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ScienceDirect

Energy Procedia 122 (2017) 985–990

Energy Procedia

www.elsevier.com/locate/procedia

CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland

Handling thermal comfort in economic model predictive control schemes for demand response

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Abstract

Addressing thermal comfort is an important aspect of applying economic model predictive control (E-MPC) schemes with the objective to perform demand response (DR), e.g. minimize operational cost. This paper compares the performance of four E-MPC schemes using both single-objective and multi-objective formulations to address thermal comfort. It is difficult to proclaim the superior formulation as the notion of thermal comfort is a subjective matter. However, the single-objective problem formulation proposed in this paper contains a parameter, ε_{max}, which describes the maximum acceptable deviations from the preferred indoor air temperature. This parameter can be regarded as a user-defined indicator of the acceptable deviations from the preferred temperature or, in other words, their 'DR willingness'.

Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale

Keywords: Themal comfort; Demand Response; Single objective optimization; Multi objective optimization; Economic model predictive control

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Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale
10.1016/j.egypro.2017.07.458

1. Introduction

Economic model predictive control (E-MPC) of building energy systems is an optimization based control scheme that uses a model of the building thermodynamics, forecasts of disturbances and measurements of the building state to determine a sequence of optimal control actions. Applying E-MPC together with time-varying energy prices to minimize the space heating operational cost and perform demand response (DR) have been investigated in several studies [1-4]. These E-MPC schemes achieve economic benefits by using the thermal capacity of the structural mass as storage by charging and discharging it with the room heating system in periods with low or high prices, respectively. The schemes therefore result in fluctuating indoor temperatures, and it is therefore necessary to ensure that economic benefits are not violating the thermal comfort of the occupants.

A simple E-MPC formulation in this regard is to assume that occupants are comfortable as long as temperatures are within a predefined comfort band, e.g. defined by a preferred temperature and an acceptable deviation from it. Using this comfort formulation, several studies have suggested significant cost savings and DR potentials. Halvgaard et al. [5] minimized the operational cost of a heat pump and achieved cost savings of 25% compared to traditional control. Pedersen et al. [4] optimized the space heating operation in a multi-apartment building which, compared to a conventional PI-controller, achieved cost savings of up to 6% and reduced energy consumption in peak-hours with up to 47%. Vrettos et al. [1] applied E-MPC for heat pump operation and achieved cost savings of 18.4% compared to a rule-based controller. However, an E-MPC scheme using this comfort formulation will often result in the controller tracking either the upper or the lower boundary of the comfort band [4]. This behavior means that the air temperature rarely is equal to the preferred temperature specified by the occupants. Another shortcoming of this formulation is that the building has no downward flexibility to offer in periods where the lower comfort bound is tracked, i.e. it is not possible to reduce the space heating demand if this service is requested by the supply side [6].

Another approach to ensure comfort is to formulate a multi-objective optimization (MOO) problem, i.e. simultaneously minimize operational costs and thermal comfort violations [2, 7-10]. Avci et al. [2] used an E-MPC scheme to minimize energy consumption and penalize temperature deviations from the preferred temperature, and introduced a discomfort tolerance index to weigh the objectives. Compared to a baseline controller, the E-MPC scheme reduced operational cost with 13% while increasing the mean temperature with 0.15°C. Morales-Valdés et al. [8] evaluated several MOO formulations and suggested to include Fanger's predicted mean vote (PMV) index or predicted percentage dissatisfied (PPD) index in the cost function which, however, led to a nonlinear optimization problem. Therefore, Cigler et al. [7] proposed a convex approximation of the PMV index in the cost function. However, including the PMV index in the cost function relies on assumptions regarding clothing level and metabolic rate, as well as measurement of air speed, relative humidity and the mean radiant temperature. Furthermore, the performance reported in the above-mentioned MOO studies depends on the selection of the assigned relative weights which essentially vary in time as they depend on the building conditions.

Current studies address thermal comfort in E-MPC formulations very differently, which may affect the reported DR potentials. This paper therefore reports on a simulation-based study, where the performance of an E-MPC scheme using both single-objective and multi-objective formulations to address thermal comfort violations is investigated. The aim is to provide a quantitative performance assessment of the different formulations in terms of comfort violations and operational cost, and to discuss their practical implications.

2. Method

A residential building consisting of ten apartments and five stairwells located in Aarhus, Denmark, was chosen as test case. A detailed EnergyPlus (EP) model was used to represent the building to be controlled; information on geometry and thermal characteristics of the building are provided in ref. [4] in which the building is denoted retrofit8. Furthermore, 100mm insulation was added to the partitioning walls to minimize the effect of inter-zonal heat exchange and thereby allow for a decentralized control principle [11]. The E-MPC scheme was implemented in MATLAB and used to operate the space heating of the EP model through co-simulation facilitated by the Building Controls Virtual Test Bed (BCVTB) [12]. The simulations were carried out for the period December 1, 2016 to February 28, 2017, which constitutes the coldest period of the heating season in Denmark, using an EP weather file based on on-site weather measurements. Historical day-ahead power market prices (cleared for Western Denmark, DK1 region) from the simulation period were used. To ease the interpretation of the results, internal gains originating from occupants and equipment were omitted, and perfect weather and price forecasts were assumed.