Energy and Buildings 119 (2016) 293–308

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

# Predicting and characterizing indoor temperatures in residential buildings: Results from a monitoring campaign in Northern Portugal

Sara M.C. Magalhães [a,*], Vítor M.S. Leal [b], Isabel M. Horta [c]

[a] Institute of Science and Innovation in Mechanical and Industrial Engineering, Faculty of Engineering of University of Porto, Rua Dr. Roberto Farias, 4200-465 Porto, Portugal
[b] Department of Mechanical Engineering, Faculty of Engineering of University of Porto, Rua Dr. Roberto Farias, 4200-465 Porto, Portugal
[c] Department of Industrial Management and Engineering, Faculty of Engineering of University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

*Article history:*
Received 6 April 2015
Received in revised form 4 March 2016
Accepted 25 March 2016
Available online 26 March 2016

*Keywords:*
Indoor temperatures
Residential building
Cold homes
Rebound effect
Prediction models

ABSTRACT

Empirical data for residential indoor temperature and its determinants have important implications for policymakers in terms of the assessment of thermal comfort, health of occupants and the use for supporting energy demand models. With the purpose of advancing this knowledge, the indoor temperatures of 141 households in the Northern Portugal were measured at a half-hourly basis during the winter of 2013–2014. The observed mean winter daily indoor temperature at the occupied period was 14.9 °C for the bedrooms and 16.6 °C for the living rooms. The results show that indoor temperatures are significantly below the comfort levels generally accepted, which could be an indication of future potential rebound effects. Results also reinforce the idea that 'cold homes' during winter season are a reality even in the southern European countries.

Models for predicting the daily mean bedroom and living room temperature were developed using an enhanced linear regression with panel-corrected standard errors. The results showed that climatic conditions, and especially building characteristics, affect significantly the bedroom and living room's indoor temperatures.



## 1. Introduction

Recent medical research has associated low indoor temperatures to various illnesses (e.g. pneumonia, increased blood pressure, asthma, bronchitis, influenza arthritis and heart diseases) and social pathologies (e.g. depression, anxiety, constraints of mobility and isolation) [1–7]. Low indoor temperatures have also a serious impact on mortality [1,8,9]. According to [10], there are approximately 30.000–60.000 excess winter deaths in UK, and 1500–2000 in Ireland related to low indoor temperatures in dwellings. Several international standards define threshold indoor temperatures for health reasons. The proposed indoor temperatures are in the range of 18–21 °C, varying as a function of many parameters regulating thermal comfort. For instance, the World Health Organization (WHO) recommends 21 °C in the living rooms and 18 °C in the other occupied rooms to achieve an adequate standard of warmth [11]. Also, the UK Department of Environment proposes as minimum temperatures for health reasons 16 °C in bedrooms and 18 °C in living rooms [12].

Cold homes are a reality in many European countries regardless of their climatic conditions, which makes empirical investigation of winter indoor temperatures imperative. In particular, the northern, eastern and central countries have longer and colder winters, in contrast with mild and wet winters in the Mediterranean region of Europe Most of the existing studies in the literature analyze indoor temperatures in UK [3,4,8,13–22], southern [23–25] and southeast European countries [1,26], and non-European countries [27–34].

Several studies scrutinize the driving forces behind indoor temperatures [1,8,17,18,34,35] during winter/heating seasons. The studies analyzed a variety of factors (e.g. climatic conditions, building characteristics and socio-economic factors), that may explain indoor temperatures [36]. For example, Critchely et al. [8], using binary logistic regression to model dwelling and household features, concluded that cold homes predominate in pre-1930 properties where the householder remains dissatisfied with the heating system. Oreszczyn et al. [14] monitored indoor temperatures for a period of two to four weeks in over 1600 low income

*Abbreviations:* BREDEM, British Research Establishment's Domestic Energy Model; HDD, heating degree days; OLS, ordinary least squares; MAE, mean absolute error; RMSE, root mean square error; WHO, World Health Organization.

* Corresponding author.
*E-mail addresses:* sara.magalhaes@fe.up.pt, magalhaesarauk@hotmail.com (S.M.C. Magalhães), vleal@fe.up.pt (V.M.S. Leal), imhorta@fe.up.pt (I.M. Horta).

