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Technical Report TA User Project

Distributed Adaptive MPC agentS for Integrated energy Resources MAnagement in smart buildings (DAMS4IRMA)

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Table of contents

Abbreviations

DER	Distributed Energy Resource
TA	Trans-national Access
MG	Micro grid
ESS	Energy storage system
TES	Thermal energy storage
HP	Heat pump
HWT	Hot water tank
PCC	Point of Common Coupling
LC	Local controller of the heat pump
LTVMPC	Linear time variant model predictive control

Executive Summary

The DAMS4IRMA project deals with flexible loads in smart grids. It aims at the design and testing of an efficient strategy to optimize the real-time behavior of smart buildings, including different types of storages unit and energy sources such as PV panels, wind turbines and local generators, in order to introduce the highest possible level of flexibility, while preserving comfort, to be used in services to the smart (micro) grid. The DAMS4IRMA project investigates the possibility to clearly separate the user load profile from the desired comfort level, through the adoption of distributed optimization techniques, suitably tailored for the purpose. The DAMS4IRMA project thus provides a contribution to the renewable resources penetration in the market and to an acceptable level of flexibility of the load in the future smart grids.

More in detail, the addressed scenario is a smart building connected to a smart power grid including different Energy Storage Systems (ESS) - both electrical and thermal storages are here considered -, photovoltaic generators, wind turbines, hydro-power plants. The mentioned smart power grid is connected to the main distribution grid through a Point of Common Coupling (PCC). Any of these energy resources is endowed with an intelligent control: for example, a load will have a local flexible controller (Load Control - LCs) enforcing requirements fulfilment and also the necessary flexibility, a wind turbine will have a control system able to maximize energy production and performance and make reliable and adjustable production prediction, a battery will have its own charge control, and also a Microgrid Controller (MC) will be in place to manage the overall energy exchanges at the PCC. The load considered in the DAMS4IRMA project is the thermal load obtained with thermo-electrical machines like heat pumps.

The goal of DAMS4IRMA project proposal is twofold: (i) using different type of energy storages (thermal and electrical) for modification of consumer's purchasing patterns and behaviour by shifting the demand away from peak hours and (ii) design a suitable control and management architecture to ensure the required demand in a more economic and efficient manner. The selected methodological tool to obtain the above goals is the Model Predictive Control (MPC) technique, but in the form of distributed adaptive MPC (DaMPC), where a community of independent local predictive controllers interact in a cooperative and non-cooperative scheme to a global and local goal, and every controller is endowed with prediction capability and optimization facility over a future finite horizon. In the literature, the approach is novel.

In the given scenario, the project will propose and investigate a new configuration of using Thermal Energy Storage (TES) and an innovative distributed real-time optimization technique to exploit inertia and storages of energy to decouple load request to the electrical grid from the user comfort control problem.

Title:
Distributed Adaptive MPC agentS for Integrated energy Resources MAnagement in smart buildings

Acronyms:
DAMS4IRMA

Host infrastructure:
SYSLAB at PowerLabDK
Denmark Technical University (DTU) – Risø Campus

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1 Research Motivation

Nowadays the pressing on using energy in more efficient ways is very high, especially when dealing with heating systems, where reductions of consumptions immediately means economic saving and cut on pollution and CO2 production. In this context, heat pumps are becoming more and more popular, for their high level of efficiency, mainly due to its smart working principle.

On the other hand, Demand response control algorithms on buildings have been widely accepted as effective methods to improve energy efficiency of buildings and to minimize energy consumption and cost. According to the literature review, the cost-optimal energy resources management system for a combination of several energy storages (thermal and electrical) combined with smart buildings as a subset of a large smart grid is still a challenging problem. These mentioned problems motivate the development of centralized and non-centralized scheme (i.e., decentralized and distributed schemes) that utilize multiple (predictive) controllers that carry out their calculations in separate processors.

1.1 Objectives

As a matter of fact, we aim at implementing and testing in a real micro grid a novel distributed adaptive MPC strategy embedded into a multi-agent framework. More precisely, the specifically, objectives of this work include:

- Study and design of a new optimization algorithms for micro grid energy management
- Testing more accurate TES modelling in comparison to the simplified model in literatures
- Modelling and controlling an air-to-water heat pump for building energy efficiency applications
- Smart Micro grid modelling with renewable sources, storages and smart buildings
- Optimal load flow through the grid
- Price-based Demand/response optimization
- Run simulation with different scenarios and optimizing cost functions
- Assess the direct benefits of this architecture compared to actual grid management policies and power dispatching algorithms through experimental implementation.

1.2 Scope

The scope of this research projects matches the activities related to the development, design, application, construction, installation, operation, analysis and control of electric power generating and energy storage equipment (along with conventional, distributed or renewable sources, central station and grid connection). The scope also includes heat pumps application and also the role of energy storages in demand response programs.

