Energy and Buildings 43 (2011) 2449–2455

Contents lists available at ScienceDirect

Energy and Buildings

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

# Measurements of occupancy levels in multi-family dwellings—Application to demand controlled ventilation

Dennis Johansson[a,b], Hans Bagge[c,*], Lotti Lindstrii[d,e]

[a] Lund University, Building Services, Lund, Sweden
[b] Swegon AB, Tomelilla, Sweden
[c] Lund University, Building Physics, P.O. Box 118, 221 00 Lund, Sweden
[d] Karlstad University, Karlstad, Sweden
[e] WSP Construction Design, Karlstad, Sweden

ARTICLE INFO

*Article history:*
Received 19 April 2011
Received in revised form 26 May 2011
Accepted 31 May 2011

*Keywords:*
Occupancy level
Demand controlled ventilation
Dwellings
Residential

ABSTRACT

The occupancy level of dwellings is an important parameter to know to determine the energy efficiency, energy use and indoor air quality, especially in low-energy buildings where the user-related energy uses, such as household electricity and domestic hot water heating, are significant parts of the energy balance in a building. For residential buildings, there is a lack of occupancy level data, which also needs to be resolved over time, in a way so that both short term and long term variations can be described. As a part of an ongoing study, occupancy levels were measured as building average levels in 18 apartment buildings containing 342 apartments in total with readings every 30 min for more than a year. Averages and standard deviations of occupancy level, and variation in occupancy during the year, week and day respectively are presented. The results show a highly varying occupancy level over time, which indicates the potential of demand controlled ventilation in dwellings.



## 1. Introduction

The occupancy level of dwellings is an important parameter to know to determine the energy efficiency, energy use and indoor air quality, especially in low-energy buildings where the user-related energy uses, such as household electricity and domestic hot water heating, are significant parts of the energy balance in a building. A high occupancy level probably results in a higher use of household electricity and domestic hot water heating but should reduce the use of space heating due to higher internal heat gains, given that the heating control system works properly, and that the ventilation air change rate is sufficient, so that window airing is not needed to maintain the indoor air quality. To verify a building's energy performance, it is of interest to know the occupancy level and how the occupancy level varies during different times of the day, the week and the year. These variations can indicate the usefulness of demand controlled ventilation in dwellings. Constant ventilation airflows in mechanically ventilated dwellings are designed for maximum occupation, which is probably not the case during all hours of the year. This implies that dwellings are over-ventilated at times of less than maximum occupation which might result in higher than necessary energy use for heating and ventilation.

According to the Swedish building regulations [1], demand controlled ventilation is accepted in residential buildings on condition that the ventilation airflow can be individually controlled for each apartment with a minimum of 0.10 l/(s m$^2$) related to floor area when there are no occupants in the apartment and a minimum of 0.35 l/(s m$^2$) related to floor area when the apartment is occupied.

The concentration of $CO_2$ is often used to control demand controlled ventilation [2]. $CO_2$ producing processes in dwellings are, for example, the metabolism of occupants and pets, decaying organic substances, such as kitchen garbage, and combustion processes, such as the burning of candles. The authors of Ref. [3] report typical indoor air $CO_2$ concentrations between 500 ppm and 1500 ppm for mechanically ventilated dwellings, and stress that the concentrations are seldom constant and should be evaluated accordingly. The researchers in Ref. [4] monitored $CO_2$ concentrations in the living rooms of 19 dwellings in Finland during 1 week. The average $CO_2$ concentration was 570 ppm and varied between 350 ppm and 900 ppm in the different dwellings. Peak concentrations were about 1200 ppm and generally the highest concentrations were measured during the night when the occupants were at home.

People spend up to 90% of their time indoors [5]. The researchers in Ref. [6] studied occupational and energy patterns for 158 families living in the outskirts of Athens, using questionnaires. Occupancy rate patterns during the day were described for different family members and typical families, and activity patterns for different electrical appliances are presented. According to [7], the reported

* Corresponding author. Tel.: +46 46 222 96 15; fax: +46 46 222 45 35.
*E-mail address:* Hans.bagge@byggtek.lth.se (H. Bagge).

0378-7788/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2011.05.031

occupancy density in 386 Swedish apartments, based on questionnaires, was 2.1 persons per apartment and varied between averages of 1.9 and 2.5 in the studied properties.

Recommended occupation density according to Ref. [8] for use in energy simulations for Swedish conditions are, for a single room apartment, 1.42 persons and for a two bed room apartment 2.18 persons and an attendance time of 14 h per day. The average dwelling area per person in Sweden during 2009 was 57 $m^2$ for all dwelling types and 50 $m^2$ for multi-family dwellings [9]. These values are very low compared with the studied occupancy density in Hong Kong [10] that was about 12 $m^2$ usable floor area per person, which illustrates that occupancy characteristics have to be studied locally and that results are not necessary representative for other locations.

Even if some studies on occupancy levels in housing are available, they are few, and they usually did not give results over longer periods, and they do not combine occupancy levels with other energy and moisture related issues in housing. Therefore, the researchers in Ref. [11] started a holistic study of energy use and indoor climate, including measurements of household electricity use, domestic hot water use, indoor temperature, indoor relative humidity, and $CO_2$ with readings every 30 min during more than a year in several Swedish multi-family buildings at four different locations, from lat 55.6° to lat 67.9°. This article presents the part of the results on occupancy levels and an application to demand controlled ventilation. Moisture results are presented in [12,13].

