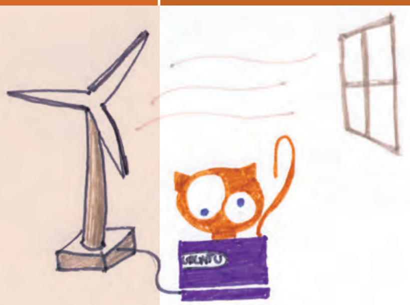
SUSTAINABLE URBAN AREAS

33

Actual energy consumption in dwellings

The effect of energy performance regulations and occupant behaviour



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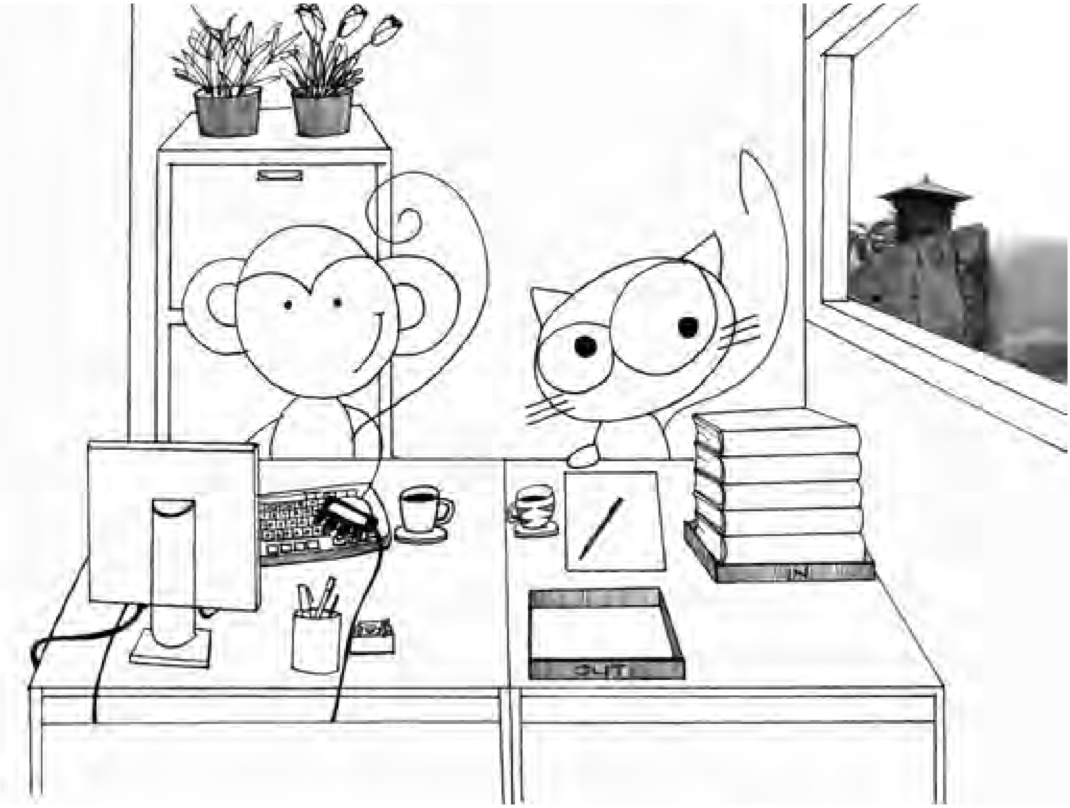
IN
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1 Introduction

1.1 Energy conservation in residential buildings

In Europe the built environment consumes 40% of the produced energy. A large proportion of this energy is consumed in residential buildings. Households account for about 30% of the total building-related energy consumption in OECD countries (Itard & Meijer, 2009). As around 30-57% of the energy consumed by households is spent on space and domestic water heating, conservation in this area is a matter of vital importance.

Residential buildings have continuously improved in efficiency. Though materials with better thermal properties and more efficient systems have lowered energy consumption for space heating in recent decades, substantial differences in energy consumption are still being observed in similar dwellings (Lutzenhiser, 1992; Jeeninga *et al.*, 2001). In 1992 Lutzenhiser showed that energy consumption in similar dwellings occupied by similar households can vary by up to a factor 3. More recently, Jeeninga *et al.* (2001) found that the actual energy consumption of households living in dwellings with the same theoretical energy performance can vary by up to a factor of two. These differences in consumption are thought to be caused by differences in occupancy patterns (Groot *et al.*, 2008; Haas *et al.*, 1998; Linden *et al.*, 2006; Branco *et al.*, 2004), by the quality of the construction (Nieman, 2007; Gommands, 2007) and by rebound effects (Haas *et al.*, 1998; Hens, 2010). These large variations can point to opportunities that can bring about further reductions in the energy consumption for space heating and boost the efforts to conserve energy worldwide.

Many governments have introduced regulations to make buildings more energy-efficient. Policies and research on energy conservation in buildings are geared primarily to saving energy through technical measures relating to the building envelope and the heating and ventilation installations. However, there are strong indications that energy-saving designs do not always result in the expected energy consumption (Branco *et al.*, 2004; Haas *et al.*, 1998). Although it is widely admitted by experts that the final energy consumption is strongly influenced by household characteristics, lifestyles and occupant behaviour, only a few attempts have been made so far to quantify and understand these factors. This research addresses the effect of energy performance regulations and occupant behaviour on energy consumption for space and water heating in residential buildings, since these are believed to be crucial in bringing about further reductions in energy consumption in the residential sector.

1.2 Background

Role of regulations in reducing energy consumption for space heating
In recent decades governments worldwide have implemented energy requirements in their building regulations in order to reduce levels of energy consumed by buildings and to promote more energy-efficient housing. Since 2006 the Energy Performance Building Directive (EPBD) has required all EU member states to enhance their building regulations by implementing performance-based energy requirements and by introducing energy-label certification schemes to lower the energy spent on heating, cooling, ventilation, lighting and domestic hot water in buildings. In the Netherlands energy consumption in new buildings has been regulated since 1975, when energy-efficiency requirements consisted of limits on transmission losses based on insulation values. Since 1995 the energy-efficiency requirements have been based on the energy performance coefficient (EPC), a non-dimensional figure that expresses the energy efficiency of a building. Therefore, this research is based on the experiences in the Netherlands with this type of regulations.

In the Dutch regulations, the EPC covers space heating, space cooling, hot tap water, humidification and the electricity needed for mechanical ventilation and lighting. The energy used for cooking and for white and brown goods is excluded since it is not building-related. The EPC calculations are based on standard occupancy conditions and fixed values for temperature settings, internal heat gains, ventilation flow rates, heating demand for hot tap water and lighting. These values are based on the standard use of building amenities according to the NEN 5128 norm (see Appendix 1).

The EPC value is obtained by correcting the total expected energy (Qpres;tot) by a neutralisation factor for the size of the dwelling. Hence, although large dwellings consume more energy, they are not penalised for their size if they have the same thermal quality as small dwellings. The detailed calculations for the EPC value can be seen in Appendix 1. The EPC is calculated with the following formula:

$$EPC = \frac{Q_{pres;tot}}{[330 \text{ x } A_{g;verwz}] + [65 \text{ x } A_{verlies}]} \text{ x } \frac{1}{C_{EPC}}$$

where,

$Q_{pres;tot}$	is the primary energy consumption in MJ
$A_{g;verwz}$	is the useful surface of the heated zones of the building in m²
$A_{verlies}$	is the heat-transfer surface of the building in m²
C_{EPC}	is a correction factor to correct for changes in the calculation method when it was changed

The total expected energy ($Q_{pres;tot}$ in MJ) is calculated as the sum of the primary energy consumption for space and water heating, ventilators, lighting, cooling, humidity, and gains from photovoltaic solar energy. The calculations for the primary energy take account of the efficiency of the installation and the distribution losses of the system, and compensate for the energy from photovoltaic systems and cogeneration.

The aim of the energy performance regulations is to lower the overall building-related energy consumption. One important aspect of the EPC is that it sets a total energy performance without prescribing specific solutions, allowing designers to make trade-offs and devise a solution from numerous options (for example, less insulation in exchange for more efficient equipment).

In 1995 the EPC stood at 1.4, a value that was easy to reach with common construction methods at that time. It was tightened to 1.2 in 1998, to 1.0 in 2000 and to 0.8 in 2006 and it will be tightened again to 0.6 in the near future. In 1995 the value of 1.0 reflected a dwelling with the best possible energy performance with the technology then available. Accordingly, before the EPC was further lowered from 1.0 to 0.8, studies were carried out to determine whether a lower value would be feasible and cost-effective. Two studies addressed the question whether the EPC set in 2000 (1.0) could be further tightened without causing economic harm to the building industry and health problems for the occupants (Beerepoot & Beerepoot, 2007). Dongen & Vos (2003) studied the relationship between self-reported health conditions and EPC values and concluded that the EPC had had no effect on (self-reported) health. In 2003 Vierveijzer & Wichers Hoeth (2003) studied the cost-effectiveness of a tighter EPC value and concluded that it was not cost-effective at the time. This study was later criticised for being over-susceptible to assumptions regarding costs and energy prices. A study carried out after the EPC was tightened to 0.8 (KPMG, 2006) concluded that, as yet, larger dwellings could not be cost-effective. This conclusion was, however, regarded as temporary as a tighter EPC value was expected to stimulate the development of new innovative technology. In 2007 Beerepoot studied the effect of the EPC on innovation in energy-saving technologies and concluded that the EPC contributed to the application of more efficient technology for conventional hot water production, but not to the dissemination of technologies regarded as innovative such as solar water boilers or heat pumps.

In 2001 Jeeninga *et al.* found only indicative differences (not statistically significant at $p<.05$ level) for energy consumption in dwellings with different EPC levels, except for categories 0.75 and 1.2. However, as the study was conducted in low-energy dwellings built before 2000 – when the EPC level was 1.0 – it is possible that 0.75 was experimental and therefore more carefully implemented. In a larger sample PRC (2004) did find statistically significant differences between EPC categories although the statistical analysis could not be checked. In a later analysis of the sample (Uitzinger, 2004) no correlation was found between equivalent gas consumption and EPC.

Influence of occupant behaviour on energy consumption
With the overall decrease in building-related energy consumption, occupant-related energy consumption is becoming all the more important (Groot *et al.*, 2008; Haas *et al.*, 1998; Linden *et al.*, 2006; Branco *et al.*, 2004). The fact that occupant behaviour may vary by up to a factor of two in similar dwellings even when systems are identical suggests that energy consumption in residential buildings is dependent on more than just the characteristics of the building and that occupant behaviour might have a deep impact on energy efficiency. The interaction between the occupant and the building (i.e. the control of the heating and ventilation systems) is thought to have a strong influence on energy consumption (de Dear, 2004; Lenzuni, 2008; Karjalalaine, 2007; Lan, 2008; Moujalled, 2008; Ye, 2006).

Socio-demographic characteristics such as household size and age of occupants have an effect on the comfort parameters in the indoor environment of dwellings. Other factors such as income, education level and country of origin might also be related to indoor comfort preferences. The energy consumption in dwellings can be further determined by cognitive factors such as attitudes and motivation to save energy and environmental concerns (Andersen, 2009; Schreiker & Shukuya, 2009).

One important aspect of occupant behaviour is the 'rebound' effect. Studies have found evidence of this effect in better insulated dwellings (Haas *et al.*, 1998). Rebound is described as a behaviour in which the energy savings achieved by improved efficiency lead to an increase in the energy spent on other household activities. In plain terms, lower heating bills are offset by a demand for more thermal comfort.

1.3 Problem definition

The goal of energy-performance regulations is to reduce building-related energy consumption in new dwellings. Studies have shown that energy regulations have effectively reduced energy consumption (Leth-Petersen and Togeby, 2001; Jeeninga *et al.*, 2001), but this effect needs to be validated since the relationship between the EPC and energy consumption is far from straightforward. In other words, the effect of the energy performance regulations on energy consumption for space heating might revolve around different factors.

The Dutch government has tightened the EPC on a regular basis. In fifteen years two studies have been conducted to assess the effectiveness of the energy performance regulations on the actual energy consumed for heating in the Netherlands. The last scientific evaluation of the effectiveness of the EPC was carried out in 2001 (Jeeninga *et al.*, 2001). Since then, the EPC has been tightened again and will probably continue to be tightened in the future. However, as little is known about the actual efficiency of this performance-based policy, a statistical evaluation is needed. Moreover, a rebound effect on energy consumption which has been found in dwellings with improved thermal properties and system efficiency (Haas *et al.*, 1998; Hens, 2010) might neutralise the effectiveness of a tighter EPC.

The aim of the EPC is to lower electricity and gas (or heat) consumption. Occupant behaviour has a stronger influence on levels of energy consumed for water heating, ventilation and lighting than on those consumed for space heating and cooling, which are co-determined by the building characteristics. In the calculations the expected energy consumption for water, ventilation and lighting is based on standard use of amenities and varies only according to dwelling size and system efficiency (i.e. for lighting a figure is multiplied by the area). According to Beerepoot (2002), the EPC is little more than a very rough indicator, since the calculations use default values and assumptions that differ from the actual conditions of use.

Since the EPC allows the designer to choose between diverse trade-offs, choices might be made in areas that depend more on occupant behaviour than on building-related energy consumption. This would apply in cases where, for example, more importance is accorded to boilers and the efficiency of ventilation systems than to thermal properties.

It is essential to assess the influence of occupant behaviour on energy performance as it may be a key factor in the realisation of improvements. Insight into the determinants of behaviour will also help in attempts to discern the effect of building regulations on energy consumption. Whereas building regulations might determine the type of building amenities on the one hand, the effect of occupant behaviour on energy consumption might be largely determined by interaction between the occupant and these amenities on the other.

Indoor conditions are largely dependent on building characteristics. However, comfort preferences can vary across households and even across people in the same household. The control of indoor conditions (ventilation, draft, temperature) could conceivably have a strong effect on the interaction between the household and the dwelling. Variations in preferences for comfort and indoor conditions have also been shown to depend on household characteristics such as age and gender and other socio-demographic variables such as income and education. These variables might be influencing energy consumption via differences in motivation and attitudes towards energy and environmental conservation. The magnitude of and relationships between building and household characteristics, cognitive variables and behaviour will be important factors in the formulation of future policies to lower behaviour-related energy consumption.

1.4 Aim of the study

Nowadays, the aim of energy performance regulations is to decrease the environmental burden imposed by the energy consumed in the built environment. However, the energy reductions for space heating might fall short of expectations. The effectiveness of energy regulations needs to be verified in order to discern whether more energy savings will be generated by tighter energy regulations. It is thought that occupant behaviour, the actual quality of the construction, and rebound effects might be undermining the effect of the regulations. The lower the energy consumption of a building, the higher the influence of occupant behaviour may be, but little is known about the ways occupants use buildings, and how this affects the use of energy. In addition, without accurate statistical data on occupant behaviour it is impossible to predict the effect of future policies on the energy-saving performance in housing.

The aim of this research is to provide insight into the effect of energy performance regulations on the energy consumption for space heating and to clarify the role of occupant behaviour in determining this effectiveness. This will enable us to establish whether tighter energy performance regulations are required and to identify the factors (building characteristics) that could be causing households to consume more energy.

1.5 Research questions

This section introduces the three main research questions and sub-questions that have been defined for this study.

Q1: What effect have energy performance regulations had on the actual energy consumption in housing?

The first research question aims to determine the effect of energy performance regulations on the actual energy consumption for space and water heating in housing built after 1995, the year when energy performance regulations were introduced in the Netherlands. It is important to determine the effect of tighter building regulations on reducing the energy spent on space heating. This question has been broken down into 3 sub-questions:

a. What is the effect of a tighter EPC value on energy consumption for heating? (Chapter 3)

b. What is the difference between the actual and predicted energy consumption? (Chapter 3)

c. Which building characteristics in the EPC have statistically a major influence on energy consumption for space heating? (Chapter 3)

Q2: What are the effects and the determinants of occupant behaviour on energy consumption?

After the effect of the EPC and building characteristics in recently built housing has been determined, the second question seeks to identify the occupant behaviour that has a major influence on energy consumption for heating and its determinants. Knowledge about the determinants of behaviour can be used to identify the factors that ought to be addressed in order to promote behaviour that leads to lower energy consumption. In addition, the development of behavioural patterns of energy consumption will provide insight into drivers of behaviour, which can then be properly addressed in policies designed to reduce energy consumption. User profiles can be used in energy calculations and simulation programmes to deliver more accurate energy predictions. The sub-questions are:

a. What is the effect of occupant behaviour on energy consumption from a statistical perspective? (Chapter 4)
b. What are the determinants of the occupant behaviour that have an effect on energy consumption? (Chapter 4)
c. What are the main patterns of occupant behaviour? (Chapter 5)
d. Which household categories show significant differences in energy-related behaviour? (Chapter 5)

Q3: What are the differences between the most important determinants of energy consumption for heating in housing built after the introduction of the EPC in comparison with the total housing stock?

When determining the building characteristics and the behaviour with the greatest influence on energy consumption the main focus should be on the most effective ways of reducing energy consumption. Comparing the differences between the total housing stock and housing built after the introduction of the EPC can help to further assess the impact of building regulations on energy consumption. The last sub-questions are therefore:

a. Which building characteristics have the strongest influence on energy consumption in the total housing stock? (Chapter 2)
b. What is the relative importance of behaviour and building characteristics on energy consumption in the total housing stock? (Chapter 2)
c. What are the differences in energy consumption between housing built after 1995 and the total housing stock? (Chapter 6)
d. What are the differences in behaviour determined by building characteristics in the total housing stock? (Chapter 6)

1.6 Research methods

This research sought to draw conclusions on the determinants of energy consumption at macro level in order to analyse the effects of national energy regulations. The study at macro level was necessary because of the large number of variables that influence energy consumption.

Statistical analyses were therefore used to determine the factors that influence energy consumption for heating. The analyses carried out in this research were exploratory in nature. The objective was to deliver relationships between different variables (occupant behaviour, household characteristics and building characteristics) which would then deepen the understanding of the relative influence and interaction between the variables and pave the way for energy-consumption predictions for certain groups.

Thanks to the use of standardisations in statistical methods (i.e. standard deviations) statistical analysis also enabled us to systematically compare recently built housing with the total housing stock and also made comparisons possible with other research and databases. This study made use of multivariate statistical analyses.

Regression analysis was used to predict energy use for heating. According to Schuler *et al.* (2000), regression equations enable the factors influencing the energy-related aspects of dwelling use to be analysed in a way that simulation tools do not. The use of micro-level data on household behaviour and energy consumption is deemed more suitable for analysing occupant behaviour (Pachauri, 2004). In addition, according to Freire *et al.* (2004), regression equations are a faster and easier tool than simulation models to predict energy consumption in a large sample of dwellings. Regression analysis has been used to understand behaviour in different climate conditions and to forecast energy demand.

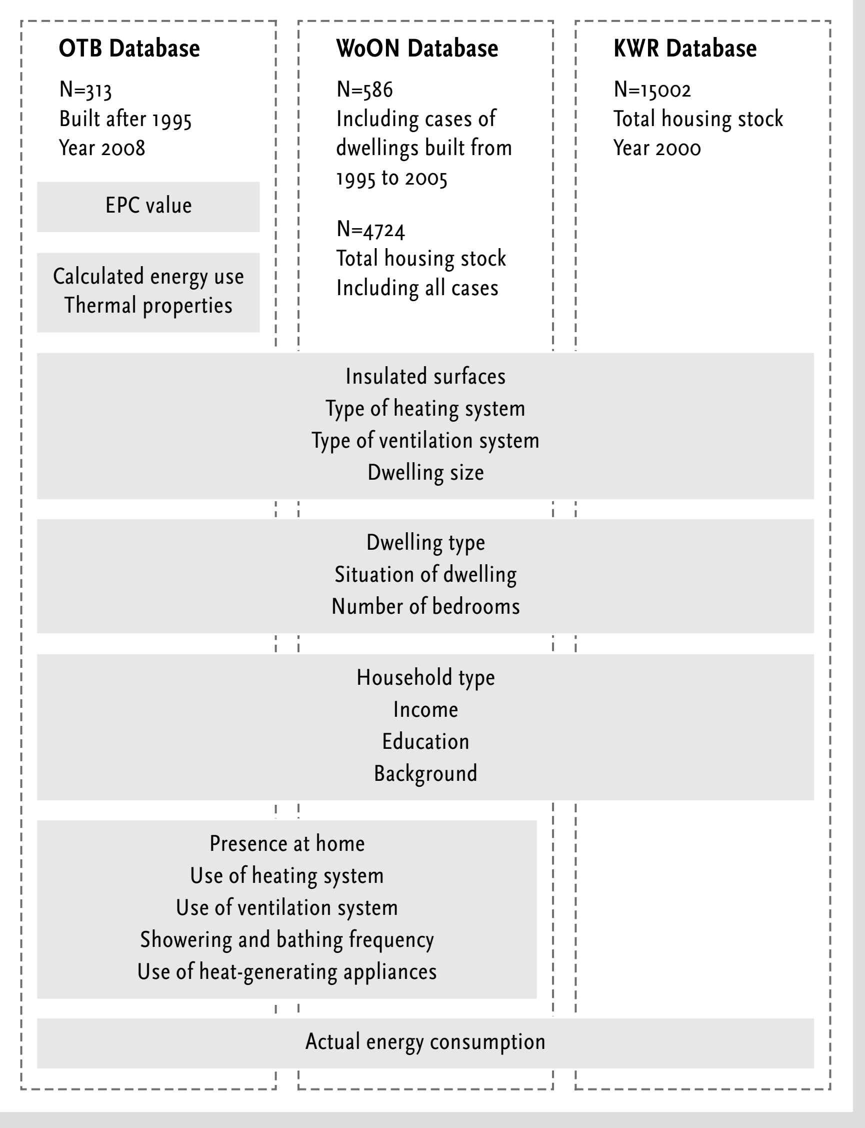
To analyse the relationships between the different types of variables, different methods were applied depending on the research question. The types of methods used are explained accordingly in each chapter.

1.7 Data

The statistical analysis required detailed data on occupant behaviour, building characteristics and household characteristics. Four types of data were needed:

1. Data on building characteristics, including the EPC value, the type of heating and ventilation system, the dimensions and characteristics of the building envelope and the heating area.

Figure 1.1 Data sources



2. Demographic data on household characteristics.
3. Data on occupant behaviour in relation to the time spent at home, the use of ventilation and heating systems, and other activities that consume gas and heat, produce heat, or are sources of pollutants.
4. Data on the actual energy consumption for space and water heating.

A large amount of detailed data and a large enough sample size were needed to carry out the statistical analysis. In addition, practical factors were taken into account to set up the data collection for the study. These factors might however have affected the representability of the data. However, the cost of the random sample in new dwellings in the Netherlands would have been prohibitive due to the amount of time needed to obtain the EPC data of all sampled houses. Since this analysis is exploratory, no large consequences were expected from this issue. Section 1.9 deals with the possible limitations of this study. In addition, an objective of the research was to study the differences in behaviour in as similar as possible dwellings, to assess the effects of preferences on the use of dwelling provisions.

OTB database

Figure 1.1 shows the relationships between the type of data used and the sources. The data on building characteristics and EPC values were taken from EPC documents obtained from municipalities or architects' firms. The data on household characteristics, occupant behaviour, and energy consumption came from the OTB survey.

The energy performance regulations were introduced in 1995, so this study concerned housing built after this date. Two districts were selected for the OTB survey and the data collection from the EPC files: Leidsche Rijn in Utrecht and Wateringse Veld in The Hague. As these were new neighbourhoods we could be sure that the sample consisted only of dwellings built after the introduction of the energy performance regulations. Secondly, a survey among households in one and the same area facilitated the acquisition of information about the EPC level of the dwellings. The chosen districts represent the current type of housing development in the Netherlands; they include rented housing and owner-occupied housing and offer a wide variety of dwelling types. In this way we can attempt to generalize the results of this study to the situation in the Netherlands.

Detailed data on building characteristics were needed for the statistical analyses. These were collected from the EPC documents, which were considered a more reliable source than reports from the occupants, though there is some degree of concern about whether the real building characteristics match those defined in the EPC documents. The data obtained from municipalities related to the EPC values and the building characteristics and focused mainly on the building envelope (insulation, type of materials and glazing) and the heating and ventilation systems. The collected information was then paired with the data from the OTB survey on a case by case basis.

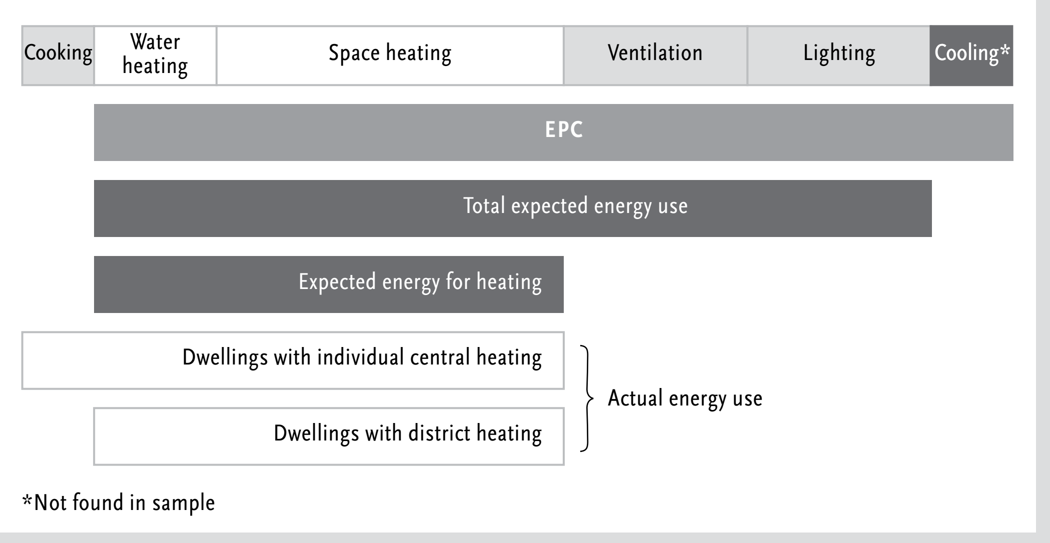
The household survey was carried out in autumn 2008. A low response rate was expected due to the length of the questionnaire and therefore, six thousand questionnaires were sent to the districts. A response rate of 5% was obtained. The low rate was also due to the discomfort that some people felt about answering questions on their lifestyle and possessions. A reminder was sent to the households to raise the response rate. Further attempts to raise the rate were stopped after reaching the desired sample size.

The sample size was determined through known formulas (Field, 2005; Tabachnick and Fidell, 2007), and by using a sample size similar to the one

Table 1.1 Response rates and available data per district

District	Response from survey	Reported energy data	EPC data	Reported energy and EPC data
Leidsche Rijn	125	94	104	86
Wateringse Veld	177	147	138	131
Unknown	11	7	0	0
Total	313	248	242	217

Figure 1.2 Build-up of the EPC and relationship with measured energy consumption



used in similar studies (Jeeninga *et al.*, 2001; PRC, 2004; Uitzinger, 2004). According to recent studies, a low response rate should not affect the results. The results from early responses have been found to be similar to results with late responses (Keeter *et al.*, 2006; Curtin *et al.*, 2000; Holbrook *et al.*, 2007). In addition, a similar response rate (5%) is common in internet surveys. The possible limitations of the low response rate are discussed in Section 1.9 and in the conclusions of this thesis.

The survey provided information on occupant behaviour, household characteristics and energy consumption. The occupant behaviour referred to the use of the heating and ventilation systems, shower and bathing frequency, and the use of heat-producing appliances and electronics. As the survey was held in the autumn, the respondents were asked to report retrospectively on their behaviour the previous winter. The questionnaire took the form of a series of tables where the respondents could fill in their behaviour and the household characteristics. A condensed version of the questionnaire is provided in Appendix 2.

The EPC could not be found for all cases, the reasons for it are: the building permit had been obtained just before the introduction of the EPC, the EPC files were missing, or the respondents did not state their address. This reduced the size of the sample for some analyses (Table 1.1).

The data on actual energy consumption was obtained from the respondents, who reported the energy consumption specified in their last available energy bill. Households in dwellings with individual central heating reported energy consumption in square metres of gas, while households in dwellings with district heating reported it in GJs.

In practice, in dwellings with an electricity and a gas connection (the most common situation in the Netherlands), the measured gas is for cooking and for space and water heating while the measured electricity is for lighting, ventilation, space cooling and appliances. In dwellings with a heat (district heating) and electricity connection the measured heat is for space and water heating, while the measured electricity is for lighting ventilation, space cooling, appliances and cooking (Figure 1.2).

Another difference between the energy data reported from homes with individual central heating and district heating is that only gas is reported as primary energy. The EPC calculates the primary energy consumption, which takes account of the efficiency of the energy distribution and conversion outside the dwelling. Hence, for the purposes of comparison, the same conversion factors as in the EPC had to be applied to the energy figures from dwellings with district heating.

Both types of dwellings were represented in the sample. Houses with district heating did not include energy for cooking and a conversion factor was needed to account for the efficiency of the system. In the Netherlands this factor is set at .95 (NEN 5128: 2004). Dwellings with a gas connection did include energy for cooking, but this was considered to be less than 5% (EuroACE, 2004) and therefore should not affect the results.

Only energy consumption for heating was considered in this research. No account was taken of energy for cooling, lighting or ventilators. Energy for heating water was also considered since it was included in the measured data on gas and heat. Data on energy consumption was compared as follows with the sum of the expected energy for space and water heating:

$$Q_{pres;\ heat+tap} = Q_{prim;verw} + Q_{prim;tap}$$

The primary energy for space heating ($Q_{prim;verw}$) and the primary energy for tap water heating ($Q_{prim;tap}$) were taken from the EPC documents (see Appendix 1 for more information on the EPC calculations).

Databases from the Ministry of Housing

Two databases from the Dutch Ministry of Housing were used to (1) validate the OTB survey with a nationwide and random sample to overcome the limitations discussed in the earlier section and, (2) analyse the situation in the building stock. The databases were KWR (Kwalitatieve Woning Registratie) and its successor WoON (Woononderzoek Nederland). While the KWR offers a very large sample (15,000 cases) and few variables about occupant behaviour, the WoON survey offers more information on occupant behaviour (use of heat and ventilation systems) in a smaller sample (4,500 cases). However, neither database contained the EPC values, since the first was carried out just few years after the introduction of the energy performance regulations and the second focused on the total housing stock and could therefore provide only the Energy Index (EI) and energy label.

