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Cooperative optimization of building energy systems in an economic model predictive control framework

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ABSTRACT

A concept of 'cooperative' optimization of building energy systems is proposed in this paper. A cooperative optimization framework for a group of buildings connected to heat pumps in the context of economic model predictive control is formulated. Two optimization scenarios have been considered for analysis – a 'selfish' optimization of an individual building and a cooperative optimization of a group of buildings. The impact of cooperative optimization on the energy usage patterns and cost of electricity for operating the heat pumps have been investigated. The proposed cooperative optimization approach is able to achieve up to 15% reduction in energy demand cost in comparison with selfish optimization. The benefits arising out of the cooperative optimization concept may be a major drive for the future smart cities and will play a significant role in advancing the concept of smart energy systems.

1. Introduction

A significant amount of research in the recent years has been devoted towards performance of building energy systems and their optimization and control. Most of the results reported in the literature are mainly focused on individual buildings, though recently groups of buildings and cities have been also considered [1,2]. In this context, further research about energy performance of a cluster of buildings is therefore needed.

Traditional controllers which are most widely used in buildings tend to be compensated and use current outdoor temperature, i.e. they are feedforward in nature [3]. These controllers may not lead to optimal energy management in buildings. In recent years, there has been significant development on control of heating, ventilation and air conditioning (HVAC) systems [4–7]. Model predictive control (MPC) in particular has gained remarkable momentum due to its suitability for control of slow dynamics systems. In the MPC framework, a numerical model of the process to be controlled is employed to predict the behaviour of the system over a certain future horizon. The predictions are used to formulate an optimization problem that aims at minimizing a prescribed objective function, typically quantifying the performance of the system. In this context, economic model predictive control (E-MPC) denotes a class of MPC strategies for which the objective function contains also economic criteria. The application of MPC in building energy control has been investigated for climate control [8–10] and appliance scheduling applications [11–14]. In [15] a randomized MPC approach based on weather and occupancy predictions is proposed to regulate comfort levels in buildings and to minimize the buildings energy consumption. Recently, a review on optimal control systems applied to energy management in smart buildings has been given by Shaikh et al. [16]. In spite of the requirement of a model and additional computation burden, the work by Privara et al. [17] is an evidence of one of the early implementation for building heating systems. The major advantage of predictive control algorithms is that the energy controllers can adjust the control input in advance of future requirements based on prediction. In this way, the effects of slow thermal dynamic response of building systems can be counteracted by the predictive control algorithm. Lee et al. [18] and Cho et al. [19] studied control methods for floor heating in Korea. They concluded from their studies that predictive control methods performed better than on/off controllers with regard to energy consumption. Ma et al. [20] and Vieira et al. [21] shows in their studies that predictive control performs better than the proportional control in context of energy and cost saving. Chen [22,23] and Pyeongchan [24] have applied model base predictive control techniques in floor heating applications. Different forms of objective functions have been explored by them leading to different formulations, such as based on minimizing the operating costs or accumulated heat supply flux with indoor temperature target interval band.

This paper proposes a formulation for cooperative optimization of a cluster of building energy system connected with heat pumps

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in the framework of an E-MPC problem [9,25]. E-MPC is particularly suitable for the implementation of the demand response approach [9,26]. The optimization problem formulated in this paper leads to the concept of a cooperative optimization. The results from the cooperative optimization scenario are compared with those from a selfish optimization of a single building using E-MPC. The impact of the proposed controller on energy usage pattern, load shifting trends and total cost of energy consumption is also investigated.

2. Review on building climate controllers

Before discussing E-MPC formulation some of the current building energy control strategies are discussed first.

2.1. Current building energy control strategies

Some of major and commonly used building HVAC control strategies are: (i) on-off temperature control, (ii) weather compensated control and (iii) PID control [7,17].

2.1.1. On-Off room temperature control

This is the simplest type of control strategy. The heating/cooling system in a room is turned on or off according to the deviation from a set point, i.e. based on an error threshold. This is implemented on a hysteresis curve. The main drawback of this controller is that it does not take into account the dynamics of the building. However, it is simple to implement.

2.1.2. Weather compensated control

This is a form of feedforward control. The temperature of the heating element/machine in the room is set according to the outdoor temperature by means of a heating curve. This curve is a function of the difference between the indoor and the outdoor temperature. This controller also does not account for the dynamics of the building. In spite of this drawback, it is a robust controller and tuning is easy.

