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Re-examination of external temperature as a predictor of energy usage in buildings

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ABSTRACT

The importance of reducing energy usage in buildings is difficult to overstate. A large part of the research interest in energy reduction focuses on the ability to accurately forecast consumption. The practise of using different forms of statistical models to achieve accurate forecasts is well established, both as an operational guide but also to accurately estimate savings following an efficiency programme. Within the range of these models, the most common form is that of regression and the simplest of these often establishes a relationship between the single predictor of external temperature and energy usage. Where an external temperature index is used in regression, the most common form is that of daily average temperature. Given the unique nature of commercial buildings, this paper seeks to examine the nature of a building's thermal response to local external temperature and examine how this parameter might influence a simple statistical model's energy prediction accuracy. Examination of three different large commercial buildings has shown that the application of daily average temperature may not provide the most accurate predictor. At a whole building level, a method has been devised to find the most influential range of external temperatures affecting energy usage.

1. Introduction

It has been estimated that 40% of total energy usage is expended by buildings in the EU and the US with approximately 50% of this attributable to commercial buildings. Estimates would suggest that within the commercial building sector, 50% of energy usage is being expended by heating, ventilation and air-conditioning (HVAC) plant [1] and this would imply that the scale and use of this plant in commercial buildings accounts for over 10% of all energy usage in the EU and US. The International Energy Agency [2] has shown that the level of energy usage in the commercial buildings sector is increasing year on year.

Throughout the world, but particularly in developed countries, commercial buildings with artificial internal environments have become the norm, even in locations where a temperate external environment exists, such as in many parts of Western Europe and the US. These buildings have been designed to ensure a comfortable environment for occupants and that environment is commonly delivered by HVAC plant. The control of that plant is often performed by a Building Management System (BMS). Understanding where this energy is used and how it might be better controlled has become an imperative.

The ability to accurately forecast energy consumption in commercial buildings has been an active research topic for some time. Given the frequent paucity of data available from buildings, the ability to glean useful energy forecasts from the very small datasets has become of interest. The value of building energy forecasting has been expounded upon many times [3–5].

The principal driver behind the use of energy by HVAC plant in commercial buildings is the provision of occupant comfort. Indeed, the design and sizing of HVAC plant is dictated mainly by the occupant comfort standards and their recommendations. Two comfort models are widely used within these standards, namely heat balance [6] and adaptive [7]. In this paper, the adaptive model is relevant since it relates occupant comfort directly and solely with external temperature and, given the nature of HVAC energy use in providing this comfort, the external temperature is of particular interest.

In forecasting energy use in buildings, data can be available from many sources. Historically, monthly utility bills have provided researchers with energy usage information and this data was frequently used in conjunction with the average external monthly temperature available from the national weather service [8,9]. As 15 or 30 min interval energy usage data became available, the analysis methods used to forecast quickly advanced from regression models to time series analysis [10] to methods such as neural networks [11] and other expert systems.

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There is a common trend among these methods in comparing the actual energy usage with the equivalent prediction parameter (s) over a particular period. These parameters might include external weather factors (such as temperature, humidity and solar radiation), but in some cases, analyses have been completed using other internal environmental factors such as space temperatures or flow temperature from boilers or chillers.

It has been shown that external temperature is by far the most important predictor of energy consumption in commercial buildings [9,12–14] and the most common forms of that predictor appears to be the average daily or average hourly temperature. This average is readily available from the national weather service making it simple to source even though it is not usually recorded locally at the building in question. Given the unique nature of energy usage and the external façade of commercial buildings and the plant that operates within them, questions have arisen as to the simple determination of how buildings respond uniquely to external temperature and why their energy usage should consistently depend upon the average daily external temperature.

The objective of this paper is to re-examine the external temperature predictor in light of the uniqueness of these buildings and their individual responses to thermal stimuli. A second objective is to examine the influence this unique relationship between external temperature and the building has on the ability to more accurately forecast energy consumption using simple prediction models. To deliver on these objectives, a pilot building, P1, was chosen to establish the principle along with two test buildings, T1 and T2 to test the rigour of the method. All data from these buildings has been recorded on a 15-minute interval basis which is in keeping with measurements taken by most building management systems (BMS).