KWR database

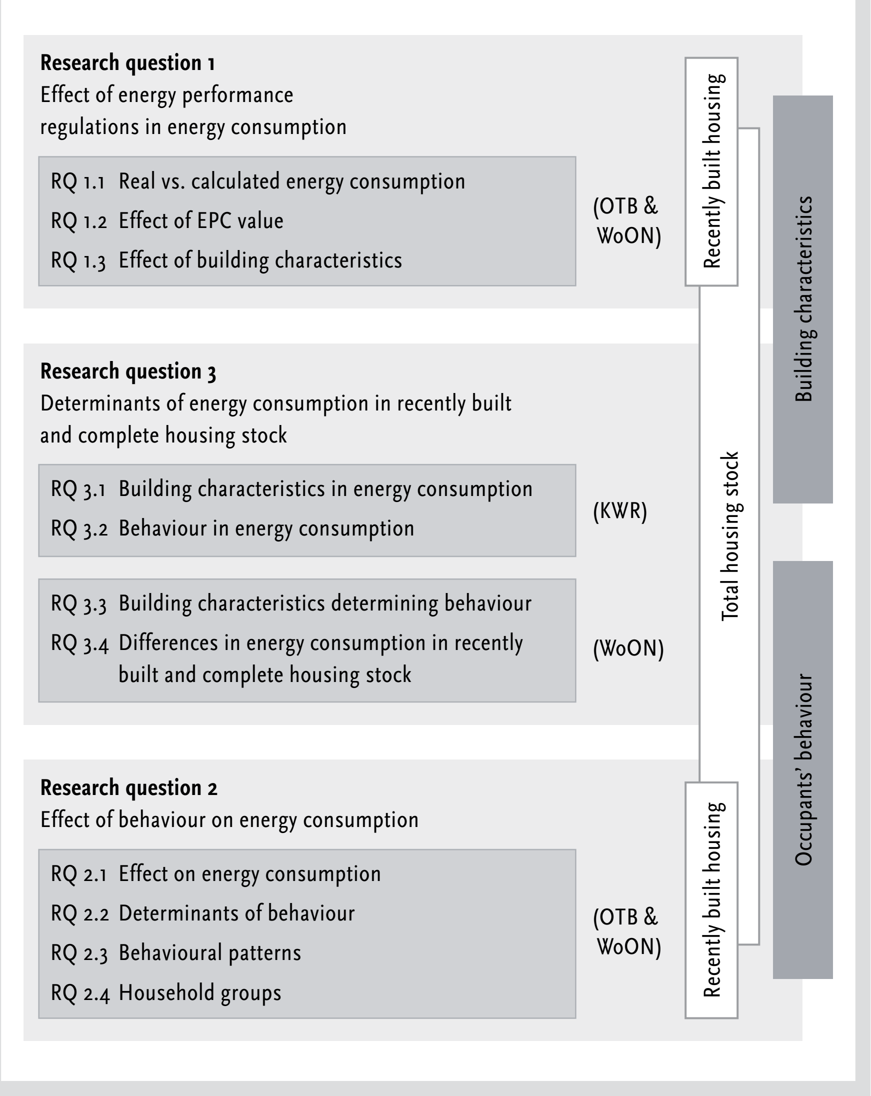
The most recent version of the KWR, completed in 2000, includes data on housing quality in a sample of 15,000 houses across the Netherlands. It took the form of an interview-based survey which collected data on, amongst others, household characteristics and the use of the dwelling, including presence at home, and heating and ventilation behaviour. This database also contains data from the inspection of the building characteristics of the dwelling, such as the percentage of insulation per surface, type of materials, or type of heating system. Data for three years of energy consumption were obtained from energy providers.

The KWR has three major advantages: the sample size was quite large, it was carried out randomly across the Netherlands, and it includes data on building characteristics, household characteristics and occupant behaviour. The main disadvantage of the KWR is that it contains very few behaviour variables. Secondly, there were wide variations in the number of cases in each category and the majority of cases were relevant to only one or two categories. Dichotomous variables were therefore used to indicate the presence or absence of a type of behaviour or particular building characteristic. The KWR database was used for the preliminary studies in this research because the WoON database was still unavailable.

WoON database

The WoON database of the Dutch Ministry of Housing (www.vrom.nl) is assumed to be representative of the Netherlands. This survey was carried out in 2005 (becoming available in 2008) and contains a sample of 4,500 cases. The data was obtained from a household survey, dwelling inspections and reports on energy consumption in the dwellings. The survey asked the occupants about their behaviour. The WoON database contained more data on variables about occupant behaviour and more detailed data from the building inspections than the KWR.

Figure 1.3 Data used per research question



1.8 Relationship between research questions and data

The OTB database was used for research questions 1 and 2, which address the effect of the energy performance regulations (research sub-questions 1.1-1.3 and 2.1-2.2) and occupant behaviour on energy consumption in recently built housing. The WoON database was used to validate the subsequent analyses. The OTB database was also used to determine behavioural patterns and household types in sub-questions 2.3-2.4. This part was not validated with the WoON survey because the database did not contain the required data (see Figure 1.3).

The third research question, which regards the total housing stock, was answered by an analysis with the KWR and the WoON database. The KWR was used for sub-questions 3.1-3.2 on the determinants of energy consumption in the total housing stock. The WoON database was used for sub-questions 3.3-3.4 to analyse the effect of building characteristics on the housing stock and to compare this with the situation in recently built housing (Figure 1.3). In the figure, question 3 is shown between questions 1 and 2 because it deals with both building characteristics and occupant behaviour.

1.9 Limitations

The results of this study might be limited due to the nature of the sample. First, the OTB survey might be limited due to the low response rate. A random sample across the Netherlands could not be provided since two complete districts were specifically chosen with a view to obtaining data on the EPC values. To determine the effect of the low response rate, the household characteristics in both samples were analysed. It was found that the only difference consisted in a higher than average education and income in the OTB database. However, these deviations from the national averages might have been caused by the fact that this study – for reasons explained earlier – focused only on recently built houses.

The results of the OTB survey were therefore compared with the results of the WoON survey. Analyses similar to those applied with the OTB sample were carried out by way of validation. These are discussed accordingly in each chapter.

Furthermore, there were two concerns regarding the quality of the data: (1) the survey collected 'retrospective' data on occupant behaviour, which are less reliable than monitored data; (2) there may be differences between the actual building characteristics and those described in the EPC document (for example, the infiltration values are only theoretical).

The reliability of 'real-time' data (such as diaries) is also open to question. The best way to obtain high-quality data on occupant behaviour is to monitor the actual indoor parameters and HVAC settings, but this is a time-consuming and expensive option. A survey proved the most appropriate instrument to collect data for the statistical analysis of a large number of factors, as intended in this research.

The OTB sample was chosen to be representative for the type of dwelling (flats, detached houses, etc.) but it did not cover all types of HVAC systems currently used in the Netherlands. There were few dwellings with balanced ventilation and no dwellings with heat pumps in the sample. And there were only a few cases of dwellings with solar boilers. The WoON database did, however, contain cases of dwellings with balanced ventilation and heat recovery.

Figure 1.4 Research framework

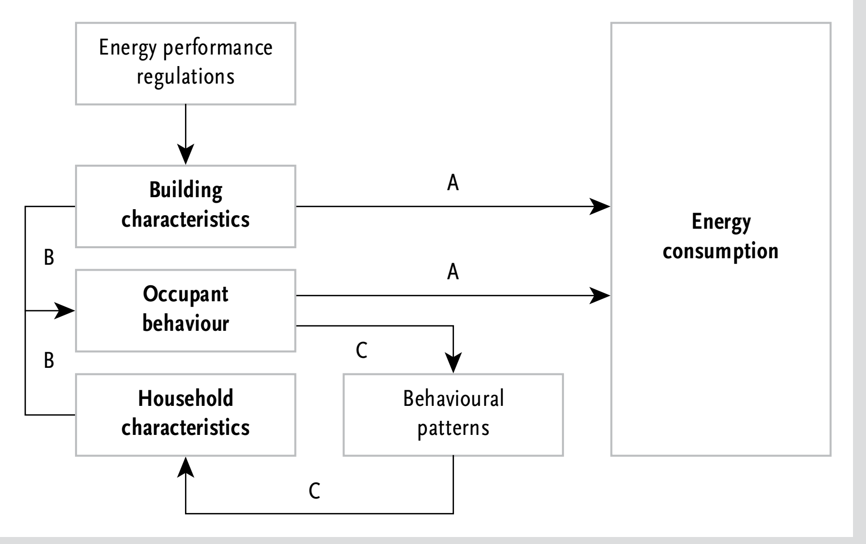
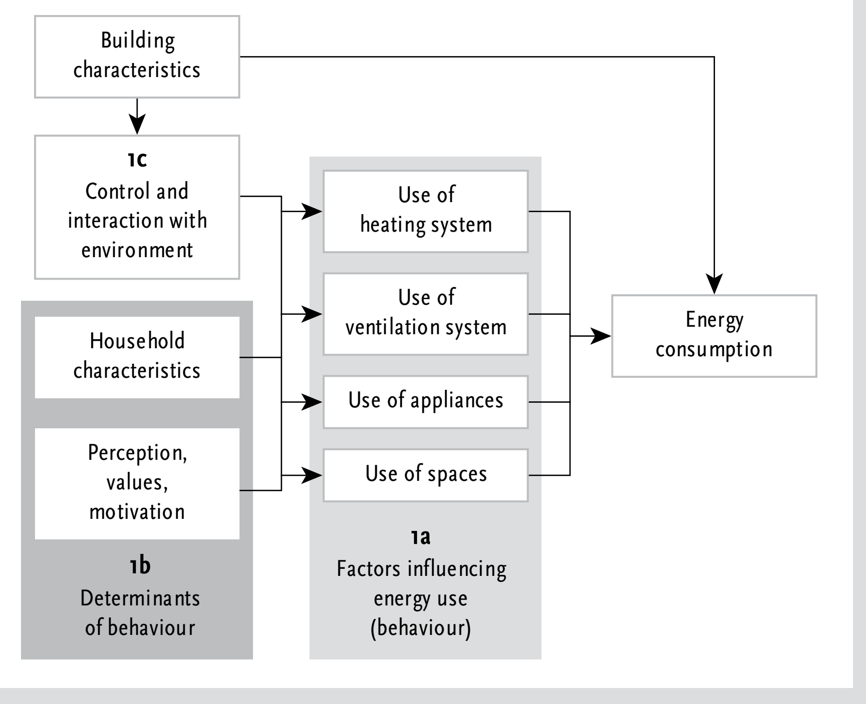
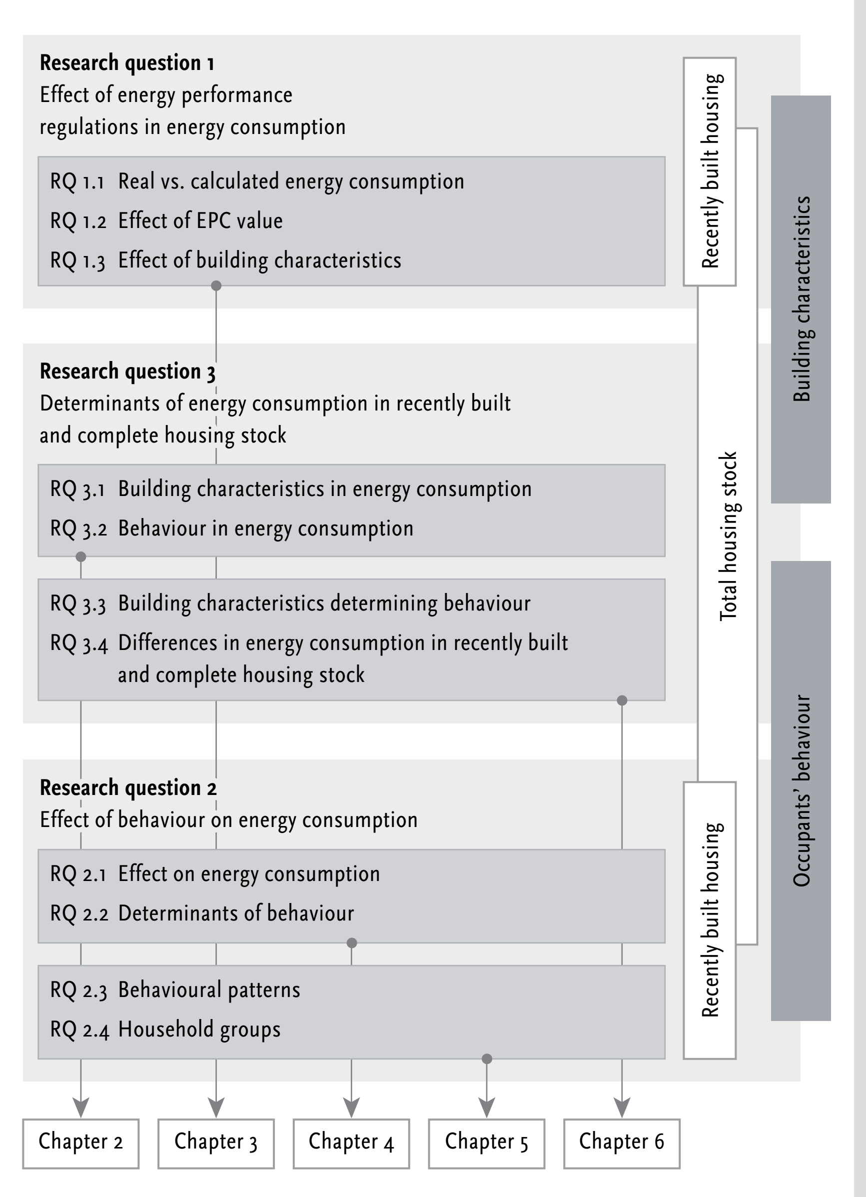


Figure 1.5 Framework for occupant behaviour and energy consumption



Even with the limitations imposed by quality of data, the results of this study provide an insight into the role of energy performance regulations in reducing energy consumption for heating. Energy performance regulations have been used in the Netherlands for 15 years, thus providing an opportuni-

Figure 1.6 Relation between chapters and research questions



ty to test this type of regulations, which are being implemented in other European countries in the framework of the EPBD.

1.10 Structure of thesis

The framework for this research is shown in Figure 1.4. The research contains four main components influencing energy consumption: building characteristics, energy performance regulations, occupant behaviour and household characteristics. Building characteristics and occupant behaviour affect energy consumption for space and water heating (A). The energy performance coefficient (EPC) determines the thermal properties of housing and the efficiency of systems which, in turn, influence energy consumption. The influence of occupant behaviour on energy consumption may be partly determined by building and household characteristics (B). Behavioural patterns can be observed depending on the use of heating and ventilation systems and on household characteristics. If behavioural patterns could be identified, households could be classified into user profiles (C).

In the total housing stock energy consumption is influenced by more types of building characteristic, since there is greater variation in, for example, insulation levels, HVAC systems, and dwelling size. Occupancy patterns can be observed in recently built housing which are different from those in the total housing stock. It is important to recognise the building characteristics that contribute to such differences and that could cause a rebound effect.

A distinction is drawn between behaviour and use (Kanis, 1998). Behaviour is defined as all the activities that people perform in the house, while use refers to the direct interaction between an occupant and an action to achieve a goal. In this study, behaviour was instead defined as the use of space, systems and other amenities within the house that can influence energy consumption for space and water heating, such as the use of heating and ventilation systems, opening windows and grilles, bathing and showering frequency, use of space and use of heat-generating appliances and electronics.

Occupant behaviour (1a) is believed to be influenced by household characteristics, lifestyle, and cognitive variables (motivation, values and attitudes) (1b). But it can also be influenced by the interaction between the user and the building (1c) and the thermal properties of the building. This research focuses solely on the building and household characteristics that influence occupant behaviour (Figure 1.5).

Figure 1.6 shows the relationship between the chapters and the research questions. Chapter 2 addresses sub-questions 3.1-3.2 regarding the relative effect of building characteristics and occupant behaviour on the total housing stock. Chapter 3 addresses the effect of energy performance regulations in recently built houses, followed by an analysis of the effect of occupant behaviour in Chapter 4. Chapter 4 also studies the determinants of occupant behaviour. This forms the basis for the analysis in Chapter 5, which aims to determine behavioural patterns for user profiles in recently built houses. The total housing stock is studied again in Chapter 6, where the determinants of behaviour are analysed in order to draw a comparison with the situation in recently built housing. The conclusions and recommendations are presented in Chapter 7.

References

Andersen, R.V., J. Toftum, K.K. Andersen & B.W. Olessen (2009), 'Survey of Occupant Behaviour and Control of Indoor Environment in Danish Dwellings', **Energy and Buildings, 41**, pp. 11-16.

Becker, R. & M. Paciute (2009), Thermal Comfort in Residential Buildings – Failure to Predict by Standard Model, **Building & Environment, 44**, pp. 949-960.

Beerepoot, M. (2002), **Energy regulations for new building. In search of harmonisation in the European Union**, Delft University Press, Delft.

Beerepoot, M. & N. Beerepoot (2007), Government Regulations as an Impetus for Innovations, Evidence for Energy Performance Regulation in the Dutch Residential Building Sector, **Energy Policy, 35**, pp. 4812-4825.

Branco, G., B. Lachal, P. Gallinelli & W. Weber (2004), Expected versus Observed Heat Consumption of a Low Energy Multifamily Complex in Switzerland based on Long-term Experimental Data, **Energy and Buildings, 36**, pp. 43-555.

Brown, Z. & R.J. Cole (2009), Influence of Occupants' Knowledge on Comfort Expectations and Behaviour, **Building Research & Information, 37** (30), pp. 227-245.

Conner, C.C. & R.L. Lucas (1990), **Thermostat related behavior and internal temperatures based on measured data in residences**, PNL-7465, Richland, WA: Pacific Northwest Laboratory.

Curtin, R., S. Presser & E. Singer. (2000), The Effects of Response Rate Changes on the Index of Consumer Sentiment, **Public Opinion Quarterly, 64** (4), pp. 413-428.

de Dear, R. (2004), Thermal Comfort in Practice, **Indoor Air**, 14 (7), p. 32.

Dongen, F.E.F. & H. Vos (2003), **Relatie EPC niveau en zelfgerapporteerde gezondheidseffecten. Analyse op basis van geïntegreerde data uit twee onderzoeken**, Rapport 2003-46, Delft TNO-INRO.

Field, A. (2005), **Discovering statistics using SPSS: and sex, drugs and rock'n' roll**, 2nd ed., Sage, London.

Freire, R.Z., G.H.C. Oliveira & N. Mendes (2004), Development of regression equation for predicting energy and hydrothermal performance of building, **Energy and Buildings, 40**, pp. 810-820.

Gommans, L.J. (2008), Energie prestaties van energie-efficiënt gebouwen: tussen ontwerp en werkelijkheid, **TVVL magazine, September 2008**, pp. 18-24.

de Groot E., M. Spiekman & I. Opstelten (2008), Dutch Research into User Behaviour in Relation to Energy Use of Residences, **Proceedings PLEA Conference.**

Haas, R., H. Auer & P. Biermayr (1998), The Impact of Consumer Behaviour on Residential Energy Demand for Space Heating, **Energy and Buildings, 27**, pp. 195-205.

Hens, H., W. Parijs & M. Deurinck (2010), Energy Consumption for heating and rebound effects, **Energy and Buildings, 42**, pp. 105-110.

Holbrook, A., J. Krosnick, & A. Pfent. (2007), The Causes and Consequences of Response Rates in Surveys by the News Media and Government Contractor Survey Research Firms, in: Lepkowski, James M., N. Clyde Tucker, J. Michael Brick, Edith D. De Leeuw, Lilli Japec, Paul J. Lavrakas, Michael W. Link, & Roberta L. Sangster (eds.), **Advances in telephone survey methodology**, New York, Wiley.

Itard, L. & F. Meijer (2008), T**owards a Sustainable Northern European Housing Stock: Figures, facts and future**, IOS Press, Amsterdam.

Jeeninga, H., M. Uyterlinde & J. Uitzinger (2001), **Energieverbruik van energiezuinige woningen**, Report ECN & IVAM, ECN-C-01-072.

Kanis, H. (1998), Usage centered research for everyday product design, **Applied ergonomics, 1** (29), pp. 75-82.

Karjalalainen, S. (2007), Gender Differences in Thermal Comfort and Use of Thermostats in Everyday Thermal Environments, **Building and Environment**, 42, pp. 1594-1603.

Keeter, S., C. Kennedy, M. Dimock, J. Best & P. Craighill (2006), Gauging the Impact of Growing Nonresponse on Estimates from a National RDD Telephone Survey, **Public Opinion Quarterly, 70** (5), pp. 759-779.

KPMG (2006), **Analyse aannames Regeleffecttoets aanscherping EPC woningen**, KPGM Business Advisory Service.

Lan, L., Z. Lian, W. Liu & Y. Liu (2008), Investigation of Gender Difference in Thermal Comfort for Chinese People, **European Journal of Applied Physiology**, 102 (4), p. 471.

Lenzuni, P., D. Freda & M. Del Guadio (2008), **Classification of Thermal Environments for Comfort Assessment**, The Annals of Occupational Hygiene doi:10.1093/annhyg/mep012.

Linden, A.L., A. Carlsson-Kanyama & B. Eriksson (2006), Efficient and Inefficient Aspects of Residential Energy Behaviour: What are the policy instruments for change?, **Energy Policy, 34**, pp. 1918-1927.

Lutzenhiser, L. (1992), A Question of Control – Alternative patterns of room airconditioner use, **Energy and Buildings, 18**, pp. 193-200.

Moujalled, B., R. Cantin & G. Guarracino (2008), Comparison of Thermal Comfort Algorithms in Naturally Ventilated Office Buildings, **Energy and Buildings, 40** (12), pp. 2215-2223.

NEN 5128 (2004), **Energy Performance of Residential functions and residential buildings: determination method**, ics 91.120.10, March.

Nevius, M.J. & S. Pigg (2000), **Programmable thermostats that go berserk? Taking a social perspective on space heating in Wisconsin**, ACEEE Summer Study in Energy Efficiency in Buildings.

Nicol, J.F. & M.A. Humphrey (2009), New Standards for Comfort and Energy Use in Buildings, **Building Research & Information, 37** (1), pp. 68-73.

Nieman (2007), **Eindrapportage woonkwaliteit binnenmilieu in nieuwbouwwoning**, Report Wu060315aaA4.PK, VROM Inspectie Regio Oost, Arnhem.

Pachauri, S. (2004), An Analysis of Cross-sectional Variations in Total Household Energy Requirements in India using Micro-survey Data, **Energy Policy**, 32, pp. 1723-1735.

Papakostas, K.T. & B.A. Satiropoulos (1997), Occupational and Energy Behaviour Patterns in Greek Residences. **Energy and Buildings, 26**, pp. 207-213.

PRC Bouwcentrum BV (2004), **EPC en energieverbruik nieuwbouwwoningen**, Report Novem, Kompas Utrecht.

Schweiker, M. & M. Shukuya (2009), Comparison of Theoretical and Statistical Models of Air-Conditioning-Unit Usage Behaviour in a Residential Setting under Japanese Climatic Conditions, **Building and Environment**, 44, pp. 2137-2149.

Schuler, A., C. Weber & U. Fahl (2000), Energy Consumption for Space Heating of West-German Household: empirical evidence, scenario projections and policy implications, **Energy Policy, 28**, pp. 877-894.

Shipworth, M., S.K. Firth, M.I. Gentry, A.J. Wright, D.T. Shipworth & K.J. Lomas (2010), Central heating thermostat settings and timing: building demographics, **Building Research & Information, 38**, pp. 50-69.

Tabachnick B.G. & L.S. Fidell, (2007), **Using multivariate statistics**, 5th ed., Pearson Education, Inc., USA.

Uitzinger, J. (2004), **Analyse EPC en energieverbruik bij woningen**, Report IVAM/ SenterNovem.

Vierveijzer, P. & A. Wichers Hoeth (2003), **Regeleffecttoets, Aanscherping van de EPC van te bouwen woningen naar 0.8**, Amersfort, DHV, Website: www.vrom.nl, accessed July 2009.

Ye, X.J., Z.P. Zhou, Z.W. Lian, H.M. Liu, C.Z. Li & Y.M. Liu (2006), Field Study of a Thermal Environment and Adaptive Model in Shanghai**, Indoor Air, 16** (4), pp. 320-326.


UBUNTU

2 The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock

Guerra-Santin, O., L. Itard & H. Visscher (2009), The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy and Buildings, 41, pp. 1223-1232.

Abstract
As a consequence of the improved quality of thermal properties of buildings due to energy regulations, overall energy use associated with building characteristics is decreasing, making the role of the occupant more important. Studies have shown that occupant behaviour might play a prominent role in the variation in energy consumption in different households but the extent of such influence is unknown. The impact of the building's thermal characteristics on space heating demand has been well studied. There is however, little work done that incorporates the impact of consumer behaviour. This study aims to gain greater insight into the effect of occupant behaviour on energy consumption for space heating by determining its effect on the variation of energy consumption in dwellings while controlling for building characteristics. The KWR database from the Ministry of Housing in the Netherlands was used. This study showed that occupant characteristics and behaviour significantly affect energy use (4.2%), but building characteristics still determine a large part of the energy use in a dwelling (42%). Further analysis showed that some occupant behaviour is determined by the type of dwelling or HVAC systems and, therefore, the effect of occupant characteristics might be larger than expected, since these determine the type of dwelling.

2.1 Introduction

Diverse factors have caused an increase in energy use throughout the world. Globalisation has spread the lifestyle of the most developed Western countries worldwide, changing the expectations about the quality of life in many societies to a point where sustainability is no longer possible on a large scale. One of the aspects of lifestyle that causes a high environmental burden in developed countries is the use of energy in buildings. Worldwide, the building industry and the built environment are some of the largest contributors to energy and material use. In the northern part of the European Union, 41% of total final energy consumption comes from buildings, with 30% being used in residential buildings (Itard & Meijer, 2008) According to EuroAce (2004) 57% of the energy consumed in buildings is used for space heating, 25% for hot water, 11% for lighting and electrical appliances, and 7% for cooking.

Due to the importance of a good quality of the indoor environment and the problems caused by high energy consumption, governments have enacted a series of policies and regulations aimed at increasing the energy efficiency of dwellings and ensuring a good indoor environment. An example of such initiatives is the EPBD, which from 2003 obliged all European member states to implement performance-based energy regulations aimed at decreasing energy consumption in buildings in relation to heating, cooling, ventilation, lighting and domestic hot water. In addition, efforts to construct low energy buildings can be observed in several projects and studies worldwide. Nevertheless, energy savings due to energy conservation measures are suspected to be lower in reality than predicted (Branco *et al.*, 2004; Haas *et al.*, 1998; Hirst & Goeltz, 1985).

The importance of building characteristics has been determined in diverse studies. Leth-Petersen & Togeby (2001) studied the influence of building regulations on energy use, finding that they have been important in reducing energy consumption in new buildings. As a consequence, overall energy use associated with building characteristics is decreasing, making the role of the occupant even more important (Haas *et al.*, 1998; de Groot *et al.*, 2008; Papakostas & Sotiropoulos, 1997). In the Netherlands, Beerepoot & Beerepoot (2007) found that energy performance regulations have been successful in conserving energy. Nevertheless, the variation in energy consumption is still large for dwellings with the same characteristics.

Studies have shown that occupant behaviour might play a prominent role in the variation in energy consumption in different households (Branco *et al.*, 2004; Jeeninga *et al.*, 2001), but the extent of such influence is still unknown. The impact of the building's thermal characteristics on space heating demand has been well studied, quantified and validated from the viewpoint of individual buildings and building simulation, and can now be found in various handbooks (for example, Clarke, 2001; Ashrae, 2005; ISO, 2004; ISO, 2008). There has, however, been little work done on the impact of the thermal characteristics of building stock from a statistical perspective. There is also little work that incorporates the impact of consumer behaviour (Haas *et al.*, 1998). In addition, there is little information on the effect of occupant behaviour taking into account building and household characteristics.

This study aims to gain greater insight into the effect of occupant behaviour on energy consumption for space heating by determining its effect on the variation of energy consumption in dwellings while controlling for building characteristics. In addition, this study aims to determine the respective effect of building and occupant attributes on energy use, and the relationship between them. The research questions of the study are:

1. What are the most important characteristics of the building and occupancy (defined as household characteristics and occupant behaviour) that affect energy use for space heating?
2. How much of the variation in energy use can be explained with a model combining both types of variables?
3. What is the relationship between building and occupancy characteristics?

Section 2.2 will provide a literature survey which will determine the parameters used in the model, while Section 2.3 will present the analysis methods and data used. Section 2.4 will present the results of the statistical analyses, firstly introducing the differences in energy use for different types of dwellings with different levels of insulation, and secondly introducing the results of the regression analysis and its comparison with a model containing only occupant-related variables. Section 2.5 will provide the conclusions of the study and make recommendations for further research.

2.2 State of the art

The actual amount of energy used in buildings is often different from the calculated or expected energy use. According to Haas *et al.* (1998), energy savings due to conservation measures will be lower in practice than those calculated because the impact of consumer behaviour is neglected. The difference between actual and predicted energy use depends on the final realisation of the construction and the technical installations (Elkhuizen *et al.*, 2006; Nieman, 2007), and on the utilisation of the dwelling's systems, such as interior temperature and ventilation rate (Branco *et al.*, 2004). For example, in this experimental study by Branco *et al.* (2004), conducted over three years in multi-family buildings in Switzerland, the real energy use was 50% higher than the estimated energy use (246 MJ/m^2 as opposed to 160 MJ/m^2), the differences being due to the real conditions of utilisation, the real performance of the complete technical system and the actual weather conditions. According to the results of an empirical study in the Netherlands by ECN and IVAM (2001), an energy intensive lifestyle in a very energy efficient residence can lead to higher energy use than an energy extensive lifestyle in a less energy efficient residence. In a study on the effect of an energy audit on energy use in dwellings in the USA, Hirst & Goeltz (1985) found that less energy was saved than was predicted by the audit.

Energy use for space heating depends on the heat gains and losses of a dwelling, which are determined by its technical and architectural characteristics on the one hand and by the behaviour of the residents on the other (Papakostas & Sotiropoulos, 1997). The parameters influencing energy demand for space heating are: the thermal quality of the building, building

Table 2.1 International references per type of study

Building characteristics		**Household characteristics**	
Urbanisation rate	Assimakopoulos 1992 (Greece, empirical)	Age respondent, household size, income	Liao & Chang 2002 (USA) Assimakopoulos 1992 (Greece) Jeeninga *et al.* 2001 (the Netherlands) Vringer 2008 (the Netherlands) Sardianou 2008 (Greece) Lenzen *et al.* 2006 (International) Schuler *et al.* 2000 (Germany) Pachauri 2004 (India) Hirst & Goeltz 1985 (USA, monitoring) Biesiot & Noorman 1999 (the Netherlands)
Vintage of building	Assimakopoulos 1992 (Greece) Leth-Petersen & Togeby 2001 (Denmark) Liao & Chang 2002 (USA) Hirst & Goeltz 1985 (USA, monitoring)	Ownership	Leth-Petersen & Togeby 2001 (Denmark)
Design of dwelling	Assimakopoulos 1992 (Greece) Leth-Petersen & Togeby 2001 (Denmark) Haas *et al.* 1998 (Australia) Liao & Chang 2002 (USA) Sonderegger 1977-78 (USA) Sardianou 2008 (Greece) Lenzen *et al.* 2006 (International) Schuler *et al.* 2000 (Germany) Pachauri 2004 (India)	**Behaviour**	
		Preferences in space heating	Leth-Petersen & Togeby 2001 (Denmark) Haas *et al.* 1998 (Australia) Linden *et al.* 2006 (Sweden) Jeeninga *et al.* 2001 (the Netherlands) Tommerup *et al.* 2007 (Denmark, monitoring)
Insulation	Assimakopoulos 1992 (Greece) Haas *et al.* 1998 (Australia) Sonderegger 1977-78 (USA) Hirst & Goeltz 1985 (USA, monitoring)	Presence at home and hot water use	Papakostas & Satiropoulos 1997 (Greece) Boonekamp 2005 (the Netherlands, simulation model)
Heating systems	Leth-Petersen & Togeby 2001 (Denmark) Hirst & Goeltz 1985 (USA, monitoring)	Ventilation	Iwashita & Akasaka 1997 (Japan, monitoring) Ernhorn 1988 (Germany, monitoring) Liddament & Orme 1998 (UK, monitoring)
Energy type	Leth-Petersen & Togeby 2001 (Denmark)	Values	Vringer *et al.* 2007 (the Netherlands)

type, occupant behaviour and climate. Table 2.1 presents international studies that relate energy use to building characteristics, household characteristics and occupant behaviour. These are explained in more detail in the following subsections. More detailed results from international studies and their comparison with the results of this study can be found in the discussion section.

