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Model-based controllers for indoor climate control in office buildings – Complexity and performance evaluation

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ABSTRACT

Model-based controllers are equipped with an integrated control model and utilize information about disturbances that act on the process. It is well established that the performance of building automation systems can be drastically improved by model-based controllers, but, they also lead to a substantial increase of complexity which is an obstacle for large scale implementation. In this work, model-based controllers with different measured disturbances as exogenous inputs and different types of control models were evaluated to explore the possibility of reducing complexity without compromising performance. The work was performed in a simulated environment and focuses on temperature and CO_2 concentration control in individual office rooms during periods that are dominated by occupancy. All relevant internal and external disturbances in office environments were considered as both single input and combined inputs to six different control models. The key finding is that controllers with simplified control models and fewer exogenous inputs can perform almost as well as more complex controllers.

1. Introduction

Buildings are increasingly expected to meet higher requirements such as being sustainable and energy efficient at the same time as a healthy and comfortable indoor environment should be achieved. Approximately 40% of the global energy is used in buildings whereof about half is used for heating, ventilation and air-conditioning (HVAC) in industrialized countries. At the same time, there are large room for energy efficiency improvements to reduce the running costs and CO_2 emissions. Since energy efficiency measures must be economical feasible in both the existing building stock and in new constructions, there is a demand for energy saving technologies that are relatively easy to implement. A key technology to meet all of these requirements is to improve the building automation system. Such measures can be both cost effective and result in substantial energy savings at the same time as a desirable indoor environment can be maintained or even improved [1].

Model-based controllers refer to a group of controllers that utilize information about the intensity and type of disturbances that act on the process. The disturbances can either be measured or estimated and are used as exogenous inputs to an internal control model. The control model predicts or estimates the corresponding impact on the controlled variables and sequently adjusts the control signals to achieve the desired behaviour of the process. Preferably, the prediction or estimation should be combined with state feed-back based on measurements of the controlled variables. In this way, unmeasured disturbances and errors in the control model are compensated for. Model-based controllers for building automation have been investigated in several works before. Most of the recent ones focused on a type of model-based controller referred to as model predictive controller (MPC). The input to an MPC is usually disturbances and/or state measurements. At each time-step control signals are generated by solving a constrained optimal control problem using a dynamic control model and a cost function. In [2–4] MPCs were used in office buildings and both internal and external disturbances were investigated as controller exogenous inputs. In several works [4–8], weather forecasts were used for example to maximize the renewable part of the energy usage or to optimize the heat stored in the building structure. In the light of these cited works, it is clear that model-based controllers have a large potential for improving the building automation system. A desirable indoor environment can be achieved while the energy usage is decreased substantially compared to when more conventional control systems are used. However, the main obstacle for implementation is that model-based controllers have the tendency of drastically increase the complexity of the control system. In general, the cited works investigated the performance of

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Nomenclature

C	thermal capacity (J/°C)
c	CO_2 concentration (ppm)
c_p	specific heat capacity (J/(kg K))
E	total energy usage, weighted sum of energy terms (W)
h	hour
$\dot{M}$, $\dot{c}$	CO_2 flow rate (ml/s)
n	number (-)
Q	thermal energy (J)
$\dot{Q}$	thermal power (W)
t	Celsius temperature (°C)
u	general input signal
V	volume (m^3)
$\dot{V}$	volume flow rate (m^3/s)
W	electric work (J)
$\dot{W}$	electric power (W)
y	general output signal

Greek letters

τ	time (s)
ρ	density (kg/m^3)

Subscripts

act	activation
adj	adjacent
s	supply
sp	setpoint
r	room

extensive and complex model-based controllers and the measured disturbances were evaluated as lumps which means that their relative value as input were not identified. Hence, the possibility of reducing the complexity of the disturbance sensor system and the control model were not fully addressed.

In order for model-based controllers to be used on a large scale in building automation, a standardized and easy solution must be available. The complexity, and also the performance, depends both on the design of the control model and the design of the disturbance sensor system. Within the group of model-based controllers, the complexity of the control model can range from a full MIMO (Multiple-Input, Multiple-Output) dynamic representation of the process to a simple linear SISO (Single-Input, Single-Output) representation. A complex control model requires an extensive tuning process, both if black-box or physical models are used, as well as continuous maintenance to update for changes of the process. When it comes to the disturbance sensor system, the number of measured disturbances and their measurability determines the complexity of the sensors, but the signals must also be correctly processed in the control model which requires tuning and programming. Further, each measured disturbance is also associated with a cost of hardware (sensor and wires) and labour. Two of the most commonly controlled variables in buildings are the indoor air temperature and the CO_2 level that in turn are indicators for thermal climate and IAQ (Indoor Air Quality) respectively. Both, but especially the temperature, are at each time affected by a large number of intermittent disturbances. However, depending on the occupant activity and type of building some have larger influence than others. To reduce the complexity of model-based control systems, it is of importance to limit the number of exogenous inputs and only target the disturbances that have a large impact on the performance of the building automation system. The rest of the disturbances should preferable be managed by state feed-back.

1.1. Purpose and procedure

This paper investigates model-based controllers for local air temperature and CO_2 control in office buildings through simulations. The aim is to explore the possibility of reducing complexity without compromising control performance. The most common office related disturbances were used as exogenous inputs to six different control models with a varying level of complexity that stretches from a large number of model parameters to just one. In this way, the disturbances that first and foremost should be measured were systematically pointed out and the performances of different control models were determined. Two office rooms that are different both from a structural and occupant activity point of view were considered in the investigation. The rooms were subjected to external and internal intermittent disturbances with patterns that correspond to an office building in Swedish summer or winter climate. The outcome of the investigation is two model-based controller designs referred to as design A and design B. Design A has the highest performance among all of the investigated controllers and has no restrictions on which control model or exogenous inputs that are used. In design B, a simplified control model is instead combined with the exogenous inputs that were shown to have significant impacts on performance. Control performance was indicated by energy usage and peak power and the results are presented as the relative savings by replacing feed-back controllers without information about disturbances.

1.2. Contribution

Complexity contra performance of model-based controllers is the focus of this work and the papers [9] and [10] are closest to that spirit. In [9], an MPC with occupancy as exogenous input was evaluated for indoor climate control and two types of HVAC systems were considered; one with fast responding water-based heating and cooling but no ventilation and the other with ventilation but slow reacting water-based heating and cooling. The value of utilizing predicted or measured occupancy was investigated and one of the main conclusions was that predictions do not lead to any significant increase of performance compared to measurements. Since predictions are increasing the complexity of the control system, the question of complexity contra performance was addressed, even though from another point of view compared to the current work since only measurements were considered here. Also in [10], the value of using occupancy as a controller input was investigated. In this case, the task was to control an all-air HVAC-system and a control model simpler than MPC was also considered.

There are several aspects that distinguish the current work from [9] and [10]. For example, the investigations are considering different HVAC-systems as well as different variants of building structure, type of room and ambient climate. But in particular, there are four features that make the current work unique on a more fundamental level. First, one of the main focuses in the current work is to determine the performance of simplified control models. In [9], MPC controllers were used throughout the study and in [10] one control model simpler that MPC was evaluated. Second, CO_2 control (or rather modulating control of an IAQ indicator) was not investigated in the cited works. Third, only occupancy was considered as exogenous input in the cited works while all relevant disturbances are evaluated in the current one. Finally, the control strategies in both [9] and [10] use temperature and/or ventilation set-back (i.e. relaxed comfort criterions) during vacant periods which presumably have a significant effect on the results. In contrast, the current work focuses on the performance of model-based controllers during periods that are dominated by occupancy. The