2.1.3. PID control

This is one of the most popular industrial control strategies [27,28]. This is a feedback control strategy and can take into account some information about the system dynamics and heating/cooling temperature is determined according to the room temperature set-point error. PID controllers are widely used in industrial applications but they do not account for outdoor temperature explicitly in the design of the control law. Further, in the case of multiple input multiple output (MIMO) systems the tuning of multivariable PID controllers is still a challenging task in practice. Hence, the use of such controllers are limited in controlling HVAC systems for buildings.

2.2. Model identification

In comparison with the model free approach, model-based control offers the advantage of providing useful design indications through simulations at a design stage. The model-based approach is also well-suited for the application of optimal control strategies in which the control algorithm is re-cast as an optimization problem (e.g. MPC), with the possibility of modelling physical constraints. The performance of a model-based controller is, however, heavily dependent on the accuracy of the model, i.e. on how good the model is in predicting the behaviour of the real system.

Thanks to the advances in sensing and metering technologies, data-driven characterization of the heat dynamics of buildings has gained particular attention in recent years due to the increased availability of detailed data. The integration of knowledge of the physical characteristics of the building (in terms of equations describing the underlying physics) with building energy performance data leads to a grey-box system identification approach [29]. The use of grey-box models for modelling of heat dynamics of buildings has been investigated in the literature in [30].

For the purpose of illustration of the concept proposed in the present paper, the approach described in [25,30] has been adopted to model the thermal dynamics of a building subjected to multiple heat inputs, including floor heating and solar radiation. The modelling approach is briefly outlined in Section 3.

3. Building energy system with heat pump and economic-MPC

For the purpose of formulating the problem a simplified model for thermal dynamics in a building including heat pump is developed following [25]. The building considered is connected to a ground-source heat pump through floor heating pipes and it is subjected to solar radiation and outdoor ambient temperature. As the dynamics of a heat pump is much faster as compared to the thermal dynamics of a building in general, the amount of heat transferred by a heat pump can be represented by the following algebraic equation:

$$Q_c = \eta W_c \tag{1}$$

where Q_c = heat transferred from the condenser to the water, η = coefficient of performance of the heat pump, W_c = work done by the compressor. The simplified model of the building energy balance with a heat pump under the assumption discussed previously can be represented by the following three differential equations [25]

$$\begin{aligned} C_{p,r}\dot{T}_r &= (UA)_{fr}(T_f - T_r) - (UA)_{ra}(T_r - T_a) + (1-p)\phi_s \\ C_{p,f}\dot{T}_f &= (UA)_{wf}(T_w - T_f) - (UA)_{fr}(T_f - T_r) + p\phi_s \\ C_{p,w}\dot{T_w} &= \eta W_c - (UA)_{wf}(T_W - T_f) \end{aligned} \tag{2}$$

where the state variables T_r, T_f and T_w represent the room air temperature, the floor temperature and the water temperature in floor heating pipes, respectively. The external disturbances considered in the simplified model are the ambient air temperature T_a and the solar radiation power ϕ_s. In (2), $C_{p,r}$, $C_{p,f}$ and $C_{p,w}$ denote the heat capacity of the room air, of the floor and of the water in floor heating pipes, respectively; $(UA)_{ra}$, $(UA)_{f,r}$ and $(UA)_{w,f}$ represent the heat transfer coefficients between room air and ambient, floor and room air, water and floor, respectively. The parameter p is the fraction of incident solar radiation on floor and η is the compressor coefficient of performance (COP).

The system of differential equations (2) can be used to develop a state-space model of the building energy system with a heat pump with

$$\begin{aligned} \dot{x} &= [A]\{x\} + [B]u + [E]\{d\} \\ y &= [C]\{x\} \end{aligned} \tag{3}$$

In (3) the states are $\begin{bmatrix} T_r & T_f & T_w \end{bmatrix}^T$ and the control input is $u = W_c$; the disturbances are $\{d\} = \begin{bmatrix} T_a & \phi_s \end{bmatrix}^T$; and the output variable is the indoor temperature $y = T_r$. These lead to the matrices in the state-space model [25].

MPC is an advanced control method which stems from applications in process control industries in late 70s and early 80s [31]. MPC represents a class of control strategies where the model of the system of the process is explicitly considered and the control input is determined based on the minimization of an objective function with certain constraints. The optimization is performed iteratively over a finite horizon with a multi step-ahead control action prediction and is updated in time progressively. There have been several attempts to use MPC for HVAC control system [32–36] in