2.2.1 Household characteristics

Household characteristics have been found to influence energy use for heating in residential buildings. According to several authors, age is an important characteristic determining energy use. In general, older households tend to consume more energy than younger households, especially for space heating (Liao & Chang, 2002; Linden *et al*., 2006). The number of occupants in the dwelling is also an important parameter for energy use. Linear correlations between household size and energy use have been found in several international studies (Table 2.1).

Household income has proven to be an important factor in determining energy use. For example, in a study based on the expenditure and energy use of 2,800 households in the Netherlands, Vringer (2005) found that a 1% increase in income results in a 0.63% increase in energy use. However, he admits that within the same income category the bandwidth of energy use is substantial and therefore not all the variation can be explained by income. Biesiot & Noorman (1999), using data from household budget surveys, energy prices and the primary energy requirements of goods in the Netherlands, found an almost linear relationship between expenditure and energy use, confirming that the higher the disposable yearly income, the higher the energy requirements.

Leth-Petersen & Togeby (2001) found that more energy is used in rented dwellings compared to those which are owner-occupied. This was linked to the costs of the energy required for heating being included in the rent, and to multi-family dwellings with collective metering.

2.2.2 Behaviour

Motivation is thought to have a great influence on the variation in energy consumption in different households (Vringer & Blok, 2007; Linden *et al.*, 2006). There are differences in energy use that are not explained by occupant characteristics such as household size, level of education and age distribution (Vringer & Blok, 2007). Vringer *et al.* (2007) investigated the effect of value patterns, motivation and problem perception in relation to climate change on energy use in the Netherlands, taking into account household socioeconomic differences. They found no significant differences between the energy requirements of groups with different value patterns, with the exception that 4% more energy is used by families that are least motivated to save energy.

According to some authors, occupant behaviour affects energy use to the same extent as mechanical parameters such as equipment and appliances (Haas *et al.*, 1998), causing variations in energy use as large as a factor of two in similar dwellings with identical equipment and appliances. In an empirical study of 600 households in Sweden, Linden *et al.* (2006) found that households living in detached houses have to accept lower indoor temperatures than households living in flats. In addition, they found that for households living in dwellings where the energy bill is paid collectively, the indoor temperature is higher by about 28^{0}C, indicating that the differences are more likely to be due to occupant behaviour than to building characteristics.

Furthermore, some authors have found evidence of a rebound effect. Haas *et al.* (1998) argued that increases in energy efficiency will lead to cheaper prices for the service provided and a substantial increase in service and energy demand. This is supported by the fact that some authors have found no linear relationship between energy use for space heating and the thermal characteristics of a building, while a linear relationship has been found between energy demand for space heating and indoor temperature (Haas *et al.*, 1998). Indoor temperature is often different for different types of buildings and heating systems due to occupant preferences and consumer behaviour (Leth-Petersen & Togeby, 2001), which may also depend on the thermal quality of the building and the climate (Haas *et al.*, 1998).

Ventilation and air infiltration are important factors with respect to energy use because in more thermally efficient buildings these become the dominant thermal loss mechanisms (Liddament & Orme, 1998). Some studies suggest that ventilation from windows accounts for a large percentage of the ventilation rate in occupied dwellings (Iwashita & Akasaka, 1997). Iwashita & Akasaka (1997) undertook ventilation measurements in Japan, finding that there are large differences between the mean ventilation rate during occupancy of the dwellings and the mean ventilation rate during non-occupancy (doors and windows closed), and that a large percentage of the total air change rate (87%) is due to the behaviour of the occupants. Erhorn (1988) in a study in Germany found that natural ventilation is most frequent in bedrooms, followed by children's rooms and living rooms. A correlation between ventilation habits and outdoor air temperature and wind velocity were also found, and in general it was found that night-time ventilation occurs less frequently than daytime ventilation.

The use of a heating system has been found to be an important factor in determining energy use in residential buildings. Several authors have found linear relationships between temperature setting and energy consumption (see Table 2.1). The presence of people at home has also been found to influence energy use for space heating (Papakostas & Sotiropoulos, 1997).

2.3 Data and analysis methods

The data used for this study comes from the *Kwalitatieve Woning Registratie* (KWR) of the Ministry of Housing of the Netherlands (VROM). The most recent version of this survey was completed in 2000 and includes data on housing quality in a sample of 15,000 houses across the Netherlands. It was an interview-based survey which included, among other categories, data on household characteristics and the use of the dwelling, such as presence at home, heating and ventilation behaviour. The database also includes data from the inspection of the building characteristics of the dwelling, such as the percentage of insulation per surface, type of materials, or type of heating system. The data for three years of energy use was obtained from energy providers.

The KWR database has the advantage of the sample size being quite large (around 15,000 cases) and that it was carried out randomly across the Netherlands. In addition, it includes data on building characteristics, household characteristics and occupant behaviour. The main disadvantage is that the behaviour variables are in the form of categorical values. These variables, such as presence of people at home and ventilation frequency, had to be re-categorised. In addition, the number of cases in each category differed greatly, with the majority of cases being relevant to only one or two categories. Therefore, dichotomous variables were used, indicating the presence or absence of a type of behaviour or particular building characteristics. The year of publication of the database might also be considered a disadvantage, but changes in time or energy prices are not considered in this study.

The analysis methods used in this study were a two-way between groups ANOVA and regression analysis with SPSS. The two-way ANOVA was first used to determine the variations in energy use for heating in different types of dwellings with different insulation levels, and to determine the variation in energy use not accounted for by these main building characteristics.

For the regression analysis, three types of variables were used: building characteristics, household characteristics and occupant behaviour. Building characteristic variables are those related to the type of dwelling (detached or free-standing, corner, row, double, flats and maisonettes or two-floor flats), size of dwelling, type of insulation and the presence of various kinds of rooms. Household characteristics define the users of the dwelling, such as age, number of people in the household and income. Occupant behaviour is based on lifestyle and the preferences of the occupants in relation to the use of heating and ventilation systems.

Multiple regression analysis was used in order to determine the respective influence of building characteristics and occupant behaviour on energy use. According to Schuler *et al.* (2000), regression equations allow an analysis of factors influencing energy-related aspects of dwelling use and choice that simulation tools do not. The use of micro-level data on household behaviour and energy use is more suitable to analyse the nature of user behaviour (Pachauri, 2004). In addition, according to Freire *et al.* (2004), regression equations are a faster and easier way to predict energy use in a large sample of dwellings than are building simulation tools. Regression models have been used to understand behaviour in different climate conditions and for energy demand forecasting. These models usually include energy demand, energy prices, disposable yearly income, geographic, socioeconomic, demographic and dwelling characteristics (Assimakopoulos, 1992), but not occupant behaviour or preferences.

Regression analysis was used to model the energy consumption in dwellings in relation to occupant behaviour and building characteristics. To determine the effect of occupant behaviour and household characteristics in the model, the regression analysis was carried out in steps in order to control for building characteristics. The variables were entered into the model with respect to their importance as determined by a preliminary stepwise regression analysis and the literature study in Section 2.2.

2.3.1 Transformed variables

Most of the variables were shown to be parametric (no large kurtosis or skewness and normally distributed in graph) and as having linear relationships, the only exceptions being the dependent variable of 'energy for space and water heating (MJ)' and the variable of 'useful living area'. Therefore, both variables were transformed according to their characteristics (Field, 2005): the variable 'energy used' was transformed into its square root and 'useful living area' was transformed with logarithm 10. Nevertheless, further analysis showed no differences in the results or assumptions for models run with the variable 'energy used' and the transformed variable of 'energy used', therefore, the non-transformed variable was used for an easier interpretation of the results. The variables related to insulation and glazing were modified so they could be entered into the regression. Since the variables had a large number of values at either zero or 100 and very few values around the middle, the variables were transformed into dichotomous variables, with any value under 10% equal to zero and values above 10% equal to 1.

Dichotomous variables were also used for 'thermostat as temperature control', 'heating included in rent', 'presence of bath' and 'open kitchen'. 'Home tenure', originally classified into 'private rent', 'social rent' and 'owned', were recoded dichotomously using 'private rent' and 'others' because the last two were shown to be not significant. 'People at home during the day' and 'people at home during the weekend', originally classified into: 'almost always', 'very variable', '50-50' and 'occasionally or never', were converted into the dichotomous variables 'almost always home' and 'other'.

Dummy variables were used for the type of dwelling. The free-standing dwelling was used as a reference because it is considered to be the most energy-consuming type of dwelling. Therefore 'free-standing dwelling' does not appear in the model.

2.3.2 Missing data and univariate outliers

There was missing data for some variables, such as construction year (in 24 cases), temperature setting (in 6 cases), glass insulation (in 4 cases) and local heating in living room (in 7 cases) in a total sample of 14,848. These values were replaced by the mean in the case of continuous variables and by the mode in the case of dichotomous variables, because the very small number of cases should not affect the model.

Using scatterplots, univariate outliers were found in the following variables:

construction year, temperature setting during the day, night and evenings, number of rooms in the dwelling and household size. There were 224 outliers for construction year, while for the rest of the variables, less than 50 cases were found. The outliers were analysed and found to be real values and were therefore left in the sample.

2.4 Results

In this section, the results of the statistical analysis will be described. Firstly, the statistical differences between different combinations of building characteristics are examined. This is followed by a description of a regression model. Finally a second regression model and correlations are used to analyse other relationships between variables.

2.4.1 Differences in energy use per type of dwelling and insulation level

The difference in energy use between different types of dwellings can be seen in Figure 2.1. Free-standing houses consume more energy than other types of dwellings, with the mean for detached houses more than double the mean for flats. In addition, the graph shows the standard deviation for each type of dwelling, meaning that the variation in energy use per type of dwelling is large. Figure 2.2 shows the mean for energy use and standard deviations for different types of insulation level. Energy use in better insulated houses is lower than in less insulated houses, but the standard deviations are also large. In order to test statistically the effects of type of dwelling and insulation level, a two-way ANOVA analysis was carried out. The results are described in the following section.

2.4.2 Results of analysis of variance

A two-way ANOVA was conducted to determine the variance in energy use in different types of houses with different levels of insulation. The variables included were the categories of dwelling – free-standing, double, corner, row dwellings, flats and maisonettes – and the classification of insulation level – 1 being less than 25%, 2 being between 25% and 50%, 3 being between 50% and 75% and 4 being more than 75% – .

The results show that there is a main effect of type of dwelling on energy use ($p < 0.01$). As can be seen from Figure 2.3, detached dwellings in general have a higher energy use than all other dwellings, followed by double dwell-

Figure 2.1 Mean and standard deviation for energy use (MJ/year) per type of dwelling

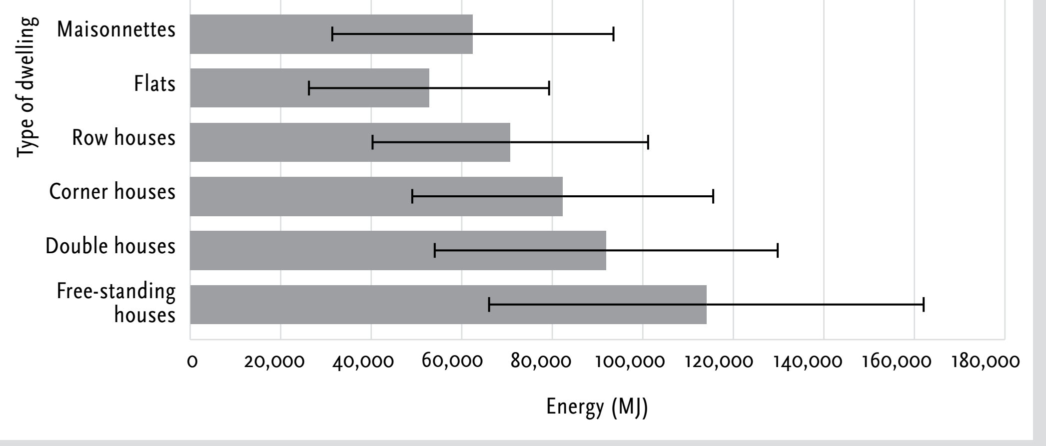
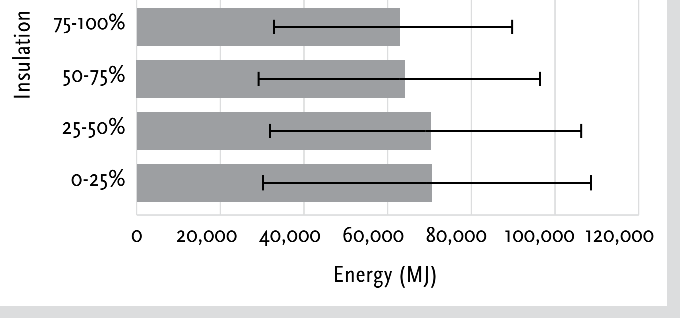


Figure 2.2 Mean and standard deviation for energy use (MJ/year) per insulation degree category



ings, corner dwellings, row dwellings, maisonettes and flats. Statistically significant differences between all types of dwellings were found.

Furthermore, there is a main effect for class of insulation level ($p < 0.01$). Statistically significant differences are observed between all levels of insulation. Finally, the results show an interaction effect between insulation level and type of dwelling ($p < 0.01$). In general, the highest insulation classification is related to the least energy use. However, this is not the case for flats. Flats with Type 4 insulation classification levels are related to more energy use than flats with Type 3 and Type 2 insulation classes, which could be explained by the fact that insulation Type 2 and Type 3 are misrepresented in the sample. The results can be graphically seen in Figure 2.3, where the estimated marginal means on energy use are presented for different combinations of type of dwelling and insulation degree. Flats use visibly less energy than any other type of dwelling, followed by maisonettes and row houses. It is also apparent that the higher the insulation classification, the less energy is used. The results from the analysis are in accordance with other studies and theories. Table 2.2 shows the number of cases and percentage of the sample for each type of dwelling and insulation level.

Figure 2.3 Mean energy use per type of dwelling and insulation level

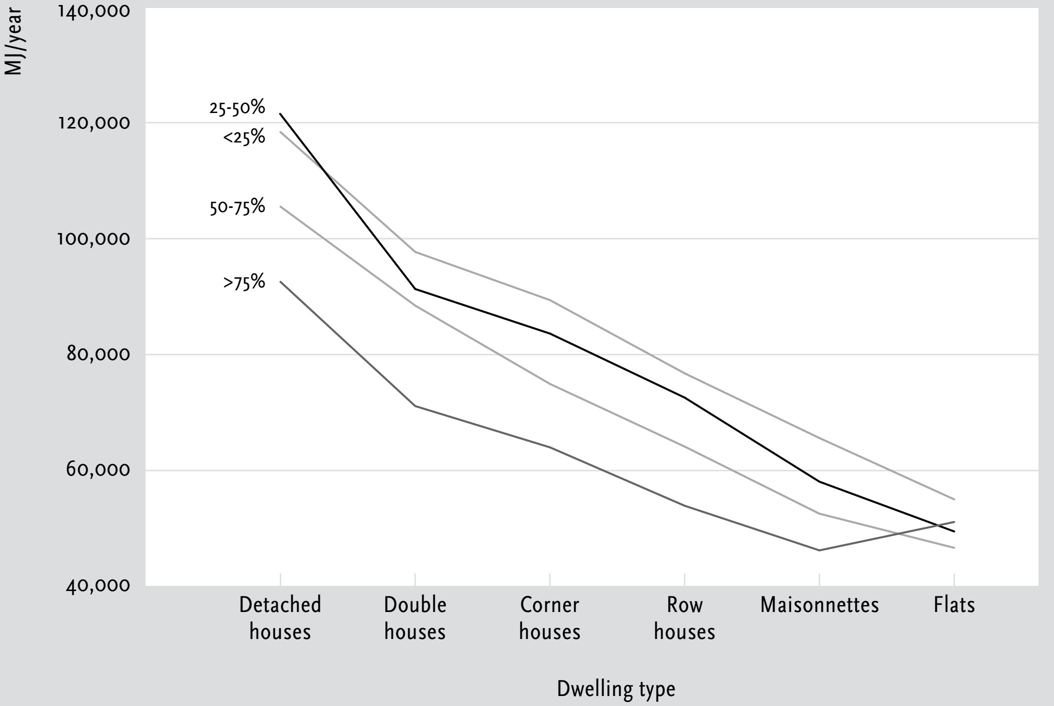


Table 2.2 Mean and standard deviation for continuous variables

	Mean	SD
Energy for space and water heating (MJ)	69,345.30	36,247.55
(LOG) useful living area (m^2)	1.95	0.17
Construction year	1,944.43	29.73
Number of rooms	3.95	1.33
Number of heated bedrooms	0.89	1.19
Temperature during the night (in degrees Celsius)	14.76	2.27
Temperature during the evening (in degrees Celsius)	20.28	1.62
Temperature during the day (in degrees Celsius)	19.29	2.23
Age of respondent	51.00	17.00
Household size	2.13	1.18
Income (in euros)	23,866.71	16,496.91

Table 2.3 Number of cases and percentage of cases for dichotomous variables

	Number of cases	Percentage
Type of dwelling: maisonettes	1,634	11.0%
Type of dwelling: flats	5,583	37.6%
Type of dwelling: row houses	3,718	25.0%
Type of dwelling: double houses	1,014	6.8%
Type of dwelling: corner houses	1,766	11.9%
Insulation of façade	4,991	33.6%
Double glazing	10,968	73.9%
Insulation on ground	2,115	14.2%
Insulation of windows	3,161	21.3%
Insulation in roof	5,376	36.2%
Thermostat as temperature control	9,209	62.0%
Insulation of central-heating pipes	2,474	16.7%
Presence of garage	2,418	16.3%
Presence of shed	7,356	49.5%
Presence of basement	4,307	29.0%
Open kitchen	4,377	29.5%
Presence of bath	5,468	36.8%
Local heating in living room	5,160	34.8%
Always people during weekends	11,211	75.5%
Always people during day	7,707	51.9%
Private rent	5,165	34.8%
Heating included in rent	1,441	9.7%

2.4.3 Regression model for prediction of energy use for space and water heating

A screening of the variables was done in order to determine the variables to be used in the regression model. Firstly, important variables were identified according to the hypothesis as well as other studies; secondly, a stepwise regression analysis was performed to determine the statistically significant contributors to energy use. The selected variables were then introduced into a standard regression analysis. Variables related to ventilation behaviour were found to be not significant and therefore they were left out of the model.

Table 2.3 presents the variable means and standard deviations. The number and percentages of cases for dichotomous and dummy variables are shown in Table 2.2. The equation of the regression model describes the consumption of energy for space heating at the building level on the basis of technical characteristics of the building, occupant behaviour and household characteristics. The regression model consists of three steps: a first step including building characteristics, a second step introducing dummy variables for type of dwelling and a third step introducing behaviour variables. According to the model

Table 2.4 B, Standard deviation of B and Beta of regression model

	B	Std. Error B	Beta
(Constant)	82,434.12	17,531.15	
Step 1. Dwelling characteristics (R^2 = 38%)			
(LOG) Useful living area	68,736.65	2,366.59	.321***
Construction year	-99.80	8.78	-.082***
Insulation of façade	-6,692.96	569.73	-.087***
Double glazing	-5,237.98	561.27	-.063***
Insulation on ground	-6,334.36	728.50	-.061***
Insulation of windows	-2,178.48	574.95	-.025***
Insulation in roof	-975.71	558.56	-.009
Insulation of central-heating pipes	842.58	269.11	.020**
Number of rooms	1,535.17	276.52	.056***
Presence of garage	3,644.77	729.16	.037***
Presence of shed	1,592.32	517.13	.022**
Presence of basement	2,725.45	515.13	.034***
Open kitchen	-1,660.54	523.42	-.021**
Presence of bath	3,072.89	527.10	.041***
Thermostat as temperature control	5,755.98	597.38	.077***
Step 2. Type of dwelling (R^2 = 3.8%)			
Maisonettes	-32,400.93	1,210.10	-.280***
Flats	-25,891.05	1,192.08	-.346***
Row houses	-25,437.80	1,031.46	-.304***
Double houses	-11,594.73	1,175.94	-.081***
Corner houses	-14,497.99	1,089.24	-.129***
Step 3. Household characteristics and behaviour (R^2 = 4.2%)			
Number of heated bedrooms	3,895.47	198.05	.128***
Temperature during the night	834.98	158.40	.037***
Temperature during the evening	972.92	102.46	.061***
Temperature during the day	765.48	124.28	.047***
Local heating in living room	861.76	556.05	.011
Age of respondent	136.19	15.84	.064***
Household size	544.86	241.67	.018*
Private rent	1,515.68	499.62	.020**
Income	.09	.02	.043***
Heating included in rent	3,152.95	807.26	.026***
Always people during weekends	2,210.64	565.78	.026***
Always people during day	2,722.26	528.71	.038***

Dependent variable: energy for heating MJ.
R^2 = .379 for step 1, ΔR^2 = .038 for step 2, ΔR^2 = .042 for step 3.
* = < 0.05, ** = < 0.01 and *** = < 0.001

(Model 1), 37.9% (R^2 = 0.379) of the variability in energy use is accounted for by building characteristics. An additional 3.8% (R^2 = 0.038) is accounted for by the type of dwelling. The addition of behavioural predictors caused the variation to increase by 3.4.2% (R^2 = 0.043).

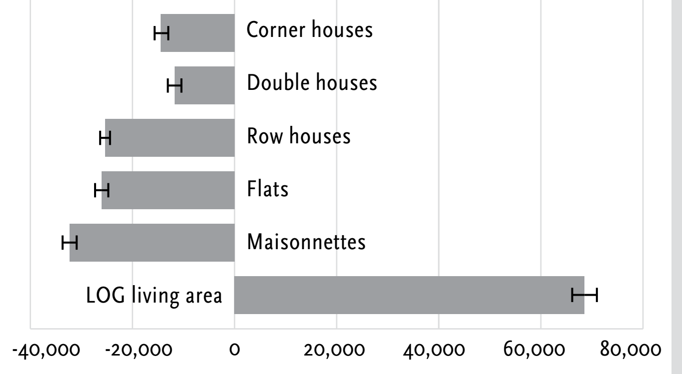
The assumption of independent errors (autocollinearity) has almost certainly been met, the Durbin Watson value being very close to 2 (2.008). A 95% confidence interval for B showed that the model is good. The model seems not to have collinearity problems, because tolerance values and VIF are within the limits. The analysis of residual statistics revealed that there are no large problems with outliers in the model. The values on Cook's Distances all lie well below 1, there are only 58 (0.4%) beyond 3 times the Leverage Value. In 3.2% of the cases there is a large Mahalanobis distance (approximately, a critical value of Chi-square of 54 for a model of 32 variables), and less than 2% of cases are beyond 3 standard residuals. The covariance ratio and DFBeta statistics were also examined and there were no cases found that would have a large influence on the regression parameters. Therefore we can conclude that our model is fairly accurate. In addition, when the regression analysis was run without outliers and compared with the model with outliers (standard residuals, covariance ratio, Mahalanobis distance and leverage values), no large differences in the outcome were found.

In Table 2.4, the coefficients of B and Standard Error of B as well as the standardised coefficient Beta for all variables in steps 1 (building characteristics), 2 (type of dwelling) and 3 (occupant behaviour) of the model are shown. Most of the predictors are statistically significant at the .001 level, with the exception of 'open kitchen' and 'presence of shed', which are significant at the .01 level, 'household size' at a 0.05 level, and 'insulation in roof' and 'local heating in bedroom', which are not significant.

The regression model predicting the energy for heating can be summarised as:

Energy for space and water heating per year = 82,434.12 (LOG useful living area) (68,736.65 MJ) + (construction year) (99.80 MJ) + (insulation of facade) (6692.96) + (double glazing) (5237.98) + (insulation on ground) (6334.36) + (insulation of windows) (2178.48) + (insulation in roof) (975.71) + (insulation of pipes) (842.58) + (number of rooms) (1535.17) + (garage) (3644.77) + (shed) (1592.32) + (basement) (2725.45) + (open kitchen) (-1660.54) + (bath) (3072.89) + (thermostat) (5755.98) (maisonette) (32,400.93 MJ) + (flat) (25,891.05) + (row) (25,437.80) + (double) (11,594.73) + (corner) (14,497.99) heated rooms) (3895.47) + (temperature during the night) (834.98) + (temperature during the evening) (972.92) + (temperature during the day) (765.48) + (local heating in living room) (861.76) + (age respondent) (136.19) + (household size) (544.86) + (private rent) (1515.68) + (income) (0.094) + (heating in rent) (3152.95) + (always people weekdays) (2210.64) + (always people weekends) (2722.26).

Figure 2.4 Energy saved or spent for an increase of one unit in LOG living area, and by type of dwelling in comparison to detached dwellings



Building characteristics

The B coefficient indicates to what degree each predictor affects the outcome if the effects of the other predictors are held constant. It can be seen that '(LOG) useful living area' is one of the most important predictors of the outcome according the standardised Beta coefficient. The estimate has the expected positive sign, which is in accordance with energy prediction theory at the building level.

The vintage of the dwelling is also important in predicting energy use. Newer dwellings use less energy, also expected by the theory.

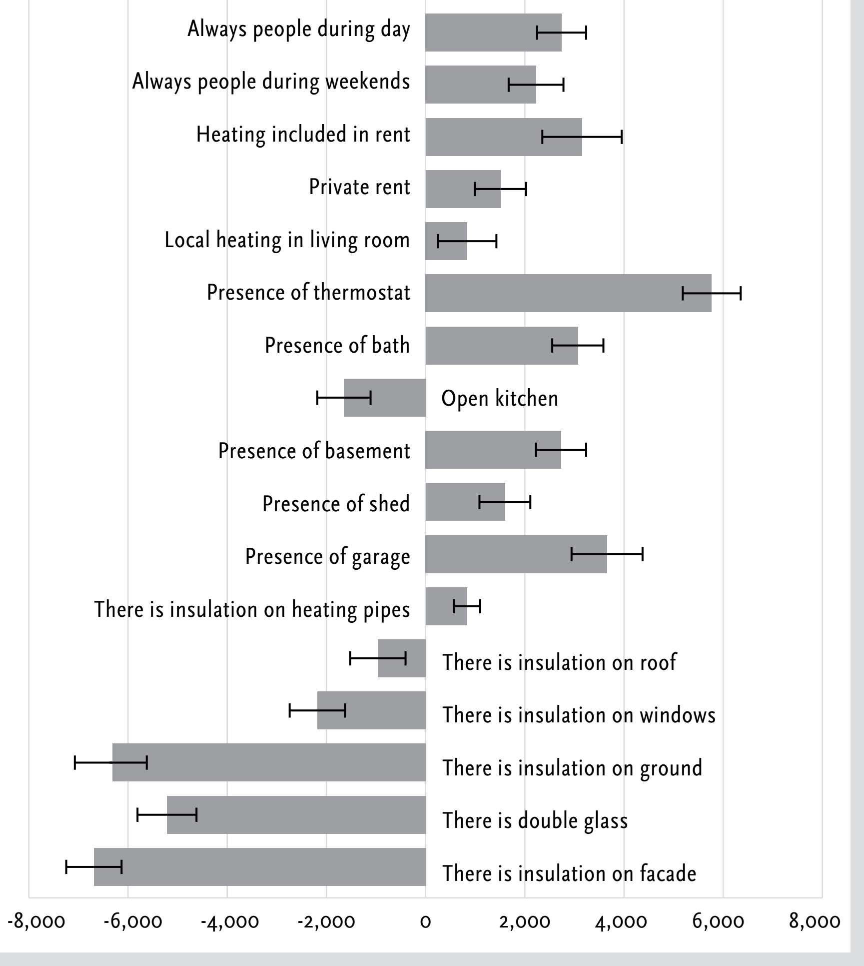
The sign of predictors related to insulation are all in accordance with what was expected. The Beta values show that the type of insulation with the most influence in relation to reducing energy use is insulation of the facade, followed by double glazing, insulation on the ground and insulation of windows, although the differences between insulation on the ground and of the facades are small. Insulation in the roof was shown to be not significant. With one of the lowest Beta values, the insulation of central-heating pipes causes more energy use, which was not expected, since insulation should decrease energy use.

The use of a thermostat for temperature control was shown to increase energy use, in contrast to houses with temperature control in the form of taps. This could be explained by the fact that in dwellings with a thermostat occupants are more aware of the temperature in the home and therefore tend to turn it on more often that those without a thermostat.

Energy use increases with each extra room in the dwelling, as well as with the presence of a garage, shed and basement, possibly because such places are heated. However, if an open kitchen is present, energy use is reduced. The presence of a bath also increases energy use for water heating.

Using dummy coding to analyse the effect of type of dwelling on energy use, and taking a detached dwelling as a reference, we can see that less energy is used in maisonettes, followed by flats and row houses, which show little difference in energy use. Double dwellings and corner houses also use less energy than detached houses. This indicates that the dwellings that perform

Figure 2.5 Energy saved or spent when a variable is present, in comparison to cases when the variable is not present



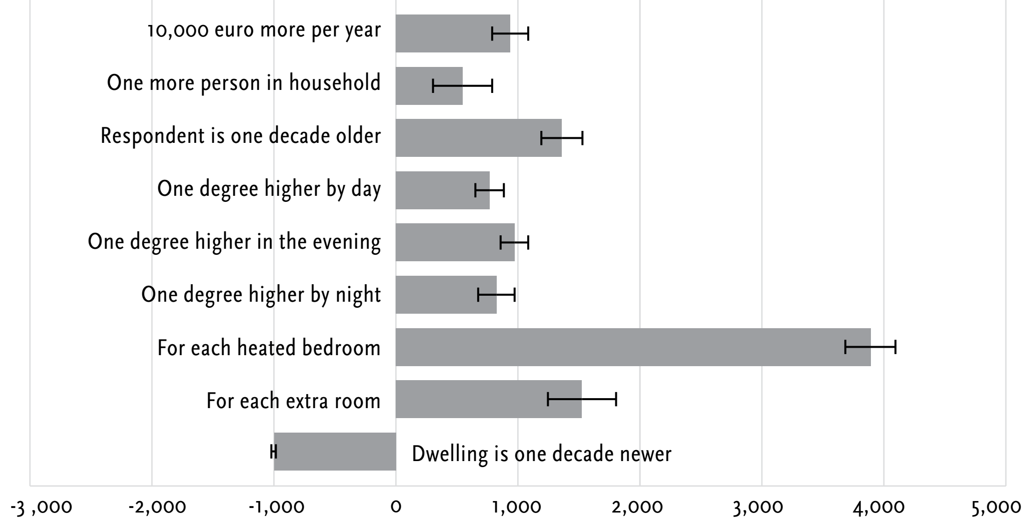
better in terms of energy use are maisonettes, followed by flats and row houses.

Occupant characteristics and behaviour

After controlling for building-related variables, the quantity of heated bedrooms is the variable with the most influence on the model in relation to occupant behaviour, and one of the most important predictors in the model. This variable has more influence on the model than the number of rooms in the dwelling.

The setting of temperature during the evening and night has a greater influence than the setting of temperature during the day. Per degree of increase in temperature during the evening and night, energy use increases by 989.692 and 969.028 MJ, respectively, while during the day it increases by 736.348 MJ. This has a large impact because of the large variation in temperature preferences. The presence of local heating in the living room was found

Figure 2.6 Energy saved or spent for an increase of one unit in a continuous variable



to be not significant.

In dwellings where there is always somebody at home during the day, more energy is used than in houses where there is nobody home during the day or where the presence of people during the day varies considerably. This also applies for the weekend: in houses where there is always somebody home more energy is used than in dwellings where nobody is home or where this varies considerably.

