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Method for simulating predictive control of building systems operation in the early stages of building design

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A B S T R A C T

A method for simulating predictive control of building systems operation in the early stages of building design is presented. The method uses building simulation based on weather forecasts to predict whether there is a future heating or cooling requirement. This information enables the thermal control systems of the building to respond proactively to keep the operational temperature within the thermal comfort range with the minimum use of energy. The method is implemented in an existing building simulation tool designed to inform decisions in the early stages of building design through parametric analysis. This enables building designers to predict the performance of the method and include it as a part of the solution space. The method furthermore facilitates the task of configuring appropriate building systems control schemes in the tool, and it eliminates time consuming manual reconfiguration when making parametric analysis. A test case featuring an office located in Copenhagen, Denmark, indicates that the method has a potential to save energy and improve thermal comfort compared to more conventional systems control. Further investigations of this potential and the general performance of the method are, however, needed before implementing it in a real building design.

1. Introduction

In the European Union (EU), the Energy Performance of Buildings Directive [1] has been introduced as a regulatory initiative to improve the energy performance of buildings. The building industry is thus obliged to produce buildings with low energy consumption during operation. At the same time, occupants have some expectations with regard to the thermal indoor environment which are the main reason for any heating and/or cooling energy demand. In a temperate climate like Denmark's, one of the consequences of low energy building design is that the heating period is decreased. This results in an increase of the transitional periods between the heating and cooling seasons. Transitional periods are the periods of the year where the energy demand may fluctuate between heating and cooling on a daily basis. Energy-efficient control of building systems operation in these periods is a challenge. One example is control of night ventilation in office buildings as a measure to prevent mechanical cooling in the day time. Buildings in a temperate climate are highly amiable to this type of free cooling and it is therefore an important measure in a low-energy design. Night ventilation is conventionally made available at a certain date defined as the start of the cooling season, which ignores days in transitional periods when night ventilation might have been an energy-conserving measure. Another example is control of solar shading. Appropriate use of solar shading may prevent overheating but inappropriate use may increase heating requirement due to loss of solar gain and increased use of electrical lighting. The development of new concepts for the control of building systems operation is therefore needed to minimise energy demand while maintaining comfort.

The current research efforts on improving control of building systems evolve around the concept of predictive control. Much of the current research on predictive controllers is based on stochastic models [2,3], fuzzy logic control [4–6], or neural networks [7–10]. Common for these approaches is that they have no underlying physical model of the system and process being controlled. Instead these so-called "black-box" models use observed data, e.g. outdoor temperature, etc., as input to a statistically derived model which maps input to variables of interest, e.g. the indoor operative temperature. With the proper training these models may over time obtain the sufficient knowledge regarding the interactions between the elements of the controlled system or the interactions between the controlled system and the outdoor climate to make appropriate predictions. The limitations are that the training needed often is extensive, and that they may not provide reliable predictions in areas in which they were not trained [11]. Clarke et al. [12] consider these limitations as a crucial argument for the use of

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Nomenclature

n	the current time step (–)
Q_{sun}	actual average solar irradiance in time step n (W/m^2)
Q^*_{sun}	hourly forecast of solar irradiance of the remaining hours of the period to which the time step n belongs (W/m^2)
$Q^*_{sun,av}$	mean forecasted solar irradiance of the remaining hours of the period to which the time step n belongs (W/m^2)
Q^{**}_{sun}	hourly forecast of solar irradiance for the following period (W/m^2)
$T_{c,min}$	minimum temperature for thermal comfort (°C)
$T_{c,max}$	maximum temperature for thermal comfort (°C)
$T_{c,av}$	mean value of temperatures for thermal comfort (°C)
T_{out}	actual outdoor temperature in time step n (°C)
T^*_{out}	hourly forecast of outdoor temperature of the remaining hours of the period to which time step n belongs (°C)
$T^*_{out,av}$	mean forecasted outdoor temperature of the remaining hours of the period to which time step n belongs (°C)
T^{**}_{out}	hourly forecast of outdoor temperature of the following period (°C)
T_s	actual wall surface temperature at the end of time step n (°C)
T_a	actual air temperature at the end of time step n (°C)
T^*_a	predicted air temperature at the end of the period to which time step n belongs (°C)
T^*_w	predicted internal wall temperature at the end of the period to which time step n belongs (°C)
$T_{a,0}$	actual air temperature at the beginning of time step n (°C)
$T_{w,0}$	actual wall temperatures at the beginning of time step n (°C)
$T^*_{a,0}$	predicted air temperature at the beginning of the following period (°C)
$T^*_{w,0}$	predicted wall temperatures at the beginning of the following period (°C)
T_{op}	actual operative temperature in time step n (°C)
T^*_{op}	predicted operative temperature at the end of the period to which time step n belongs (°C)
T^{**}_{op}	the maximum predicted operative temperature in the following period (°C)
T'_{op}	operative temperature in time step n with *hr, shd, mvent* and/or *nvent* (°C)
$T_{set,cool}$	cooling set point for time step n (°C)
$T_{set,heat}$	heating set point for time step n (°C)
$T^*_{set,cool}$	predicted cooling set point for time step n (°C)
hr	heat recovery rate for mechanical ventilation system (–)
shd	predicted solar shading factor (–)
mvent	predicted mechanical ventilation rate (l/s per m^2)
nvent	predicted venting rate (l/s per m^2)

