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Mixed methods approach to determine occupants' behaviour – Analysis of two case studies

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ABSTRACT

Research has shown the large effect that occupants have on buildings' performance. Uncertainties related to the actual energy consumption of buildings increase the risks for the investments in low carbon technologies. Monitoring building occupancy can potentially decrease these uncertainties by providing more information about the occupants and their behaviour. The objective of the investigation is to establish an approach to inform the design process (e.g. building simulation) by addressing the complexity of occupants behaviour. The approach integrates information on occupants' behaviour and attitudes regarding energy use and indoor conditions to determine the requirements for building simulation and energy calculations. This paper presents the results of two monitoring campaigns in which the approach was employed. The monitoring campaigns focused on two owner-inhabited apartments in Spain and three social rental dwellings in The Netherlands. The results have given first insights of the power of the methodology to obtain detailed and understandable data on the occupancy patterns. This investigation highlighted the importance socio-economical status and attitudes towards energy conservation on occupants' behaviour in residential buildings. The methods described in this paper can be readily used to develop occupancy and heating profiles for monitored households to be used in building simulation programs.

1. Introduction

Building research in recent years has shown differences between the actual and expected energy performance of buildings [1–5]. Some of these differences have been attributed to the effect of occupants' behaviour [6]. There are several ways in which occupants influence the performance of buildings, but they can be categorised into two main well documented effects: the rebound effect [7] and the pre-bound effect [8]. In the context of energy consumption in buildings, the rebound effect relates to occupants using more energy than expected after (and as a consequence of) the implementation of low carbon technologies. On the other side, the pre-bound effect refers to occupants using less energy than expected, usually as a consequence of assuming an average behaviour or household size. While the rebound effect is thus, a consequence of the interaction between people and buildings, and the (lack of) feedback to the user, the pre-bound effect is a consequence of the wide differences between household types and occupants' preferences, attitudes and lifestyles. Both effects have consequences on the financing and payback periods of low carbon technologies. Uncertainties in the actual energy consumption of buildings (and thus, on the actual energy savings) increase the risks for the investment in the technologies. Monitoring building occupancy and performance can potentially decrease the risk of both types of effects by providing more information about the occupants and their behaviour (reference modelling), and by providing occupants with the necessary feedback to decrease their energy consumption (reference behaviour). For example, post-occupancy studies aim at evaluating the performance of new or renovated buildings. The monitoring process can highlight problematic issues regarding indoor environmental quality or energy consumption, and can indicate strategies for improvements [9].

In this research, we focus on the pre-bound effect. As mentioned before, pre-bound effects are found when the actual energy consumption is lower than expected, as consequence of considering average households or behaviour during the design phase of the building. Previous research has shown the uncertainties of building simulations related to the assumptions made about the building operation and internal heat gains both in new and renovated buildings [10]. Occupancy monitoring in this regard, aims to

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provide relevant information to support accurate building simulations, therefore improving the energy calculations and the sizing of installations.

The objective of the investigation is to apply an approach to inform the design process of renovation projects by addressing the complexity of occupants behaviour. The approach integrates information on occupants' behaviour and attitudes regarding energy use and indoor conditions to inform the design process of specific projects. Therefore this investigation does not seek to generalise the results from the monitoring campaigns, but to highlight the relationships between occupants' behaviour, socio-economical characteristics of the users, and thermal comfort preferences. This paper presents the results of two monitoring campaigns in which the approach was employed.

2. Literature study

A large number of studies have aimed at understanding occupants behaviour in buildings. Monitoring building occupancy allows the investigation of three different aspects influencing building performance: occupants' behaviour, occupants' requirements (related to household composition and lifestyle), and occupants' attitudes towards sustainability. Previous research has documented the effect of these aspects in energy consumption [11].