Household characteristics

More energy is used in larger and older households. Income was also found to be a determinant of energy use, as does the type of tenure of a dwelling. More energy is used in privately rented dwellings than in those with socially subsidised rent or privately owned. This could be due to the lower quality of privately rented dwellings compared to others. In addition, in houses where heating is included in the rent, more energy is used.

2.4.4 Prediction of energy use for heating according to individual building characteristics and occupant behaviour

With the results of the regression model, we can predict the amount of energy that can be saved depending on individual building characteristics, occupant behaviour and household characteristics. Figure 2.4 shows the energy prediction for different types of dwellings, which are the most important predictors in the model. In comparison to detached dwellings, row houses, flats and maisonettes can save twice as much energy as a corner or double house. As can be seen in Figure 2.4, more energy use is expected for each one-unit step of (LOG) living area in a dwelling.

Figure 2.5 shows the energy prediction for a dwelling, based on the pres-

Table 2.5 Comparison of Beta values of regression model with behaviour model

Dwelling characteristics	Beta second model	Beta model building
(LOG) Living area	.321***	.352***
Construction year	-.082***	-.065***
Insulation of façade	-.087***	-.086***
Double glazing	-.063***	-.062***
Insulation on ground	-.061***	-.065***
Insulation of windows	-.025***	-.020**
Insulation in roof	-.009	-.020**
Insulation of heating pipes	.020**	.021***
Number of rooms	.056***	.087***
Presence of garage	.037***	.045***
Presence of shed	.022**	.028***
Presence of basement	.034***	.040***
Open kitchen	-.021**	-.029***
Presence of bath	.041***	.039***
Presence of thermostat	.077***	.084***
Type of dwelling		
Maisonettes	-.280***	-.295***
Flats	-.346***	-.352***
Row houses	-.304***	-.316***
Double houses	-.081***	-.082***
Corner houses	-.129***	-.134***

Dependent variable: energy for heating MJ.
* =< 0.05, ** = < 0.01 and *** = < 0.001

ence of a building characteristic or behaviour. For example, when an open kitchen is present, a reduction of 1,700 MJ/year is expected, in comparison to cases where no open kitchen is present. The most important variables are the presence of insulation and the presence of a thermostat for temperature control.

Figure 2.6 shows the energy prediction for continuous variables, indicating the energy saved or spent for an increase of one unit of the variable. For example, for an increase of 10,000 euros per year in income, 1,000 MJ/year more energy will be used.

Figures 2.4-2.6 show the importance of a variable in relation to other variables. Of the behaviour variables, the presence of people during the day and on weekends is as important as the presence of a bath or basement, or the insulation of windows. A degree Celsius higher in the temperature setting is as important as insulation in the roof or an increase in income by 10,000 euros. Heating an extra bedroom increases energy use by 4,000 MJ/year, while having double glazing decreases energy use by 5,000 MJ/year.

Table 2.6 Comparison of Beta values of regression model with building model

Household characteristics and behaviour	Beta second model	Beta model behaviour
Number of heated bedrooms	.128***	.216***
Temperature during the night	.037***	.108***
Temperature during the evening	.061***	.000
Temperature during the day	.047***	-.011
Local heating in living room	.011	.105***
Age of respondent	.064***	.161***
Household size	.018*	.159***
Private rent	.020**	.012
Income	.043***	.172***
Heating included in rent	.026***	-.039***
Always people on weekends	.026***	.051***
Always people during the day	.038***	.064***

Dependent variable: energy for heating MJ.
* = < 0.05, ** = < 0.01 and *** = < 0.001

2.4.5 Second regression model

A second regression model determining the influence of a building's characteristics while controlling for household characteristics and behaviour, showed large differences in comparison to the original model. $R^2 = .20$ for the first step (only behaviour and household characteristics), $R^2 = .225$ for the second step (building characteristics), and $R^2 = .033$ for the third step (dwelling type). Table 2.5 compares the Beta values of the original model to a model with only building characteristics and Table 2.6 compares the regression model with a model with only behaviour and occupant variables. The differences between the main model and the model with only building characteristics are not large. In the behaviour model, there are behaviour variables with large partial correlations, which in principle would indicate a greater influence in the model. Nevertheless, these variables are correlated to variables of building characteristics. Therefore, correlations between variables are further analysed in this section.

For local heating in living room, the Beta value increased from being not significant to .105 and significant at the .001 level. Correlations were found with thermostat and construction year. Partial correlations were used to explore the relationship between these variables, finding a medium negative partial correlation between local heating in living room and the presence of a thermostat ($r = .386$, $p < .001$), meaning that the presence of a thermostat is associated with no local heating in the living room. A small negative correlation was found between local heating and construction year ($r = .271$, $p < .001$), indicating the presence of local heating in the living room of older houses

The influence of age of respondent also increased in the behaviour model. A positive small partial correlation was found with useful living area ($r = .021$, $p < .05$) and with construction year ($r = .141$, $p < .001$), indicating that old households have larger and older houses than young households.

Positive medium partial correlations were found between household size and useful living area ($r = .330$, $p < .001$), and household size and number of rooms ($r = .424$, $p < .001$), with large households being associated with larger dwellings. Therefore, the increase in the Beta value in relation to household size is a result of these correlations.

The influence of income increased from a Beta value of .043 to .172 and was found to have a positive medium correlation with useful living area ($r = .345$, $p < .001$), indicating that households with larger incomes have larger dwellings than lower-income households.

The influence in the model due to the number of heated bedrooms also increased in the behaviour model. Positive small partial correlations were found with the presence of a thermostat ($r = .220$, $p < .001$), number of rooms ($r = .257$, $p < .001$), household size ($r = .247$, $p < .001$), and income ($r = .109$, $p < .001$), and a negative small partial correlation was found with age of respondent ($r = .044$, $p < .001$).

A correlation with the presence of a thermostat seems to be the cause of the larger influence of temperature setting during the night in the behaviour model. Small positive partial correlations were found for temperature setting during the night and income ($r = .066$, $p < .001$), household size ($r = .058$, $p < .001$) and thermostat ($r = .231$, $p < .001$).

The influence of temperature setting during the evening and during the day was reduced in the behaviour model. Very small negative correlations were found between temperature during the evening and income ($r =.046$, $p < .001$) and household size ($r = .045$, $p < .001$) and there was a small correlation with age of respondent ($r = .147$, $p < .001$) and presence of a thermostat ($r = .128$, $p < .001$). Small partial correlations were found for temperature setting during the day with income ($r = .138$, $p < .001$), age of respondent ($r = .277$, $p < .001$) and presence of a thermostat ($r = .186$, $p < .001$).

The presence of a thermostat was found to have a small negative correlation with private rent ($r = .261$, $p < .001$) and heating included in rent ($r = .212$, $p < .001$). In the case of private rent, the Beta value was reduced, while for heating included in rent the value became negative. In both cases this change in the Beta value was due to the fact that variation associated to thermostat was included in variables with a larger influence on the model, such as number of heated bedrooms, local heating in living room, and temperature setting.

Due to the fact that temperature settings seem not to have a high correlation with the building characteristics introduced in the model, partial correlation was used to further explore the relationship between temperature settings and energy quality score as defined in the KWR survey. According to Pearson's correlation, there was a very small correlation between energy quality scores and temperature setting during the evening ($r = .023$, $p < .01$), during the night ($r = .037$, $p < .001$) and during the day ($r = .017$, $p < .05$). Therefore, it seems that thermal quality has little influence on the temperature settings in dwellings.

2.5 Discussion

In this study, the results showed that 42% ($R^2 = .379$ for step 1, $\Delta R^2 = .038$ for step 2) of the variation in energy use can be attributed to building characteristics. This is similar to the conclusions of a study conducted by Sonderegger (1977-1978) over 6 months in 205 houses in the USA, where the physical features of dwellings (number of rooms, glass insulation, etc.) explained 54% of the variation in energy use. In Sonderegger's study, 71% of the unexplained variation was caused by occupant patterns, while in our study only 7.2% of the unexplained variation can be explained by occupant patterns. In contrast, using four regression models based on household energy use in Germany, Schuler *et al.* (2000) found very low B coefficient values when only the household characteristics were included in the model – with household size and age being statistically significant. In a model that only used building characteristics, a higher explanatory power was found (11.7-14.9%), while slightly better results were obtained combining both models. Using multivariate regression, Pachauri (2004) found that household socioeconomic characteristics, and dwelling attributes influence the total household energy requirements in India, with income being the most important variable, explaining 61.4% of the 66.4% of explained variance due to all the variables: age, dwelling size, household size, region, type of dwelling (multi-family or single family) and agriculture as activity. In our research, income did not seem to have such a large effect because dwelling size and other income-affected building characteristics such as dwelling size were introduced first into the model. In addition, socioeconomic differences between the countries could also explain the differences.

According to our results, insulation and the presence of a thermostat have, respectively, a positive and negative impact on energy use. Hirst & Goeltz (1985) found that both factors are important for energy use, with both related to energy savings. Therefore, a more detailed analysis of the effect of thermostats should be carried out.

The vintage of the building was found to have a positive correlation to energy use. Similar results were found by Leth-Petersen & Togeby (2001) in Denmark and Liao & Chang (2002) in the USA.

In studies by Haas *et al.* (1998) in Australia and Sardianou (2008) in Greece, no linear relationship was found between energy use for space heating and the thermal quality of a building, a result that could be due to a different climate. In contrast, insulation was found to be a statistically significant factor in our research, although a very small correlation was found between temperature settings and the thermal quality of the building. In addition, in an international study of energy requirements, Lenzen *et al.* (2006) found significant differences in average energy requirements at equal income levels due to energy conservation technology.

The impact of the differences in the thermal quality of a building does not depend on the type of heating system (Haas *et al.*, 1998). In our research, the type of heating system was not included in the regression model because it was not found to be statistically significant during the screening of variables.

Sardianou (2008) found that dwelling size is a factor influencing energy use, while Sonderegger (1977-78) found that the number of rooms is also a determinant of energy use. Both these findings correspond with those of the present research.

The results of the regression model revealed that temperature setting is important in determining energy use, a similar finding to other international studies. Haas *et al.* (1998) found that temperature levels and the setting of thermostats significantly influence energy demand in Australia. An empirical study by ECN and IVAM in the Netherlands (Jeeninga *et al.*, 2001) involving 180 households, showed that differences in heating demand is mainly determined by set-point heating temperature. In an empirical study in Sweden, Linden *et al.* (2006) found that preferences for indoor temperature are contributing factors for energy requirements. Calculations by Tommerup *et al.* (2007) based on single-family houses in Denmark revealed that the increase in energy consumption is about 10% per degree of indoor temperature.

The dependent variable in the regression model includes energy used for heating water, therefore the presence of a bath was shown to be significant. In other studies, shower and bathing behaviour also influenced energy requirements for water heating (Jeeninga *et al.*, 2001; Linden *et al.*, 2006).

Income was found to be positively correlated to energy use, similar to the results of Biesiot & Noorman (1999), who found an almost linear relationship between expenditure and energy requirements for direct and indirect energy needs in the Netherlands. Vringer (2005) found that a 1% increase in income results in 0.63% increase in energy use; however, there were large deviations.

According to a literature survey in the Netherlands by Groot *et al.* (2008), household size, age, presence at home, income, shower and bathing behaviour, and heating behaviour influence energy use. Through statistical analysis of household energy use in Greece, Sardianou (2008) found that the age of the respondent, household size and ownership were influencing factors on space heating demand. Liao & Chang (2002) found that rented houses, the age of the respondent and the household size were positively correlated with more energy use. Lenzen *et al.* (2006) found that socioeconomic factors such as the age of the respondent and household size generally have similar influences on energy requirements in different countries, also similar to the results of our study.

Occupant behaviour and household characteristics seem to only predict 5% of the variance in energy use in comparison to building characteristics. However, the data on behaviour does not seem to be ideal for regression analysis due to the fact that most of it is presented in the shape of categorical values and not in continuous variables. To resolve this problem, most of the behaviour variables were transformed into dichotomous variables. Although some variables proved to be significant, other parameters such as ventilation behaviour, which has been proven to have an effect on energy use in other studies (Haas *et al.*, 1998), were not found to be significant in this study. Therefore further research on behaviour should be carried out in relation to the effect of the use of mechanical and natural ventilation, and their relationship to the use of the heating system.

2.6 Conclusions

The objective of this study was to determine the respective importance of building characteristics, household characteristics and occupant behaviour on energy use for space and water heating in the Netherlands. The KWR database from the Ministry of Housing in the Netherlands was used. The study consisted of statistical analysis using variables based on the results of other research.

This study showed that occupant characteristics and behaviour significantly affect energy use (4.2% of the variation in energy use for heating), but building characteristics still determine a large part of the energy use in a dwelling (42% of the variation in energy use for heating). Nevertheless, a comparison with a second model showed that some occupant behaviour is determined by the type of dwelling or HVAC systems and, therefore, the effect of occupant characteristics such as income or household size might be larger than expected, since these determine the type of dwelling.

According to the model generated, insulated surfaces decrease the energy used in dwellings, with exception of the insulation of piping which tended to increase energy use. A more detailed analysis should be undertaken to discover the reason for this. Energy use also tends to decrease in newer buildings and in non-detached dwellings. The presence of a thermostat, garage, shed and basement tend to increase energy use, probably because they affect the behaviour of the users, for example, in their use of rooms or heating in these areas. Having an open kitchen decreases energy use, probably because of the heat generated by cooking and the use of appliances. The presence of a bath increases energy use related to water heating.

The continuous presence of people at home increases energy use in comparison to cases when the users are almost never home or their presence is very variable. Energy use increases when more rooms are heated and with higher temperature settings.

The household characteristics that seem to have an effect on energy use are the age of the respondent, household size and income, all having a positive correlation. In cases of private rent, energy use also increases, probably because privately rented houses are often less energy efficient than socially subsidised rental accommodation and dwellings that are owner-occupied. In cases where heating is included in the rent, energy use also tends to increase.

The presence of a thermostat seems to have a large effect on occupant behaviour. Correlations were found between temperature setting and the number of heated bedrooms. The reason for this effect should be studied further.

Temperature setting seems to be an important predictor of energy use. Small correlations were found between the temperature setting and occupant characteristics, with income and age being significantly correlated to temperature, but having a very low effect. Alternatively, very low though significant correlations were found between the energy quality score of the dwellings and temperature setting, meaning that temperature preferences might be more important that the thermal properties of the dwelling. Therefore the relationship between energy qualities and temperature preferences should be further studied.

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References

Ashrae, ASHRAE Handbook Fundamentals, www.ashrae.org, 2005.

Assimakopoulos, V. (1992), Residential energy demand modeling in developing regions. The use of multivariate statistical techniques, **Energy Economics 14** (1), pp. 57-63.

Beerepoot, M. & N. Beerepoot (2007), Government regulations as an impetus for innovations.Evidence for energy performance regulation in the Dutch residential building sector, **Energy Policy** 35, pp. 4812-4825.

Biesiot, W. & K.J. Noorman (1999), Energy requirements of household consumption: a case study of NL, **Ecological Economics** 28, pp. 367-383.

Branco, G., B. Lachal, P. Gallinelli & W. Weber (2004), Predicted versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data, **Energy and Buildings** 36, pp. 543-555.

Clarke, J.A. (2001), Energy Simulation in Building Design, Butterworth, Heinemann.

Elkhuizen, P.A., J.E. Scholten, E.G. Rooijakkers, J. de Knegt & L. Deutz (2006), **Kwaliteitsborging van installaties – Evaluatie van bestaande instrumenten en een visie voor toekomst**, Report TNO bouw/Halmos for SenterNovem.

Erhorn, H. (1988), Influence of meteorological conditions on inhabitants' behavior in dwellings with mechanical ventilation, **Energy and Buildings** 11, pp. 267-275.

EuroACE (2004), **Towards Energy Efficient Buildings in Europe**, final report June (ec.europa.eu).

Field, A. (2005), **Discovering statistics using SPSS: and sex, drugs and rock'n' roll**, 2nd ed., Sage, London.

Freire, R.Z., G.H.C. Oliveira & N. Mendes (2004), Development of regression equation for predicting energy and hydrothermal performance of building, **Energy and Buildings** 40, pp. 810-820.

Groot, de E., M. Spiekman & I. Opstelten, (2008), **Dutch Research into User Behavior in relation to energy use of residences**, Proceedings PLEA Conference, 2008.

Haas, R., H. Auer & P. Biermayr (1998), The impact of consumer behavior on residential energy demand for space heating, **Energy and Buildings** 27, pp. 195-205.

Hirst, E. & R. Goeltz (1985), Comparison of actual energy saving with audit predictions for homes in the North Central Region of the USA, **Building and Environment** 20 (1), pp. 1-6.

ISO 13790, (2004), **Thermal Performance of Buildings – Calculation of Energy Use for Space Heating**, www.iso.org.

ISO 13790, (2008), **Energy Performance of Buildings – Calculation of Energy**

Use for Space Heating and Cooling, www.iso.org.

Itard, L. & F. Meijer, (2008), **Towards a Sustainable Northern European Housing Stock. Figures, Facts and Future**, IOS Press, Amsterdam.

Iwashita, G. & H. Akasaka (1997), The effects of human behavior on natural ventilation rate and indoor air environment in summer. A field study on southern Japan, **Energy and Buildings** 25, pp. 195-205.

Jeeninga, H., M. Uyterlinde & J. Uitzinger (2001), **Energieverbruik van energiezuinige woningen**, Report ECN & IVAM, ECN-C-01-072.

Lenzen, W., H. Cohen & S. Pachauri (2006), A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan, **Energy 31**, pp. 181-207.

Leth-Petersen, S. & M. Togeby (2001), Demand for space heating in apartment blocks: measuring effect of policy measures aiming at reducing energy consumption, **Energy Economics 23**, pp. 387-403.

Liao, H.C. & T.F. Chang (2002), Space-heating and water-heating energy demands of the aged in the U.S., **Energy Economics** 24, pp. 267-284.

Liddament, M.W. & M. Orme (1998), Energy and ventilation, **Applied Thermal Engineering 18**, pp. 1101-1109.

Linden, A.L., A. Carlsson-Kanyama & B. Eriksson (2006), Efficient and inefficient aspects of residential energy behavior: what are the policy instruments for change?, **Energy Policy** 34, pp. 1918-1927.

Nieman (2007), **Eindrapportage woonkwaliteit binnenmilieu in nieuwbouwwoning**, Report Wu060315aaA4.PK, VROM Inspectie Regio Oost, Arnhem.

Pachauri, S. (2004), An analysis of cross-sectional variations in total household energy requirements in India using micro-survey data, **Energy Policy** 32, 1723-1735.

Papakostas, K.T. & B.A. Sotiropoulos (1997), Occupational and energy behavior patterns in Greek residences, **Energy and Buildings** 26, pp. 207-213.

Sardianou, E. (2008), Estimating space heating determinants: an analysis of Greek households, **Energy and Buildings** 40, pp. 1084-1093.

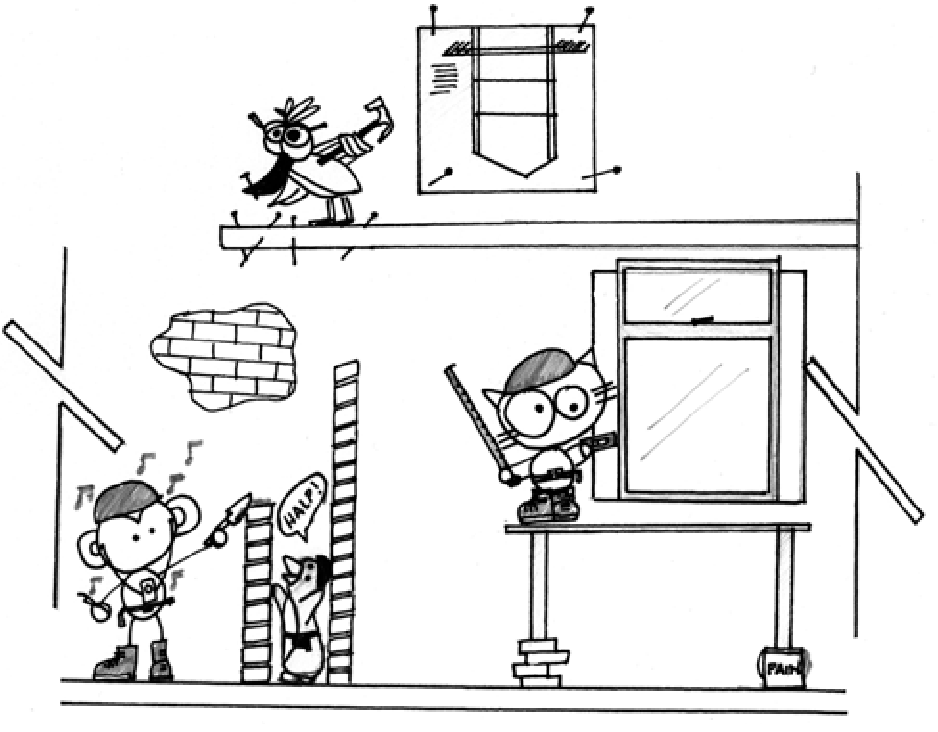
Schuler, A., C. Weber & U. Fahl (2000), Energy consumption for space heating of west-German household: empirical evidence, scenario projections and policy implications, **Energy Policy** 28, pp. 877-894.

Sonderegger, R.C. (1997-1998), Movers and stayers: the resident's contribution to variation across houses in energy consumption for space heating, **Energy and Buildings 1**, pp. 313-324.

Tommerup, H., J. Rose & S. Svendsen (2007), Energy efficient houses built according to the energy performance requirements introduced in Denmark in 2006, **Energy and Buildings 39**, pp. 1123-1130.

Vringer, C.R. (2005), **Analysis of the Requirements for Household Consumption**, Netherlands Environmental Assessment Agency, Bilthoven, thesis.

Vringer, K. & T.A.K. Blok (2007), Household energy requirement and value patterns, **Energy Policy** 35, pp. 553-566.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3 The effect of energy performance regulations on energy consumption

Abstract
Governments have developed energy performance regulations in order to lower energy consumption in the housing stock. Most of these regulations are based on the thermal quality of the buildings. In the Netherlands the energy efficiency for new buildings is expressed in the EPC (energy performance coefficient). Studies have indicated that energy regulations are successful in lowering the energy consumption in residential buildings. However, the actual energy consumption is usually different from the expected energy consumption. This paper explores the effectiveness of energy performance regulations in lowering the energy consumption of dwellings built in the Netherlands after 1996. The effect of the EPC and thermal characteristics on energy consumption was determined by statistical analyses of data on actual energy consumption. The results showed that lower EPC levels are not related to lower energy consumption. The expected energy requirement did, however, show a medium-sized correlation with the actual energy consumption. Further analysis showed that only 18 to 22% of the variation in energy consumption could be explained with the building characteristics in the EPC calculation. The large unexplained share suggests that other factors such as occupant behaviour and the actual properties of the dwelling could be undermining the effectiveness of the regulations.

3.1 Introduction

Worldwide, the built environment consumes 41% of the energy produced in developed countries. Of all the phases in the life-cycle of buildings the user phase is the most energy-intensive (Itard & Meijer, 2008). In recent decades, governments all over the world have included energy requirements in their building regulations in a bid to lower energy consumption in the housing stock. Most of these regulations are based on the thermal quality of the buildings and thus aim to reduce the energy spent on heating space.

Since 2003 the Energy Performance Building Directive has required all EU member states to implement performance-based energy regulations (European Commission, 2003 MB) to lower the energy required for heating, cooling, ventilation, lighting and domestic hot water in buildings. In the Netherlands energy consumption in new buildings has been regulated since 1975. Prior to 1995 energy-efficiency regulations consisted only of limits on transmission losses based on insulation values. In 1995 they were expanded to include the EPC (energy performance coefficient), a non-dimensional figure that expresses the energy efficiency of a building on the basis of the energy consumed for heating, hot water, lighting, ventilation, humidification and cooling. The EPC is determined by dividing the calculated energy requirement of a building by a standardised energy performance, which is based on the heat-transfer surface and the total heated area of the dwelling.

The EPC applies a correction for building size to avoid penalising larger dwellings. It sets a limit on energy consumption, allowing designers to make trade-offs and devise a solution from many options (e.g. using more insulation or more energy-efficient systems). In 1996 the EPC stood at 1.4, a value that was easy to reach with common construction methods at the time. It was tightened to 1.2 in 1998, to 1.0 in 2000 and to 0.8 in 2006. In addition to the EPC, the energy regulations in the Netherlands apply an $R_c \geq 2.5$ m²K/W for external walls, roofs and ground floors and a U≤ 4.2 W/m²K for windows, doors and window frames.

Various studies have indicated that energy regulations have been successful in lowering energy consumption in residential buildings. Leth-Petersen & Togeby (2001) found that building regulations have played a key role in lowering energy consumption in new dwellings. They recorded annual energy reductions of 3.5 to 4.8% depending on the type of heating system, though they do stress that some of this result might be due to the independent effect of better insulation, glazing and more efficient boilers. In a Dutch study on the effect of EPC values in ten low-energy projects (146 dwellings) Jeeninga *et al.* (2001) found that the energy requirement is determined primarily by the building envelope (R_c, U-value of glazing) and the type of dwelling besides the indoor temperature. They found only indicative differences (not statistically significant at $p<.05$ level) for energy consumption in dwellings with different EPC levels except for categories 0.75 and 1.2. In yet another Dutch study Beerepoot & Beerepoot (2007) concluded that energy performance regulations have led to the utilisation of more energy-efficient systems.

However, other studies have shown that the actual energy consumption is usually different from the predicted energy consumption. For example, Branco *et al.* (2004) found that actual energy consumption was 50% higher than expected in energy-efficient multifamily dwellings in Denmark. They concluded that the difference was due to the exclusion of the actual utilisation conditions and the actual system performance. After discerning a rebound effect of 15-30%, Haas *et al.* (1998) argued that energy savings from conservation measures would be lower than calculated. During a dwelling audit in the USA, Hirst & Goeltz (1985) also found that energy savings were lower than predicted. Some studies have established no relationship between energy consumption and the thermal quality of buildings (Haas *et al.*, 1998; Sardianou, 2008).

In the previous chapter, which used statistical analysis to determine the effect of building characteristics, household characteristics and occupant behaviour, indicated that 42% of the variation in energy consumption could be explained by building characteristics. Caldera *et al.* (2008) and Tiberiu *et al.* (2008) identified a relationship between energy consumption and certain building characteristics, including the shape of the dwelling and U-values.

The EPC aims to reduce the overall building-related energy consumption in dwellings. In NEN 5128:2001 the EPC is defined as an instrument to assess energy reduction. In this chapter we explore the role of energy performance regulations in lowering the energy consumption for space heating in dwellings built after 1996, the year in which new energy requirements were introduced in the Netherlands. The aims are (1) to determine the extent of the influence of the EPC level on reductions in energy consumption for heating; (2) to determine whether tighter regulations could help to further reduce energy consumption for space heating; and (3) to identify scope for improvement in the regulations in order to bring about a further reduction in energy consumption for heating. We achieved the third aim by studying the building characteristics (included in the EPC) that have a larger influence on energy consumption for space heating.

The effect of the EPC value and thermal characteristics on energy consumption was determined by statistical analyses of data on actual energy consumption in Dutch dwellings. The OTB Research Institute carried out a survey on housing built after 1996 and paired the data from the respondents with data from EPC calculation files kept by the municipalities. Both the data and the methods are discussed in Section 3.2 Section 3.3 deals with the relationship between the actual energy consumption and the energy performance regulations. Section 3.4 extends the results to a larger sample using a database from a national household survey. The discussion is presented in Section 3.5 and the conclusions in Section 3.6.

3.2 Data and methodology

During the past fifteen years only three surveys have been conducted to assess the effectiveness of the energy performance regulations on the actual energy consumed for heating in the Netherlands. The first was carried out by Jeeninga (2001) on a sample of 146 dwellings, the second by PRC and Uitzinger (2004) on a sample of 649 dwellings, and the last in 2008 by the authors of this paper on a sample of 313 dwellings. In this paper we focus on the sample from 2008, the OTB sample.

The data were drawn from two sources: a survey among households in two districts in the Netherlands (OTB survey) and EPC files from municipalities and architects' firms. The EPC files belonged to the dwellings where the survey was conducted, thus enabling us to match the response from the survey with the data on building characteristics.

The OTB survey was carried out simultaneously in two districts in the Netherlands in autumn 2008. To ensure that the dwellings in the sample fell within the timescale of the EPC we specifically chose districts that were built after

Photo right
Leidse Rijn

Photo left
Wateringse Veld

the EPC had been introduced. The districts were also chosen because they were representative of the Dutch situation in terms of dwelling type, heating system and ventilation. The sample size was 313 households. The districts are described in detail below.

3.2.1 Districts

The chosen districts were Wateringse Veld in The Hague and Leidsche Rijn in Utrecht. Construction started in Wateringse Veld (WV) in 1996 and was still underway when the survey was being conducted (www.wateringseveld.nl). Leidsche Rijn is a district in Utrecht. Construction began in 1997 and will continue till 2025 (www.utrecht.nl).

Figure 3.1 shows the main characteristics of the sample: district, type of dwelling, EPC value and type of ventilation. All the dwellings in Wateringse Veld had individual central heating as opposed to Leidsche Rijn, where all but four had district heating. Balanced ventilation was better represented in Wateringse Veld, which also had a wider range of EPC values. Most dwellings in Leidsche Rijn had an EPC of 1.0 or 1.2, whereas all EPC values were represented in Wateringse Veld. There were far fewer maisonettes and detached houses in the sample than terraced houses, corner houses and flats. However, terraced and corner houses and flats are more common in the Netherlands.

