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Trial results from a model predictive control and optimisation system for commercial building HVAC

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ABSTRACT

This paper presents the results from two real-world trials of an optimised supervisory model predictive control (MPC) system for heating, ventilation and air conditioning (HVAC) in commercial buildings. The system learns a model from historical data and uses weather forecasts and a given temperature set-point profile to predict building zone conditions and thermal comfort with the aim of optimising building controls for a number of HVAC zones throughout a day. The multi-objective optimisation minimises running cost and CO_2 emissions, subject to operator preferences, while constraining occupant thermal discomfort to an acceptable range to find the best zone temperature set-point schedule for the building. This schedule is then applied to the building by a feedback control loop, which balances the power supplied to each zone for heating, cooling and ventilation.

A complementary online occupant comfort feedback tool was deployed to all occupant computers in the trial office buildings. This tool allows occupants to submit feedback on their thermal comfort and satisfaction at any point in time via electronic surveys, as well as allowing these surveys to be issued to occupants at scheduled times. This feedback fine-tuned the thermal comfort model used to constrain the optimisation, allowing for errors in the comfort model to be compensated. Thermal comfort feedback was also used to measure and compare relative occupant comfort levels with a baseline.

This control system was trialled on two office buildings in Australia, over two winter months and results compared with the performance of the incumbent building management and control system (BMCS). An average energy reduction of 19% and 32% was achieved in the two buildings over 51 and 10 days of operation respectively without substantially affecting measured or modelled occupant thermal satisfaction levels.

1. Introduction

This paper presents a supervisory control and optimisation system for commercial HVAC systems, aimed at minimising energy consumption and occupant thermal discomfort, and an accompanying online occupant comfort feedback tool which can be installed on occupant computers.

Occupant feedback from the comfort feedback tool is used to assess the impact of the optimised HVAC control strategy, to fine-tune the standard comfort model used in the optimisation process and to inform users of the state of the HVAC system, such as when natural ventilation or economy modes are active.

The supervisory HVAC control and optimisation system (referred to hereafter by the authors' internal designation '*Opti-COOL*' interfaces with a commercial building management & control system (BMCS) to read required data from HVAC zones and air handling units (AHUs) and to perform required control actions. It learns a model that can be used to predict zone conditions and comfort levels using information about HVAC power consumption and weather, which is used to discover the optimal power consumption schedule throughout the day-balancing cost, energy and emissions while maintaining comfort. The control module then overrides zone or supply air set-points to balance the heating/cooling power supplied to each zone and to track the best power profile from the optimisation.

Both systems were installed in two office buildings on the east coast of Australia and trialled over two months during winter to evaluate their energy savings potential. Thermal comfort levels were monitored throughout the trials to ensure consistency with pre-trial levels.

2. Background

Model predictive control (MPC) has been widely used for some form of building HVAC optimisation. The majority of work to date concentrates on examining control strategies for specific

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subs-systems [1], applying offline optimisation of particular buildings or building configurations using simulation models [2], or considers only specific approaches such as set-point resetting, peak demand limiting or load shifting [3–5], or examines techniques using small-scale test beds [6,7]. Whole building optimisation and control simulations such as in [8–12] can take further advantage of the full range of operating building modes, and incorporate important objectives such as energy market tariff structures, peak demand, emissions from a variety of energy sources, and occupant thermal comfort constraints. Multiple conflicting objectives often arise when deciding on an operating schedule and it is important to allow the operator to make the final decision, for example by making trade-offs between comfort, cost and emissions or between chilled water temperature and pump usage, such as in [13,14]. A flexible multi-objective optimisation [15] provides a balanced method to achieve this aim.

While building control simulations claim significant performance improvements over traditional controllers, it is also very important to evaluate such control strategies outside pure simulation, in real operational buildings, wherein additional constraints such as bandwidth-limited building-level networks, occupant comfort complaints, faulty or missing sensors, bad design and commissioning errors all play important roles in the ultimate gains that can be made from widespread deployment of such predictive control systems. Only a small body of work has taken this extra step and trialled building optimisation approaches beyond simulation in operational buildings, such as [16,17], which trialled simple strategies for peak demand management. Even fewer publications report trials of more advanced MPC approaches in full-size buildings under normal operational conditions. One rare example of a real-world trial of whole-building MPC is [18] which demonstrated a 60% energy savings over the week-long trial period using a predictive controller in a specially retrofitted army building in Illinois; though it is unclear how difficult this system would be to install in other large buildings, and changes in occupant comfort, beyond temperature setpoint and CO_2 levels, were not compared with the standard control system's performance.

