional on/off control

The investigations in Appendix F (item a) above) showed that the two tools are capable of emulating a current typical uncoordinated on/off control of the telestats of an underfloor heating system. In the OPSYS project, this is called the baseline as this is the current situation, which more advanced control strategies should be compared to.

3.2 Energy Flexibility

Appendix G (item b) above) shows a slightly more advanced control of the heat emitting system than a), however, it still does not include real combined control of the heat pump. The aim of this controller is to obtain energy flexibility for performing peak shaving during the Danish cooking peak. Both tools showed that they can increase the room air temperatures before the cooking peak, decrease the set point at the beginning of the cooking peak and again resume the heating when one room needs heating. The test, therefore, also showed that the test rig is capable of testing more advanced control of the telestats.

The tests in Appendix G showed that even with a simple on/off control, energy efficiency may be obtained. It is, however, assessed that a Model Predictive Controller will be able to obtain much more energy flexibility as this type of controller may include a forecast of not only the weather and the use of the building, but also include a forecast of electricity prices.

3.3 Model Predictive Control

Model predictive control (MPC) is an advanced method of process control, which is used to control a process while satisfying a set of constraints. Model predictive controllers rely on dynamic models of the process, most often linear empirical models obtained by system identification. The main advantage of MPC is that it allows the current timeslot to be optimized, while keeping future timeslots in account. This is achieved by optimizing a finite time-horizon, but only implementing the current timeslot and then optimizing again, repeatedly. Thus, MPC has the ability to anticipate future events and can take control actions accordingly.

The investigated MPC controller incorporates two control loops as seen in figure 3.1: a local controller, which controls the telestats and the forward temperature, and a supervisory controller, which optimizes the overall performance of the system.

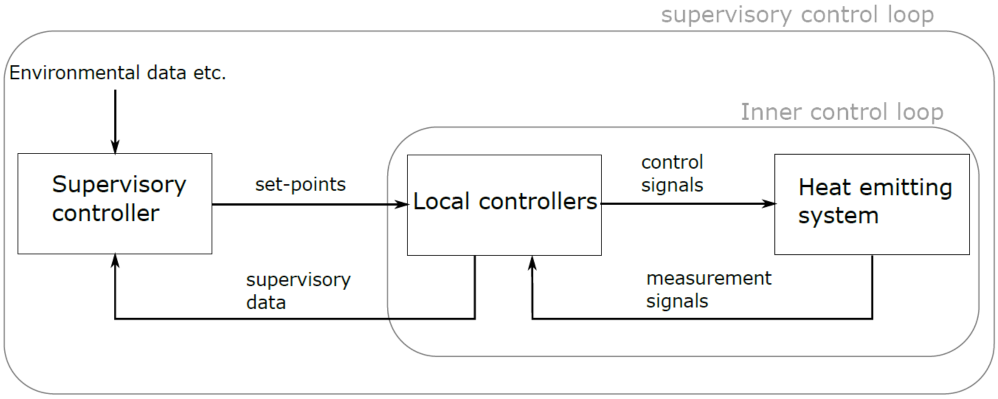

Figure 3.1. The two control loops of the investigated controller.

The air temperature of each room was expressed using an ordinary differential equation:

$$M_z \, c_{\text{pair}} \, \dot{T}_{\text{ai}} = d_{\text{ai}} \, \dot{m}_{\text{ai}} \, UA_{\text{hi}} \left((T_{\text{f}} + T_{\text{ri}})/2 - T_{\text{ai}} \right) + Q_{\text{inti}} + Q_{\text{shi}} + UA_{\text{ci}} (T_{\text{amb}} - T_{\text{ai}})$$

Please refer to Appendix E for further details.

An optimization problem was formulated and solved iteratively.