2 State-of-the-Art

According to the recent researches, energy use in buildings currently account for about 32% of global total final energy consumption in the world and also responsible for 36% of the EU CO_2 emissions [1] [2]. Both energy performance and load management in buildings are two significant issues to achieve the EU Climate & Energy objectives, namely the reduction of a 20% of the Greenhouse gases emissions by 2020 and a 20% energy savings by 2020 [3]. All of these reasons induced researchers to turn toward demand side management and advanced loads control of domestic smart grid technologies, namely smart building connecting to the smart power grid.

The introduction of Distributed Energy Resources (DERs) (e.g. household, industrial consumers and electric vehicles), together with the introduction of more information and communication technology in the electricity system provides interesting and novel automated Demand Side Management (DSM) opportunities at the end user level. Accordingly, demand side management (DSM), including everything that is done on the demand side, represents an integral part of smart grids [4] [5] [6] [7]. A wide range of demand response (DR) programs and tariffs are already offered by utilities [8] [9] [10] that have been settled to use the available energy more efficiently and to encourage customer response and competitive energy retailers. End-use customers, in order to handle their electric service requirements and costs, can invest in energy efficiency or participate in a variety of DR activities such as shifting loads (air conditioner or Heat-pump usage or TES charging) to off-peak hours. Patteeuw et al. [11] showed that load shifting affects to reduce the electricity cost for low-energy buildings with heat pumps. Hedegaard and Balyk [12] presented a model that facilitates analyses of individual heat pumps and complementation of heat storages in integration with the energy system. By operating for hours with low marginal electricity costs, they found benefits in flexible operation of heat pumps. Arteconi et al. [13] showed that a heat pump with radiators or a floor heating system coupled with a thermal storage tank is a good tool for DR. They achieved a good control of indoor temperature since the heat pump is switched off during peak hours and the electricity cost was reduced by ‘‘time of use” tariff.

Demand response control algorithms on buildings have been widely accepted as effective methods to improve energy efficiency of buildings and to minimize energy consumption and cost [14].
MPC is now recognized as a very powerful approach with well-established theoretical foundations and proven capability to handle a large number of industrial control problems [15]. MPC naturally enters the picture as a control algorithm that can systematically incorporate all the aforementioned predictions to improve building thermal comfort, decrease peak load, and reduce energy costs [16]. MPC for building climate control was investigated in several papers, such as references [16] [17] [18] [19] [20], mainly with the purpose of increasing the energy efficiency. The potential of MPC in power management was investigated in [21] [22]. Basically, MPC based methods can be classified into three categories that are centralized, decentralized and distributed. As the matter of fact, the use of centralized scheme may not be able to apply in practical due to the large size of the system that raise significant problems in computation, communication burdens, reliability as well as scalability. These mentioned problems motivate the development of non-centralized scheme (i.e., decentralized and distributed schemes) that utilize multiple (predictive) controllers that carry out their calculations in separate processors. Distributed approaches can be divided into cooperative and non-cooperative schemes. Opposed to non-cooperative schemes, where the local controllers have different, possibly conflicting, objectives with or without considering all possible behaviors of the neighboring subsystem, the local controllers in cooperative methods optimize the same global cost function [13].

According to the literature review, the cost-optimal energy resources management system for a combination of several energy storages (thermal and electrical) combined with smart buildings as a subset of a large smart grid has not been investigated sufficiently. In this project, we will test a new configuration and control methodology of integrated energy Storages and renewables in order to minimize the energy consumption without sacrificing the occupant thermal comfort.

3 Executed Tests and Experiments

This research study aims at modelling and controlling an air-to-water heat pump for building energy efficiency applications. First, a detailed model of a generic heat pump, so-called reference model, is developed and experimentally validated. Then, the reference model is used to formulate several control-oriented models of the heat pump, namely the formulas defining the Coefficient of Performance (COP) based on increasing levels of complexity. Finally, the paper explores the impact of the simplification level of the heat pump model on the overall quality of temperature control in a building, and on electrical energy consumption. In particular, the pilot case here considered consists in a heat pump supplying water to a load through a hot water tank, and for control structure a linear time varying MPC is designed. The impact of the power peaks is also investigated, which shows the significant improvement in the COP prediction based on the level of approximation. This study shows how the load flexibility can take advantage from a correct COP prediction. The results can be seamlessly extended to the application of the real-time pricing, where the prediction of the COP trajectory can be used for the economic load shifting, thanks to the inertia of the hot water tank and the load.

3.1 Test Plan

Nowadays the pressing on using energy in more efficient ways is very high, especially when dealing with heating systems, where reductions of consumptions immediately means economic saving and cut on pollution and CO_2 production.

In this context, heat pumps are becoming more and more popular, for their high level of efficiency, mainly due to its smart working principle. These devices, with respect to boilers, work with electrical power only, so heat transferred to the environment does not come directly from fuel combustion. Moreover, unlike classic booster heaters, heat pumps work on the principle of the steam compression cycle: a refrigerant fluid flows in a closed cycle and changes phase, absorbing heat from an external source like air, water or soil, and releasing heat indoor in winter (and vice versa in summer).