The ultimate aim of any HVAC system is to ensure the thermal comfort of a building's occupants and so a method of measuring thermal comfort objectively is needed. Typically, models such as [19] and industry standards [20,21] are used to estimate thermal comfort based on environmental conditions. These models have been validated in a range of climatic conditions and geographical locations and are a good general representation of how occupant thermal comfort perception varies with environmental conditions. However, even these comfort models can lack specificity when dealing with a particular building, its location and the subjectiveness of human comfort perception of a particular group of occupants. A wide-scale study of the biases in the predicted mean vote (PMV) model [22] concluded that calculated PMV often differs markedly and systematically from the occupants' actual mean vote, and it generally overestimates the subjective warmth of people in warm environments, leading to excessive cooling and therefore energy wastage in hotter climates. The online comfort feedback tool presented here helps address such issues by using real-time comfort measurements to help adjust for bias in the PMV model. The *OptiCOOL* system then incorporates this feedback to fine-tune the zone set-points and more closely match the HVAC control with what the occupants are actually reporting, maintaining more comfortable conditions.

An earlier trial by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), conducted during summer 2007 on an 11-floor, 10,000 m^2 office building in Melbourne VIC Australia, experimented with zone and global temperature setpoint adjustments and measured the resulting thermal conditions and change in resulting energy consumption [23]. While this trial showed the expected power reduction from relaxing global setpoint constraints, it also highlighted the imperfect cooling energy distribution amongst the zones that results from this simplistic approach – hot and cold spots from the non-uniform cooling throughout the zones increased occupant discomfort. Clearly, a more intelligent and balanced approach was required, and these observations led to the development of the *OptiCOOL* control system presented herein, which addresses these problems through whole-building energy optimisation with per-zone comfort balancing.

More recently, a study of a commercially available technology based on the *OptiCOOL* system was evaluated by the US-based Argonne National Laboratory in an 18,600 m^2 commercial building with 7 AHUs and 700 occupants. This evaluation demonstrated 25–45% energy savings, depending on the ambient temperature, while maintaining a predicted percentage [of occupants] dissatisfied (PPD) of less than 10% [24].

The theory behind the *OptiCOOL* system and early simulation and single-zone trials have been presented in [25,26]. This paper builds further upon these publications, presenting more details on the simulation model, comfort feedback mechanism, and most importantly, the real-world trial results from this technology operating in two actively occupied buildings for an extended period of time. It also discusses the benefits of correcting errors in the de facto standard PMV model using this novel occupant comfort feedback desktop application, and the use of this signal as a primary control signal for HVAC zones. Finally, we give practical advice for operating such a trial based on the lessons learnt in the deployment and operation of *OptiCOOL* over the course of these trials.

3. Theory

3.1. Thermal comfort

Human perception of thermal comfort is highly subjective, and modelling it accurately for the purposes of predicting occupant comfort from measured environmental conditions is an active area of research, with de facto standard models having been shown to bias predictions such that excess cooling energy is often consumed unnecessarily [22]. Given that the primary aim of building HVAC systems is to maintain a level of occupant thermal comfort, it is critical to have an accurate comfort metric by which to govern system control. To this end, we have developed and trialled a real-time occupant thermal comfort measurement tool to complement the de facto standard PMV model, which takes the form of an online application enabling wide-scale comfort surveying and a status indicator of the HVAC operating mode.

More specifically, the application:

a) Provides occupants with an online electronic survey form (see Fig. 1), based on the de facto standard 7-point thermal sensation scale [20], to assess the actual mean vote (based on PMV) and a measure of satisfaction [27]. This feedback can be initiated by occupants, typically only when they are uncomfortable, or scheduled. Scheduled surveys can be intrusive (unable to be dismissed until complete) or non-intrusive (can be closed without completing).
b) Allows a researcher or building operator to pervasively issue the same survey form to occupant's computer screens, allowing a time synchronised sample of comfort to be taken from all occupants who participate.
c) Gives occupants a graphical indicator about the status of the HVAC system operational mode by changing the colour of a tray icon and showing popup notifications when important state transitions occur (see Fig. 2). Recognised modes include HVAC