3.2.2 Energy consumption

The respondents were asked to report their energy consumption from the last available annual energy bill. The energy data were corrected using heating degree days (HDD), based on the period from October 2006 to September 2007

Figure 3.1 Main building characteristics in the sample: number of cases for Wateringse Veld (WV) and Leidsche Rijn (LR), type of dwelling, EPC category and type of ventilation system

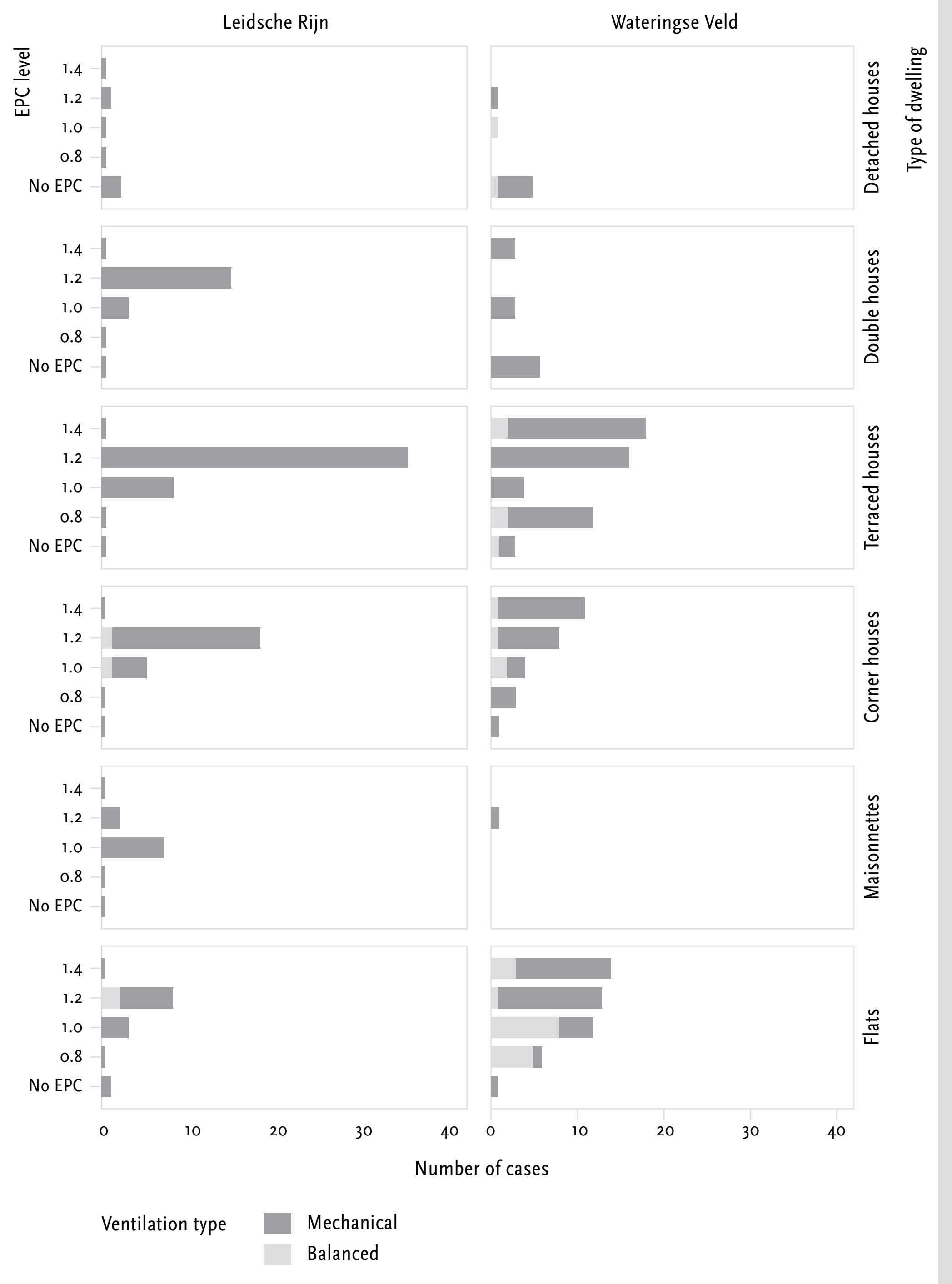


Table 3.1 Response rates and available data per district

District	Response from survey	Reported energy data	EPC data	Reported energy and EPC data
Leidsche Rijn	125	94	104	86
Wateringse Veld	177	147	138	131
Unknown	11	7	0	0
Total	313	248	242	217

(2264.3 heating degree days for Utrecht and 2186.9 for The Hague), since the years of the reported energy consumption ranged from 2005 to 2008. The HDD were taken from the Dutch Meteorological Institute (KNMI - Koninklijk Nederlands Meteorologish Instituut) obtained from www.kwa.nl. The HDD were weighted degree days. They used a baseline temperature of 18^0C.

Two types of energy for heating were used in the districts: heat (dwellings with district heating) and gas (dwellings with individual central heating). The energy reported from gas-heated dwellings included energy for space heating, water heating and cooking. The energy data from dwellings with district heating included energy consumption for space and water heating, but not for cooking, since these households cooked with electricity. Only gas was reported as primary energy. District heating is considered to have an efficiency of .95 in the Netherlands (NEN 5128: 2004). Energy for cooking and differences in system efficiency might therefore have had a slight effect on the reported energy consumption. However, gas for cooking was not expected to exceed 5% (EuroACE, 2004).

This study focused on energy consumption for heating and included the energy consumption for heating tap water, which also figures in the EPC calculation. Not all cases could be used in the analysis because some of the energy consumption reports were incomplete or flawed. Table 3.1 shows the number of cases per district with energy data that could be used for the analysis.

3.2.3 EPC calculation

The EPC data were obtained from municipalities, where they are kept according to requirements in the Dutch Building Decree, and were paired with the survey data. The EPC was not available in all cases. This was due to several reasons: building permission had been obtained just before the introduction of the EPC, the EPC files were missing, or the respondents did not state their address. This reduced the size of the sample (Table 3.1).

The EPC calculation takes account of the characteristics of the dwelling, the efficiency of the installations and standardised occupant behaviour based on an average Dutch household. The EPC document contains data on surfaces, U-values, infiltration level, type of heating system and type of ventilation system. The EPC calculation is one of the documents required to obtain a building permit. The building characteristics that are defined in the documents and used to calculate the EPC value should be the actual characteristics of the dwelling.

The EPC is calculated as follows:

$EPC = Q_{pres;tot} / (330 \times A_{g;verw} + 65 \times A_{verlies}) \times (1/ C_{EPC})$

The total expected energy consumption ($Q_{pres;tot}$ in MJ) is the sum of the primary energy required for space and water heating, the auxiliary energy for the heating system, and the energy required for ventilators, lighting and humidification based on standard data. The calculations for the primary energy take account of the efficiency of the installation, the distribution losses of the system, and the efficiency of electricity generation. Compensation for the energy obtained with photovoltaic systems is also included.
The total heated area ($A_{g;verw}$ in m²) is the sum of the useful area of heated zones. The total heat-transfer surface of the building ($A_{verlies}$ in m²) is calculated by multiplying the heat-transfer surfaces by a correction factor determined by the type of boundary: heated space, ground floor or basement, exterior or water, and unheated spaces. CEPC is the correction factor for updates in methodology and has a fixed value for each update. The calculation of the EPC value is presented in more detail in Box 3.1.

The variables obtained from the EPC are shown in Table 3.2. These variables were checked for normality and outliers with the Kolmogorov-Smirnov test, and for kurtosis and skewness. Outliers were found on heat-transfer surface, total heated area, open surface (windows and doors) and closed surface (external walls), but they seemed to be real values (associated with large houses). Variables were therefore converted for normality.

3.2.4 Methods of analysis

The relationship between the building characteristics and the actual energy consumption was determined with statistical analyses performed with SPSS (www.spss.com). Lower energy consumption was expected in dwellings with lower EPC values. Section 3.1 reports a one-way ANOVA test that was used to discern whether statistically significant reductions in energy consumption occurred in dwellings with lower EPC values.

As explained in Section 2.3, the EPC calculation takes account of the energy required for space and water heating, ventilators, humidification, cooling and lighting. As this research was concerned with space and water heating (gas and heat) we did not study the energy required for electricity. In addition, no cooling or humidification equipment was found in the sample. Thus, subsequent analyses focused on the expected energy consumption for space and water heating ($Q_{pres;verw+tap}$) (for details see Box 3.1). Since the building characteristics described in the EPC document are supposed to be the actual building characteristics, the expected energy consumption should be closely relat-

Box 3.1 EPC calculation

The EPC is calculated with the following formula:

$$EPC = \frac{Q_{pres;tot}}{[330 \times A_{g;verwz}] + [65 \times A_{verlies}]} \times \frac{1}{C_{EPC}} \qquad (1)$$

where,

$Q_{pres;tot}$ is the value of the primary energy consumption in MJ, determined by eq. 2

$A_{g;verwz}$ is the value of the useful surface of the heated zones of the building in m^2

$A_{verlies}$ is the value of the heat-transfer surface of the building in m^2

C_{EPC} is the correction factor for changes in the methodology

The required energy (MJ) is calculated with the following formula:

$$Q_{pres;tot} = Q_{prim;verw} + Q_{prim;hulp;verw} + Q_{prim;tap} + Q_{prim;vent} + Q_{prim;vl} \qquad (2)$$

where,

$Q_{prim;verw}$ is the primary energy consumption for space heating in the building

$Q_{prim;hulp;verw}$ is the primary auxiliary energy consumption for space heating

$Q_{prim;tap}$ is the primary energy consumption for water heating

$Q_{prim;vent}$ is the primary energy consumption for ventilators

$Q_{prim;vl}$ is the primary energy consumption for lighting

To determine the total heat-transfer surface of the building, the surfaces are multiplied by a reduction factor determined by the type of space limiting with the surface. The *primary energy*

▶

ed to the actual energy consumption. First, a paired-sample t-test was applied to determine whether the actual energy consumption differed from the expected energy consumption for space and water heating. To further analyse the relationship between the EPC and the actual energy consumption and to identify scope for improvement in the energy regulations, Pearson product-moment correlation coefficients, independent-sample t-tests and one-way ANOVA tests were used to investigate relationships between the actual energy consumption and the building characteristics that were used to calculate the expected energy consumption for space heating ($Q_{prim;verw}$).

Since the survey was not applied randomly across the Netherlands, it is extended in the second part of this paper with the aid of the WoON (Woononderzoek Nederland) database of the Dutch Ministry of Housing (www.vrom.nl), which is representative of the Dutch building stock but does not contain data on EPC values. The results were then compared with the results of the OTB database. This validation is presented in Section 3.4.

consumption for space heating is calculated by dividing the energy needed for space heating by the efficiency of the installations. The energy needed for space heating is determined by subtracting the effective heat gain from the heat loss.

Heat loss takes account of the transmission and ventilation loss. It considers the difference between the average indoor (18°C) and average outdoor (5°C) temperature multiplied by the number of days in mega seconds (212 days). The considered indoor temperatures in Celsius degrees are:

7-17 hrs = 19 (living area and 2 days in sleeping area), 16 (sleeping area 5 days)

17-23 hrs = 21 (living area and 2 days in sleeping area), 16 (sleeping area 5 days)

23-7 hrs (thermostat setting) = 16 (living area and 2 days in sleeping area), 14 (sleeping area 5 days).

Heat gains take account of solar gains and internal heat gains. Solar gains are determined on the basis of orientation, reduction factors for shadows, solar entry factors and surface. Heat gains are calculated by multiplying the total heated area by 110, which is calculated by multiplying the average heat-gain (6.0 W/m^2) by the value of the length of the considered period (212 days) in mega seconds.

The *primary energy consumption for heating water* is determined by the gross energy requirement minus the yearly input of solar energy (in the case of a solar boiler) and divided by the efficiency of the tap water system. The gross energy requirement is calculated with the gross energy in the bathroom and sink installations divided by the efficiency of the systems.

The *primary energy consumption for ventilators* is determined by the energy consumption of the ventilator divided by the efficiency of the electricity. The calculation assumes that mechanical ventilators are constantly working.

The *primary energy consumption for lighting* is determined by multiplying the heated area of the dwelling by a factor of 22 and dividing it by the efficiency of the electricity. The factor 22 is obtained by multiplying the electricity needed for lighting 1 m^2 of the surface (6.0 kWh/m^2/year) by 3.6, which is the conversion from kWh to MJ).

Source: NEN 5128

3.3 Results

3.3.1 Differences in the energy consumption for space and water heating for different EPC values and types of dwelling

Figure 3.2 shows the mean and 95% confidence interval for energy consumption per construction period in the Netherlands (WoON database from the Dutch Ministry of Housing). Periods are defined according to important changes in the Dutch building regulations: the introduction of energy regulations in 1975 and the introduction of the Energy Performance Coefficient (EPC) in 1995. Subsequent periods refer to the tightening of the EPC value. Although energy consumption is lower in the most recent construction periods, a slight increase is observable in the last period and the differences in the last three periods do not seem to be statistically significant.
A one-way ANOVA test was conducted to detect any statistically significant differences in the energy consumption and to determine whether tighter EPC values have significantly lowered energy consumption for space and water heating. Cases were categorised according to their EPC value: 0 = no EPC, 1 = [1.21-1.40], 2 = [1.01-1.20], 3 = [0.81-1.00], 4 = [0.8]. The EPC values were not

Table 3.2 Descriptive statistics of variables from EPC calculation and OTB survey

Variable	Description	N	Mean	SD
Heat transfer surface (m^2)[1]	Sum of exterior surfaces of the dwelling in square metres, walls and floors in the ground floor are multiplied by factor .7	235	200.36	97.55
Total heated area (m^2)[1]	Area of the heated space in the dwelling	235	127.33	35.02
Heat-transfer rate of closed surfaces (Wk^{-1})[1]	Sum of surfaces of walls and roof multiplied by the U-value of the surfaces	224	54.43	22.84
Number of bedrooms	Number of bedrooms in dwelling	313	3.00	1.00
Real energy use for space and water heating (MJ/year)	Energy for water and space heating in MJ/year	240	32598.32	22764.99
Variable	**Category**	**N**	**%**	
Type of ventilation system[1]	Mechanical exhaust ventilation[2]	217	93.34	
	Balanced ventilation[3]	18	7.66	
	Total	235	100.00	
Type of heating system[1]	Individual central heating	124	52.77	
	District heating	111	47.23	
	Total	235	100.00	
Type of temperature control	Manual valves in radiators	81	26.04	
	Manual thermostat	79	25.40	
	Programmable thermostat	151	48.55	
	Total	311	100.00	
EPC value[1]	0.8	21	8.27	
	1.0	50	19.69	
	1.2	118	46.46	
	1.4	46	18.11	
	None	19	7.48	
	Total	254	100.00	
Infiltration rate[1,4]	.65	38	16.81	
	1.0	97	42.92	
	1.2	27	10.63	
	1.4	64	28.32	
	Total	226	100.00	

1 Variables obtained from EPC document.
2 Mechanical exhaust ventilation: these systems extract indoor air from a house while air from outside infiltrates trough leaks in the building shell and through passive vents like grilles or windows (US Department of Energy, 2006).
3 Balanced ventilation: these systems supply and exhaust approximately equal quantities of fresh outside air and polluted inside air, respectively. A balanced ventilation system has two fans and two duct systems (US Department of Energy, 2002), one for the supply and one for the exhaust. Heat recovery in a heat exchanger is applied between the warm exhaust air and the cold supply air.
4 Air volume flow rate through construction (cracks) in dm^3/s under a pressure difference of 10 Pa.

Figure 3.2 Mean and 95% confidence interval for energy consumption per construction period

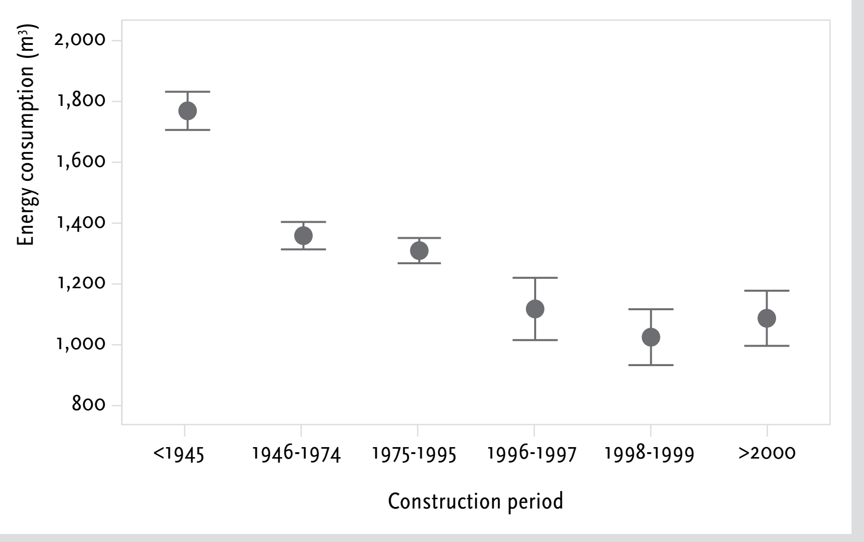
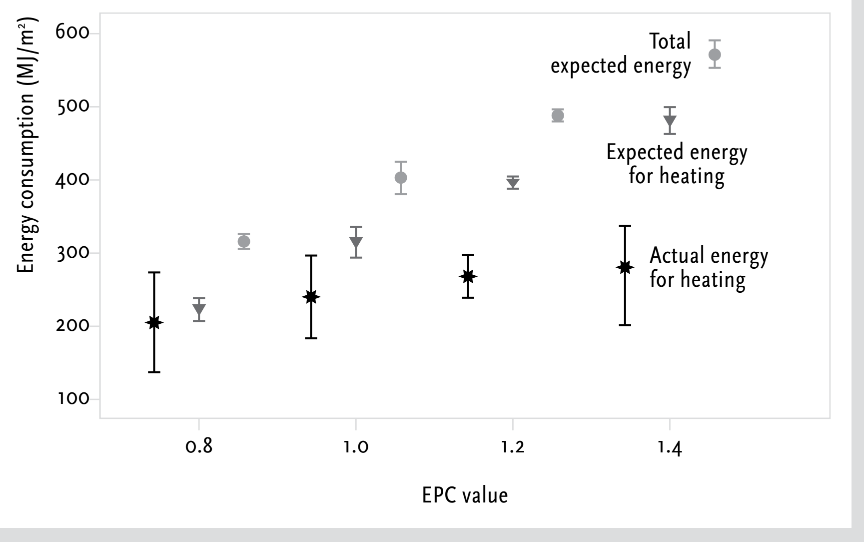
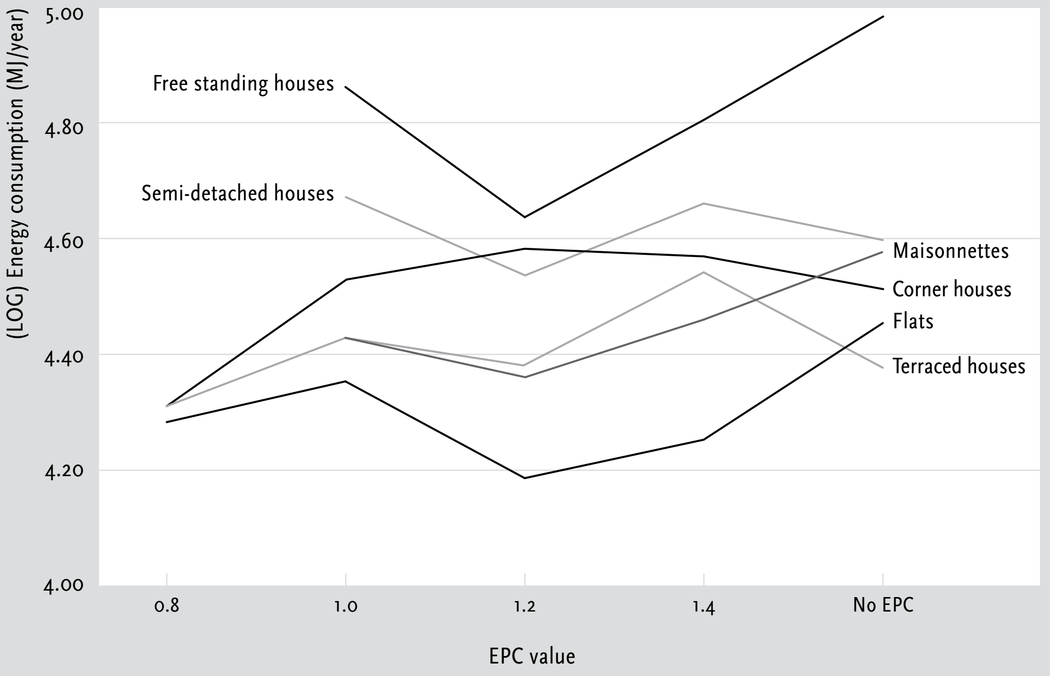


Figure 3.3 Mean and 95% confidence interval for the actual energy consumption (MJ/m²), total expected energy (MJ/m²) and expected energy for heating (MJ/m²) per EPC value



necessarily related to the year when the EPC was tightened, since lower EPC values than those required by the regulations were also found in the sample. The number of cases in each category is listed in Table 3.2. The ANOVA results revealed a statistically significant difference between the EPC categories ($p < .001$). Post-hoc analyses were then performed to identify the EPC categories with differences in energy consumption. A Tukey test revealed that statistical differences existed only between dwellings with and without an EPC

Figure 3.4 Mean LOG energy consumption for different combinations of dwelling type and EPC



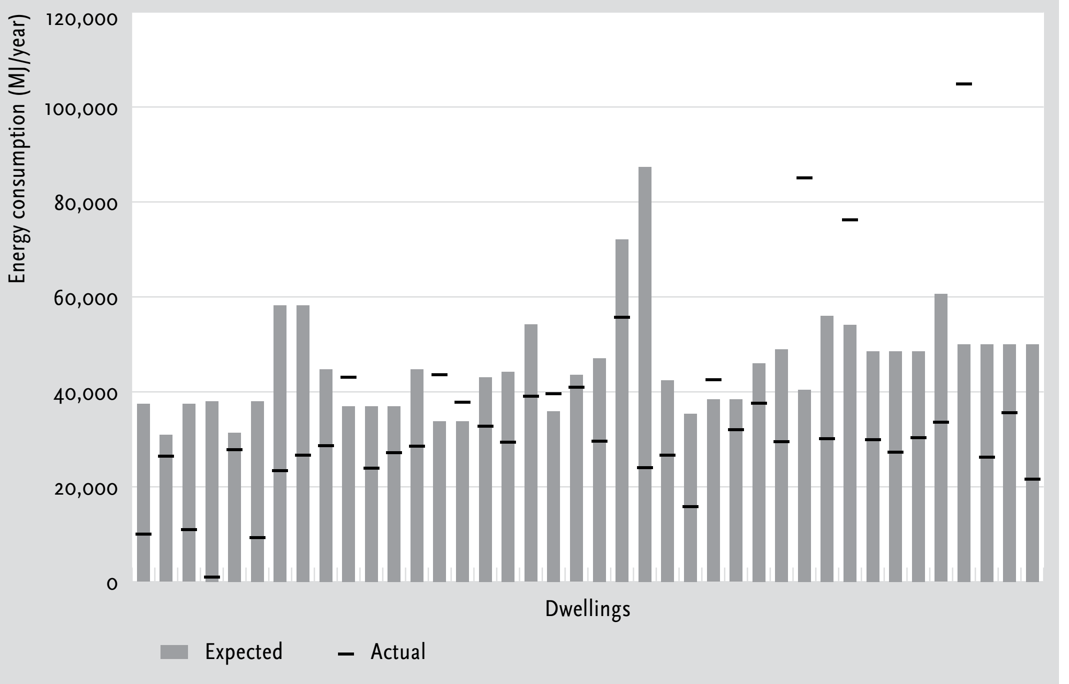
category. There were no statistically significant differences in the energy consumption of dwellings with different EPC values. However, an indicative reduction in energy consumption is observable for the EPC value of 0.8 (Figure 3.3).

The results from the ANOVA test are further illustrated in Figure 3.4, which shows the energy consumption per dwelling type and EPC, taking account of the effect of the type of dwelling. The results seem to indicate that though reductions in energy consumption occur in dwellings with lower EPC values, they are not statistically significant.

3.3.2 Real and predicted energy consumption

As mentioned in Section 3.2, the EPC takes account of different thermal characteristics of buildings when determining the energy required for space heating. Lower EPC values do not indicate lower energy consumption as energy consumption can vary widely within a value due to the neutralisation factor. The predicted energy consumption for space and water heating ($Q_{pres;verw+tap}$) should be closely related to the actual energy consumption since this step has no correction for building size. A Pearson's correlation test was carried out to determine the relationship between the actual and predicted energy consumption. The calculated energy consumption refers here to the sum of the energy requirement for space and water heating in the EPC document ($Q_{prim;verw\,+\,tap}$), corrected for the heating degree days in the period 2006-2007. A positive correlation was found between the actual and predicted energy con-

Figure 3.5 Actual and expected energy consumption per dwelling



sumption (ρ=.391, p<.001, N=185). This indicates that the actual energy consumption is lower in dwellings with lower energy predictions ($Q_{pres;tot}$).The correlation was, however, of medium size.

To check the accuracy of this prediction, a paired t-test was carried out between the expected energy consumption ($Q_{pres;tot} = Q_{prim;verw} + Q_{prim;tap}$) and the actual energy required for space and water heating. The test revealed a statistically significant difference between expected energy consumption (M=47527.68, SD=18931.46) and actual consumption (M=30232.94, SD=18496.72) [t(184)=5.636, p<.001] (η^2=.31). Contrary to assumptions, the actual energy consumption was lower than expected. Figure 3.5 illustrates this by showing the difference per district between the actual and expected energy consumption for a random selection of cases in the sample.

The EPC value did not seem to be related to energy consumption. However, energy consumption did show a medium-sized statistically significant correlation with the expected energy consumption for heating. As the EPC value was calculated with the expected energy consumption ($Q_{pres;verw+tap}$), other factors in the formula could have been affecting the relationship between the EPC and the actual energy consumption. These differences might have been attributable to the neutralisation factor (330 x $A_{g;verw}$ + 65 x $A_{verlies)}$ or the inclusion of the electricity required for ventilators and lighting and auxiliary energy for the heating system. Analyses were therefore carried out between (1) the total expected energy consumption ($Q_{pres;tot}$) and the actual energy consumption, and (2) between the EPC and the expected energy consumption ($Q_{pres;tot}$ and $Q_{pres;verw+tap}$).

On the one hand, a Pearson's correlation test showed that the total expected energy consumption ($Q_{pres;tot}$) was positively correlated to the actual energy consumption (ρ=.378, p<.001, N=185). The expected energy consumption for space and water heating ($Q_{pres;verw+tap}$) was also correlated to the actual energy consumption [ρ=.391, p<.001, N=185). Thus, we conclude that the inclusion of energy consumption for ventilators and auxiliary energy for the heating system in the EPC does not affect the relationship between the EPC value and the actual energy consumption.

On the other hand, ANOVA tests showed that the total expected energy consumption ($Q_{pres;tot}$) was statistically significantly different for different EPC values [F(3,59.51)=47.47, p<.001]. The same results were found for the expected energy consumption for space and water heating ($Q_{pres;verw+tap}$) [F(3,58.32)=56.24, p<.001]. Likewise, the expected energy consumption for space and water heating ($Q_{pres;tot}$ and $Q_{pres;verw+tap}$) normalised per 'total heating area' turned out to be statistically significantly different for different EPC values [F(3,65.49)=413.94, p<.001 and F(3,56.80)=228.78, p<.001 respectively]. However, the relationship between the EPC and the expected energy consumption was much clearer when normalised per 'total heated area'. Hence, the normalisation factor might have had a small effect on the relationship between the actual energy consumption and the EPC value, although, as seen before (Figure 3.3), no statistically significant difference was found for the actual energy consumption normalised per 'total heated area'.

3.3.3 Effect of thermal quality on energy consumption in dwellings

Under the energy performance regulations, the designer may choose from different options to achieve the expected energy performance. The fact that energy consumption for space and water heating is not statistically significant in dwellings with different EPC values might be explained by trade-offs during the design/calculation phase (i.e. between energy-efficient systems and thermal properties). Designers could be opting to reduce energy consumption in ways that are, in reality, less effective. A decision was therefore taken to investigate the relationship between building characteristics and the actual energy consumption. The analyses were conducted without normalisation per total heated area because the effect of dwelling size needed to be determined in relation to other factors. Moreover, as heated area correlated with all the other variables, multicollinearity problems were avoided.

Medium-sized positive statistically significant correlations were found between energy consumption on the one hand and 'number of bedrooms', 'heat-transfer surface' and 'heat-transfer rate of the closed surface' on the other. A small positive correlation was found between 'total heated area' and energy consumption (see Table 3.3 for statistics).

Table 3.3 Pearson product-moment correlation coefficients for building-related variables in OTB survey

Variable	Variable	Statistic	N
(LOG) Energy use (MJ/year)	Number of bedrooms	r = .311*	240
	Heat-transfer surface (m^2)	r = .366*	191
	Heat-transfer rate f closed surface (Wk^{-1})	r = .331*	180
	Total heating area (m^2)	r = .262*	240

* = < .001

Table 3.4 Statistics from independent t-tests and one-way ANOVA for building-related variables in OTB survey

Variable	Statistic	Mean (SD)	
Ventilation type	t(216) = 2.962**	Mechanical exhaust ventilation	M = 4.42 (.30)
		Balanced ventilation	M = 4.20 (.28)
Heating system type	t(216) = 0.704 (NS)		
Type of temperature control	F(2,236) = 3.380*	Manual valves in radiator	M = 4.36 (.35)
		Manual thermostat	M = 4.38 (.31)
		Programmable thermostat	M = 4.44 (.32)
Type of dwelling	F(5,242) = 9.984***	Detached houses	M = 4.85 (.23)
		Semi-detached houses	M = 4.52 (.18)
		Terraced houses	M = 4.34 (.31)
		Corner houses	M = 4.49 (.16)
		Maisonette	M = 4.37 (.27)
		Flat	M = 4.25 (.41)
Infiltration level	F(3,181) = 0.413 (NS)		

Dependent variable: (LOG) Energy use (MJ/year).
(LOG) means that the variable was transformed into a normal distribution with logarithm base 10.
* = < .05, ** = < .01, *** = < .001, NS = not statistically significant.

Analyses were performed to ascertain whether energy consumption was influenced by type of heating and ventilation system, type of temperature control and infiltration level (see Table 3.4 for statistics). An independent-sample t-test compared the energy consumption of dwellings with different types of ventilation and heating systems. A significant difference was found between the energy consumption for mechanical ventilation and balanced ventilation. However, the differences in the means were very small (η^2=.033). Although, as shown in Table 3.4, energy consumption is indicatively higher in centrally heated dwellings, no statistically significant difference in the energy consumption was found at a level of .05. However, it should be noted that the energy consumption in dwellings with individual central heating is primary energy, whereas no account is taken of system efficiency in dwellings with district heating (though the difference would be only 5%).

A one-way ANOVA test was conducted to explore the differences in energy consumption for dwellings with different systems of temperature control, namely: manual valves in radiators, manual thermostats, and programmable thermostats, although these are not taken into account in the EPC calculation. A statistically significant difference was found at $p<.05$ level for all types of temperature control. Post hoc comparisons using the Tukey HSD test indicated a statistically significant difference between the energy consumption for manual valves in radiators and for programmable thermostats.

A one-way ANOVA test did not point to any statistically significant differences in the case of dwellings with different levels of infiltration. (It should be noted that these values came from the EPC calculations and not from the actual infiltration rates in the dwellings.)

The correlation between the actual and the expected energy consumption turned out to be medium-sized. This difference was further explored by applying a regression analysis to determine the variance in energy consumption explained with the thermal properties in the EPC calculation. The regression model can predict 18.6% of the variance in energy consumption with two variables: 'heat-transfer surface' and 'number of bedrooms'. Standardised Beta coefficients showed that 'heat-transfer surface' was the most important variable in the model. The accuracy of the model was tested by analysing the assumptions that led to the belief that the model was fairly accurate (see Table 3.5 for statistics). The equation can be summarised as follows:

(LOG) Energy for heating per year = 3.996 + (heat-transfer surface) (.001) + (number of bedrooms) (.071)

Thus, energy for space heating is mainly determined by the size of the dwelling. The results reported in this section seem to indicate that energy consumption is more influenced by the thermal characteristics than by the type of heating and ventilation systems. That said, only 18% of the variation is explained. Another 82% is still to be accounted for.

3.4 Validation of the results with a nationwide survey (WoON database)

The OTB survey was performed in two selected districts, and a low response rate was obtained because of the length of the questionnaire and detailed questions. This might also have caused limitations in the results of this analysis. The results were therefore validated with the WoON database of the Dutch Ministry of Housing.

The WoON survey was carried out in the Netherlands by the Ministry of Housing in 2005 (www.vrom.nl). It consisted of two questionnaires for occupants and a dwelling inspection. The energy data in the database refer to the actual gas used in the dwelling within a year. The sample consisted of 4,724 cases. In the validation, only houses built after 1996 (according to the inspec-

Table 3.5 B, Standard error of B and Beta of regression model with building variables in OTB survey

	B	Std. Error B	Beta
(Constant)	3.996	.069	
Heat-transfer surface	.001	.000	.325*
Number of bedrooms	.071	.020	.232*

Dependent variable: (LOG) Energy for space and water heating in m^3/year.
(LOG) means that the variable was transformed into a normal distribution with logarithm base 10.
R^2 = .186 (percentage of the variation on energy use explained with the model).
* = < 0.001

tors) were included in the analysis. This sub-sample consisted of 584 cases. Descriptive statistics for the variables taken from the WoON survey for new housing can be found in Table 3.5.

