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Evaluating the potential of simulation assisted energy management systems: A case for electrical heating optimisation

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ABSTRACT

Buildings consume a significant amount of energy worldwide in maintaining comfort for occupants. Building energy management systems (BEMS) are employed to ensure that the energy consumed is used efficiently. However these systems often do not adequately perform in minimising energy use. This is due to a number of reasons, including poor configuration or a lack of information such as being able to anticipate changes in weather conditions. We are now at the stage that building behaviour can be simulated, whereby computer programs can be used to predict building conditions, and therefore enable buildings to use energy more efficiently, when integrated with BEMS (i.e. simulation assisted control [1]). In this paper we demonstrate a low cost BEMS that uses building simulation to predict optimised electrical heating startup control points. Those that use electricity for heating in Scotland, where this study was based, tend to be fuel-poor, hence there is a strong case for optimisation, particularly when electricity costs nearly three times as much as the equivalent unit of gas for heating applications. The proposed system demonstrated a 50% energy saving in the reduced heating time compared to scheduling when retrospectively evaluated.

1. Introduction

Buildings account for 40% of energy consumption worldwide and 30% of global carbon emissions [2]. As the population expands, this statistic is set to rise. A significant amount of the energy required in a building, is used to maintain a comfortable environment for the occupants. If the control of that energy is used inefficiently, it can lead to 'sick' buildings.

It is estimated that nearly 90% of buildings unfortunately have inapplicable or ineffective controls [3], but if they were to be rectified, there could be energy savings up to an additional 20% [4]. This is clearly a worrying statistic, and if it is addressed there is great potential to save significant amounts of energy worldwide.

Building controls have now evolved considerably into integrated building energy management systems (BEMS), which are dedicated systems installed to manage building services and energy consumption, whilst maximising comfort for occupants. Though BEMS are reserved for larger buildings, smart home systems for residential settings are now becoming common-place (e.g. Google Home). In this paper, the term *energy management system* is sometimes used interchangeably for BEMS and smart home systems.

Energy management systems are based on fixed rule sets which means they have to be adapted throughout the year, leading to a maintenance overhead. Furthermore, there are a multitude of factors to consider such as the time of day, the location of zones and occupancy profile which would contribute to internal heat gains [5]. Inappropriate selection of the parameters of the control strategies can cause both local and supervisory control loops to oscillate [5]. However building simulators and emulators can provide an efficient method of testing control strategies and software during the development and commissioning stages. For example, dynamic simulation tools can be used to test a control algorithm at difficult operating conditions (such as extreme thresholds) [5].

Taking this a step further, recent studies have been investigating the use of simulation assisted control (SAC), whereby simulation output is used directly in the control core of BEMS [6]. Consequently, such innovations are required more than ever, as fuel poverty is becoming an increasing problem, even for well developed countries such as Scotland.

1.1. Fuel poverty

Fuel poverty is defined in Scotland if a household is required to spend more than 10% of its income in order to maintain a satisfactory heating regime. If a household is spending more than 20% of its income on heating it is in extreme fuel poverty [7]. At present,

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54% of households in Scotland that use electricity for their heating are in fuel poverty [7]. Not only that, these homes are also in the lowest efficiency bands [8]. Furthermore a satisfactory heating regime is defined in [8] as 21 °C in the living room and 18 °C in all other rooms for 9 hours a day during the week and 16 hours a day during the weekend. This currently equates to a significant 74% of energy spend in an average household to satisfy this regime [8]. Much can be done therefore to improve this. The Scottish government have further recognised that energy saving technologies should be used in the development of the latest fuel poverty strategy -*'The new fuel poverty strategy should acknowledge and address a fourth driver of fuel poverty which is how people use energy in their homes'* [9]. In [9] it was also recognised that though most households in Scotland report actively using heating controls, other research had identified [10] that many people find heating controls hard to use, are confused about the different controls, and are uncertain over how to best use the timings and settings. With regards to timing and efficiency there is therefore scope to make use of technologies such as building simulation to help inform decisions for heat settings (such as optimum start setpoints).