The investigation showed that the considered MPC outperforms the traditional PI controlled on/off regulation of the heating system with a 9-13 % lower electricity consumption to the heat pump for the investigated two-day period: 9 % lower electricity demand when the prediction horizon was only one step (with a duration of 10 minutes) and 13 % lower at a prediction horizon of five steps. This has been obtained with a mean decrease of the opening time of the telestats as well as a decrease of the mean opening degree of the telestats and thereby a lower mean mass flow rate in the system. The number of position changes of the telestats was, however, up to five times higher for the MPC control than for the PI control. This leads to a decrease of the required forward temperature from the heat pump of 0.3-0.9 K. The COP of the system was increased with 2.1-2.3 %.

The lower increase in COP compared to the high decrease in electricity consumption may be explained by the fact that the heat input to the house was decreased as well, but without jeopardizing the comfort in the house. However, it is the cost of the electricity to the heat pump and not the COP, which matters for the house owner. A decrease of the electricity consumption of the 8-13 % is quite high, especially when considering that the COP of the PI control was just below 3.9, which is a rather high efficiency. This means that the reduction of the electricity demand will be even higher for less good performing heat pump installations.

The above results are very encouraging and leads to the conclusion that MPC is a promising candidate for optimized control of heat pump installations, where the performances of both the heat pump and the heat emitting system are optimized jointly.

3.4 Artificial Neural Network

Distinct from MPCs, ANNs are data driven, which means that they do not need a pre-tuned model of the house and the system. The ANN controller, however, needs a "learning" period in order to tune the controller to the specific case. This means that this type of controller is highly very dependent on good measurements from the house and the system.

Figure 3.2 shows the learning configuration and the control configuration of an ANN controller. For further information, please see Appendix E.

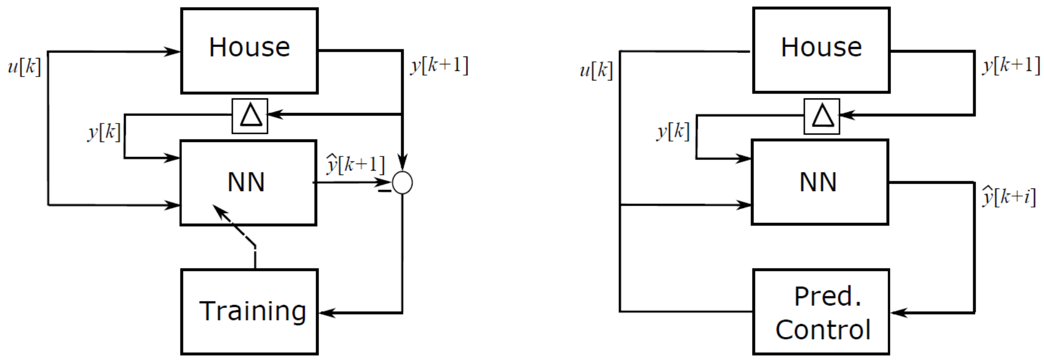

Figure 3.2. Learning and control setup.
Left: training configuration; u is provided externally, e.g. by a controller or as a pseudo-random signal, and a training algorithm adjusts the ANN model weights to minimize the prediction error of the network.
Right: control configuration; the trained ANN model provides predictions of future outputs for a predictive controller, which in turn generates control signals. Δ is a delay operator.

ANN controllers for deceasing the forward temperature from a heat pump were tested during a period of 14 days. The investigated ANN controllers needed different amounts of input – please see the conference paper included in Appendix E. The investigation shows a decrease in the forward temperature of between 0.7 and 1.5 K, depending on the applied ANN controller. This reduction of the forward temperature was achieved without jeopardizing the comfort in the house. The reduction of the forward temperature was obtained from the same very efficient heat pump installation as used when investigating the MPC.

Unfortunately, the time did not allow for the development of an ANN controller optimizing both the performance of the heat pump and the heating system. However, it is anticipated that similar good results as obtained for the MPC controller may be obtained.

3.5 Conclusion

The development of the two OPSYS tools required more time than anticipated leaving less time to develop and test new control strategies.