3.4.1 Relationship between energy indicators and energy consumption (WoON database)

The WoON database does not provide information on the EPC level, but it does contain the Energy Index (EI). As this energy indicator is comparable only with the EPC, an analysis was performed to validate the results reported in Section 3.1.

The EI calculation takes account of the thermal characteristics of the dwelling by applying the following formula:

$$EI= Q_{tot} / (155.A_g + 106.A_{verlies} + 9560)$$

in which Qtot is the calculated total energy consumption in MJ and it takes account of the primary energy required for space and water heating, auxiliary electrical energy for pumps and ventilators, lighting, and energy from PV cells. It is therefore very similar to the EPC calculation. Ag is the total heated area and Averlies the sum of all heat-transfer surfaces weighted by a factor 'd'; which is 0.7 for walls/floors at ground level or crawl space, and 1 for all others. As illustrated in Section 2.2, the same characteristics figure in the EPC calculation.

The variables 'actual energy consumed' and 'Energy Index' were converted with squared root and logarithm 10 for normality. The results of a Pearson correlation showed no correlation between (SQRT) 'actual energy consumed' and (LOG) 'Energy Index' [r=-.018, n=563, p=.667] and therefore delivered similar results to those obtained for the EPC value.

Table 3.6 Variables from WoON survey

Variable	Description	N	Mean	SD
Heat-transfer surface (m^2)	Sum of exterior surfaces of the dwelling in square metres, walls and floors on the ground floor are multiplied by a factor .7	586	138.80	77.63
Total heated area (m^2)	Area of the heated space in the dwelling	586	130.83	74.61
Open surface (m^2)	Sum of surfaces of doors, panels and windows	586	29.59	13.34
Non-insulated open surface (m^2)	Sum of surfaces of non-insulated doors, panels and windows	435	2.97	1.91
Insulated open surface (m^2)	Sum of surfaces of double or insulated doors, panels and windows	586	27.73	13.42
Energy for water and space heating (m^3/year)	Actual energy used for water and space heating per year	586	1068.89	676.32
Energy Index	Energy indicator	586	2.04	.80
Number of bedrooms	Number of bedrooms in the dwelling	586	4.02	1.33
Variable	**Categories**	**N**	**%**	
Type of ventilation system	Mechanical	476	82.2	
	Balanced	103	17.8	
	Total	586	100	
Type of heating system	Individual central heating	488	83.8	
	District heating	94	16.2	
	Total	582	100	

Table 3.7 B, Standard error of B and Beta of regression model with building variables in WoON survey

	B	Std. Error B	Beta
(Constant)	-.547	3.476	
(LOG) Heat-transfer surface	13.558	2.062	.374**
Number of bedrooms	.997	.406	.140*

Dependent variable: (SQRT) energy for space and water heating in m^3 gas.
(LOG) means that the variable was transformed into a normal distribution with logarithm base 10.
R^2 = .228 (percentage of the variation on energy use explained with the model).
* = < 0.05, ** = < 0.001

3.4.2 Relationship between building characteristics and energy consumption (WoON database)

The relationship between different building characteristics and energy consumption was investigated with a regression analysis which ascertained the generalisation of the results derived from the OTB survey. Non-normal variables were converted for normality with either squared root or logarithm

Table 3.8 Statistics from independent t-tests and one-way ANOVA for building-related variables and energy use in WoON survey

Variable	Statistic	Mean (SD)	
Ventilation type	$t(585) = 1.298$ (NS)	Mechanical	M = 31.74 (9.47)
		Balanced	M = 30.40 (9.09)
Heating type	$t(581) = 3.999$*	Central	M = 32.38 (8.00)
		District	M = 25.52 (14.42)

Dependent variable: (SQRT) Energy use (m^3/year).
(SQRT) means that the variable was transformed into a normal distribution with square root.
* = < 0.001, NS = not statistically significant.

10. The variables for the analysis are shown in Table 3.6, the statistics can be seen in Table 3.7.

The WoON database does not contain information on the U-values of the surfaces. The variables 'open surface', 'non-insulated open surface', and 'insulated open surface' are therefore not the same as the variables in the OTB database.

A regression analysis was carried out so that a comparison could be drawn with the results of the OTB regression model, described in Section 3.3. To enable comparability, the same variables were added to a model in the same order as in the OTB database. These variables were: 'number of bedrooms', '(LOG) heat-transfer surface', 'non-insulated open surface', 'insulated open surface', and 'total heated area'. The regression model could predict 22.8% of the variation in energy consumption (SQRT m^3 gas), only 4% more than the OTB model. In the OTB model, the variables 'insulated open surface', 'non-insulated open surface, and 'total heated area' were found to be statistically significant. The same relationship was found in the WoON database. Energy consumption is largely dependent on the size of the dwelling, but the explained percentage is relatively small. The equation can be summarised as follows.

(SQRT) Energy for heating per year = -.547 + (LOG heat-transfer surface) (13.558) + (number of bedrooms) (.997)

Independent sample t-tests were carried out to determine any differences in energy consumption (SQRT m^3 gas) between dwellings with different heating and ventilation systems. No statistically significant differences were found between dwellings with mechanical and balanced ventilation (statistics in Table 3.8). These results do not correspond with the results from the OTB analysis, though the effect of ventilation on energy in the WoON survey was very small. On the other hand, significant differences were found between houses with central heating and district heating. This formed a point of contrast between the two databases and might be partially explained by the fact that, in the WoON database, the actual energy consumption for dwellings with district or block heating was corrected to take account of the primary energy consumption.

3.5 Discussion

3.5.1 Relationship between the Energy Performance Coefficient and actual energy consumption

No statistical differences in energy consumption were found for dwellings with different EPC values (.8, 1.0, 1.2, and 1.4), though we did find statistical differences between dwellings built before and after the introduction of the EPC. This indicates that a reduction in energy consumption is seen in dwellings built after the introduction of the regulations. The results of the tests suggest that tighter EPC levels do not necessarily reduce the energy consumption for space heating. An analysis using the WoON survey of the Ministry of Housing in the Netherlands showed no statistical correlation between energy consumption and the Energy Index, an energy indicator similar to the EPC.

Since the aim of the EPC is to realise an overall reduction in energy consumption, the calculations also take account of the energy required for lighting, cooling and hot water. This factor does not affect the relationship between the EPC and the actual energy consumption for space heating because standardised behaviour is used and the energy required for water, ventilation and lighting is therefore based solely in the ‘total heated area’ of the dwelling. Other results showed that the normalisation factor for dwelling size does not pose a problem in the correlation with the actual energy consumption. These results are in line with those of Jeeninga *et al.* (2001) in the Netherlands, who found only indicative differences (not statistically significant at $p<.05$ level) in energy consumption in dwellings with different EPC levels, except for categories 0.75 and 1.2. However, as the study was conducted in low-energy dwellings constructed before 2000 – when the EPC level was 1.0 – it is conceivable that 0.75 was experimental and was therefore more carefully implemented. In a larger sample, PRC (2004) found strong statistically significant differences between EPC categories. Although the statistical analysis could not be checked and there were concerns about the validity of the results (Itard *et al.*, 2009), it still suggested that the effect of a tighter EPC is better observed in a larger sample. A later analysis of the sample (Uitzinger, 2004) did not, however, find any correlation between equivalent gas consumption and EPC.

3.5.2 Actual and expected energy consumption

A positive medium-sized correlation was found between the actual and expected energy consumption. This points to a relationship between building characteristics and actual energy consumption. A closer look at the sample revealed that the actual consumption was higher than the predicted consumption. This difference is believed to be caused by the differences between the occupant behaviour considered in the calculations and the actual behaviour of the occupants in the sample.

3.5.3 Relationship between building characteristics and energy consumption

The determinants of actual energy consumption were further determined by statistical analyses of building characteristics. The results showed correlations between the actual energy consumption for water and space heating and the thermal properties of the building. In the OTB sample statistically significant differences were found for different types of ventilation systems and temperature control, though the differences in energy consumption for different ventilation types were very small. An analysis of the effect of the heating system on the actual energy consumption showed no statistically significant difference for the OTB database and a small significant difference for the WoON database. The differences between the databases may stem from the fact that the OTB database includes district heating data after taking account of system efficiency, while the WoON database does not. These results indicate that thermal characteristics have a greater effect than system efficiency on energy consumption.

The validation model based on the WoON database delivered similar results with a slightly larger sample size and a random distribution across the Netherlands. The main differences lay in the larger percentage of variation in energy consumption explained in the WoON sample (18% in OTB, 22% in WoON). Nevertheless, the results of both databases show correlations between thermal characteristics and energy consumption, specifically in relation to the size of the dwelling.

Jeeninga *et al.* (2001) and Uitzinger (2004) found similar results for the effects of building characteristics, although the regression model in (Uitzinger, 2004) claimed to predict 70% of the variation which is in contradiction with other literature sources. Comparable results were found by Vringer (2005) for household characteristics and occupant behaviour: households that were motivated to save energy consumed 4% less energy than households that were not. In a regression model compiled by Schuler *et al.* (2000), building characteristics predicted from 11.7 to 14.9% of the variation. The percentage of unexplained variation in energy consumption is thought to be caused by two factors: the actual characteristics of the building and the actual occupant behaviour.

Studies have indicated that the unexplained percentage could be related to practices whereby buildings are not realised according to the official EPC specifications and to HVAC services that are run very differently than assumed on paper. A report by Nieman (2007) showed that 25% of dwellings in a sample of 154 fell short of the EPC requirements: the EPC was incorrectly calculated but the building permit was still issued. The realisation of 50% of the dwellings was not in accordance with the data used to calculate the EPC. In a 17-year study that monitored the energy performances of energy-efficient buildings Gommans (2008) found that 40% of solar boilers functioned and only 25% of heat pumps reached the expected efficiency. This was essentially due to realisation faults, lack of control and lack of continuous monitoring. Another study by Elkhuizen *et al.* (2006) in office buildings showed that better monitoring could deliver energy savings of up to 28%.

The low correlation between the actual and expected energy consumption might be also be due to differences in occupant behaviour. A regression model of the building characteristics in the EPC calculation can explain 18 to 22% of the variation in energy consumption, but that still leaves 78 to 82% unexplained. The role of occupant behaviour is analyzed in the following chapter.

3.6 Conclusions

The aim of this study was to explore the role of energy performance regulations in lowering the energy consumption for space heating in dwellings that were built after these regulations were introduced. In addition, an analysis was carried out regarding the reductions in energy consumption after the regulations had been tightened.

Although the EPC does not aim specifically to reduce energy consumption for space heating, reductions in this area may be expected. That said, dwellings with lower the EPC values do not appear to be correlated to less energy consumption for space and water heating, even when the type of dwelling or total heated area is taken into account.

The lack of correlation between EPC values and energy consumption for heating might be due to three factors: (1) the normalisation factor per dwelling size might have a small effect on the correlation between the EPC and energy consumption; however this does not have an effect on the relationship between the expected and actual energy consumption; (2) the differences between the building characteristics as described in the EPC calculations and the actual building characteristics (e.g. actual infiltration level); and (3) the effect of occupant behaviour on energy consumption. The first factor might have an effect on the relationship between the EPC value and the actual energy consumption, while the other two might have an effect on the unaccounted 78-82% of the variation in energy consumption identified in this research.

A lower EPC value is expected to reduce energy consumption because it increases the energy efficiency of buildings. When the dwellings are built according to the regulations, those with lower EPC would have a lower consumption of energy if occupancy conditions are maintained equal in all dwellings. In this case, the energy performance regulations would be effectively reducing the energy consumption in newly built dwellings. However, the actual conditions of utilization are not the same in all dwellings. This fact undermines the effectiveness of the energy performance regulations, since the range of behaviour hinders the effect of higher energy efficiency of dwellings. Nevertheless, the regulations have ensured that more energy efficient dwellings are being built.

3.7 Recommendations for policy and practice

The fact that actual energy consumption for water and space heating showed a small correlation with the expected energy consumption and the fact that no differences in energy consumption were found in dwellings with different EPC values indicate that other factors besides building characteristics are having a strong effect on energy consumption. These factors are believed to be related to actual occupant behaviour and the actual properties of the dwellings. Further energy reductions could be achieved by focusing on changes in occupant behaviour in relation to the use of the heating and ventilation systems. In addition, thermal quality seems to be more effective than heating-system efficiency in reducing energy consumption for space heating.

The higher expected energy consumption in comparison to the actual energy consumption suggests large differences between the assumed and the actual occupant behaviour. More accurate information on the actual occupant behaviour and the identification of behaviour patterns to build energy-user profiles might improve the energy predictions in the energy performance regulations. Although accurate energy prediction is not the aim of the EPC, a better estimation of the actual energy performance and the actual energy savings expected from the introduction or tightening of building regulations, could be achieved.

Infiltration values, insulation levels and other building characteristics might, in reality, be different from those stated in the EPC calculation, thereby undermining the effect of the energy performance regulations. Further research should be aimed at determining whether the real quality of dwellings corresponds with the characteristics described in the EPC document and at finding better methods to guarantee the quality of the construction work.

In previous studies correlations were found between building characteristics, occupant behaviour and household characteristics. To gain deeper insight into the real effect of building regulations on energy consumption, it is necessary to understand the influence of building characteristics on occupant behaviour, especially in terms of the rebound effect identified in other studies. Such an effect might also be undermining the effectiveness of building regulations.

Given that a tighter EPC did not lower energy consumption for heating and that 78 to 82% of the variation in energy consumption is still unexplained, it might be sensible to search for more efficient means to further lower the energy consumption of recently built housing. This could be achieved by ensuring correct realisation and monitoring of the calculated performances, by paying attention to the knowledge needed by contractors, by implementing an effective building control process (Visscher *et al.*, 2003) and by the implementation of policies directed to influence occupant behaviour.

References

Beerepoot, M. & N. Beerepoot (2007), Government Regulations as an Impetus for Innovations. Evidence for Energy Performance Regulation in the Dutch Residential Building Sector, **Energy Policy, 35**, pp. 4812-4825.

Branco, G., B. Lachal, P. Gallinelli & W. Weber (2004), Expected versus Observed Heat Consumption of a Low Energy Multifamily Complex in Switzerland based on Long-term Experimental Data, **Energy and Buildings, 36**, pp. 543-555.

Caldera, M., S.P. Corgnati & M. Filippi (2008), Energy Demand for Space Heating through a Statistical Approach: application to residential buildings, **Energy and Buildings, 40**, pp. 1972-1983.

Elkhuizen, P., J.E. Scholten & E. Rooiakkers (2006), **Quality Control of HVAC services: evaluation of existing instruments and a vision for the future** [in Dutch], TNO Bouw/Halmos report for Senter Novem.

Gommans, L.J. (2008), Energie prestaties van energie-efficiënt gebouwen: tussen ontwerp en werkelijkheid, **TVVL magazine, September 2008**, pp. 18-24.

Haas, R., H. Auer & P. Biermayr (1998), The Impact of Consumer Behaviour on Residential Energy Demand for Space Heating, **Energy and Buildings, 27**, pp. 195-205.

Hirst, E. & R. Goeltz (1985), Comparison of Actual Energy Saving with Audit Predictions for Homes in the North Central Region of the USA, **Building and**

Environment, 20 (1), pp. 1-6.

Itard, L. & F. Meijer (2008), **Towards a Sustainable Northern European Housing Stock. Figures, facts and future**, IOS Press, Amsterdam.

Itard, L., A. Meijer & O. Guerra Santin (2009), **Consumentenonderzoek Lenteakkoord**, OTB/TU Delft report, Delft.

Jeeninga, H., M. Uyterlinde & J. Uitzinger (2001), **Energieverbruik van energiezuinige woningen,** Report ECN & IVAM, ECN-C-01-072.

Leidelmeijer, K. & P. van Grieken (2005), **Wonen en Energie. Stook- en ventilatiegedrag van huishoudens**, Report RIGO/VROM 86430.

Leth-Petersen S. & M. Togeby (2001), Demand for Space Heating in Apartment Blocks: measuring effect of policy measures aiming at reducing energy consumption, **Energy Economics, 23**, pp. 387-403.

NEN 5128 norm (2001).

NEN 5128 (2004), **Energy Performance of Residential functions and residential buildings: determination method**, ics 91.120.10, March.

Nieman (2007), **Eindrapportage woonkwaliteit binnenmilieu in nieuwbouwwoning**, Report Wu060315aaA4.PK, VROM Inspectie Regio Oost, Arnhem.

Olofsson, T., S. Andersson & J.U. Sjogren (2009), Building Energy Parameter Investigations based on Multivariate Analysis, **Energy and Buildings, 41**, pp. 71-80.

PRC Bouwcentrum BV (2004), **EPC en energieverbruik nieuwbouwwoningen**, Report Novem, Kompas Utrecht.

Sardianou, E. (2008), Estimating Space Heating Determinants: an analysis of Greek households, **Energy and Buildings, 40**, pp. 1084-1093.

Schuler, A., C. Weber & U. Fahl (2000), Energy Consumption for Space Heating of West-German Household: empirical evidence, scenario projections and policy implications, **Energy Policy, 28**, pp. 877-894.

Sonderegger, R.C. (1977-78), Movers and Stayers: the resident's contribution to variation across houses in energy consumption for space heating, Energy and Buil**dings, 1**, pp. 313-324.

Tiberiu, C., J. Virgone & E. Blanco (2008), Development and Validation of Regression Models to

Predict Monthly Heating Demand for Residential Buildings, **Energy and Buildings, 40**, pp. 1825-1832.
Uitzinger, J. (2004), **Analyse EPC en energieverbruik bij woningen,** Report IVAM/ SenterNovem.

Visscher, H.J., F.M. Meijer & L. Sheridan (2003), **Effective and efficient building control**, proceedings CIB-CTBUH International Conference on Tall Buildings, Strategies for performance in the aftermath of the World Trade Centre, Malaysia, 8-10 May, pp. 721-726.

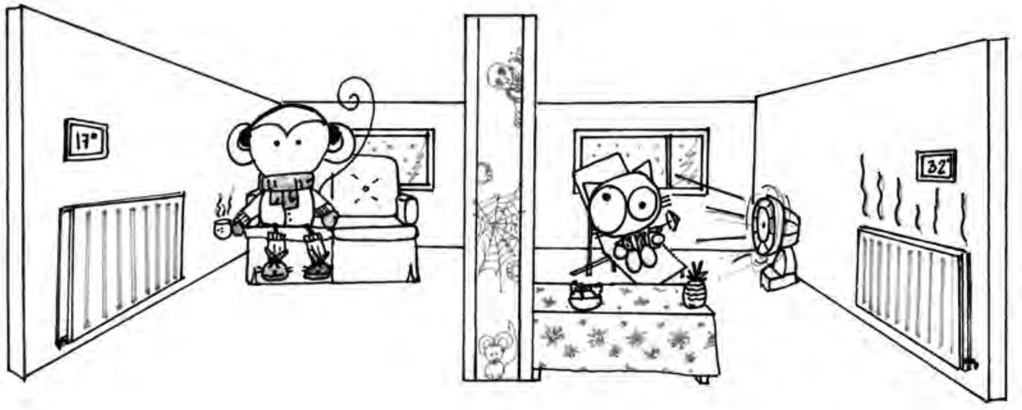
Vringer, C.R., 2005, **Analysis of the requirements for household consumption**, Netherlands Environmental Assessment Agency, Bilthoven [thesis, ISBN 90-6960-1303].

Website: www.kwa.nl, accessed August 2009.

Website: www.utrecht.nl, accessed July 2009.

Website: www.vrom.nl, accessed July 2009.

Website: www.wateringseveld.nl, accessed July 2009.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4 Occupants' behaviour Determinants and effects on residential heating consumption

Guerra-Santin, O. & L Itard (2010), Occupants' behaviour: determinants and effects on residential heating consumption, Building Research & Information, 38 (3), pp. 318-338.

Abstract
What are the key determinants and effects of occupants' behaviour on energy use for space heating? Statistical analyses were carried out on energy use and self-reported behaviour data from a household survey in the Netherlands. Results showed that the number of usage hours for the heating system have a stronger effect on energy consumption than temperature setting. Small correlations were found between energy use and the ventilation system, since most households barely use the ventilation system. The main building characteristic determining behaviour is the type of temperature control. Households with a programmable thermostat were more likely to keep the radiators turned on for more hours than households with a manual thermostat or manual valves on radiators. In relation to household characteristics, the presence of elderly persons in the household proved to be a determining factor in the use of the heating system and ventilation. As a result of wide variations in preferences and lifestyle, occupant behaviour has emerged as an important contributor to energy use in dwellings. The results indicate that the type of heating and ventilation system has an influence on occupant behaviour.

4.1 Introduction

Although building characteristics are known to have a significant effect on energy consumption, their influence in residential buildings has decreased in recent years because governments worldwide have introduced regulations and policies to raise energy performance in the built environment. These regulations are designed first and foremost to increase system efficiency and to improve the thermal properties of new buildings. Meanwhile, renovation programmes are being launched to raise the energy performance of existing buildings.

In 1995 the energy efficiency regulations in the Netherlands were expanded to include the EPC (Energy Performance Coefficient). The EPC is calculated on the basis of the energy used for space and water heating, ventilation, lighting, the efficiency of the installations, and the size of the dwelling. The calculation of energy used for space heating also takes account of solar and internal heat gains and losses through transmission.

These measures, along with ongoing improvements to systems efficiency, materials and construction methods, have significantly reduced the amount of energy used for space heating (Leth-Petersen & Togeby, 2001; Beerepoot & Beerepoot, 2007; Jeeninga *et al.*, 2001). However, studies have indicated that as buildings become more energy-efficient, the behaviour of occupants plays an increasingly important role in consumption (Jeeninga *et al.*, 2001; de Groot *et al.*, 2008; Haas *et al.*, 1998; Papakostas & Satiropoulos, 1997; Andersen *et al.*, 2009). Indeed, the wide variation in energy consumption in buildings with the same physical characteristics is attributed to differences in occupancy patterns (Jeeninga *et al.*, 2001; Haas *et al.*, 1998; Linden *et al.*, 2006; Branco *et al.*, 2004) and differences between the calculated and real performance.

Occupancy patterns may be determined by lifestyle, preferences, attitudes, perceptions of comfort, personal background and household characteristics (Andersen *et al.*, 2009; Schweiker & Shukuya, 2009). The results of a study in Japan by Schweiker & Shukuya (2009) indicate that the way people use heating systems is determined more by personal factors such as experience, attitude and origin than external conditions. In a Danish study on behaviour, control of HVAC systems and indoor environment, Andersen *et al.* (2009) found that ventilation and heating behaviour is influenced by, amongst others, perception, gender and ownership.

The use of heating and ventilation systems can also be influenced by the type of HVAC system in the dwelling. Various authors (Nicol & Humphreys, 2009; de Dear, 2004; Lenzuni *et al.*, 2008; Karjalalainen, 2007; Lan *et al.*, 2008; Moujalled *et al.*, 2008; Ye *et al.*, 2006; Fundamentals volume of the ASHRAE Handbook, 2005) contend that a dynamic interaction between the occupants and the building is crucial in raising levels of comfort. Becker & Pacuik (2009) maintain that thermal adaptation processes are linked to contextual variables such as local climate, occupant expectations and ability to control the environment. Their results of a survey that collected data on hygro-thermal conditions and occupant behaviour pointed to a relationship between thermal responses and control and interaction processes in the indoor environment. According to Brown & Cole (2009), the interplay between knowledge, personal control of HVACs and comfort is complex, since there is a relationship between knowledge and control, but no relationship with comfort.

Several studies have focused on the effect of the type of thermostat control on energy use, based on the assumption that households with programmable thermostats set the temperature at a lower level when nobody is home or during night time (setback behaviour). Therefore, a reduction on energy use is assumed in households with programmable thermostat in comparison to households with manual thermostats or no thermostat control.

Nevius & Pigg (2000) carried out a study in 299 houses. They asked the thermostat setting during determined times of the day and the average number of hours per week present at home. They found that the presence of thermostat has a minimal effect on energy use, and temperature settings do not significantly differ between dwellings with programmable thermostats and dwellings with manual thermostat. In a study on 427 households, Shipworth *et al.* (2010) found that in dwellings with thermostats, the mean temperature setting is slightly lower than in dwellings without thermostat. They also found that households with programmable thermostat keep the heating system on for a longer time than households with manual thermostats, though the difference was not statistically significant at .05 level.

In a survey on 279 houses in California, Lutzenhiser (1992) found that households with manual thermostats used less energy in comparison to households with programmable thermostats. According to him manual control involves the deliberate cooling of people or the deliberate preparation of cool space for people, while automatic cooling occurs regardless of occupancy or activity.

Conner & Lucas (1990) measured indoor temperature and gathered data on self-reported heating behaviour on 400 households. They found that temperature setting in dwellings with programmable thermostats decreased only by 0.5^0F in comparison to dwellings with manual thermostats. They conclude that programmable thermostats do not significantly decrease the incidence of setback behaviour.

In a previous chapter (Chapter 2) it was found that 42% of the variation in the energy consumed in the Dutch housing stock for heating space and water could be explained by type of dwelling, type of HVAC system, and insulation level. An additional 4.2% could be explained by household characteristics and occupant behaviour. The household characteristics that influenced energy consumption were size, age of respondent, type of ownership, and income. The behavioural influences were the number of heated bedrooms and thermostat settings. Nevertheless, only few variables related to occupant behaviour were investigated. The first part of this study (previous chapter), on the effect of building regulations on energy consumption in dwellings that were built after the introduction of the energy performance regulations, highlighted the importance of insulation levels in the variation in energy consumption. That said, there are still wide variations in the energy consumption of dwellings with the same EPC. These could be caused by the actual thermal quality of the dwellings and by differences in occupant behaviour.

Energy consumption could be reduced still further if we had a clearer idea of occupant behavioural patterns (trends in the use of heating and ventilation systems) that underlie the wide variation in energy consumption. In this paper we seek to determine the importance of occupant behaviour in levels of energy consumption in dwellings built after 1995, the year when energy performance requirements were introduced in the Netherlands. The ultimate aim is to ascertain how occupant behaviour influences the effectiveness of building regulations and to gain insight into the relationships between behaviour, HVAC systems and household characteristics.

The following research questions are addressed:
1. What behavioural patterns can be observed in dwellings built after the introduction of new building regulations in the Netherlands?
2. How does occupant behaviour affect energy consumption?
3. Is there a difference in the use of heating and ventilation systems in dwellings with different ventilation systems and temperature control?
4. Do households with different characteristics display a difference in the use of heating and ventilation systems?

Figure 4.1 shows the framework of this research. Firstly the effect of occupants' behaviour on energy use is analysed (3a); secondly the relationship between occupant's behaviour and building characteristics is investigated (3b); and last, the relationship between behaviour and households' characteristics is studied (3c). Section 4.2 describes the data and methodology, Section 4.3 presents the results of the study, Section 4.4 contains an extension of the analysis, Section 4.5 presents the discussion, and Section 4.6 sets out the conclusions and makes recommendations for further research.

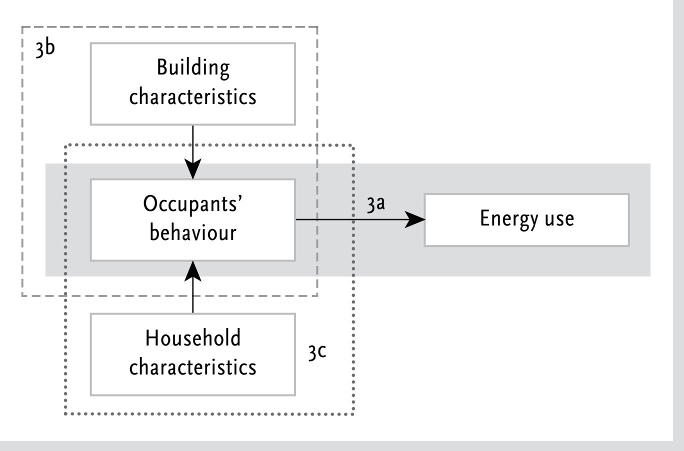
4.2 Data and methodology

The study consisted of a statistical analysis of a household survey carried out by the OTB Research Institute for Housing, Mobility and Urban Studies in the Netherlands. The objective of the OTB survey was to obtain detailed data on occupant behaviour and to pair it with building characteristics defined in the EPC calculation. The survey consisted of a paper questionnaire sent to all households in two previously selected districts in the Netherlands. The survey was carried out simultaneously in the districts in autumn 2008. The districts were built after the introduction of the Dutch energy performance regulations. Districts were selected to ensure the possibility of gathering data about the EPC level from either municipalities or architect offices.

The questionnaire was sent to a total of 7,000 households in both districts, with a response rate of 5% (313 usable cases). The low response rate was caused by the length and detail of the questionnaire and by the fact that respondents felt uncomfortable with providing personal information about their lifestyle and personal belongings.

As some sectors of society, such as students and low-income households, were implicitly excluded, the survey was compared with the WoON (Woononderzoek Nederland) database from the Dutch Ministry of Housing. The WoON database contains random cases across the country, but with less detailed data on heating and ventilation behaviour, and no information about the EPC level. The type of data collected is explained further in the following subsections.

Figure 4.1 Research framework



4.2.1 Building characteristics

The studied districts are Leidsche Rijn in Utrecht and Wateringse Veld in The Hague. The construction of Leidsche Rijn (LR) began in 1997 and will be complete by 2025. The construction of Wateringse Veld (WV) began in 1996 and will be complete by 2011. There are eight zones in these districts, but they could not all be included in the sample as some are still unoccupied or under construction.

Both districts contain the types of housing that are representative for the Netherlands: detached, semi-detached, terrace, corner houses, maisonettes (two-floor flats) and flats. The dwellings in Wateringse Veld have individual central heating systems, while almost all the dwellings in Leidsche Rijn have district heating (four exceptions). The houses in Leidsche Rijn have mechanical exhaust ventilation and the houses in Wateringse Veld have both mechanical exhaust ventilation and balanced ventilation (see Table 4.1 for definitions). The data on building characteristics were obtained from EPC files provided by municipalities and architects. These data were matched with the survey responses.

There were three types of heating control in the sample: manual valves in radiators, manual thermostat and programmable thermostat. Dwellings with manual valves in radiators in addition to a manual or programmable thermostat were categorised according to the type of thermostat. Only a few dwellings had balanced ventilation, which is normal for houses in the Netherlands. The variables for the building characteristics are shown in Table 4.1.

4.2.2 Household characteristics

The analysis took account only of the household characteristics that had been proven important in other studies. The information gathered with the survey is related household demographics such as household size, age of occupants, main occupation, hours of work or study outside the house, house-

Photo right
Wateringe Veld

Photo left
Leidsche Rijn

hold income, years of residence in the house and type of previous dwelling. As some authors had reported a relationship between age and energy consumption, the dichotomous variables 'presence of elderly persons in the household' and 'presence of children in the household' were analysed. Elderly was defined as occupants over the age of 65 and children as occupants under the age of 12. Educational level was defined as a categorical variable comprising three groups: lower education, middle education or technical education and higher education. Income level was defined as a categorical variable (according to the Dutch Central Bureau Statistics) and refers to the total household income (for definitions see Table 4.1).

The current use of the heating and ventilation system could also be influenced by the set-up in the previous house. Since the survey was carried out in relatively new dwellings, the respondents were asked to state whether they had previously lived in a single-family or multi-family dwelling (for definitions see Table 4.1).