1.2. Building simulation

Using building simulation early in the building design process, can have a substantial impact on the building performance [11]. Building simulation software permit a wide range of physical attributes to be applied in a building model and analysed, such as thermal loads (e.g. TRNSYS) and lighting luminance (e.g. Radiance). They can take into account the full spectrum of building losses and gains, from the internal and external environment.

Generally losses are through the fabric of the building. However energy gains in a building can be from lighting, equipment, occupancy, windows (solar radiation) and heating. Losses are generally transmitted through windows, walls, ceilings, floors, roofs, doors, infiltration and ventilation. These are all parametric inputs in a building simulator.

Building simulators can be used to test out various occupancy profiles and usage scenarios that could occur in building, with respect to energy use and balances. For the case of efficient use of heating, there are opportunities to predict control strategies and integrate them into the control core of an energy management system. Consideration of the building form, via building simulation can further take into account internal and environmental factors, and thus aid in the decision making process of maintaining a stable energy efficient heating regime.

1.3. Objectives

This study explores the benefits of a low power computing implementation of a simulated assisted energy management system for houses that use electrical heating. Though electricity is not the dominant energy demand, the electrification of space and water heating has also recently started to gain traction as a strong option for achieving a low carbon buildings sector [12]. Note in Scotland, and in the rest of the UK, heating forms the major demand, where there is minimal cooling requirement for the domestic scenario. The exploration will evaluate the potential for savings in a test house developed for the purpose of energy efficiency optimisation through the use of smart technologies. The structure of the paper is as follows. Section 2 provides the background to the work. Section 3 discusses the experiment setup, Section 4 elaborates on the results and Section 5 concludes the paper.

2. Background

In the UK, much has been done to improve insulation characteristics of houses, with millions of homes having insulation upgraded (cavity walls and loft) as part of low carbon framework for significant reductions in energy by 2020 [13].

However there has been a lack of research to address heating systems, in terms of improving control strategies, that take into account environmental factors and conditions, though there has been a growing trend in internet connected 'smart' heating control devices that give occupants more options for control and 'learn' how they use it. These do little more than guess schedules such as the Nest learning thermostat [14], after a period of learning how occupants set temperatures throughout the day. Other examples of smart heating control devices, include the Tado [15], which guesses arrival times based on GPS coordinates, and the British Gas Hive system [16]. These systems rely on understanding human behaviour in an attempt to better control heating beyond predefined rules, which are commonly used to schedule heating. Energy management systems are often programmed with static rule based schedules, which are not optimised to react to changes in a building's use, which can often be dynamic (e.g. occupancy variation, change in climate).

A better method would be to employ a predictive control strategy that can supersede traditional rules based systems. There are two main techniques for predictive control in buildings that are currently being researched to improve control in building energy management systems. These are model predictive control (MPC) and simulation assisted control (SAC). Both techniques rely on being able to accurately forecast conditions based on various environmental factors, though can differ in their approaches, and some literature occasionally describe them as being essentially the same due to the fact they both use models for prediction. Mahdavi was one the first proponents of SAC identifying it as a separate method altogether, claiming *'This concept, which should not be confused with model-predictive control, involves the incorporation of explicit numeric performance simulation in the control core of buildings' environmental systems'* [17]. To further this point, MPC requires modelling of the building derived from first order principles or system identification. This requires model training; for example neural networks can be used for this purpose as black box models. Once the model is trained, it is a simplified, though highly focused, representation of the building control systems, rather than a representation of the complete building. The introduction of another parameter into the model, would require further retraining. On the other hand SAC utilises a full building model, allowing more diverse use cases to be applied and other control strategies to be explored, without having to go through a process of training and data collection for model verification. A lack of information in a building model may require model calibration to fit parameters, similarly to the MPC method, however this may lead to an incorrect physical model representation. For the case of smaller buildings, such as houses, the knowledge-based SAC approach can be viewed as more desirable, as they do not have complex HVAC systems that MPC data-driven methods often seek to optimise. Examples of approaches which are highly focused on optimum HVAC control, were performed by [18,19] and [20]. There is as yet no studies for SAC in smaller buildings such as houses, which this paper addresses.

2.1. Simulation assisted control

Whereas MPC techniques use a black or grey box method to modelling, simulation assisted control takes the white box method or physical model approach and requires a full building model and a validated building simulator such as ESP-r.