physically-based models, or "white-box" models, in the development of predictive control instead of black-box models. They suggest a control concept based on a detailed building simulation program to make real-time control decisions. They demonstrate the feasibility of the concept by making a reasonable prediction of the optimum start time for a heating system in a test case. Mahdavi [13] also suggests the use of building simulation for predictions to enhance the control of building systems operation. The overall concept is to utilise a virtual building model to move forward in time to predict the building's response to alternative control scenarios, and use actual recorded data to calibrate the virtual model to improve its predictive potential. Mahdavi [14] has also developed a controller for simulation-based real-time control of lighting and shading systems. Tests of the controller prototype show promising results in terms of recommending appropriate real-time control states. Henze et al. [15,16] apply building simulation and weather forecasts for predictive control of cool storage systems in office building. Test cases in both references demonstrate a potential for substantial reductions in utility cost and cooling-related on-peak electrical demand in a subtropical arid climate. Wittchen et al. [17] also apply building simulation and weather forecasts to predict appropriate set points and air flows in the control of night ventilation. A test case featuring a building in a temperate climate indicates a theoretical annual energy saving of 5% and improvements in the thermal indoor climate compared to a conventional control system. The Model Predictive Control algorithms developed in the 3 year long interdisciplinary project OptiControl indicates a theoretical energy saving potential of 16–41% varying with location (in central and south Europe), building case, and technical system characteristics [18]. Coffey et al. [19] presents a software framework what could be characterised as a "grey-box" approach to predictive control since it combines physically-based models with a generic (stochastic) algorithm. The results from a case study demonstrate that the framework can be used to minimise cooling demand through optimal demand response using zone temperature ramping in an office space.

So, current predictive control systems have demonstrated a potential for energy savings and improvements in thermal indoor environment and visual comfort. Predictive control is therefore a potential energy-saving design option when designing new low-energy office buildings. As for all alternative design options, it is desirable to know the impact of predictive control before implementing it in an actual building design. Furthermore, the use of a predictive control could become a facilitating feature in a building design process where building simulation is used to generate design input through parametric analysis of energy performance and indoor environment by varying geometry, building elements and systems, e.g. as described by Petersen and Svendsen [20]. A variation of geometry, building elements and systems may trigger a need for adapting the configuration of the building systems control to maintain thermal comfort and/or prevent unnecessary energy use. This adjustment may require a number of manual iterations before an appropriate configuration is found. Predictive control is automating this adaption and thus reduces the need for time-consuming iterations. This automatic adaption is also relevant in actual building systems operation. Conventional control of building systems are mainly rule-based or reactive, i.e. controlled with respect to real-time measurements of internal conditions and external gains. The consequence is a risk of discomfort and increased use of energy, especially in the fluctuating transitional periods. These problems could be minimised by using a predictive control system which enables the building systems control to react proactively to an energy demand that may fluctuate between heating and cooling on a daily basis. The aim of this paper is therefore (1) to enable building designers to predict the annual performance of a predictive control system in the early stages of building design, (2) facilitate and automate the configuration of the building systems control when performing parametric analysis in the early stages of building design, and (3) to make an initial investigation of the method's potential for energy savings and thermal comfort improvements. The scope of these aims is limited to apply for office buildings only.