The case study of this research is an air-to-water heat pump, that is used to heat up a Hot Water Tank (HWT). The energy stored in the HWT can be then used to heat any kind of loads, for example space heating of residential buildings. The heat storage (HWT) is useful for many reasons. First, it helps to reduce the peak energy consumptions, thanks to its thermal inertia. It also has a positive impact on the Coefficient of Performance (COP) of the heat pump, in that the heat pump can be brought to work where its efficiency is higher. This is particularly true when combined with low-temperature heat emission systems such as radiant-floor heating. This paper investigates to which extent it is possible to exploit the variability of the COP to further improve the building efficiency, and how detailed the COP should be to obtain this result.

Heat pump functionality is well-studied in literature with detailed thermodynamic models. The economic control and energy management programs, however, need a control-oriented model to provide a simple but accurate estimation and prediction of the COP of the heat pump.

The present study aims at extending the contribution of the presented scientific papers, and provide a more comprehensive approach. First it aims at formulating both a reference (detailed) model, validated through real experiments, and a control-oriented model for a real heat pump used in a real case study. Then, the control-oriented models are used inside optimal control problems suitably formulated according to the Model Predictive Control (MPC) technique, and the impact of their level of approximation validated against the overall control performances.

More specifically, a detailed thermodynamic model of the heat pump including all main components, i.e. compressor, evaporator, expansion valve and condenser, is modelled and simulated based on the Thermolib Library. The reference model is then initially tuned based on the available data sheet information. Afterward, the inner control loops inside the heat pump, operating limitations and the COP profile are tuned and validated experimentally with tests on the real heat pump at SYSLAB, Department for Electrical Engineering, Risoe Campus, Denmark Technical University

(DTU), based on different weather and load conditions.

The validated reference model is then used as the baseline for generating data in a wide range of conditions, with different values of input power, inlet water temperature into the heat pump and different weather conditions. Different types of interpolations are developed to fit all the test cases. Those formulas are basically a quadratic and linear combination of subsets of the main factors that affect the heat pump COP, such as external air temperature, external humidity (they play an important role in the evaporator stage), backward water temperature in condenser stage and compressor power. A significant number of tests are performed on the considered real heat pump. It is also proved that the dependency on only one of the many factors, like air temperature, is not enough to formulate a reliable model-based controller. The obtained functions are then exploited to provide the COP estimation. Proven the fact that some of the developed models are useful for model-based control technique, an MPC is finally formulated, and their capabilities checked against the validated reference model.

3.2 Standards, Procedures, and Methodology

The heat pump considered in this paper is a typical modulating air-to-water heat pump, conceived for residential buildings. In this paper, the testing is made on a Viessman Vitocal-200s Type AWB 201.B13 [23] [24] to make a real implementation and validation of the proposed models and algorithms. The experiments have been implemented in the SYSLAB of Denmark Technical University, Riso Campus. The lab is equipped with a heat pump, a hot water tank, a modulating valve and a heat exchanger as load (Figure 1).

Figure 1: Picture of real heat pump Viessman Vitocal-200s Type AWB 201.B13 in DTU lab.

A reference model of heat pump, containing the main thermodynamic components, is modeled in Matlab Simulink environment using the Thermolib Library [25], which is used as a benchmark for the control study. The physical properties of fluids involved in the thermal cycle come from REFPROP database (NIST Reference Fluid Thermodynamic and Transport Properties Database). The reference model is then tuned based on the available information in datasheet of the heat pump and is also experimentally validated.

The tuning of the reference model is more complex than one could expect, mainly due to the many unknown parameters of the real heat pump, undescribed local control algorithms used for the compressor power control and also water flow rate control in the condenser heat exchanger. Therefore, as a first step, the reference model is tuned using the test cases reported in the datasheet to preliminary tune the heat pump model regardless of its control algorithms. Subsequently, more detailed real test cases have been implemented to retune and validate the reference model, along with its inner control algorithms.

For control design, a suitable simplified model should be developed. From a control point of view, a heat pump can be seen as a heat generator which amplifies the electrical power used by compressor and delivers thermal power. Accordingly, any heat pumps can be defined and modelled by its coefficient of performance (COP), which relates the compressor power P_{hp} to the thermal power Q_{hp}, as follows:

$$Q_{\mathrm{hp}} = \mathrm{COP}\ P_{\mathrm{hp}}$$

As it is well-studied in literature, the COP of a heat pump depends on many physical parameters, such as outside temperature, outside humidity, power frequency and backward water temperature to the condenser heat exchanger. Hence, a sensitivity analysis has been conducted using the validated reference model to better understand the impacts of different parameters on the heat pump COP variation. Then, several equations of first and second order are identified to be used as the control-oriented model of the heat pump, with increasing level of accuracy.

the predictive capability of the models is also investigated through an application scenario, where the load is served by a heat pump and hot water tank. For simplicity, a simple model of the radiant-floor building [26] [27] is considered to evaluate the capability of the proposed control-oriented model of the heat pump in terms of prediction and control. The results can be easily generalized for any other kind of load.