4.2.3 Occupants' behaviour

The questionnaire included questions on household characteristics, use of heating and ventilation systems, showering and bathing frequency and energy consumption. The occupants were asked to fill in tables, showing the use of the systems and the time spent at home on weekdays and weekends in winter and summer. Since the survey was carried out in autumn, they were asked to consider their behaviour for a summer and winter week without extreme weather conditions (too much wind, rain or cold). Tables were used to collect data on the duration and times that the heating and ventilation systems were used; and on the use of the different rooms in the house.

The data collected in the survey took as far as possible the form of continuous variables. All variables were checked for normality and outliers. A Kolmogorov-Smirnov test was performed to check for kurtosis, skewness and normality of distribution. The non-normal variables were checked for outliers. Since outliers seemed to be accurate data, non-normal variables were either transformed according to their shape with base 10 logarithm or square root (Field 2005), or converted into categories. In cases where this was not possi-

Table 4.1 Household and building characteristics in OTB survey

Variable	Categories
Elderly	Presence of elderly persons in the household (yes/no)
Children	Presence of children in the household (yes/no)
Education level	Lower education; middle (middle general or lower technical education); higher (higher technical or high education)
Income level according to Centraal Bureau voor de Statistiek (CBS) (2008)	1 Below median (< € 28,500) 2 Median (€ 28,500-€ 34,000) 3 1-2 times median (€ 34,000-€ 56,000) 4 Above 2 times median (> € 56,000)
Type of ventilation system	Mechanical exhaust ventilation: these systems extract indoor air from a house while air from outside infiltrates trough leaks in the building shell and through passive vents like grilles or windows (US Department of Energy, 2002). Balanced ventilation: these systems supply and exhaust approximately equal quantities of fresh outside air and polluted inside air, respectively. A balanced ventilation system has two fans and two duct systems (US Department of Energy, 2002), one for the supply and one for the exhaust. Heat recovery in a heat exchanger is applied between the warm exhaust air and the cold supply air.
Type of temperature control	Manual valves in radiators Manual thermostat (non-programmable thermostat) Programmable thermostat (or clock thermostat)
Type of previous dwelling	Multi-family dwelling: a dwelling located in a building that contains other dwellings Single-family dwelling: a building containing one dwelling unit (a detached house, a terraced house)

ble, non-parametric tests were used. The statistics and number of cases for behaviour variables are can be found in Table 4.2a-b.

Statistical analyses with SPSS (www.spss.com) were conducted to determine the relationships and differences between the variables and energy consumption. In the first part of the study, which investigated relationships between energy use and occupant behaviour, Pearson product-moment correlation coefficients were applied for continuous variables; independent-samples t-tests were applied for dichotomous variables; and one-way ANOVA and Chi-square tests for categorical variables. Regression analyses were carried out to determine the variability in energy consumption explained by behaviour. The second part of the study concentrated on the relationship between occupant behaviour (use of heating and ventilation systems) and type of temperature control, ventilation systems and household characteristics. Since these variables were categories in most cases, ANOVA and Chi-square tests were used to determine the relationship between them.

4.2.4 Energy consumption

The respondents were asked to report the energy consumption from their last available energy bill. The energy data was corrected using heating degree days, based on the period 2006-2007 (2,264.3 heating degree days for Utrecht and 2,186.9 heating degree days for The Hague), since the years of the report-

Table 4.2a Descriptive statistics of continuous and categorical variables in the OTB survey

Variable	Definition	Mean	SD	N
Energy	Energy for space and water heating per year	34520.17	24774.55	240
	(LOG) Energy for space and water heating per year	4.45	.31	240
Thermostat	Highest chosen setting	20	7	290
	Hours in highest chosen setting	11	5	236
	Lowest chosen setting	15	14	299
	Hours in lowest chosen setting	13	5	236
	Highest chosen temperature*hours	210	105	218
	(SQRT) Highest chosen temperature*hours	14	4	218
Radiator	Hours per day radiator on in living room	16	9	313
	Hours per day radiator on in bedrooms	24	3	313
	Hours per day radiator on in bathrooms	12.71	11.5	230
	Hours per day radiator on in the attic	10.81	11.05	74
	Hours per day radiator on in entrance	5.97	9.98	285
	Hours per day radiator rest of the house	20	20	313
Grilles	Hours per day grilles open in living room	14	11	313
	Hours per day grilles open in bedrooms	16	11	313
	Hours per day grilles open in bathrooms and in the attic	5	10	313
	Hours grilles (total)	80	48	270
	(LOG)Hours grilles (total)	1.81	.41	257
Windows	Hours per day windows open in living room	6	8	124
	Hours per day windows open in bedrooms	18	18	268
	Hours per day windows open in bathrooms and attic	9	9	83
	Hours windows open (total)	21	22	289
Showers	(LOG) Showers in minutes per week	1.67	.30	303
Baths	Number of baths per week	1.35	.61	313
Use of space	Number of bedrooms used as living area	2.31	.96	313

▶

ed energy used ranged from 2005 to 2008.

Two types of energy for heating are used in the studied districts: heat (dwellings with district heating) and gas (dwellings with individual central heating). The energy reported from dwellings using gas included energy for space heating, water heating and cooking. The energy data from dwellings with district heating includes energy used for space and water heating, but not for cooking since these households cooked with electricity. Only gas was reported as primary energy. The generation of district heating is considered to have an efficiency of .95 in the Netherlands (NEN 5128: 2004). Energy for cooking and differences in system efficiency might therefore have had a slight effect on the reported energy use. However, gas for cooking is not expected to exceed 5% (EuroACE, 2004).

Table 4.2b Descriptive statistics of continuous and categorical variables in the OTB survey

Variable	Category	N	%
Ventilation system	Ventilation category 1: 1 to 3 hours in lowest setting and rest off/always off	51	16.3
	Ventilation category 2: 1 to 3 hours in highest setting and rest off	110	35.1
	Ventilation category 3: 1 to 3 hours in lowest setting and rest in highest setting/24 hours in highest setting/half in lowest and half in highest setting	67	21.4
	Ventilation category 4: 24 hours in lowest setting	25	8.0
	Ventilation category 5: 1 to 3 hours in highest setting and rest in lowest setting	60	19.2
Type of temperature control	Manual valves in radiators	81	26.0
	Manual thermostat	79	25.4
	Programmable thermostat	151	48.6
Ventilation system	Mechanical exhaust ventilation	217	92.3
	Balanced ventilation	18	7.7
Attic as living area	No	257	82.1
	Yes	56	17.9
Windows open in living room	Always closed	189	60.4
	Open for more than 1 hour	127	39.6
Radiators on in living room	Less than 5 hours radiators on in living room	72	23.0
	6-18 hours radiators on in living room	72	23.0
	Radiators always open in living room	169	54.0
Radiators on in bedrooms	Radiators always closed in bedrooms	117	41.0
	1-18 hours radiators on in bedrooms	65	22.8
	Radiators always open in bedrooms	103	36.1
Radiators on in bathrooms	Radiators always closed in bathrooms	50	21.7
	1-18 hours radiators on in bathrooms	73	31.7
	Radiators always open in bathrooms	107	46.5
Radiators on in entrance	Radiators always closed in entrance	194	68.1
	1-18 hours radiators on in entrance	27	9.5
	Radiators always open in entrance	64	22.5
Windows open in living room	Windows always closed in living room	179	59.1
	Windows open for 1 hour in living room	35	11.6
	Windows open for 2-6 hours in living room	56	18.5
	Windows open for more than 7 hours in living room	33	10.9
Windows open in bedrooms	Windows always closed in bedrooms	34	11.3
	Windows open for 1-3 hours in bedrooms	99	32.6
	Windows open for 4-20 hours in bedrooms	94	31.0
	Windows open for more than 21 hours in bedrooms	76	24.8

Not all cases were used in the analysis because the reported energy use was incomplete or faulty. Table 4.3 shows the number of cases per district con-

Table 4.3 Available energy data per district

District	Response from survey	Reported energy data
Leidsche Rijn	125	94
Wateringse Veld	177	147
Unknown	11	7
Total	313	248

taining data in energy that could be used for the analysis.

4.3 Results: analysis of OTB survey

The results are presented in three sections. The reported behaviour is described in Subsection 4.3.1 and the effect of occupant behaviour on energy consumption in Subsection 4.3.2. The analysis of the determinants of behaviour is presented in Subsection 4.3.3, starting with the effect of type of temperature control and ventilation, followed by the effect of household characteristics on behaviour.

4.3.1 Reported behaviour

Four domains of behaviour or preferences were defined: (1) use of heating system, (2) use of ventilation system, windows and grilles, (3) use of rooms and presence at home, and (4) showering and bathing frequency. The responses are discussed in the subsections below.

Use of heating system

The occupants were asked to report the thermostat setting per hour on weekdays and at weekends. The majority (74.4%) reported a preferred highest setting of 19-200C within a sample range of 15-30^{0}C. It also emerged from the reports that a large percentage (61.2%) of the respondents kept a lowest setting of 15^{0}C within a range of 10-20^{0}C (Figure 4.2). The actual variation in the highest and the lowest setting was not very great in the sample, but there were wide variations in the number of hours that the occupants kept the thermostat at the chosen highest setting for both weekdays and weekends (Figure 4.3).

The occupants were also asked about the hours that the radiators were kept open in each room (Table 4.2). About half the respondents (54%) reported that they always kept the radiator on in the living room; in the rest of the cases the distribution was between 0 and 18 hours. In all the other rooms most cases fell at either 0 or 24 hours with few values in the middle (Table 4.2b).

The obtained data was basis for a set of variables that took account of the highest chosen thermostat setting and the number of hours that this setting was retained. The variable ‘hours radiators open in bedrooms’ was based on the bedroom where the radiator was on for more hours. In most cases, one or two bedrooms were ventilated for far more hours than the others, so a nor-

Figure 4.2 Highest temperature during weekdays

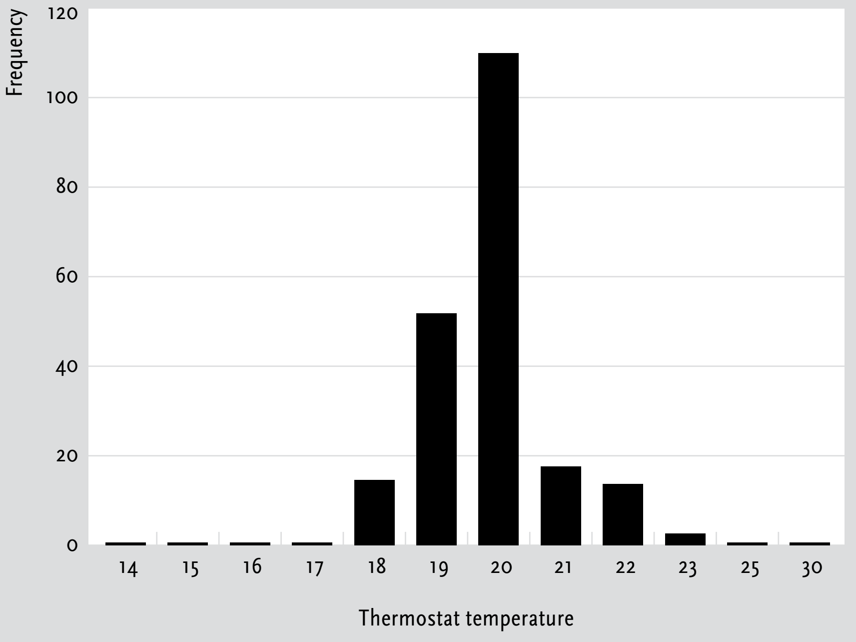
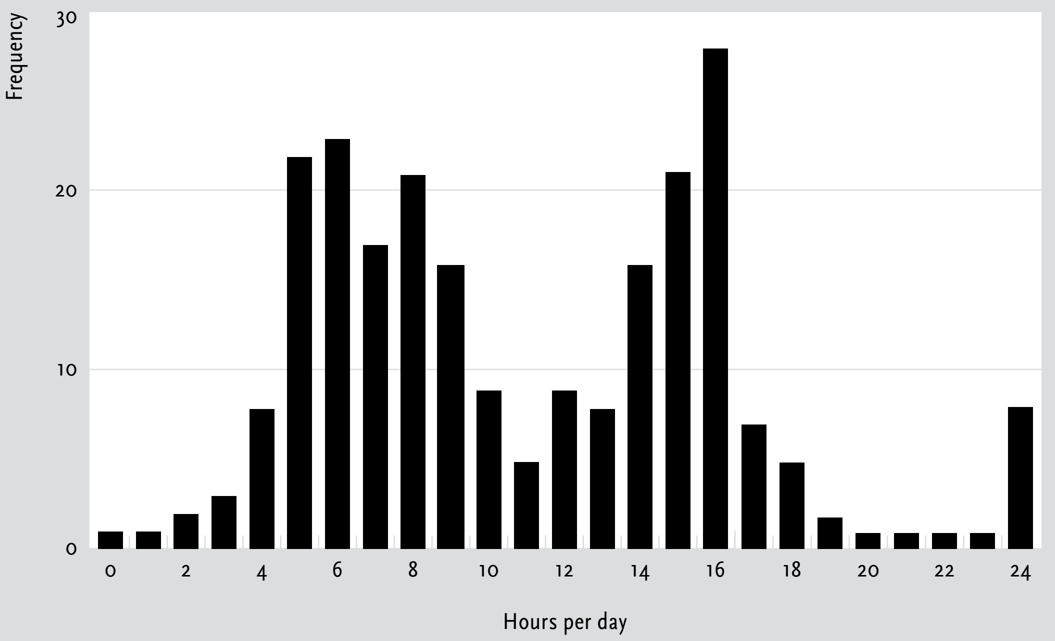


Figure 4.3 Hours of highest temperature during weekdays



malisation per number of bedrooms was not the best option for large dwellings with few occupants (Table 4.2a).

Ventilation: windows, grilles and mechanical ventilation

40% of the respondents reported that they opened the windows in the living room for a few hours a day in the winter. Only 8.1% kept them open all the time. A larger percentage always kept the windows open in the bedrooms, attic and bathrooms. Table 4.2b shows the statistics for open windows.

Grilles for air supply were mostly either open or closed all day in all rooms in all dwellings. More than half the respondents said that they always kept the grilles open in the living room and bedrooms. Most respondents said that the grilles in the remaining space were kept closed (bathroom, attic, entrance). Table 4.2a shows the statistics for open grilles per room.

The respondents were asked to report the setting of the ventilation system (mechanical exhaust or balanced) per hour. Most said that the ventilation was almost always off or in the lowest setting and that they increased the setting when cooking or taking a shower. Table 4.2b shows the statistics for hours per setting per week. Five main patterns of use were found (see Table 4.2b).

Showers and baths

The users reported the number of showers taken by each family member per week and the usual duration. The duration in minutes of the shower use (for the complete household) per week was divided by household size. Users also reported the number the times a week that the bath was used (Table 4.2a). Table 4.2a-b presents the variables used in the analysis.

4.3.2 Effect of occupant behaviour on energy use

This section explores the relationships between occupant behaviour and energy use. A variety of statistical tests were used according to the characteristics of the behaviour variables. For parametric variables (normal form) Pearson product-moment correlation coefficients were used to determine the effect of behaviour on energy use. Pearson's ρ correlation coefficients were used for continuous but non-normal variables. For dichotomous variables, independent-samples t-tests were used to determine differences on energy use for different groups. For categorical variables, one-way ANOVA tests were used to determine the difference on energy use among groups.

A small positive correlation was found between 'energy use' and number of bedrooms used as a living area, hours in highest chosen temperature setting, hours with grilles open (transformed with base 10 logarithm), and with the hours with radiators on in living room, bedrooms, bathrooms, and entrance. No correlations were found at a significance level of .05 for the highest or lowest temperature setting (see Table 4.4 for statistics).

Since the data on gas use includes the energy used for heating water, the correlation between showers and baths frequency and energy use was ana-

Table 4.4 Pearson product-moment correlation coefficients for behaviour variables and energy use in OTB survey

Energy variable	Behaviour related variables	Statistic (+)	N
(LOG) Energy for heating (MJ/year)	Hours radiators on in living room	r = .269***	221
	Hours radiators on in bedrooms	ρ = .205***	215
	Hours radiators on in bathrooms	ρ = .193***	176
	Hours radiators on in entrance	ρ = .174***	215
	Number of bedrooms used as living area	r = .267***	233
	Hours in highest chosen temperature setting	r = .180*	176
	Highest chosen temperature setting	NS	
	(LOG) hours grilles open	r = .254***	194
	Hours windows open	NS	
	Showers in minutes per week / household size	NS	

* =< .05, ** = < .01, *** = < .001, NS = not statistically significant.
(+) Pearson's r is used for parametric data, Pearson's ρ is used for non-parametric data.

lysed for the dwellings with individual central heating. A small correlation was found between baths per week and energy use. No correlation was found with baths per week.

To analyse the effect of open windows, a dichotomous variable was created since most households either have the windows always closed during the winter, or open them only for a few hours. An independent-samples t-test was conducted to compare energy use for dwellings where windows are open for more than one hour in the living room and dwellings were windows are always closed. A small-effect (η^2=.018) positive statistically significant difference was found with houses where windows are open.

The correlations between the variables were studied and the most important variables in each group (those which explain most of the variation in energy use) were introduced into a regression model. These were 'windows open in living room' (open window=1, closed window=0), 'highest chosen temperature multiplied per hours' (transformed with square root for normality), 'hours radiators on in rest of house', and 'hours grilles open' (transformed with base 10 logarithm for normality). Further analysis showed that 'hours grilles open' was not statistically significant in the model. A second model containing only statistically significant variables was then introduced; this explains 11.9% of the variation in energy consumption in dwellings. Assumptions were checked to test the accuracy of the model. The assumption of independent errors (testing the lack of correlation between residuals) was almost certainly met, with the Durbin Watson value very close to 2 (1.653). A 95% confidence interval for B showed that the model was good. The model did not seem to have collinearity problems as the tolerance values and VIF were within the limits. The analysis of residuals statistics had shown that there were no major problems with outliers in the model. The values on Cook's Distances were all well below 1; only 2 cases (1.4%) exceeded 3 times the Leverage Value; 1% of the cases had a large Mahalanobis distance (a critical Chi-square value of approximately 15 for a model of 3 variables) and less than 2.5% (4 cas-

Table 4.5 B, Standard error of B and Beta of regression model with behaviour variables

	B	Std. Error B	Beta
(Constant)	4.254	.087	
Windows are open in living room	-.130	.042	-.227**
(SQRT) Highest temperature * hours	.012	.006	.148*
Hours radiators on in rest of house	.003	.001	.193**

Notes: Dependent variable: (LOG 10) Energy for space and water heating in MJ per year.
R^2 = .119 (percentage of the variation on energy use explained with the model).
* =< 0.05 and ** =< 0.01

es) were beyond 3 standard residuals. Covariance ratio and DFBeta statistics were also revised and no cases were found that could have a strong influence on the regression parameters. We can therefore conclude that the model was fairly accurate. More information about the model can be found in Table 4.5. The equation can be summarized as follows.

LOG energy for heating = 4.254 + (open windows in living room) (-.130) + (SQRT highest temperature multiplied per hours) (.012) + (hours radiators on in rest of house) (.003)

The model therefore indicates that longer periods on a high temperature are related to energy use. The hours that radiators are on in spaces other than living room and bedrooms are also an important factor. Radiators in the living room are usually on in all houses and correlate to the duration on the use of the thermostat; therefore it does not appear to be significant in the model. Radiators in bedrooms are usually closed, while the variation in the use of radiators in bathroom and entrance is larger across households. Dwellings where windows are closed are related to more energy use, which contradicts the fact that more ventilation should lead to more energy use, although this variable has a small effect on energy use. This might be caused by the fact that occupants consciously ventilating the living room for a few hours might turn off the heating during these hours. The fact that the mechanical ventilation system is used scarcely in all households, and the grilles are mostly open in all households as well may explain the fact that ventilation does not influence the variation on energy use in the sample.

4.3.3 Determinants of the use of heating and ventilation systems

Interaction with the environment can affect occupant behaviour. The type of ventilation system and temperature control can have an indirect influence on choices and behaviour patterns. In the sample there were three types of temperature control: programmable thermostat, manual thermostat and manual valves in radiators. The effect of the type of ventilation systems is not reported since both type of systems present in the sample (mechanical exhaust and balanced) are controlled in the same manner and therefore no relationship

Table 4.6a Statistics from Chi-square tests, independent t-tests and one-way ANOVA tests for variables related to building and household characteristics and behaviour in OTB survey

(Characteristic variable * behaviour variable) Pearson's Chi-square	Categories	Manual valves	Manual thermostat	Programmable thermostat	Total
Type of temperature control * Hours radiators open in living room $\chi^2(4) = 80.227$***	Always closed	34	17	21	72
	1-18 hours	38	14	20	72
	Always open	9	48	110	167
	Total	81	79	151	311
Type of temperature control * Hours radiators open in bedrooms $\chi^2(4) = 20.950$***	Always closed	34	32	50	116
	1-18 hours	30	14	21	65
	Always open	15	26	62	103
	Total	79	72	133	284
Type of temperature control * Hours radiators open in bathrooms $\chi^2(4) = 17.119$**	Always closed	19	12	19	50
	1-18 hours	28	16	29	73
	Always open	13	26	67	106
	Total	60	54	115	229
Type of temperature control * Hours radiators open in entrance $\chi^2(4) = 35.839$***	Always closed	70	55	69	194
	1-18 hours	4	7	16	27
	Always open	5	10	48	63
	Total	79	72	133	284
Type of temperature control * Categories use of ventilation system $\chi2(8) = 23.914$**	Ventilation cat. 1	13	22	15	50
	Ventilation cat. 2	28	24	59	110
	Ventilation cat. 3	10	14	43	67
	Ventilation cat. 4	4	10	10	24
	Ventilation cat. 5	12	23	25	60
	Total	67	93	151	331

▶

was found with behaviour. Household characteristics that could affect energy use, such the presence of children and elderly persons, type of previous dwelling, income, household size and education were also analysed.

Relationship between type of temperature control and occupant behaviour

In this section, Pearson's Chi-square tests are used to determine whether different types of temperature control have an effect on occupant behaviour. Chi-Square tests are used because behaviour variables were non-normal and had to be converted into categorical variables (categories can be seen in Table 4.6a-c).

Pearson Chi-Square tests were carried out to test the effect of the type of temperature control on the hours that radiators were open in different rooms. Statistically significant differences were found for the hours with the radiator open in the living room, bedrooms, bathroom and entrance (see statistics in Table 4.6a). In all cases a programmable thermostat was associated with more

Table 4.6b Statistics from Chi-square tests, independent t-tests and one-way ANOVA tests for variables related to building and household characteristics and behaviour in OTB survey

		No	Yes	Total
Working home or housework * Hours radiator on in living room $\chi^2(2) = 13.158^{***}$	Always closed	61	11	72
	1-18 hours	42	30	72
	Always open	108	59	167
	Total	211	100	311
Working home or housework * Hours radiator on in attic $\chi^2(2) = 9.368^{**}$	Always closed	22	3	25
	1-18 hours	15	4	19
	Always open	15	14	29
	Total	52	21	73
Presence of elderly people * Categories of use of ventilation system $\chi^2(4) = 19.074^{***}$	Ventilation cat. 1	35	15	20
	Ventilation cat. 2	97	13	110
	Ventilation cat. 3	64	3	67
	Ventilation cat. 4	23	2	25
	Ventilation cat. 5	46	15	60
	Total	265	47	312
Presence of elderly people * Hours windows open in bedrooms $\chi^2(4) = 9.668^{*}$	Closed	32	1	33
	1 hr	37	4	41
	2-5 hrs	60	16	76
	6-20 hrs	62	14	76
	> 21 hrs	68	7	75
	Total	259	42	301
Presence of elderly people * Hours windows open in living room $\chi^2(3) = 13.254^{**}$	Always closed	70	2	72
	1 hour	58	14	72
	> 2 hours	137	31	168
	Total	265	47	312

▶

hours of open radiators. This was followed by a manual thermostat. No statistically significant differences were found on the highest temperature or on the hours in this setting among the three types of temperature control.

Statistically significant differences were found in the use of mechanical ventilation systems for dwellings with different types of temperature control. A connection emerged between type of temperature control and categories of ventilation system. Independent of the type of control, all households had a preference to keep the ventilation system on the highest setting for a few hours and off for the rest of the time. In addition, households with manual thermostats also kept the system in the highest setting or lowest setting for a few hours and turned it down the rest of the time. Households with programmable thermostats kept a combination between the lowest and highest setting. The relationship between temperature control and behaviour is shown in Figure 4.4, statistics can be seen in Table 4.6a.

Table 4.6c Statistics from Chi-square tests, independent t-tests and one-way ANOVA tests for variables related to building and household characteristics and behaviour in OTB survey

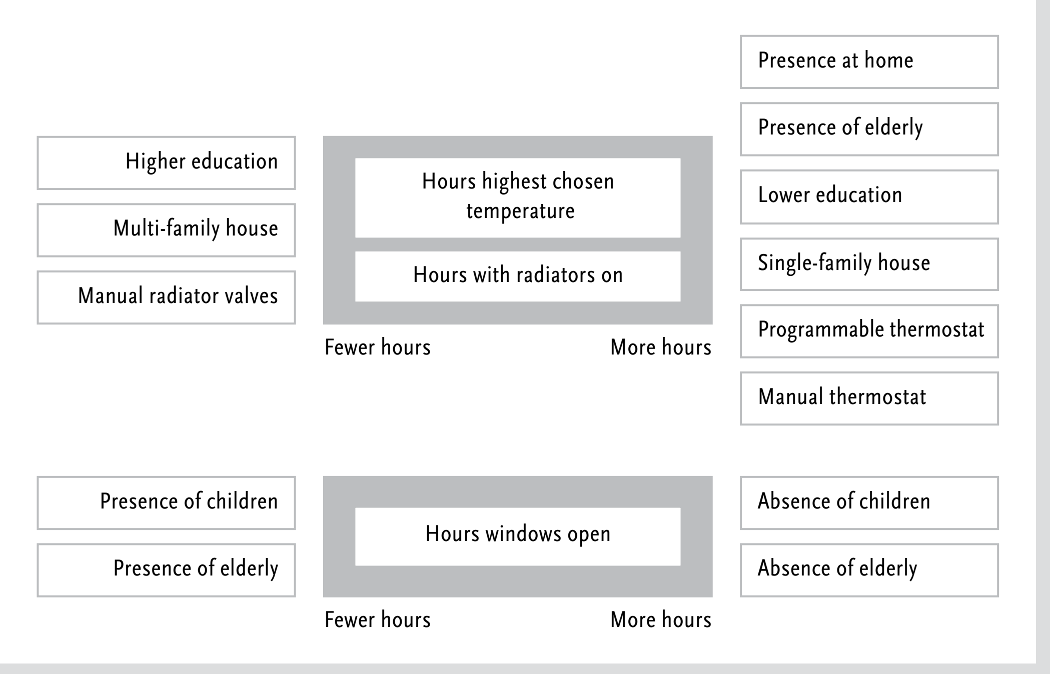
		Multi-family house	Single-family house	Total
Previous house * Hours radiators open in living room $\chi^2(2) = 6.103$*	Always closed	41	31	72
	1-18 hours	39	33	72 168
	Always open	70	98	
	Total	150	162	312
Previous house * Hours radiators open in bedrooms $\chi^2(2) = 9.037$*	Always closed	63	54	117
	1-18 hours	38	29	65
	Always open	37	66	103
	Total	136	149	285
Previous house * Hours radiators open in bathrooms $\chi^2(2) = 9.687$**	Always closed	31	19	50
	1-18 hours	37	36	73
	Always open	39	68	107
	Total	107	123	230
Previous house * Hours radiators open in entrance $\chi^2(2) = 10.675$**	Always closed	105	89	194
	1-18 hours	11	16	27
	Always open	20	44	64
	Total	136	149	285
(Characteristic variable * behaviour variable)	**Statistics (t-tests and ANOVA)**	**Mean (SD)**		
Presence of elderly people * Hours highest chosen temperature	$t(63.265) = -2.379$*	Yes M = 12.5 (3.85) No M = 10.72 (5.44)		
Working home or housework * Hours in highest chosen setting	$t(178.85) = -4.637$***	Yes M = 13.10 (4.15) No M = 10.09 (5.47)		
Previous house * Hours in highest chosen setting	$t(234) = -2.075$*	Multi-family M = 10.23 (5.33) Single-family M = 11.65 (5.13)		
Education level * Hours in highest chosen setting	$F(2,27.018) = 4.084$* (+)	Lower M = 13.44 (2.46) Middle M = 11.02 (5.03) Higher M = 10.81 (5.46)		

* = < .05, ** = < 0.01, *** = < 0.001, NS = not statistically significant.
(+) Welch statistic is reported because the assumption of homogeneity of variances was violated. The statistic is an alternative to F-ratio derived to be robust when homogeneity of variance has been violated (Field, 2005).

Relationship between household characteristics and occupant behaviour

The relationship between the use of heating system and households' characteristics was analysed. The household characteristics taken into account are: income, education level, household size, presence of elderly and children, presence at home, and the type of previous house. The statistical tests used depended on the type of variables. Household characteristics were in categories (see Table 4.1), while behaviour variables were in continuous form. Some behaviour variables had to be recoded as categorical variables using 25% distributions because of their non-normal shape. Independent-samples t-tests

Figure 4.4 Relationships between the type of temperature control, household characteristics, and use of heating system in the OTB survey



were used to determine the differences on behaviour in dichotomous household variables. One-way ANOVA tests were used for households' characteristics with more than two levels. Pearson's Chi-square tests were used to determine whether different behaviour can be observed in different groups of households. Statistics can be seen in Table 4.6b-c.

Household size and income turned out to be unconnected to any of the types of behaviour defined for the use of heating and ventilation systems in this study; although statistically significant differences were found on the energy used per type of income group [$F(3,220)=3.111$, $p<.05$] and household size [$F(4,66.414)=4.548$, $p<.05$], both with a small effect size.

An independent-samples t-test uncovered a relationship between the presence of elderly persons in the household and the number of hours that the thermostat is at the highest chosen setting. The presence of elderly persons is related to more hours using the heating system (see Table 4.6c). In addition, Chi-square tests showed that the presence of elderly persons was associated with fewer hours per day of open windows in the living room and in the bedrooms. The presence of elderly persons was further associated with the use of the ventilation system; they preferred to keep the system at the highest chosen setting for a few hours and the rest of the time at the lowest chosen setting or off.

A further Chi-square test showed that the presence of children at home was associated with keeping the windows closed in the living room. Presence of children did not appear to be related to the use of heating system.

Though no relationship was found between educational level and energy use, statistically significant differences were found in hours at the highest chosen setting on weekdays for households from different educational levels, albeit with a very small effect size [ω=.024]. A higher education level was related to fewer hours at the highest chosen setting (Table 4.6c). The presence of people at home was associated with longer hours with the heating system at the highest setting (Table 4.6c) and longer hours with radiators on (Table 4.6a).

Behavioural patterns in a previous house could influence behavioural patterns in a new house. A T-test showed that households that had previously lived in a single-family dwelling were more likely to have the thermostat at the highest chosen setting for a longer time than households that had previously lived in a multi-family dwelling (Table 4.6c). Pearson's Chi-square tests revealed that the type of previous house was associated with the hours that the radiator was on in the living room, the bedrooms the bathrooms; and the entrance. In all cases, households that had previously lived in a single-family dwelling were more likely to keep the radiators open for longer time (Table 4.6b). Figure 4.4 shows the relationship between occupant behaviour, type of temperature control and household characteristics. Presence of thermostat, single-family houses, presence at home, lower education and presence of elderly are all related to more hours on the use of radiators and thermostats.

