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Impact of adaptive comfort criteria and heat waves on optimal building thermal mass control

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Abstract

This article investigates building thermal mass control of commercial buildings to reduce utility costs with a particular emphasis on the individual impacts of both adaptive comfort criteria and of heat waves. Recent changes in international standards on thermal comfort for indoor environments allow for adaptation to the weather development as manifested in comfort criteria prEN 15251.2005 and NPR-CR 1752.2005 relative to the non-adaptive comfort criterion ISO 7730.2003. Furthermore, since extreme weather patterns tend to occur more frequently, even in moderate climate zones, it is of interest how a building's passive thermal storage inventory responds to prolonged heat waves. The individual and compounded effects of adaptive comfort criteria and heat waves on the conventional and optimal operation of a prototypical office building are investigated for the particularly hot month of August 2003 in Freiburg, Germany. It is found that operating commercial buildings using adaptive comfort criteria strongly reduces total cooling loads and associated building systems energy consumption under conventional and building thermal mass control. In the case of conventional control, total operating cost reductions follow the cooling loads reductions closely. Conversely, the use of adaptive comfort criteria under optimal building thermal mass control leads to both lower and slightly higher absolute operating costs compared to the optimal costs for the non-adaptive ISO 7730. While heat waves strongly affect the peak cooling loads under both conventional and optimal building thermal mass control, total cooling loads, building energy consumption and costs are only weakly affected for both control modes. Passive cooling under cost-optimal control, while achieving significant total cost reductions of up to 13%, is associated with total energy penalties on the order of 1–3% relative to conventional nighttime setup control. Thus, building thermal mass control defends its cost saving potential under optimal control in the presence of adaptive comfort criteria and heat waves.

Keywords: Low-energy office buildings; Thermal comfort; Adaptive comfort models; Cooling energy; Thermal mass control; Night ventilation; Weather data analysis; Heat waves

1. Introduction

Cooling of commercial buildings during hot summer periods places a considerable peak demand on an electrical utility grid; electrical demand and time-of-use (TOU) utility rates are designed to encourage shifting of electrical loads to off-peak hours. Typically on-peak hours are enforced during business working days, and off-peak hours at night and on weekends. The standard building control strategy, termed nighttime setup temperature control, operates the building temperature within a comfort range during occupancy; when the building is unoccupied the temperature setpoint is set to a high value and the space temperature is allowed to float. This control strategy ignores the thermal capacitance of the building structural mass that could be harnessed to reduce cooling-related operating costs because the building structural mass represents a passive building thermal storage inventory that can serve as a heat sink.

As an illustration, passive cooling has a long history in European architecture where the more moderate climate allows for the building itself to be harnessed as a thermal storage system with the opportunity to reduce the need for chilled water equipment. Current European building designs employ large areas of exposed building mass, solar control using actuated external shading devices, nighttime ventilation, and ground-coupled heat pumps.

The basic principle of building precooling is to run the chiller and air-handling equipment during off-peak hours to charge the thermal mass and to use air-side free cooling to the extent available. During occupancy the optimal controller

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maintains temperature and/or humidity within specified ranges. Throughout the expensive on-peak period, the thermal mass is discharged to reduce mechanical cooling and thus electrical consumption and demand requirements. By setting building zone temperature setpoints in an appropriate (possibly optimal) fashion, the passive storage inventory is harnessed and the resultant thermal load shifting will help reduce costly on-peak electricity consumption and demand and thus reduce operating costs. Furthermore, building thermal storage inventory for both heating and cooling will gain importance as it offers the possibility to more strongly utilize uncontrolled renewable energy sources such as wind and solar.

The purpose of this article is to evaluate the potential of optimal control for passive thermal energy storage to reduce utility costs with a particular emphasis on the impacts of comfort criteria and heat waves. Recent changes in pertinent international standards on thermal comfort for indoor environments allow for some adaptation to the weather development, i.e., they account for the human's ability to adapt to persistently hot or persistently cold weather periods. Changes in allowable temperature limits for the indoor environment will thus affect the energy consumed to operate the building energy systems under both conventional (nighttime setup) and optimal precooling operating strategies. Moreover, extreme weather patterns tend to occur more frequently even in moderate climate zones [23]. This article will assess the individual and compounded effects of adaptive comfort criteria and heat waves on the conventional and optimal operation of a prototypical office building for the particularly hot month of August 2003 in Freiburg, a city located in southwest Germany.

2. Methodology

To investigate the impact of adaptive comfort criteria and weather pattern stability (summer heat waves) on building thermal mass control, we adopted the following methodology:

(1) Selection of a representative low-energy office *building model* with respect to the building structure, HVAC systems, and building utilization (low internal gains and external shading devices).
(2) Selection of *weather data* that contain sufficiently extreme features both in terms of average temperature as well as the occurrence of multi-day heat waves. Two distinct data sets, one with and one without heat waves, are generated from this weather data file.
(3) Calibration of the building model with *measured data from an actual building*, the Fraunhofer Institute for Solar Energy Systems located in Freiburg, Germany, to investigate whether the building adopted for this study is suitable for the application of adaptive comfort criteria. The purpose of this comparison is confirm whether the building model adopted behaves similarly to an actual passively cooled building. Moreover, we adopted the rationale that a building that would be considered suitable for passive cooling would also be considered suitable for adaptive comfort criteria when actively conditioned.
(4) Selection of three *comfort criteria*: ISO 7730.2003 as the internationally accepted (non-adaptive) standard on thermal comfort; prEN 15251.2005 and NPR-CR 1752.2005 as two adaptive thermal comfort criteria.
(5) Conducting *monthly simulation runs* for both conventional nighttime setup control as the reference case and optimal building thermal mass control for the selected two weather data sets and three comfort criteria.
(6) The *evaluation of the results* is conducted by means of a monthly energy cost analysis utilizing a dynamic building energy simulation program coupled to a popular technical computing environment. Quantitative comparisons will be presented for the conventional strategy (nighttime setup control) as the reference strategy and the cost-optimal building thermal mass precooling strategy.
(7) Deriving *general conclusions* from the individual results.

3. Review of building thermal mass control

3.1. Modeling results

Several simulation studies have shown that proper precooling and discharge of building thermal storage inventory can attain considerable reductions of operating costs in buildings. These savings result from both utility rate incentives (time-of-use and demand charges) and improvements in operating efficiency due to nighttime free cooling and improved chiller performance (lower ambient temperatures and more even loading). Ranges of 10–50% in energy cost savings and 10–35% in peak power reductions over night setup control were documented in a comprehensive simulation study [1]. The savings were highest when cool ambient temperatures allowed for free cooling. Other modeling studies yielded similar results [2–6]. Common to these simulation studies is that the level of savings and the superior control strategy strongly depend on the investigated HVAC system and on the climate. For the references cited in this section, peak energy cost savings for cooling were 10–30%, whereas maximum HVAC electrical demand was reduced by as much as 40% depending on the optimization cost function. Yet, improper application of precooling could actually result in costs that exceed those associated with conventional control.

3.2. Experimental results

A few controlled laboratory experiments have been conducted to demonstrate load shifting and peak reduction potential associated with the use of building thermal mass. An experimental facility at the National Institute of Standards and Technology (NIST) was used to study the use of building thermal mass to shift cooling loads [7]. Several heuristic strategies were evaluated in the facility that was designed to represent a zone in a small commercial office building and configured as an interior zone without ambient coupling. Compared to night setup control, peak cooling demand was lowered by up to 15%.

A more recent set of experiments performed at NIST validated the potential for load shifting and peak cooling load reduction associated with optimal control [8]. Here, a model of