3.3 Test Set-up(s)

The predictive capability of the models is investigated through an application scenario, where the load is served by a heat pump and hot water tank. For simplicity, a simple model of the radiant-floor building [26] [27] is considered to evaluate the capability of the proposed control-oriented model of the heat pump in terms of prediction and control. The results can be easily generalized for any other kind of load.

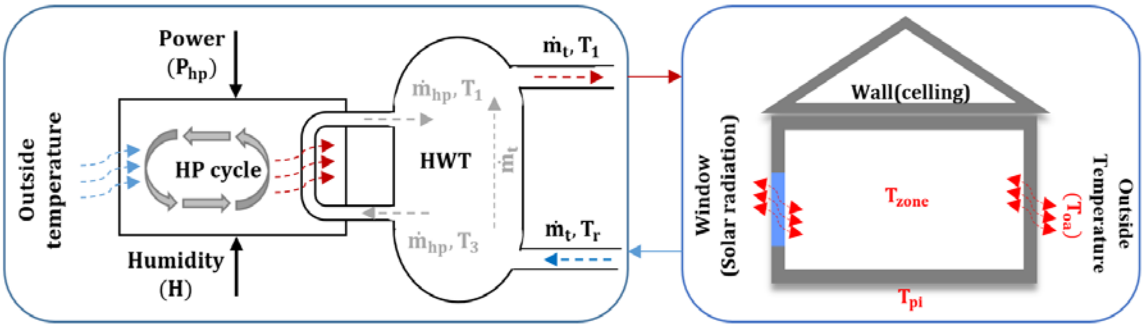

Figure 2 Overall scheme of thermal plant

As it is illustrated in Figure 2, the heat pump under study consists of 3 main control loops, namely main heat pump cycle, heat pump-water tank cycle and load water cycle. The first two is enforced by the control of the heat pump designed by manufacturer, while the load water cycle is under control of MPC developed in this paper.

The real heat pump model is characterized by a heavy nonlinear behaviour due to variable water flow rate in the heat pump water cycle and the nonlinearity of the heat pump model itself. The proposed MPC, however, is based on a linear model of the system including the 3 layers of the HWT, 4 states for the load and the heat pump is modelled by its COP as studied in [26] [27]. In this case, at each time instant *k,* the heat pump COP can be estimated though the proposed COP functions obtained by the data-driven identification methods. As the COP of the heat pump varies over the time a linear time-varying model predictive control, labelled LTVMPC in the following, will be tested.

More specifically, N_p-step prediction of heat pump COP can be calculated through the state and input prediction of the system together with weather forecasting. Hence, the control system is initialized with a predefined feasible trajectory for any state variables, power input, outside temperature and humidity and then updated at every sampling time using the trajectory computed by the MPC algorithm in the previous sampling time and available weather forecast. This technique will be successively repeated.

Considering the control objective together with the plant model, the main objective of the LTVMPC algorithm is to minimize the predicted heat pump power consumption $\mathrm{P_{hp}}(i|k), i = k, \dots, k + \mathrm{N_p} - 1$, (in Watt) at each sampling instant *k* for a given prediction horizon $\mathrm{N_p}$, while respecting the operational constraints and actuator's limitations. Accordingly, for a given state estimate $\hat{\mathrm{x}}(k|k)$ of the system, the cost function of the optimal control problem can be defined as follows:

$$\mathrm{J} = \sum_{\mathrm{p}=0}^{\mathrm{N_p}-1} \boldsymbol{\Upsilon}_{\mathbf{p}} \mathrm{P_{hp}}(k + \mathrm{p}|k) + \boldsymbol{\Upsilon}_{\boldsymbol{\epsilon}} \epsilon + \mathrm{V^{term}} \qquad (2)$$

Subject to the system's dynamic

where, the terminal cost $\mathrm{V^{term}}$ approximates the infinite horizon cost as follows,

$$\mathrm{V^{term}} = \hat{\mathrm{x}}^{\mathrm{T}}\big(k + \mathrm{N_p}\big|k\big)\, \boldsymbol{\Upsilon}_{\boldsymbol{V}}\, \hat{\mathrm{x}}\big(k + \mathrm{N_p}\big|k\big) \qquad (3)$$

and $\boldsymbol{\Upsilon}_{\mathbf{p}}$, $\boldsymbol{\Upsilon}_{\boldsymbol{\epsilon}}$ are, respectively, the weighting coefficients of the power consumption and slack variable terms, while $\boldsymbol{\Upsilon}_{\boldsymbol{V}}$ is supposed to be a positive-definite square matrix.