### 1.1. Objectives

The aim of this study was to measure the occupancy level in multi-family dwellings based on the $CO_2$ concentration of the indoor air, to present averages and standard deviations of occupancy level, and to study the variation in occupancy during the year, week and day respectively. Another aim was to apply the measured occupancy to a life cycle cost analysis of demand controlled ventilation, including initial costs for construction and running costs for energy and maintenance, to compare it with a constant airflow system.

## 2. Methods

### 2.1. Measured and calculated parameters and definitions

By taking measurements in the exhaust air of residential buildings, a large number of apartments could be included in the study at a reasonable cost, compared with taking measurements in every individual apartment. On the other hand, it is not possible to find distributions between apartments inside a certain residential building or distributions between different rooms in an apartment. Measurements of $CO_2$ were carried out every 30 min to make it possible to obtain daily and weekly time distributions as well as daily and weekly spans. Measurements were carried out during at least one year, to obtain annual time distribution and to be able to evaluate the method during different outdoor conditions.

Occupancy levels were calculated based on the measured $CO_2$ concentrations, indoors and outdoors, and the ventilation airflow. The ventilation airflow was constant and taken from commissioning measurements. The production of carbon dioxide can be described by Eq. (1) where $C_p$ is the carbon dioxide production in l/s, $C_{in}$ is the carbon dioxide volume concentration in the exhaust air, and $C_{out}$ is the carbon dioxide volume concentration in the outdoor air and $q$ is the ventilation airflow of the building in l/s including leakage. It is assumed that there is no buffering. The effect of buffering and time lags will be a matter for future analysis. If a single person produces $c_p$ l/s carbon dioxide indoors, Eq. (2) gives the equivalent number of persons, $n$, in the building. $C_p$ can be corrected for other producing or reducing sources in the building. This gives the equilibrium state of occupancy, as there is a transient build up and a transient decay time. Due to the linearity, the average will be described by Eq. (2). The error is a time lag in the occurrence of occupancy.

$$C_p = (C_{in} - C_{out})q \tag{1}$$

$$n = \frac{C_p}{c_p} \tag{2}$$

Since the metabolic rate varies with activity level, age, sex and weight, an average $c_p$ has to be determined. Ref. [14] gives values per body weight for adults, as an average of men and women, as 0.17 l/(s kg) while sleeping, 0.26 l/(s kg) while sitting and 0.30 l/(s kg) while standing. The researchers in Ref. [15] analysed carbon dioxide generated by children, based on Ref. [16]. Children produce 1.74 times as much $CO_2$ as adults per kg body mass. The average weight of adult Swedes, if it is assumed that there are equal numbers of men and women, is 74.5 kg [17]. For the estimation of $c_p$, it was assumed that people spend 14 h a day in their homes [8]. It was assumed that 8 h were spent sleeping, 4.5 h sitting and 1.5 h standing. If it is assumed that children on average weigh half as much as adults, and 83% of the population are adults, the average $c_p$ became 15.0 l/h. Different ratios between the assumed parameters would give different results, corresponding to Eq. (2). Only adults would give a $c_p$ of 15.9 l/h while only children, which is rather unrealistic, would give a $c_p$ of 10.7 l/h, resulting in an error in $n$ of −6% and 40% respectively. In a multi-family dwelling, the given assumption resulting in a $c_p$ of 15.0 l/h was considered appropriate. It would be possible to try to vary $c_p$ over the day, but that would introduce several uncertain parameters.

In this article, the occupancy level is generally shown as the absolute occupancy level, $O_a$, i.e., the number of persons per apartment area, which is abbreviated to p/$m^2$. In the analysis, the word 'span' is used to describe the difference between a maximum and minimum value during a certain period of time. Daily span means the highest 30-min occupancy level reading minus the lowest 30 min occupancy level reading during a 24-h calendar day period. Weekly span means the highest minus the lowest daily average occupancy level during a calendar week, Monday to Sunday.

### 2.2. Measuring equipment and possible errors

The measurement sensors were placed in the central exhaust close to the exhaust fan before possible heat recovery coils. The indoor carbon dioxide sensors were calibrated every 6 months. The manufacturer, SenseAir, stated the error of the carbon dioxide sensor as ±30 ppm ±3% of the reading with a repeatability error of ±20 ppm ±1% of the reading, but to reach this accuracy, the sensor must be calibrated. It is probable that the error corresponds to the total error due to the rather long times between calibrations, if absolute values are of interest. If variations during periods of a week or less are of interest, the relevant error is most probably the repeatability error. At a measured value of 700 ppm, this means ±51 ppm and ±27 ppm respectively. At outdoor values of approximately 400 ppm, this means ±42 ppm and ±24 ppm respectively. Logger errors were small in comparison, ±2.5% of the reading according to the manufacturer Onset, with an almost zero repeatability error. The airflow measurements can have a typical error of ±10% with a repeatability of ±5% [18]. For daily and weekly variations it is probable that the error corresponds to the repeatability, which gives a probable occupancy level error of ±8.7%. For annual variations and seasonal variations, the probable occupancy level error becomes ±17%. It was not stated whether the $CO_2$ sensor error was related to indoor temperature, that was fairly constant, or rel-