In this study, for comparisons drawn between various single predictor regression models and given the energy data is constant across the various models, the coefficient of determination (R-Sq), the root mean square error (RMSE) and amount of variation of this error or the coefficient of variation of RMSE (CV(RMSE)) have been calculated and compared. The mean square error is equal to the model variance for single regression models.

2. Pilot building

P1 is a medium sized single-tenant office building located in Western Europe in a temperate climate. The building comprises six floors over a basement car-park and contains approximately 11,000 m² of usable space. The building is of concrete construction built with columns and cast in-situ flooring slabs. P1 operates as a mixed-mode building with operable glazing.

2.1. Pilot building behaviour

Every building is likely to respond uniquely to changes in external temperature. When a commercial building is at rest, that is, with no mechanical heating or cooling, no occupant activity or solar gain, there are still small and well distributed heat sources present. For example, lighting and office equipment often run at times when the building is not operational. The pilot building (P1) chosen for this study met the eligibility requirements of (a) centrally controllable plant, (b) the presence of a fully functional BMS and (c) a willingness of behalf of the building operators to allow limited experimentation while preserving occupant comfort temperatures during occupied hours. While at rest, an examination of the P1 internal and external temperature profiles shows internal space temperature responding to the external temperature but with a delay or lag (see Fig. 1). The internal temperature profile approximately follows the external temperature profile with a delay of several hours, but not precisely. Fig. 1 also shows that the scale of change of the internal temperature is only a fraction of the scale of change of the external temperature. In this work, this delay will be referred to as the Natural Thermal Lag or NTL. The NTL is a building-wide parameter which takes account of the general construction features and flaws of the building in question. Care must be taken in deciding on the measurement point for the internal temperature. In this case, an open plan area on an intermediate floor, not directly exposed to solar gain and serving up to 20 occupants was chosen as a representative internal space.

The at rest internal temperature in the figure is seen to rise slightly during the day, despite no mechanical heat or cooling being supplied, in response to the rise in external temperature. The relationship between external and internal temperatures is not causal in real-time; there is a natural lag which can vary from building to building. This lag is assumed to depend on many factors including the building's envelope, permeability and the difference between external and internal temperatures, ΔT, amongst others. It is expected that during winter, given the larger ΔT, losses from a building would be at a faster rate and, therefore, would exhibit a lower NTL.

Examining the graph in the figure, the reaction of the internal space temperature to changes in external temperature can be estimated at approximately eighteen 15-minute periods or about 4.5hours. Based on practical experience, the measurement interval of 15 minutes was chosen as this interval is the most common used by the BMS in commercial buildings. Given the small amount of heat being provided to P1 during the weekends, the rise in internal temperature could be due to a slowing down of heat losses from P1, due to a rising external temperature, resulting in small internal gains. The external temperature data in Fig. 1 was locally recorded on the roof of P1 by a weather station installed for the purpose of this study.

Given the importance of ΔT in overall heat loss or gain to P1, and the suggested variation in lag due to ΔT, it will be shown presently that for P1, the NTL will vary with ΔT.

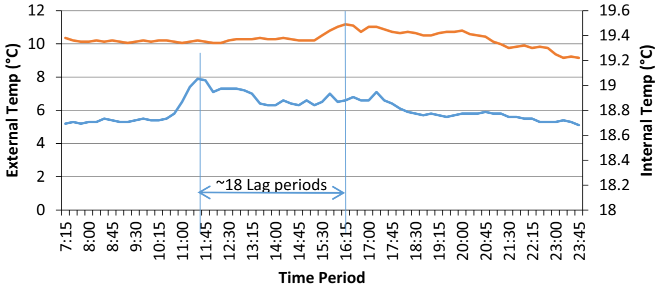

Fig. 1. P1 Internal (red) and external (blue) temperature profiles 31st March 2013. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)