Moreover, the slack variable ϵ is linearly penalized in the cost function and used as follows:

$$18^{\circ\mathrm{C}} - \epsilon \le \mathrm{T}_{zone}(k) \le 18^{\circ\mathrm{C}} + \epsilon \qquad (4)$$

This relaxation is used to guarantee feasibility at any time instant. T_{zone}[°C] represents the average air temperature of the building.

Moreover, HWT is vertically numbered from top to bottom, where T_1*(k)*, T_2*(k),* and T_3*(k)* are the first, second and third layer, respectively. The objective of the MPC is to minimize the electricity cost, while satisfying the requested tank temperature imposed by the following constraints:

$$\begin{aligned} 20^{\circ\mathrm{C}} &\le \mathrm{T_1}(k) \le 60^{\circ\mathrm{C}} \\ 20^{\circ\mathrm{C}} &\le \mathrm{T_2}(k) \le 60^{\circ\mathrm{C}} \qquad (5) \\ 20^{\circ\mathrm{C}} &\le \mathrm{T_3}(k) \le 60^{\circ\mathrm{C}}, \end{aligned}$$

resulting from actuators limitations. It is worth noticing that the buffer tank temperature is limited by a minimum value of 20°C to prevent any frost problem in the evaporator side. In this case according to the requested building air set point and also considering the energy loss of the pipes, the requested tank temperature is always more than 20°C.

According to the experimental analysis on the real heat pump, the forward water temperature $T_F(k)$ of the heat pump to the HWT is constrained to be no more than 5°C above the backward water temperature, which is basically the bottom layer of the HWT. This is due to the physical properties of the refrigerant and the technical characteristics of the machine. Hence, the following constraint is imposed to the LTVMPC in order to prevent any unacceptable control actions.

$$\mathrm{T_F}(k) - \mathrm{T_3}(k) \leq 5 \qquad (8)$$

Where,

$$\mathrm{T_F}(k) - \mathrm{T_3}(k) = \frac{\mathrm{COP}(k)\, u_1(k)}{\dot{\mathrm{m}}_{\mathrm{hp}}(k)\, C_v} \qquad (9)$$

$\dot{\mathrm{m}}_{\mathrm{hp}}[kg/s]$ and C_v[J/kg K] are water mass flow rate in heat pump water cycle and water specific heat, respectively.

Furthermore, a 150m^2 radiant floor building is considered as the load which is well-isolated and has a big inertia due to the high thermal capacity of the walls and pavement which provide a time-constant of about 15 hours in both charging and discharging mode. On the contrary, the pavement transmittance is selected quite larger than the wall transmittance in order to have bigger heat transfer through pipelines and less heat losses through the walls, as follows:

$$\begin{aligned} \frac{\mathrm{T_{zone}}}{\mathrm{T_1}} &= \frac{0.8471}{55481\,\mathrm{s}+1} \\ \frac{\mathrm{T_{zone}}}{\mathrm{T_{oa}}} &= \frac{0.1521}{56188\,\mathrm{s}+1} \end{aligned} \qquad (10)$$

Subsequently, the proposed building is served by the validated heat pump model together with the HWT which are all simulated in the Matlab Simulink environment using the Thermolib Library and considered as the reference model. The reference model is also equipped with an inner controller (already validated) which regulates the requested forward temperature provided by LTVMPC by acting on the compressor power frequency. Eventually, the real COP value of the reference model is calculated at the end of each time interval to be then compared by the proposed COP model.

The scheme of the overall control system has been shown in Figure 3.

