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Can HVAC really learn from users? A simulation-based study on the effectiveness of voting for comfort and energy use optimization

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ABSTRACT

The usage of Building Automation Systems (BAS) and Energy Management Systems (EMS) is indeed becoming ever more common and sophisticated, and seeking to promote energy savings by integrating new sources of data, such as user preferences, in real-time. This paper reviews the existing systems and proposes an innovation in HVAC systems management: a system that tracks the occupants' preferences, learns from them, and manages HVAC automatically. Our hypothesis was that by developing a learning system based on feedback acquired through the mobile devices of room occupants to optimize the control of a HVAC system, in order to minimize energy consumption while maximizing average user comfort.

A prototype solution is described and evaluated by simulation. We show that ambient intelligent systems can be used to control a building's EMS, effectively reducing energy consumption while maintaining acceptable comfort levels. Our results indicate that employing a k-means machine learning technique enables the automatic configuration of an HVAC system to reduce energy consumption while keeping the majority of occupants within acceptable comfort levels. The developed prototype provides occupants with feedback on ambient variables on a mobile user interface.

1. Introduction

IoT-enabled technology in Home Automation and Ambient Intelligence environments has been brought about by Wireless Sensor Networks to interconnect objects and thereby enabling the automatic acquisition and exchange of sensed data.

To fully exploit the potential of these networks of objects, the application of Artificial Intelligence (AI) approaches has been proposed to make Internet objects more intelligent (Arsenio et al., 2014; COSTA et al., 2015; HUI, SHERRATT, & SÁNCHEZ, 2017). This paper focuses on the use of AI strategies for a particular domain of IoT Application: a voting mechanism for a building's occupants, together with a machine learning approach for controlling a building's HVAC system which reduces energy consumption while keeping acceptable comfort levels.

Ideally, thermal comfort should be high, while the energy spent should be kept low. However, this does not hold for most of the time. It is well-known that higher comfort levels may require consumption of more energy. There is, of course, an unavoidable trade-off between energy consumption and occupant comfort. A poorly tuned system originates energy waste by consuming more energy than would be necessary, and simultaneously keeping users uncomfortable. However, a typical scenario is that of consuming too much energy while users would be willing to reduce their high comfort levels to an extent, due to eco-friendly concerns. Moreover, it has been demonstrated that occupants can tolerate more than the typical 2 °C variation allowed in commercial systems (ASHRAE, 2010). Also, paradoxically, occupants often complain about excessive heating in the winter, and cooling in the summer (Federspiel, Rodney, & Hannah, 2003; Gunay et al., 2017).

The issue, as addressed in this paper, becomes the estimation of the comfort level corresponding to the minimum energy that occupants are willing to accept. Hence, the proposed system addresses the optimization of the energy waste in the abovementioned energy-comfort trade-off, by allowing occupants to vote. This voting provides feedback to the system, which will operate based on a majority of votes. It therefore incentivizes user-participation in making buildings energy-efficient. Previous research also shows that users will feel happier if they can exert control over temperature settings (Karjalainen & Koistinen, 2007; Mansur, Carreira, & Arsenio, 2014).

Maximizing group occupant comfort from individual preferences is challenging due to the contradictory nature of preferences. Even if it is

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possible for occupants to change HVAC system settings, it may still be difficult to reach a consensus setpoint value so that every single occupant feels comfortable. Previous studies have focused mostly on enabling individual occupant comfort (Daum, Haldi, & Morel, 2002; Jazizadeh, Marin, & Becerik-Gerber, 2013). To date, there is no platform that maximizes comfort by collecting information on the occupants' preferences and (i) computes a setpoint which will control the temperature based on their feedback, (ii) encourages occupants to save energy by presenting them with information on the other occupants' votes, (iii) takes into account occupants preference history to improve decision-making, and (iv) makes automatic decisions to configure the HVAC subsystem automatically.

This article describes an approach that enables occupants of a given room to give their opinion on an HVAC system setpoint configuration optimizing for energy-comfort trade-offs. Specifically, the contributions of this study are the following:

- We propose a system that incorporates dynamic user feedback control loops to optimize the energy/comfort trade-off considering occupants' votes. Our proposal operates based on the majority of votes instead of reacting to individuals' votes.
- A machine-learning algorithm is proposed which calculates a temperature setpoint that best fits overall user suggestions and finds the most appropriate action to minimize energy consumption, while at the same time maximizing users' comfort.
- Simulation results validate that the algorithm is successful in automatically configuring an HVAC system to reduce energy consumption while keeping the majority of occupants within acceptable comfort levels.