A traditional on/off control (baseline) and an on/off control for obtaining energy flexibility were successfully tested in both the test rig and with the annual simulation program.

A Model Predictive Controller (MPC) was developed and investigated. The investigation showed that significant savings are achievable when controlling the heat pump and the heat emitting system together. Savings of the electricity demand to the heat pump of up to 13 % were found for the investigated period. These savings were obtained even when the overall COP of the system was as high as 3.9 with the traditional PI controller. The hypothesis of achieving savings up to 25 % for a heat pump installation with traditional control and a SPF (mean seasonal COP) of around 3, therefore, seems realistic.

A developed Artificial Neural Network (ANN) controller showed a reduction of the forward temperature for the investigated period of up to 1.5 K for the same very efficient heat pump installation as investigated with the MPC.

However, both MPC and ANN controllers require more computational resources than traditional PI controllers, but certainly not prohibitively so. All the control simulations documented above were carried out on a completely standard pc using Matlab, Modelica, and off-the-shelf Python libraries. It is estimated that the supervisory controller in either nonlinear MPC or ANN configuration, can easily be implemented and executed on a Raspberry Pi with 0.5 GB RAM or similar industry-standard hardware. Furthermore, the supervisory control configuration makes it reasonably easy to interface with the heat pump and the underfloor heating subsystems.

The above results are very encouraging and leads to the conclusion, that MPCs and ANNs are promising candidates for optimized control of heat pump installations, where the performances of both the heat pump and the heat emitting system are optimized jointly. Thus, the problems with poorly performing heat pump installations documented in (Poulsen et al, 2017) may most likely be solved by switching from a traditional PI control to an advanced combined control.

Unfortunately, the performances of the advanced controllers were not tested in the OPSYS test rig, nor were their annual performances determined. An application for a follow-up of the OPSYS project has, therefore, been submitted with the aim of developing both software and hardware of a prototype controller, which is capable of optimizing the performance of heat pump installations. The software will be based on the above described findings.

4 Conclusion

The aim of the OPSYS project was to develop and test optimized control strategies for making heat pump installations more efficient. To facilitate this, two tools have been developed: the OPSYS test rig and the OPSYS annual simulation program.

The OPSYS test rig and the annual simulation program were tested simulating traditional on/off control of the heating system. The two tools gave realistic and comparable results. Then, the two tools were tested with a more advanced control for obtaining energy flexibility to deliver services to the electrical grid. Again, the two tools gave realistic and comparable results, which show that they can be used for investigating more advanced control strategies.

Two more advanced controllers: a Model Predictive Controller (MPC) and an Artificial Neural Network (ANN) controller were investigated next using the annual simulation tool. Savings of the electricity demand to the heat pump of up to 13 % was found for the investigated periods. These savings were obtained even when the overall COP for the system was as high as 3.9 with the traditional PI controller. Thus, the hypothesis of achieving savings up to 25 % for a heat pump installation with traditional control and a SPF (mean seasonal COP) of around 3 seems realistic.

MPC and ANN controllers require more computational resources than traditional PI controllers, but certainly not prohibitively so. It is estimated that the supervisory controller, in either nonlinear MPC or ANN configuration can easily be implemented and executed on e.g. a cheap Raspberry Pi with 0.5 GB RAM or similar industry-standard hardware. Furthermore, the supervisory control configuration makes it reasonably easy to interface with the heat pump and the underfloor heating subsystems.

The above results are very encouraging and lead to the conclusion that MPCs and ANNs are promising candidates for optimized control of heat pump installations, where the performances of both the heat pump and the heat emitting system are optimized jointly. Therefore, the problems with poorly performing heat pump installations documented in (Poulsen et al, 2017) may most likely be solved by switching from traditional PI control to advanced combined control.

Due to the promising results, it is recommended that the work of the OPSYS is continued in a follow-up project.

5 References

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