http://dx.doi.org/10.1016/j.enbuild.2016.03.064
0378-7788/

dwellings, and assessed the determinants of indoor temperatures through tabulation and regression methods. The authors concluded that temperatures were influenced by building characteristics (e.g., the age of construction, and the thermal performance of the building), and household features (e.g., the number of occupants, and the age of householdís representant). Also, Hutchinson et al. [18] investigated the extent to which low indoor temperatures in homes can be due to dwelling and household characteristics using tabulation and logistic regression methods. Data of low-income homes, from five urban areas in England, was analyzed. The authors concluded that property and household characteristics provide only limited justification for low winter indoor temperatures, presumably because of the influence of other factors including personal choice and behaviour. French et al. [37] verified that heating type, climate and house age are the key drivers for the living room temperatures. On average, houses heated by solid fuel are the warmest, and houses heated by portable liquefied petroleum gas and electric heaters are the coldest. Over the winter period, living rooms are below 20 °C for 83% of the time, and living rooms are typically the warmest areas. The relationship between aspects of building quality and indoor temperature has been previously quantified in the study of Haas et al. [38]. Authors registered higher indoor temperatures in more insulated dwellings. Another important factor was whether the heating system was centrally controlled and the surface area of the dwelling [36]. Mateo et al. [39] applied different machine learning techniques along with other classical ones for predicting the temperatures in different rooms. In addition, Kelly et al. [35] predicted indoor temperatures in English homes using panel methods. The model predicted average daily temperatures using both technical and social household variables, explaining about 45% of the variation in indoor temperatures. In particular, the number of occupants, household income and occupant age were found to be the most important drivers of indoor temperature. Finally, Santamouris et al. [1] found strong correlations between the minimum indoor temperatures and the level of thermal losses of the dwellings, and also between the income levels and the environmental and energy parameters, using regression analysis.

Empirical data for residential indoor temperatures and heating patterns have important implications for policymakers for the development of programmes to improve indoor thermal comfort and health conditions. It also has an important role to support energy demand models for the building stock [40]. The provision of accurate information on indoor temperature and heating patterns (i.e., on occupant behaviour [41]) has become increasingly important over the last decade, as governments worldwide move to adopt policies aimed at reducing carbon emissions through improvements to the building stock [26]. Despite the availability of many energy models to support energy planning and policy development, it is not often clear which assumptions for indoor temperature and heating patterns estimations are being made and their empirical basis. In most cases operating conditions (i.e., occupant behaviour) are considered standard/reference, rather than actual measured conditions [26,42,43]. For instance, the British Research Establishment's Domestic Energy Model (BREDEM) assumes that living room is heated to 21 °C and other premises to 18 °C for 9 h on weekdays and for 16 h on weekends [26,44]. However, some authors found out that homes displayed on average lower indoor temperatures during assumed heating periods, and significantly shorter durations of heating than models usually assume. For example, Huebner et al. [45] concluded that currently used reference assumptions of heating demand and heating duration do not accurately reflect the living room temperatures in England. Also, Kane et al. [46] studied the heating patterns in 249 dwellings in Leicester in UK, and concluded that indoor temperatures were much lower than those often assumed by BREDEM-based energy models. This can poses some limitations in a scenario where actual heating energy use values needs to be estimated.

Another issue that needs to be considered for effective policy making is the efficiency of the upgrade programmes to building fabrics and/or changes in heating systems, which result in higher thermal comfort levels and/or lower energy use. In this sense, the existence of living environments currently significantly below the occupant's thermal comfort levels could indicate future potential for rebound effects.

In summary, empirical data on residential indoor temperature and its determinants have important implications for policymakers not only for the assessment of thermal comfort and health of occupants, but also, for the support of energy demand models applied to the building stock [26]. To the best of our knowledge, none of the previous studies characterize indoor temperatures and heating patterns in the Portuguese residential building stock, as well as, analyze the extent to which indoor temperatures vary according to social factors, building characteristics, and climatic conditions.

The purpose of this study is thus to investigate health patterns and indoor temperature characteristics of residential building in Northern Portugal, and, also to create a model that would predict indoor temperatures suitable for the residential building stock. A monitoring campaign was undertaken to gather experimental data from a sample of 141 dwellings monitored in two different rooms (bedrooms and living room). The campaign occurred during the winter of 2013–2014, namely from 27th November 2013 to 28th February 2014, in four different geographical locations (Porto, Sabrosa, Ponte de Lima and Bragança). The data was collected at every half hour and was processed on a daily basis. In order to predict daily mean indoor temperatures based on social factors, building characteristics and climatic conditions, an enhanced linear regression model with panel-corrected standard errors was employed.

This paper offers several important contributions within this research area: (i) It represents the first statistically relevant piece of indoor temperatures and heating patterns for the Northern Portugal; (ii) It allows statistical inferences on how different social factors, building characteristics, and climatic conditions contribute towards explaining indoor temperatures in the building stock; (iii) It contributes to the development of models that can be used to predict bedroom and living rooms indoor temperatures; (iv) It offers a practical solution to modelers wishing to obtain accurate estimates of heating energy demand of the building stock, by considering more realistic indoor temperatures and heating patterns.

## 2. Data collection and sample

### 2.1. Selection of households

The monitoring campaign occurred in four locations situated in the Northern Portugal. The locations were selected aiming to capture a large range of Heating Degree Days (HDD) [47], and purchase power values (p.p. relative to the national average value of 100%) [48]. The four locations that best fitted these criteria are Porto (1610HDD, 161.65% p.p.), Ponte de Lima (1790HDD, 64.97% p.p.), Sabrosa (2380HDD, 60.31% p.p.), and Bragança (2850HDD, 96.47% p.p.). Table 1 presents the main characteristics of the four locations (mean height, mean low temperature, mean high temperature, HDD and purchasing power).

In order to distribute the temperature dataloggers to a large number of households, this study accounted with the participation of four schools (one school in each location). The schools were selected according to the number of students, the type of surrounding dwellings and their will and availability to cooperate.