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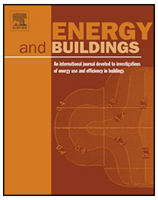

Modeling environment for model predictive control of buildings

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ABSTRACT

Model predictive control (MPC) is an advanced control that can be used for dynamic optimization of HVAC equipment. Although the benefits of this technology have been shown in numerous research papers, currently there is no commercially or publicly available software that allows the analysis of building systems that employ MPC. The lack of detailed and robust tools is preventing more accurate analysis of this technology and the identification of factors that influence its energy saving potential. The modeling environment (ME) presented here is a simulation tool for buildings that employ MPC. It enables a systematic study of primary factors influencing dynamic controls and the savings potential for a given building. The ME is highly modular to enable easy future expansion, and sufficiently fast and robust for implementation in a real building. It uses two commercially available computer programs, with no need for source code modifications or complex connections between programs. A simplified building model is used during the optimization, whereas a more complex building model is used after the optimization. It is shown that a simplified building model can adequately replace a more complex model, resulting in significantly shorter computational times for optimization than those found in the literature.

1. Introduction

Model predictive control (MPC) is an optimal control that uses a dynamic system model and predictions of future events to optimize the objective function (e.g. energy consumption or cost). MPC is already used in some process industries, and is becoming an increasingly popular research topic in buildings, demonstrating the benefits for building energy consumption and electricity cost. Based on weather and load predictions, MPC enables energy efficient strategies through the optimization of heating, ventilation and air conditioning (HVAC) system operation, while ensuring thermal comfort for occupants. For example, it can predict optimal shifting of cooling loads to night time, when the outside temperatures are lower and, therefore, the efficiency of cooling equipment is higher. Furthermore, it can result in lower cooling cost in case of utility rates that favor night operation, as well as reduction in peak loads.

The benefits of MPC for building HVAC systems have been demonstrated in numerous papers found in the literature, mainly using numerical simulations. The previous research showed that the use of MPC can result in 5–70% energy savings and 10–45% peak power savings [1–9]. The reported savings were demonstrated for both heating and cooling systems, and were strongly dependent on a climate, building type, system type and simulation assumptions. One of the crucial elements for MPC is a building model suitable for capturing a building's dynamic behavior since it can strongly influence the optimization accuracy and computational speed. Recently, important work was done on various building models for the MPC application [10–16]. Based on a comparison of models ranging from those that make use of a system's physical description to black-box models, Prívara et al. [17] suggested that methods using a physical description should be used primarily for buildings with simpler structures, while black-box models (e.g. subspace identification [18]) are much more suitable for complex structures. Prívara et al. [15] also showed that a model with a reduced set of inputs and states can have similar accuracy as a model with a full set. A weather forecast is another element that strongly influences the prediction accuracy of MPC. In a comparison of short-term weather forecasting models, Krarti and Henze [3] suggested that the bin model (which uses observations from the previous 30 and 60 days) had the best prediction accuracy. The use of this model resulted in marginally different cost savings compared to the case with perfect weather knowledge. Using the modeling environment developed by Krarti et al. [19], Henze et al. [20] also investigated different lengths of the planning horizon, where the planning horizon represents the time interval over which the cost function was evaluated.

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Nomenclature

COP	coefficient of performance (–)
c	specific heat (J/(kg K))
L	latent load (kg_w/s)
m	mass flow rate (kg/s)
OF	objective function (–)
P	power (W)
p	pressure (Pa)
Q	heating or cooling rate (W)
T	temperature (°C)
V	volume flow rate (m^3/s)
w	absolute humidity (kg_w/kg_{air})
ρ	density (kg/m^3)

Subscripts

adj	adjacent room
air	air
as	assumed
avg	average
c	condensing
cc	cooling coil
conv	convective
e	evaporating
hp	heat pump
i	internal
in	inlet
llim	lower limit
m	measured
max	maximal
o	operative
opt	optimal
rad	radiative
return	return (water)
s	supply (air)
supply	supply (water)
trans	transport
ulim	upper limit
w	water
x	ambient
z	zone

Results showed that the planning horizon on the order of 24 h is only marginally sub-optimal compared to the horizon over a simulation period of one week. Moroşan et al. [21] tested different MPC strategies for multi-zone buildings by comparing decentralized MPC, in which each zone temperature is regulated by its own controller, with centralized MPC, in which the entire multi-zone system is controlled by one MPC law. Due to the lack of thermal coupling with decentralized MPC and high computational demand with centralized MPC, the authors proposed distributed MPC with local MPCs for each zone and a communication network between them. This approach allowed for coupling between the subsystems, and resulted in reduced computational demand relative to the centralized approach.