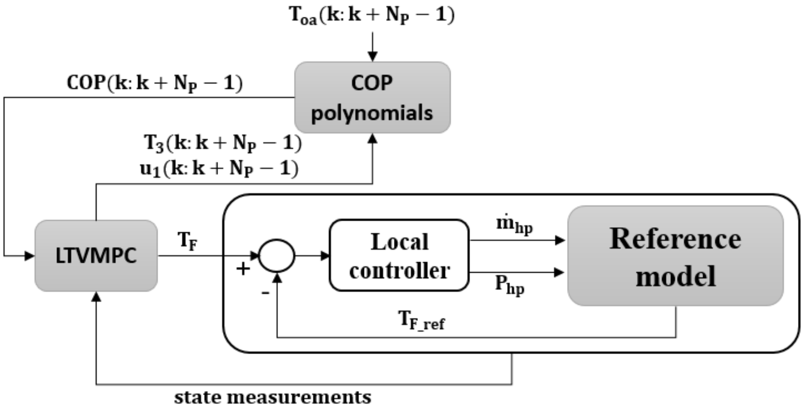

Figure 3: Overall control system scheme

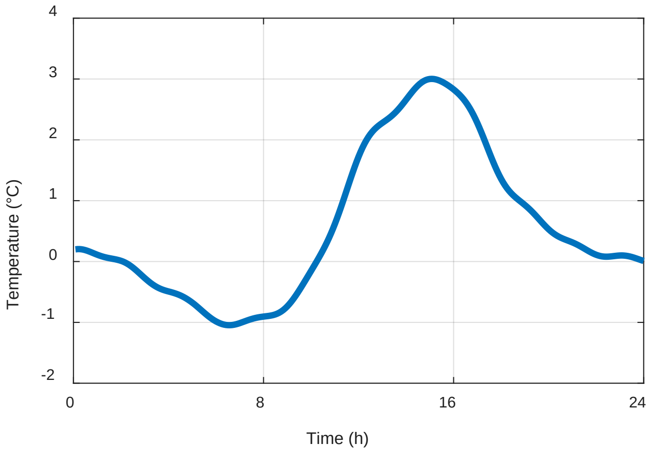

Figure 4: Outside air temperature

3.4 Data Management and Processing

The reference model is then used for the tuning based on the real experiments, under dynamic conditions. Several test cases are implemented in different weather conditions and load requests. As Figure 5 shows, the reference model can track very well the real heat pump water temperatures and power consumptions, which results in an accurate COP profile with respect to the real heat pump.

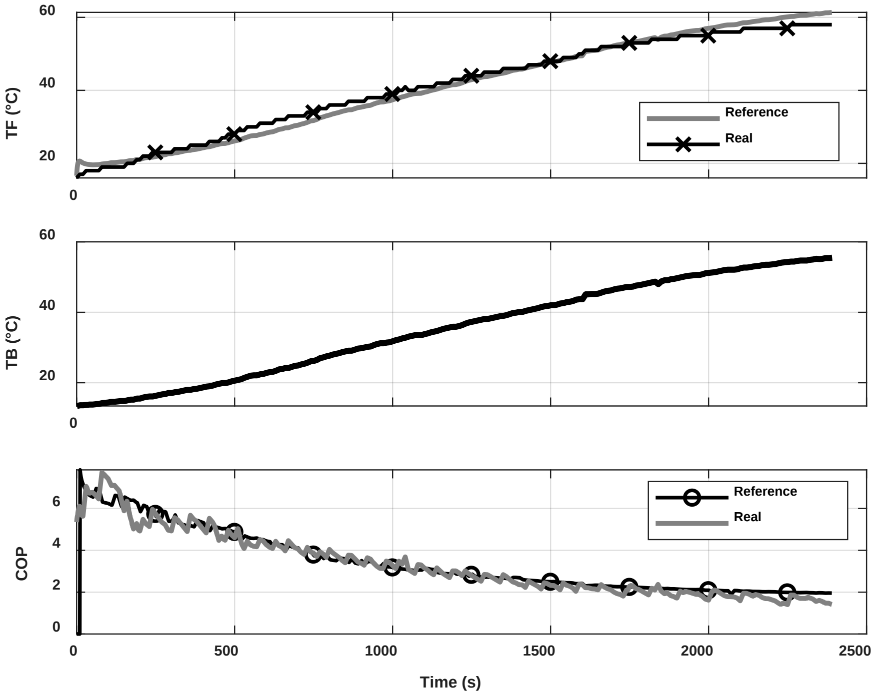

Figure 5: Comparison between reference model and real heat pump. (1) Forward water temperature (TF); (2) Backward water temperature (TB); (3) COP.

Table 1 - Comparison between datasheet and reference model

Parameters	**Datasheet**		**Reference model**	
	Test 1	**Test 2**	**Test 1**	**Test 2**
COP	3,26	4,29	3.32	4.39
TB	35 °C	35 °C	35 °C	35 °C
Air temp.	2 °C	7 °C	2 °C	7 °C
ΔT water	5 °C	5 °C	4.7 °C	4.6 °C
Compressor	100 %	100 %	100%	100%
Water mass flow rate	0.5 kg/s	0.5 kg/s	0.5 kg/s	0.5 kg/s

The numerical results obtained in a couple of those tests are also quantified and reported in Table 1, which proves the reliability of the developed reference model by evaluation of the normalized root mean square error (NMRSE) of the COP. Many more test cases have been performed, that are not reported here for the sake of brevity.

To identify the various COP models, several conditions are simulated using the reference model, using a wide range of different parameters, as follows:

- Outside temperature (Toa): -10°C to 10°C
- Outside humidity percentage (H): 40% to 100%
- Backward water temperature (TB): 20°C to 60°C
- Compressor power frequency percentage (COMP): 0% to 100%

Table 3 shows the maximum variation of the COP (ΔCOP_{MAX}) with respect to the variation of each parameter.

For each one of them, ΔCOP_{MAX} is simply the difference between the COP evaluated where the variable of interest maximizes and minimizes it, keeping all the other parameters fixed to their values, that is maximum for the COP.

