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Adaptive control strategies for single room heating

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ABSTRACT

Today advanced control techniques are used to reduce the energy demand of buildings. But often they provide higher temperatures than necessary, thus realizing less energy savings than possible. The scope of the adaptive control strategies for single room heating is the reduction of energy demand by adapting to the user's temperature demand profile. To create the demand profile, the user can provide feedback about his thermal comfort with a simple push button to the system. The system calculates a usage profile for every single room and controls the room temperature according to this usage profile. This adaptation requires no more feedback than a thermostatic valve, a necessary condition to keep the system useful for all levels of society.

This paper describes the simulative tests of this system. First simulative results show that an adaptation to the user's profile yields energy savings around 11% compared to a reference case. These energy savings do not come at the expense of the user's thermal comfort. Furthermore it can be shown that the algorithm works very user-friendly because it does not need any set-up or complex interaction besides pushing a button if in thermal discomfort.

1. Introduction

Room heating accounts for approximately a third of the European primary energy consumption. Therefore reducing the energy consumption of room heating can lead to high total energy savings. One option of reducing the energy demand would be optimizing the control strategies for room heating which comes at relatively low costs compared to other measures (e.g. retrofitting). The Institute for Energy Efficient Buildings and Indoor Climate (EBC) at the E.ON Energy Research Center of RWTH Aachen University[2] develops an adaptive control system for single room heating.

When talking about optimizing the heating system's controller, today's work often focuses on optimizing generation and distribution of heat. The works of Flórez and Barney [1,2] describe self-tuning controllers to ensure comfortable temperatures when the user enters an office and an on–off controller based on a prediction model to avoid over- and undershoots of the temperature when the user is present. Today model predictive control (MPC) is widely used as advanced control method to reduce energy demand. In comparison to a simple on–off controller or PID-controller they differ less from the reference setpoint and use less energy. MPC even allows to address uncertainties for example in occupancy or weather forecast. A major drawback is the need for an advanced model of the system under control [3–5].

Also different measures, for example adapting the heating curve, were tested. For this measure Kähler and Ohl [6] found reductions of approximately 12% in energy demand in a field test, though they provide no data if there was any influence on thermal comfort. In contrast Matthes et al. [7] concluded that there is only a minor reduction of energy demand and the risk of thermal discomfort. The research of Seifert [8] on the influence of different control measures on the saving potential of heating systems also concludes that the user behavior can influence the energy savings of an adapted heating curve.

All of the above systems assume, that the reference temperature in the room is the temperature which is necessary to supply. This must not be true as rooms may be unused but the reference temperature is still set to a high value.

A study conducted by Karjalainen [9] about the use of thermostats in Finnish homes showed that many people did not use their thermostats. Less than 20% of the respondents in this study used their thermostat more than once a week, about 60% did not use their thermostat at all, although these are very common in Finnish homes and offices. Instead of changing the thermostatic valve's setpoint, people adapted by a change of clothing or, if they were feeling

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[1] http://www.eonerc.rwth-aachen.de/aw/cms/website/zielgruppen/ shf/ebc/?lang=en.

[2] www.eonerc.rwth-aachen.de.

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uncomfortably hot, by opening the window [9]. With thermostatic valves being the most common used thermostat in Finnish home, the situation is comparable with the one in Germany.

Regarding regular changes in temperature setpoints, Lindén et al. [10] and Carlsson-Kanyama et al. [11] came to the same conclusion as [9]. Their studies were conducted in 600 households in Sweden and showed that only 38% of the people turned down room temperature at night. Reducing the temperature at day when absent was also uncommon though both of them did not give reason for that behavior. In another research by Carlsson-Kanyama and Lindén [12] it was stated that “the only way to regulate indoor temperature in many apartments is to adjust the heat by turning a knob on each radiator, and that was considered as a too laborious undertaking for daily adjustments”.

Because of the different heating systems used in Germany and the U.S. the study by Peffer et al. [13] is not directly comparable but with regards to the use of thermostats came to the similar conclusion that a temperature setback at night or when not present was uncommon.

Lowering the reference temperature can not only be done manually by the user but also automatically with a programmable thermostat, thus avoiding the need for turning temperatures down in every room. These programmable thermostats can be a centralized unit for a house or single devices for each room. While these systems take care of lowering the temperature when leaving and raising the temperature before return, they must be programmed on installation and should be adjusted to changes in behavior on a regular basis.

But as shown in Meier et al. [14] and Harris [15] these programmable thermostatic valves were often not properly set up, the set-up was not re-evaluated on a regular basis, or the scheduled heating was turned off and replaced by a constant value.