Occupants' characteristics, such as household composition and socio-economical situation have a large effect on energy consumption [12,13]. Household characteristics are important for heating demand because they determine the presence of people at home and comfort preferences, while socio-economical variables such as income, background, education level and employment can influence the attitudes of households towards energy conservation [14–17]. For example, Kane et al. [18] found that heating patterns vary depending on occupants' age and employment status. Households over 60 years old or unable to work turned the heating on earlier in the year, heated longer each day and to higher temperatures in comparison to younger households and those in employment. In a different study, Yohannis et al. [12] found that households over 65 years old are usually at home during daytime hours and have a low overnight electricity consumption; young householders (<40) tend to have active evenings but low daytime consumption; and middle age households (50–65) usually with children at home, larger homes and broader range of appliances, have higher electricity consumption in the evenings.

The integration of occupants' behaviour into building simulations is often based on assumptions rather than measured observations. Therefore, according to Virote & Neves-Silva [10], simulation tools provide a poor instrument to predict the outcome of energy efficiency measures in a building. In order to decrease the uncertainty related to occupancy in buildings, occupants' behaviour can be represented as standardized diversity factors and schedules, taking into account the relation between occupants and buildings [10,19]. Diversity profiles represent typical preference probability profiles, which are derived from long-term monitored data in different classes of buildings [19]. According to D'Oca and Hong [20], extrapolation of patterns from big data streams is a powerful analysis technique.

Table 1 shows a selection of recent building monitoring studies that are relevant for this research. From these literature studies, few papers include heating patterns, while occupancy patterns (presence of people) are a common topic in investigation of office buildings. In contrast, studies on domestic buildings often focus on metering electricity and building electricity load profiles. Within the studies to determine occupancy profiles, two main types can be distinguished: 1) determination of deterministic occupancy patterns, and 2) development of predictive models of occupancy.

2.1. Development of deterministic occupancy patterns (non-predictive)

Within this topic, most studies aim at defining occupancy patterns (meaning the presence of occupants in the building). Mahdavi & Tahmasebi [19] evaluated a number of occupancy models to explore the potential of monitored historical occupancy data to predict future occupancy. They compared the results of two previously published probabilistic models (see below) and one simple original non-probabilistic model that also relied on past observation-based data to generate daily Boolean patterns of people's presence in buildings. In a different study, D'Oca and Hong [20] applied a three-step data mining framework to discover occupancy patterns in office spaces based on a monitoring campaign. Duarte et al. [21] analysed long term occupancy sensor data on an office building and developed deterministic occupancy diversity factors for different areas in the building.

2.2. Development of predictive models of occupancy

Other monitoring studies have focused on the development of stochastic occupancy profiles. These approaches make use of mathematical models such as Markov-chains or artificial neural networks [10,22,23]. Diversity profiles, generated by these models, represent typical preference probability profiles and are derived from long term monitored data. The probabilistic models generate random non-repeating daily profiles of occupancy for a long-term (annual) building performance simulation [19]. Prediction models aim to generate artificial occupancy patterns that are similar to the actual (measured) patterns. Thus, the patterns should be in theory only applied to buildings with the same activities, same geographic area and people with same cultural background [10].

In the present research, we use a pragmatic approach to define deterministic occupancy and heating profiles based on post-occupancy monitoring. Occupancy profiles based on statistical data have been previously developed to understand trends in heating use in Dutch residential buildings [24]. However, socio-economical variables and households' attitudes have been found to have an effect on energy use and behaviour. Therefore, developing occupancy and heating profiles based on monitoring data could highlight patterns that cannot be seen in the average population, since more in-depth household information is available. Thus, we aim at determining occupancy profiles that are specific for a case study, neighbourhood or type of occupant, taking into account socio-economic variables.

3. Data analysis framework

This section introduces the cases studies, research approach, data collection method, and data analysis methods.

3.1. Case studies

Two monitoring campaigns were carried out following different monitoring setups. The first monitoring campaign (Summer 2014-Summer 2015) involved two single residential apartments located in Madrid, Spain. The second campaign involved three single-family dwellings located in Rotterdam, The Netherlands during the winter of 2014–2015. Fig. 1 shows images of the buildings. It is important to notice that both campaigns were part of collaborative studies between projects or institutes and therefore, different data collection methods were utilised depending on their availability per location.

The apartments in Madrid were located in two different buildings within the same neighbourhood. One building has been