Table 2 - Comparison between real heat pump and reference model

Parameters	**Comparison between real heat pump and reference model**	
	Test 1	**Test 2**
NRMSE of COP	0.0869	0.1240
Air temperature	9°C to 10°C	0°C to 1°C
NMRSE of ΔT water	0.0376	0.0669
Compressor	100 %	100 %
Water mass flow rate	0.5 kg/s	0.5 kg/s

Table 3 - COP maximum variation

Parameters		**Toa**	**H**	**TB**	**COMP**
ΔCOP_{MAX}	Total range	3.1	0.21	4.83	1.3
	Radiant-floor heating	3.1	0.21	2.86	1.3
	Radiator heating	1.94	0.11	1.97	0.74

The results reveal that the backward water temperature (TB) and outside temperature (Toa) are the most effective parameters and the humidity is almost negligible.

Additionally, as it is already mentioned, radiant-floor heating systems are known as the low-emission systems, which work on the lower temperature, usually in the range of 20°C to 40°C. On the contrary, the small heat exchange area of the radiator heating systems requires higher supply water temperatures, which is usually between 40°C to 60°C. Based on this observation, it would be more convenient if the operating points of the heat pump be separated into two regions based on the applications. As Table 3 shows, smaller boundaries guarantee lower variation of the COP, which results in the more accurate modelling. As expected, TB is more effective in the low-emission systems because of the lower water temperature demand, such that it is the most effective parameters in the radiant-floor buildings. However, Toa and TB have more or less the same effect in the radiator heating systems due to the high water temperature demand.

4 Results and Conclusions

As this study focuses on the impact of the COP prediction of the heat pump, the assumptions are made of the perfect prediction of the external inputs, particularly the weather temperature. The ambient air temperature profile is shown in Figure 4, which is a periodic signal representing a typical winter day in the Denmark, with a daily mean temperature of 1 °C. A sampling time of T=15 min is considered, which is suitable to guarantee the stability of the discretized model of the system. Moreover, the MPC uses a prediction horizon of 12 hours.

All simulations are based on the COP polynomials obtained based on the large boundary regions of the parameters. Moreover, at the end of this section, a comparison between the polynomials tuned in the smaller regions is also reported.

It is worth noticing that, although the power frequency is less important than the outside air temperature and backward water temperature on the COP, the unexpected power peaks can deteriorate the performance of the LTVMPC due to the sharp peaks in the COP.

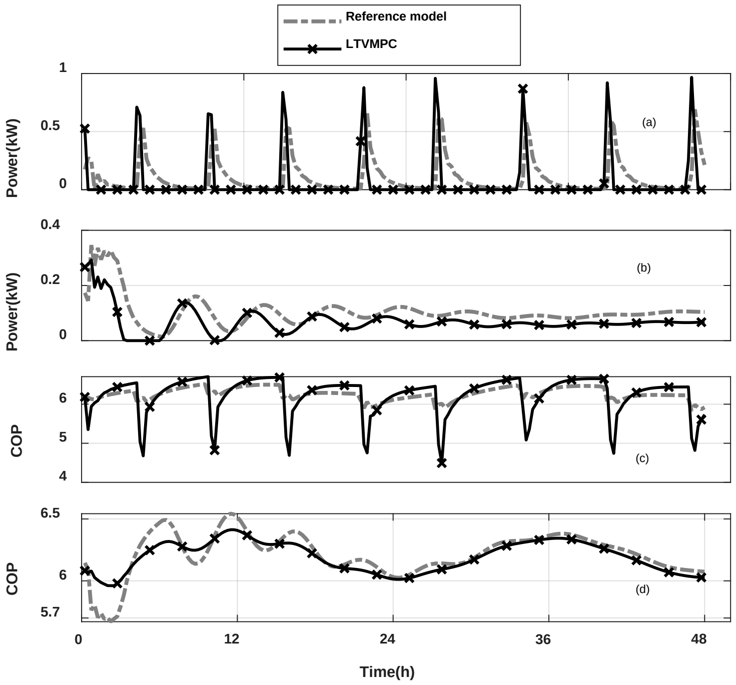

Figure 6 : Impact of power peaks: (a) Power profile without penalization (b) Power profile with penalization, (c) COP profile without penalization, (d) COP profile with penalization

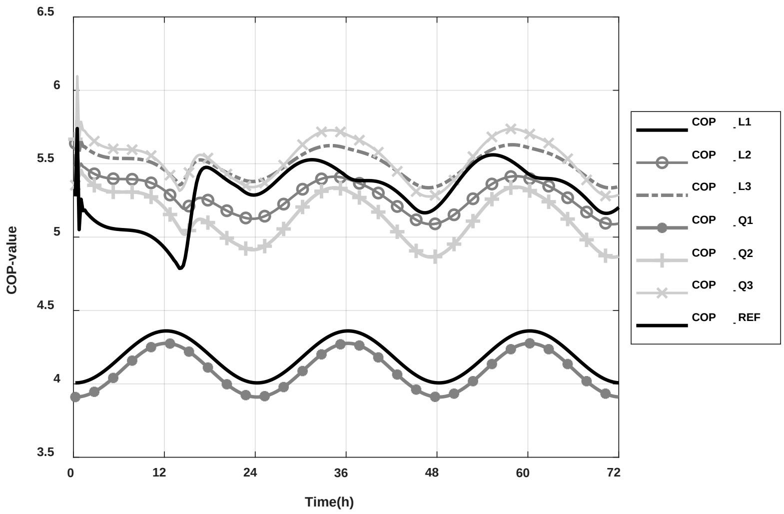

Figure 7: Comparison of COP trajectory with reference model based on different polynomials (for clarity, the two bottom lines are COP_L1 and COP_Q3).