The document is organized as follows: In the following section an analysis will be presented of previous approaches for adding intelligence to EMS for BAS. In Section 3 the proposed solution is described. Then, a simulation framework was implemented in order to experimentally test the solution, which is described in Section 4. The validation simulation is presented in Section 5. Following a critical discussion of the simulation results presented on Section 6, the main conclusions for this study and directions for future work are drawn in Section 7.

2. From building automation to building intelligence

2.1. Building automation systems

Heating, Ventilation, and Air Conditioning (HVAC) systems account for up to 60% of the total energy consumption of commercial buildings (Yang & Wang, 2013). In modern buildings, HVAC system settings are configured centrally in the management console of the Building Automation System (BAS). Despite BASs aim at saving energy while maintaining occupant comfort (Soucek & Zucker, 2012), HVAC settings are only reviewed seasonally to account for significant climate and occupancy variations. Indeed, settings are not adjusted in real-time to take into account fast dynamics of occupant preferences, leading to overcooling or overheating. In practice, since occupants cannot control the HVAC thermal settings, they may experience discomfort while the system is probably cooling or heating above what is required and consequently wasting energy. If occupants were given the opportunity to control the system, situations of excessive service delivery which consumes energy, would be less frequent.

Energy management systems (EMS) are concerned with finding sources of waste and acting to improve energy savings. EMSs corrective action also typically targets HVAC systems to reduce energy waste. However, if occupants are not in the loop, these improvements are under optimal. An intelligent climate control solution that takes into account occupant opinions regarding comfort is potentially capable of minimizing the energy consumption while maintaining the occupants' comfort. There is evidence that ventilation on demand allows up to 70% of energy saving (Hesse, Gardner, & Göpel, 2001). Studies also show that the use of occupancy detection techniques with light and HVAC systems is beneficial to energy optimization, reaching savings values from 10% up to 50% (Boman & Davidsson, 1998; Klein et al., 2012; Padmanabh et al., 2009).

2.2. Intelligent energy saving approaches

BAS and EMS can have a greater impact if occupants are in the loop and an intelligent climate control solution takes into account occupancy detection and occupant opinions regarding comfort. This section overviews different AI technologies that can be used to improve BAS with increased intelligence.

2.2.1. Multi-agent systems (MAS)

MASs are equipped with logical, intelligent agents with the purpose of solving problems that are difficult for individual agents to solve. In the specific case of building control, these agents coordinate lighting control and HVAC as efficiently as possible.

The *Multi-Agent System for Building Control (MASBO)* (Qiao, Liu, & Guy, 2006) (Booy, Liu, Qiao, & Guy, 2008) records the personal preferences of each user through wireless sensors. The Multi-Agent Comfort and Energy System (MACES) uses a multi-agent approach to control the HVAC system according to two strategies: reactive, automatically adjusting itself according to real-time occupancy; and predictive, predicting the occupancy (Klein et al., 2012). The *Intelligent Services for Energy-Efficient Design and Life Cycle Simulation (ISES)* project showed evidence that a multi-agent system controller can reduce energy consumption by 40% while keeping occupants' satisfaction at similar values to traditional control methods (Boman & Davidsson, 1998; Davidsson & Boman, 2000, 2005). It employs temperature, light and active badge sensors (to identify people in each room) for occupancy detection, using four types of agents: (i) Personal Comfort Agents, responsible for storing the personal preferences; (ii) Room Agents, for controlling particular a room's light and HVAC system; (iii) Environmental Parameter Agents, for monitoring and acting on a particular environmental parameter in a room; and (iv) Badge System Agents, responsible for tracking the occupants' position in the building and storing it in a database.

2.2.2. Adaptive control-based systems

Adaptive Control Systems adapt a controlled system in real-time, by means of parameter estimation. An Adaptive Control system can be a control system that adjusts the HVAC temperature based on occupants' preferences, which vary over time.

Adaptive Control of Home Environments (ACHE) uses a neural network to learn how to control the lighting, HVAC and water heating systems of a house (Mozer, 1998; Mozer, 2005). This project was developed with two goals in mind: to foresee the inhabitants' needs, and to ensure energy savings. The system learns the users' comfort patterns by analysing the manual adjustments (learns from user-triggered events). Another AI system (Sierra et al., 2008) also uses a neural network for minimizing energy consumption while, simultaneously, maximizing user comfort. Occupants can adjust the temperature and humidity settings on input panels located in various rooms throughout the building. The system tries to reduce energy consumption by acting upon the occupants' preferences. This action implies applying energy-saving rules that best match the occupants' needs.

2.2.3. Fuzzy logic based control

Fuzzy control systems are logic systems that provide effective means of capturing or approximate the inexact nature of the real world, employed whenever the sources of information are interpreted qualitatively, imprecisely or with uncertainty.

The iDorm project (Doctor, Hagras, & Callaghan, 2005; Hagras