From the above one must conclude that especially in residential buildings the reference temperature is set higher than necessary at least for several hours per day. This results in higher energy consumption without any positive effect on thermal comfort. A system able to learn occupancy profiles without the need of being programmed could improve energy consumption. A lot of work has been done to create models for occupancy and vacancy in offices and buildings, for example in Wang et al. [16], Page et al. [17], Richardson et al. [18]; Dong et al. [19] proposed a method to predict occupancy and occupancy duration using different sensors. They used this information in a model predictive controller. But for a wide adoption in residential buildings the number of necessary sensors is not only probably too high (and thus too expensive) but also too complex.

The suggested method in this paper is to create temperature setpoint profiles just from the user feedback to the system. For an open plan office a system to create temperature profiles was described in Murakami et al. [20], though we focused on a system with a even simpler user interface, giving the occupant just the option to describe the temperature as “too cold” or “too warm”. With our simple interface we address the need for user-friendliness. As pointed out in [12,14,15] complex interfaces can be a stumbling block for adapting energy efficient behavior. Additionally we included a learning parameter in contrast to [20], where the temperature setpoint was reevaluated on a daily basis. As a result we create temperature profiles that save energy by automatically reducing the room temperature if the room is not occupied. Furthermore these profiles can be used as input for complex control-systems, e.g. the above mentioned MPC to further reduce energy demand of the building

The algorithms to provide a continuously self-learning system were tested in a thermo-hydraulic simulation programmed in Modelica. The results of these simulations are presented in this paper.

Table 1
Room occupancy, clothing factor and metabolic rate of the simulated user.

Time	Occupied room	Clothing factor (clo)	Metabolic rate (met)	Optimal temperature (°C)
00:00–07:00	Bedroom	3.1	0.8	18
07:00–07:30	Bathroom	1.0	0.8	26
07:30–11:00	Kitchen	1.0	1.0	23.5
08:30–11:00	Study	1.0	1.0	23.5
11:00–18:00	User absent			
18:00–20:00	Living–room	1.0	1.6	18
20:00–22:00	Living–room	1.0	1.0	23.5
22:00–23:00	Bedroom	1.0	1.0	23.5
23:00–00:00	Bedroom	3.1	0.8	18

2. Methodology

2.1. Simulation environment

The adaptation algorithm was tested in a thermo-hydraulic simulation, built in the physical equation based language Modelica. Besides the Modelica standard library, the EBC developed libraries for simulation of buildings and hydraulic networks were used. The simulated apartment consisted of five heated rooms (including bath and kitchen, the corridor was unheated) with a total floor area of about 70 m^2. The insulation of the building and the choice of components was done in accordance to “Wärmeschutzverordnung 1984” (German building requirements for new buildings). Every room had one outside wall. Heat exchange between the outside or adjacent rooms was modeled. We used an n-layered wall structure, where n is the number of different materials in use. Outside walls consisted of four layers, an inner and outer layer of finnery, a 17.5 cm brick wall and 6 cm of insulation. Inner walls consisted of three layers, they did not have insulation and used 15 cm bricks. The adjacent flats were not modeled, adiabatic boundary conditions were assumed. Outside conditions were modeled with the help of the Test Reference Year (TRY) of the “Deutsche Wetterdienst” (German Weather Service), region 12. In the TRY, temperatures, direct and diffuse solar radiation and wind speed are provided on a hourly basis [21]. Effects of solar radiation were included by use of a window model in the outside walls. The U-value of the windows was $U = 2.525$ W/(m^2 K) and the solar transmission factor $g = 0.8$. Air exchange was modeled according to DIN EN 12845.

An overview of the flat’s layout and the interactions with the surroundings is provided in Fig. 1.

2.2. General simulation setup

Reference and adaptive simulation were simulated for 40 days starting on January 1st. We simulated for 40 days to give the adaptive simulation algorithm enough time to learn the user’s behavior. The temperature setpoints of the reference case remained static while the one of the adaptive algorithm changed according to the user feedback. The user had a static daily routine, meaning that he left the house every day at the same time, used every day the same rooms at the same time and kept his clothing and activity factor the same every day. The corresponding data can be found in Table 1. This simplified user behavior makes it easier to focus on the general usability of the adaptive algorithm. For further research a more volatile user routine is necessary to present more external variations to the adaptive algorithm. Especially a more complex occupancy profile as proposed in [17,18] will be used.

2.3. Reference case

To evaluate the effects of the adaptive control strategy a reference case was defined as benchmark for thermal comfort as well