In this case, a fast change in the tank temperature will be requested by the LTVMPC, which cannot be tracked by the real heat pump due to the safety reason and also operational limitation of the real heat pump. Consequently, it results in a fluctuation in the compressor power and also COP value. This phenomenon is highlighted through a test case where the LTVMPC uses the Np-step prediction of COP provided by the most complex polynomial, i.e. COP_Q3. Figure 6(c), shows the effects of power peaks on the COP prediction based on the best polynomial (COP_Q3), where there is about 20% error (in the RMSE) in COP prediction with respect to the reference model.

In order to prevent such power peaks, the variations of the electrical power of the compressor is penalized into the cost function of LTVMPC (see Figure 6.(c)), which, in turn, requires more flexibility in the load side. As Figure 6(d) shows, the COP prediction is improved and error decreases to 2% in steady state.

Moreover, the LTVMPC performance is evaluated with respect to the different heat pump COP models to witness the impact of the model complexity on the control performance. Therefore, first, the accuracy of the polynomials is evaluated in the closed loop system based on the mentioned test case, where the LTVMPC uses the NP-step prediction of COP provided by the most complex polynomial, i.e. COP_Q3. Figure 7 illustrates a comparison between the predicted COP profile obtained by the polynomials and the real COP profile reported by the reference model. As expected, COP_Q3 provides the best prediction among all COP polynomials, as it uses the quadratic term of all effective parameters already introduced. Figure 7 shows that the linear polynomial COP_L2 and COP_L3 perform almost as good, while the COP_L1 and COP_Q1, which neglect the load dependency of the COP, perform significantly worse.

Second, an analysis is conducted to evaluate the impact of each polynomial on the power consumption. The results are summarized based on 6 different simulations, where each of them uses one of the COP polynomials as the COP predictor. The numerical results show 5% more energy saving of COP_Q3 with respect to the COP_L1 during three-day simulation. COP_L2 and COP_L3 show also respectively 2% and 1.5% more energy consumption than COP_Q3, while the COP_Q2 performs almost the same as COP_Q3. Although less than expected, this improvement is still significant given the wide spread presence of the application.

Eventually, Table 4 shows the comparison of the best and worst polynomials for the proposed test case. The analysis reveals that the LTVMPC performance is mostly affected by the COP prediction during the transient parts. Also the correct selection of the boundary regions can significant impact on the energy consumption of the system. In particular, the LTVMPC shows up to 9% more energy consumption if the polynomials be tuned based on the boundary of radiator heating system, while the operating conditions of the system belong to the radiant-floor systems.

Table 4 LTVMPC evaluation in terms of energy consumption - percentage (%) shows the more energy consumption w.r.t. reference model.

Boundary region	polynomials	Total electrical energy consumption	Polynomials vs. reference model
Total	COP_L1	15 kWh	5%
	COP_Q3	14.3 kWh	0.1%
Radiant-floor	COP_L1	14.5 kWh	2%
	COP_Q3	14.3 kWh	0.1%
radiator	COP_L1	15.4	9%
	COP_Q3	14.3 kWh	0.1%
Reference model		14.15 kWh	-

5 Open Issues and Suggestions for Improvements

This study investigates the impacts of different control-oriented models of the air-to-water heat pump on the COP prediction and optimal control performance. The results show up to 5% improvement in the energy saving using more accurate model of the heat pump, under a normal tuning, and up to 9% under a tuning for target applications. This basically means that there is room to push further the energy savings, exploiting the efficiency of the HP to further improve the overall energy efficiency of a “smart building”. In addition, this difference and the proposed model can thus be employed for different applications, ranging from dynamic pricing to demand side management. Another possibility can be to act on a lower level, substituting the local controller of the HP with an optimal one, in order to integrate better the low level control of the heat pump with its usage to serve the building load.

6 Dissemination Planning

Soroush Rastegarpour, Luca Ferrarini, Lorenzo Caseri “Experimental Validation of the Control-Oriented Model of Heat Pumps for MPC Applications “, IEEE 15th International Conference on Automation Science and Engineering (CASE), Vancouver, BC, Canada, August 22-26, 2019.

7 References

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8 Annex

8.1 List of Figures

8.2 List of Tables