Only a few papers have given detailed descriptions of the tools used to simulate a building with MPC. Krarti and Henze [3] provided an in-depth overview of a simulation model in which EnergyPlus was modified and integrated with the optimization software GenOpt. The additional model was done in TRNSYS, using a version of the TRNSYS source code not commercially available [22]. Optimizing a day with 24 hourly setpoints took 1–4 h for the Nelder–Mead simplex method and 8–29 h with the OptQuest (population-based scatter search) method. Spindler and Norford [23] and May-Ostendorp et al. [24] showed that MPC can also be successful in optimizing a mixed-mode building behavior. While Spindler and Norford [23] used the data-driven, inverse model trained on a real building, May-Ostendorp et al. [24] employed the combination of EnergyPlus and MATLAB environments. Using the particle swarm optimization, May-Ostendorp et al. [24] optimized window operation in a mixed model building with a 24-h planning horizon and a 2-h optimization block. This resulted in 12 optimization variables of binary window decisions (window in position 0 or 1). The reported simulation time for 11 weeks in summer was 12 h. Corbin et al. [25] described a framework for MPC that combines EnergyPlus and MATLAB and uses the particle swarm optimization. The algorithm can be used for MPC of different building systems, which was shown for a VAV system and for a building with TABS. In the first example, having 14 daily temperature setpoints as optimization variables resulted in the simulation time of 26 clock hours to simulate one week. In the second example, it took one day of clock time to simulate one day for a building with 11 thermal zones and 12 optimization variables. Coffey et al. [26] developed a software framework for MPC that combines GenOpt and SimCon with any building energy simulation program that can read and write into a text file. The connection between SimCon and the energy modeling software TRNSYS was enabled through the building control virtual test bed [27]. To optimize one day using MPC, the reported computational time was three nights.

Although the benefits of MPC have been demonstrated in numerous research papers, important challenges that still remain are the lack of tools for the system analysis and practical challenges facing real building implementation. Findings in the literature on potential energy and cost savings are highly dependent on a variety of factors, such as the building type, internal load, climate, equipment characteristics, and controls. The use of a computer model allows for a systematic study of primary factors influencing the dynamic control and savings potential for an individual building. However, currently there are no commercially or public available tools for this type of analysis. Of the few papers in the literature that give detailed descriptions of the tools used to simulate building with MPC, most require modification of existing building simulation programs, which has been shown as challenging. One example is a severe issue with initialization of variables in building software EnergyPlus and TRNSYS, as mentioned in more detail later in this paper. Furthermore, the reported computation times are not practical for implementation in real buildings where the optimization usually needs to be repeated each hour due to uncertainties in load and weather predictions. The implementation in real buildings is somewhat inhibited by control complexity compared to conventional systems. Examples are found in the literature of simplified control strategies that would result in a near-optimal control [28], but those strategies are still obtained by using more detailed computer models.

The modeling environment (ME) presented here simulates the performance of a building in which HVAC systems are operated using MPC. It can be set to optimize a variety of HVAC systems and optimization objectives, using different planning horizons (the time interval over which the objective function is evaluated) and execution horizons (the time interval over which the control strategy is applied). The ME does not require any modification of existing building programs, only the common connection between Matlab and TRNSYS (using TRNSYS Type 155). To reduce computational time, the ME uses two building models of different complexities, where the simplified model is used in the optimization, and TRNSYS only for post optimization. This avoids complex connections between different programs and results in significantly shorter computational time, making the ME robust and suitable for implementation in real buildings.