4.4 Comparison with WoON database

Since the OTB survey was carried out in selected districts in the Netherlands, the results were compared with the WoON database of the Dutch Ministry of Housing (www.vrom.nl), which is assumed to be representative of the Netherlands. The WoON database holds data obtained from a household survey, dwelling inspections and data on energy use in the dwellings. Similar tests to those conducted with the OTB database were carried out as frequently as possible. Both surveys contained questions about occupant self-reported behaviour, but with a few differences, particularly regarding the use of the heating system. These differences and their implications for the results are discussed below. The tests for the comparison were carried out solely with dwellings built after 1995. The variables for the analysis of the WoON survey and the differences between the WoON survey and the OTB survey are shown in Table 4.7a-b. Descriptive statistics can also be found in Table 4.7a-b.

4.4.1 Effect of behaviour on energy use (WoON survey)

This section analyses the relationships between energy consumption and behaviour using the WoON survey. For these analyses, Pearson's correlations were used for continuous variables and one-way ANOVA for categorical variables (see Table 4.8 for statistics). The results of Pearson's correlations showed

Table 4.7a Descriptive statistics of continuous and categorical variables in the WoON survey

Variable	Mean	SD	N
Household size[1]	2.34	1.21	586
Number of rooms with radiator on[2]	2.68	2.37	564
Temperature thermostat in living room weekdays[2]	15.27	3.33	564
Showers in minutes per week[1]	125.33	112.99	582
Showers in minutes per week / household size[1]	54.30	41.58	582
Temperature setting day (1-5)[3]	1.87	.26	344
Temperature setting evening (1-5)[3]	2.04	.16	339
Temperature setting night (1-5)[3]	1.57	.25	350
Temperature setting weekend (1-5)[3]	1.99	.18	332
Temperature day in Centigrade degrees[3]	18.89	2.62	230
Temperature evening in Centigrade degrees[3]	20.08	2.15	242
Temperature night in Centigrade degrees[3]	15.81	2.58	208
Temperature weekend in Centigrade degrees[3]	19.62	2.11	237
Hours per week mechanical ventilation on in living room[4]	79.97	79.21	68
Hours per week mechanical ventilation on in kitchen[4]	55.51	73.80	148
Hours per week mechanical ventilation on in bedrooms[4]	98.58	79.04	43
Hours per week mechanical ventilation on in bathroom[4]	55.11	74.57	152
Hours per week grilles open in living room[1]	52.95	66.14	238
Hours per week grilles open in kitchen[1]	60.77	70.02	157
Hours per week grilles open in bedroom[1]	80.85	72.18	193
Hours per week grilles open in bathroom[1]	63.89	76.14	56
Hours per week windows open in living room[1]	7.45	22.64	573
Hours per week windows open in kitchen[1]	6.62	23.54	570
Hours per week windows open in bedrooms[1]	50.24	51.66	576
Hours per week windows open in bathroom[1]	13.28	34.34	576

▶

that the energy used in a dwelling is positively correlated with the number of rooms where the radiator is always on. In the OTB database this would be comparable with radiators that are on in different rooms.

A second Pearson's correlation test showed that higher levels of energy use are related to a higher thermostat setting during the night. No correlation was found between thermostat settings and energy use for the OTB database, although correlations were found between energy use and the hours that the thermostat is at the highest chosen setting. This difference might be due to different methods of data collection in the surveys. Even though in both surveys respondents were asked to report the thermostat setting per hour, the WoON database only contains averaged data on thermostat settings during the day, evening, night and weekends.

A correlation was found between energy use and the number of hours that grilles and windows were open in the bathroom. In the OTB database corre-

Table 4.7b Descriptive statistics of continuous and categorical variables in the WoON survey

Variable	Category	N	%
Temperature control[1]	Programmable thermostat	229	39.5
	Manual thermostat	339	58.4
	Manual valves in radiators	12	2.1
	Total	580	100
Ventilation system[1]	Mechanical exhaust	476	82.2
	Balanced	103	17.8
	Total	579	100
Heating off when ventilation via grilles[5]	Living room	48	43.2
	Kitchen	30	27.0
	Bedrooms	93	83.8
	Bathroom	36	32.4
Heating off when ventilation via windows[5]	Living room	118	43.4
	Kitchen	66	24.3
	Bedrooms	228	83.8
	Bathroom	74	27.2
Type of thermostat use[5]	Almost always on the same program	116	50.7
	The program is sometimes changed	72	31.4
	Temperature is always manually set	41	7.0

1 Same in the OTB database.
2 Data on the hours of radiators on per room are available in the OTB database.
3 Setting per hour is available in the OTB database.
4 In the OTB database all new houses have mechanical ventilation in the kitchen and bathroom.
5 Not in the OTB database.

Table 4.8 Pearson product-moment correlation coefficients for behaviour variables and energy use in WoON survey

Energy variable	Behaviour variables	Statistic	N
(SQRT) Energy for heating (m^3/year)	Number of rooms with radiator on	$r = .102$*	545
	Temperature setting by day	NS	
	Temperature setting by evening	NS	
	Temperature setting by night	$r = .163$*	540
	Temperature setting by weekend	NS	
	Hours grilles open in bathroom	$\rho = .226$*	56
	Hours windows open in bathroom	$\rho = .148$***	576
	Hours per week mechanical ventilation in bathroom	$\rho = .227$**	152
	Type of thermostat use	$F(2,221) = 5.014$**	222

* = < .05, ** = < .01, *** = < .001, NS = not statistically significant.

Table 4.9a Statistics from Chi-square tests, independent t-tests and one-way ANOVA tests for variables related to building and household characteristics and behaviour variables in WoON survey

(Characteristic variable * behaviour variable) Pearson's Chi-square	Categories	Programmable thermostat	Manual thermostat	Total
Type of temperature control * Hours per week mechanical ventilation on in living room $\chi^2(1) = 14.460$***	< 15 hrs	5	22	27
	> 16 hrs	22	12	39
	Total	27	34	66
Type of temperature control * Hours per week mechanical ventilation on in kitchen $\chi^2(3) = 27.176$***	< 3 hrs	3	35	38
	4-7 hrs	8	29	37
	8-167 hrs	12	17	29
	Always	23	15	38
	Total	46	96	142
Type of temperature control * Hours per week mechanical ventilation on in bedrooms $\chi^2(1) = 8.337$**	< 167 hrs	8	12	20
	Always	15	6	21
	Total	23	18	41
Type of temperature control * Hours per week mechanical ventilation on in bathroom $\chi^2(3) = 31.415$***	1 hr	4	32	36
	2-5 hrs	7	21	28
	6-124 hrs	9	26	35
	> 125 hrs	31	16	47
	Total	51	95	146
Type of temperature control * Hours windows open in bathroom $\chi^2(1) = 3.894$*	< 6 hrs	166	265	431
	> 7 hrs	62	65	127
	Total	228	330	558

▶

lations were found only with the number of hours that grilles were open in the dwelling and with open windows in the living room. No relationship with ventilation in bathrooms was found in the OTB database because only a few dwellings had natural ventilation in the bathrooms. In the WoON survey the number of hours using mechanical ventilation in bathrooms also seemed to be correlated with energy use. No information on the use of mechanical ventilation in bathrooms was gathered in the OTB survey because all dwellings had mechanical ventilation with only one control switch for the whole house, mostly placed in the kitchen.

4.4.2 Determinants on the use of heating and ventilation behaviour (WoON survey)

Pearson's Chi-square and one-way ANOVA tests were used to determine the relationship between occupants' behaviour on the one hand, and temperature control and type of ventilation on the other hand (see Table 4.9a-c for statistics). One-way ANOVA tests showed that type of temperature control had an effect on the number of rooms where radiators were on. The number of rooms with the radiator on was greater in dwellings with a programmable thermo-

Table 4.9b Statistics from Chi-square tests, independent t-tests and one-way ANOVA tests for variables related to building and household characteristics and behaviour variables in WoON survey

		Mechanical ventilation	Balanced ventilation	Total
Ventilation system type * Hours per week mechanical ventilation on in living room $\chi^2(1) = 9.010$**	< 15 hrs	26	7	33
	> 16 hrs	14	21	35
	Total	40	28	68
Ventilation system type * Hours per week mechanical ventilation on in kitchen $\chi^2(3) = 11.389$**	1 hr	117	8	125
	2-5 hrs	98	4	102
	6-124 hrs	129	6	135
	> 125 hrs	114	23	137
	Total	458	41	499
Ventilation system type * Hours per week mechanical ventilation on in bathroom $\chi^2(3) = 8.910$*	< 3 hrs	120	5	125
	4-7 hrs	109	7	116
	6-176 hrs	76	11	87
	Always	83	18	101
	Total	388	41	429
Ventilation system type * Heating off when ventilation via grilles $\chi^2(1) = 4.048$*	No	120	33	153
	Yes	101	13	114
	Total	221	46	267
		No	**Yes**	**Total**
Presence of elderly * Hours per week windows open in bedrooms $\chi^2(1) = 25.660$***	< 10 hrs	174	58	232
	11-96 hrs	109	49	158
	> 97 hrs	115	71	186
	Total	398	178	576
Presence of elderly * Hours per week windows open in bathroom $\chi^2(2) = 8.390$*	< 6 hrs	285	161	446
	> 7 hrs	114	16	130
	Total	399	177	576
Presence of children * Hours per week grilles open in bedroom $\chi^2(3) = 7.845$*	< 3 hrs	38	10	48
	3-80 hrs	33	24	57
	81-167 hrs	15	9	24
	Always	49	15	64
	Total	135	58	193
Presence of children * Hours per week windows open in kitchen $\chi^2(2) = 8.302$*	Closed	273	82	355
	1-6 hrs	83	37	120
	> 7 hrs	60	35	95
	Total	416	154	570
Presence of children * Hours per week windows open in bathroom $\chi^2(2) = 11.757$**	< 6 hrs	351	95	446
	> 7 hrs	69	61	130
	Total	420	156	576
Presence of children * Hours per week windows open in bedrooms $\chi^2(1) = 32.179$***	< 10 hrs	172	60	232
	11-96 hrs	100	58	158
	> 97 hrs	148	38	186
	Total	420	156	576

Table 4.9c Statistics from Chi-square tests, independent t-tests and one-way ANOVA tests for variables related to building and household characteristics and behaviour variables in WoON survey

(Characteristic variable behaviour variable)	Statistics (t-tests and ANOVA)	Mean (SD)
Type of temperature control Number of rooms with radiator on	F(3,16.825) = 16.841*** (+)	None M = 4.17 (7.16) Programmable M = 3.13 (2.46) Manual M = 2.29 (2.05) Manual valves M = 0.80 (1.03)
Type of temperature control Setting by night	F(3,346) = 4.464**	Manual valves in radiators M = 1.53 (.31) Manual thermostat M = 1.53 (.25) Programmable thermostat M = 1.61 (.22)
Presence of elderly Temperature setting day	t(163.149) = -5.703***	Yes M = 20.18 (2.17) No M = 18.30 (2.61)
Presence of elderly Temperature setting evening	t(129.652) = -2.741**	Yes M = 20.66 (2.17) No M = 19.84 (2.10)
Presence of elderly Temperature setting weekend	t(235) = -3.674***	Yes M = 20.36 (1.58) No M = 19.29 (2.23)

* = < .05, ** = < 0.01, *** = < 0.001, NS = not statistically significant.
(+) Welch statistic is reported because the assumption of homogeneity of variances was violated.
The statistic is an alternative to F-ratio derived to be robust when homogeneity of variance has been violated (Field 2005).

stat than in dwellings with a manual thermostat or manual valves in radiators (see Table 4.9c). ANOVA tests showed that the temperature during the night in dwellings with a programmable thermostat was statistically significantly higher than in dwellings with a manual thermostat or manual valves in radiators (see Table 4.9c).

Chi-square tests showed that the type of temperature control was also related to the hours that the ventilation system was on (see Table 4.9c). Households with a programmable thermostat were more likely to use the ventilation system for more hours than households with manual thermostats

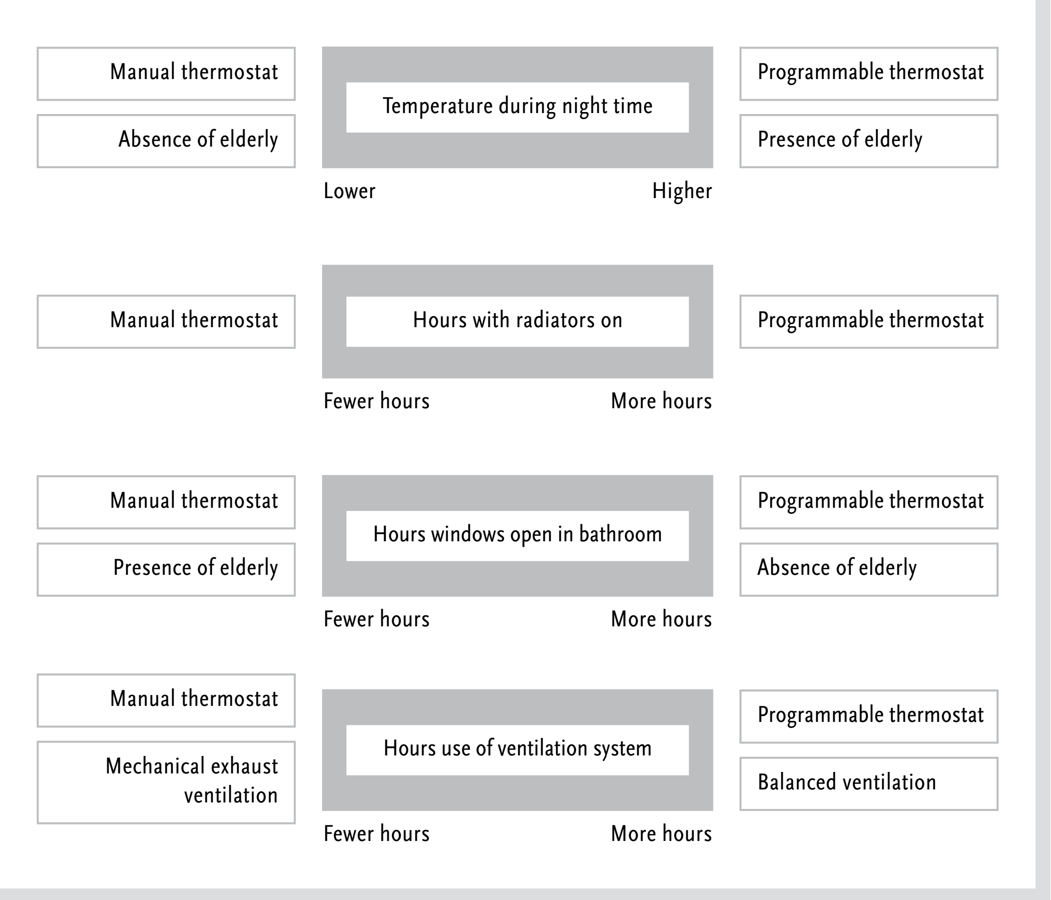
A relationship was found for the hours that windows were open in the bathroom. Households with a programmable thermostat open windows for more hours (see Table 4.9a).

Further analysis of the WoON database showed that households with a manual thermostat were 5.8 times more likely to turn off the heating when grilles were open in the living room and 2.3 times more likely to turn off the heating when windows were open in the living room (see Table 4.9b).

Dwellings with balanced ventilation were associated with more hours of ventilation than households with mechanical exhaust ventilation. A Chi-square test showed that people with mechanical ventilation were 2.2 times more likely to turn off the heating if the windows in the living room were open (see Table 4.9b). Figure 4.5 shows the relationships in the WoON database.

The results from both surveys point at the fact that programmable thermostat is related to longer hours on the use of heating system and more rooms heated. The greater variety of dwelling layouts in the WoON survey (i.e. more cases with windows in bathrooms) resulted on more insight on open windows.

Figure 4.5 Relationships between the type of temperature control, the type of ventilation, and use of heating system in the Woononderzoek Nederland (WoON) survey



4.4.3 Relationship between household characteristics and occupant behaviour (WoON survey)

An ANOVA test showed that households with elderly members were more strongly associated with higher temperature settings than households without elderly members (Table 4.9c). The presence of elderly persons was also found to be associated with fewer hours of open windows in bathrooms. Conversely, it emerged that households with elderly persons ventilated for more hours via bedroom windows (Table 4.9b).

The presence of children was associated with open grilles in the bedrooms; households without children were more likely to open the grilles either all day or not at all. In addition, households without children were more likely to keep the windows closed in the kitchen, and more likely to open them for a longer time in the bedrooms and bathrooms (Table 4.9b).

The results for household characteristics and behaviour are similar for the OTB and the WoON survey. In both databases, the presence of elderly persons was related to more hours of use of the heating system or higher temperature settings. In both surveys presence of elderly was associated with fewer hours of mechanical ventilation, fewer hours of open windows in the bathroom and fewer hours of open windows in the living room. The main difference between the surveys is that in the WoON survey; households with children were associated with hours of window ventilation. These associations were not statistically significant for the OTB survey. Households with children were, however, associated with closed windows in the living room in both surveys. Figure 4.5 shows the determinants of occupants' behaviour in the WoON survey.

4.5 Discussion

4.5.1 Effect of occupants' behaviour on energy use

Small correlations were found between energy consumption and variables relating to hours in the highest and lowest chosen setting, hours that radiators are turned on and the number of bedrooms used as a living area. The WoON database showed similar uses of heating systems as the OTB database; the number of heated rooms and the hours that the heating was turned on had an effect on energy use. However, the most important factor in energy use in the OTB database, i.e. the hours that the thermostat was at the highest chosen setting could not be verified in the WoON database because of the nature of the data. An association between the energy used and the temperature setting during the night in the WoON database did, however, give an indication of the same parameter.

The results seem to be in accordance with the results of other studies which found correlations between energy consumption and choice on temperature setting (Jeeninga *et al.*, 2001; Haas *et al.*, 1998; Linden *et al.*, 2006; Hirst & Goeltz, 1985). Linden *et al.* (2006) found that a large proportion (38%) of households lowered the temperature at night. Haas *et al.* (1998) found a relationship between indoor temperature and energy use. The results from Jeeninga *et al.* (2001) indicated that most households (73%) keep the indoor temperature at 18-20 degrees, were similar to those of the OTB survey.

Thermostat use emerged as an important factor on occupant's behaviour: households with a programmable thermostat were associated with higher temperature settings during the night time in the WoON survey, and with more hours with radiators on in the OTB survey. Nevius & Pigg (2000) found that households with programmable thermostats reported slightly higher settings than households with manual thermostats, although the differences were not statistically significant. Similar results were obtained in the WoON survey, where the differences were found to be statistically significant though with a small effect. Shipworth *et al.* (2010) found that the use of temperature controls did not reduce average maximum temperatures or hours of use, although households with programmable thermostats were found to use the heating for 0.4 hours longer than households with manual thermostats, the differences were not statistically significant. Shipworth *et al.* (2010) also found that households without thermostatic control set the temperature 0.6^{0}C lower than households with control, though the difference was not statistically significant. On the contrary, Conner & Lucas (1990) found that households with programmable thermostats set the temperature an average of 0.5^{0}F lower than households with manual thermostats, though also not statistically significant. For cooling, Lutzenhiser (1992) found comparable results: houses with manual thermostat use 21% less energy for cooling than houses with programmable thermostats. In the OTB survey, statistically significant differences on the hours than radiators are on, but not with the hours that the heating system is used. Therefore the results from the OTB survey are in agreement with past studies and offer additional information on the effect of different types of temperature control on the use of radiators.

In our study significant statistical correlations were found between energy use and bath frequency, but no correlation was found between energy use and shouwer frequency. This contradicts the results of Jeeninga *et al.* (2001) in which shouwer frequency was important contributor to energy use. In our sample, households did not use the bath often, which may be related to the type of households living in the districts of study.

Jeeninga *et al.* (2001) found that 20% of households ventilated all rooms every day by opening windows and that bedrooms were more ventilated than other rooms. Similar results were found in the OTB survey.

Statistically significant differences were found between the energy used in dwellings where windows in the living room were open and dwellings where windows in the living room were always closed. This suggests a relationship between ventilation in the living room and lower energy use. Open grilles and windows seemed to be important in both databases. Households tended to ventilate more often with grilles and windows than with a mechanical ventilation system. This corresponds with Iwashita and Akasaka (1997), who found that 87% of the total active (windows and grilles) air change was related to behaviour.

The behaviour observed in the OTB survey also seems to be in accordance with Ernhorn (1988), who found a higher frequency for natural ventilation in bedrooms, followed by children's bedrooms and living rooms. A large variation was also found in bedrooms but not in living rooms.

Maier *et al.* (2009) found that mechanical ventilation with heat recovery reduced energy use by 10-30% in low-energy houses in Germany. They (Maier *et al.*, 2009) also ascertained a poor relationship between heat consumption and hours of open windows in dwellings with natural, mechanical and heat recovery ventilation. This finding is contrary to the findings for the OTB and WoON databases, where no relationship was found between mechanical systems and energy use, but a relationship was found between energy use and natural ventilation. The difference might be explained by occupants in the OTB survey using natural ventilation more often, in combination with an inappropriate use of the mechanical ventilation systems (they were only scarcely used).

4.5.2 Regression model

A statistical regression model using occupant behaviour can predict 11.9% of the variation in energy use. The increase to 11.9% in the current study shows an increase in predictability with behaviour variables alone. In a previous study (Chapter 2) only 4.2% of the variation in energy use was explained by household characteristics and occupant behaviour (only a part of this was explained by behaviour).

The relatively small size of the OTB sample might have prevented the emergence of other small correlations with energy use. Even so, it would be difficult to find one predictor that was more important that the others, as energy use could be affected to a small extent by many different factors.

4.5.3 Determinants of behaviour: type of heating control ventilation and household characteristics

Temperature control turned out to be a very important factor in the use of heating and ventilation systems. Dwellings with a programmable thermostat were associated with more hours of heating system use, followed by dwellings with a manual thermostat. A validation conducted with the WoON database confirmed and provided more insight into the relationship between type of temperature control and behaviour. Temperature control was found to be associated with the number of rooms where the radiator was turned on. The relationship indicated that more radiators were turned on in dwellings with a programmable thermostat. A programmable thermostat for temperature control was also associated with a higher temperature during the night. The analysis of the WoON database further confirmed that temperature control was related to the ventilation of the dwelling. Households with a programmable thermostat were more likely to open windows for a longer time. It further emerged that households with a manual thermostat were more likely to turn off the heating system when windows or grilles were open.

Jeeninga *et al.* (2001) found that type of thermostat had no influence on the preferred setting. However, the OTB survey did find a relationship between type of thermostat and the hours that radiators were on while the WoON survey found a relationship between type of temperature control and the temperature at night. Again, differences might rise from differences on the variables used (hours of thermostat use instead of temperature settings). Jeeninga *et al.* (2001) also found that households with a manual thermostat tended to favour a lower setting if no-one was at home. The WoON survey indicated that households with a manual thermostat turned off the heating when windows were open. Both results point to a relationship between a manual thermostat and energy-saving behaviour.

Ventilation type turned out to be related to behaviour only in the WoON database because the low number of cases with balanced ventilation in the OTB database caused problems with assumptions in the tests. According to the results of the WoON survey, balanced ventilation was associated with more hours of ventilation and a lower probability that the heating would be turned off when the living-room windows were open.

In the OTB database, a relationship was found between the presence of elderly persons and behaviour. Households with elderly persons kept the heating at the highest chosen setting for longer and kept the radiators turned on for more hours. This behaviour might be caused by elderly people being more time at home. They also opened the living-room and bedroom windows for fewer hours, while households with children were more likely to keep the living-room windows closed. Similar results were found in the analysis of the WoON database; the only difference was that small-effect statistically significant differences for the hours that bedroom and bathroom windows were open in households with children, which were not statistically significant in the OTB survey.

4.6 Conclusions

The aim of this study was to determine the influence of occupant behaviour on determining energy use in dwellings that were built after the introduction of the Dutch energy performance requirements, and to clarify the underlying relationships between behaviour, HVAC systems and households' characteristics.

4.6.1 Occupant behaviour and energy consumption

Observed behaviour

Small variations in the highest chosen thermostat setting were found in the sample, with most occupants reporting a top setting of 19-20^{0}C. Wide variations were found for the hours that the occupants kept the thermostat at the highest chosen setting. There seemed to be greater differences in choice for the use of radiators. Half the respondents always kept the radiator on in the living room. Most respondents reported either 0 or 24 hours for all other rooms.

The majority of respondents said that the living room windows were either for a few hours or closed. A larger percentage always kept the windows open in the bedrooms, attic and bathrooms. Grilles were usually either open or closed all day in all rooms. More than half the respondents said that they always kept the grilles open in the living room and bedrooms. In the rest of the space the grilles were closed in most cases. Most respondents reported that the ventilation system was either almost always off or at the lowest setting and that they turned up the setting when cooking or taking a shower.

Influence of occupants' behaviour on energy use

The number of hours that the heating system was on at the highest chosen setting appeared to have a stronger effect on energy consumption than the highest chosen setting as such, a factor that has been usually considered in other studies. Low correlations were found between energy use and the ventilation system, since most households kept the ventilation system off or at the lowest level. Window and grilles ventilation seemed to have a stronger effect on energy use.

Influence of building characteristics on the use of heating and ventilation systems

The type of temperature control seemed to have an effect on the use of heating and ventilation systems. Households with a programmable thermostat were more likely to keep the radiators turned on for more hours than households with a manual thermostat or manual valves in radiators. Households with mechanical exhaust ventilation also tended to turn off the heating when ventilating via windows, while households with balanced ventilation tended to use the ventilation system for more hours. Therefore households with manual thermostats and mechanical ventilation tend to a more energy-conserving behaviour than households with programmable thermostats and balanced ventilation.

Influence of household characteristics on the use of heating and ventilation systems

The presence of elderly persons in the household proved to be a determining factor in the use of the heating system and ventilation; the heating was on for more hours and there were fewer hours of ventilation in households with elderly members. The effect of elderly on behaviour might be closely related to the hours present at home. The presence of children seemed to be related to the use of ventilation; households with children tended to ventilate less than households without children.

4.6.2 Methodology

The data from two surveys were analysed in this research: the survey of the OTB Research Institute and WoON database of the Dutch Ministry of Housing. In both questionnaires the respondents had to fill tables with information on how they used heating systems. This generated very detailed data. Despite the similarities in the method of data collection, the databases from the two surveys contained different types of variables for synthesising the data obtained from the questionnaire. In the WoON database, the variables consisted of the average temperature setting during four specific periods: day, evening, night and weekends. Previous analysis of the KWR database – the predecessor of the WoON survey – (see Chapter 2) had highlighted the importance of temperature settings in the housing stock. For the OTB database, lower variations on temperature settings were assumed because the thermal properties of the building stock had improved after 1995, and therefore a decision was taken to use the highest and lowest chosen temperature instead of using average setting values as is common in other studies. The number of hours that the temperature was kept at the highest and lowest chosen setting was also introduced in the database.

The different decisions that are taken when data from the questionnaires is being processed into the database can influence the results of the study. The variables in the OTB database showed a stronger correlation with energy consumption than the variables in the WoON database. This was probably due to data loss during the averaging of values. The size of the WoON sample might have led to the use of variables that contained far less data than the data collected in the survey.

Accurate energy-user profiles cannot be built without detailed data on the use of heating and ventilation systems. However, too much or too detailed data is sometimes difficult to process and analyse and might therefore compromise the quality of the data in databases, since important information could be lost. Data collection should focus on aspects of behaviour that tend to vary more widely across the population and that seem to have a stronger influence on energy use.

4.6.3 Recommendations for policy and practice

Although no statistically significant differences were found on the use of thermostat in terms of hours of use and highest setting between houses with manual and programmable thermostats, a statistically significant difference was found on the use of radiators, indicating that in dwellings with programmable thermostats occupants take less deliberate actions and leave the control to the thermostat. This gives an opportunity for improvement for example by implementing manual thermostats per room. This would give the opportunity to maintain a desired temperature per room but with enough interaction with the thermostat to achieve deliberate heating only when needed. Another possibility would be to develop another type of automatic thermostat: reacting to presence sensors for instance instead of pre-programmed time tables. In addition, we showed in the regression model that the radiators in other rooms than the living room have a significant effect. Therefore giving feedback to the user on the impact of their decisions (for example having the radiators on at the entrance and corridors) might help the occupant to reduce their energy use.

In the studied sample almost all household used the mechanical exhaust ventilation system and the balanced ventilation system in a very poor way (i.e. they hardly used it). The use of the windows in the living room was found to be an important factor of energy use. This could indicate a need for better and more occupant-friendly mechanical ventilation systems and a need for better integration within the whole system of building characteristics, household characteristics and occupants' behaviour.

4.6.4 Recommendations for further research

As a result of wide variations in preferences and lifestyle, occupant behaviour has emerged as an important contributor to energy use in dwellings built after the introduction of energy performance regulations. Since differences in occupancy patterns seem to have an influence on energy use, further research should concentrate on defining user profiles that can help to predict energy use.

The results of this study indicate that the type of heating and ventilation system has an influence on occupant behaviour. Further research should seek to determine whether behaviour is influenced by other building characteristics. This research focused on dwellings that were built within a relatively short period and thus had similar thermal characteristics and heating and ventilation systems. Differences in behaviour across the entire housing stock should be further investigated to determine the influence of a good thermal environment on occupant behaviour.

References

Andersen, R.V., J. Toftum, K.K. Andersen & B.W. Olessen (2009), Survey of Occupant Behaviour and Control of Indoor Environment in Danish Dwellings, **Energy and Buildings, 41**, pp. 11-16.

Becker, R. & M. Pacuik (2009), Thermal Comfort in Residential Buildings – Failure to Predict by Standard Model, **Building & Environment, 44**, pp. 949-960.

Beerepoot, M. & N. Beerepoot (2007), Government Regulations as an Impetus for Innovations. Evidence for Energy Performance Regulation in the Dutch Residential Building Sector, **Energy Policy, 35**, pp. 4812-4825.

Branco, G., B. Lachal, P. Gallinelli & W. Weber (2004), Expected versus Observed Heat Consumption of a Low Energy Multifamily Complex in Switzerland based on Long-term Experimental Data, **Energy and Buildings, 36**, pp. 43-555.

Brown, Z. & R.J. Cole (2009), Influence of Occupants' Knowledge on Comfort Expectations and Behaviour, **Building Research & Information, 37** (30), pp. 227-245.

Conner, C.C. & R.L. Lucas (1990), **Thermostat Related Behavior and Internal Temperatures Based on Measured Data in Residences**, PNL-7465, Richland, WA: Pacific Northwest Laboratory.

CBS (2008), Centraal Bureau voor de Statistiek, StatLine **Website statline.cbs.nl**, accessed September.

de Dear, R. (2004), Thermal Comfort in Practice, **Indoor Air**, 14 (7), 32.

de Groot E., M. Spiekman & I. Opstelten (2008), **Dutch Research into User Behaviour in Relation to Energy Use of Residences**, Proceedings PLEA Conference.

Ernhorn, H. (1988), Influence of Meteorological Conditions on Inhabitants' Behaviour in Dwellings with Mechanical Ventilation, **Energy and Building, 11**, pp. 267-275.

EuroACE (2004), **Towards Energy Efficient Buildings in Europe**, final report June (ec.europa.eu).

Field, A. (2005), **Discovering Statistics Using SPSS**, 2nd Edition, SAGE Publications, London.

Haas, R., H. Auer & P. Biermayr (1998), The Impact of Consumer Behaviour on Residential Energy Demand for Space Heating, **Energy and Buildings, 27**, pp. 195-205.

Hirst, E. & R. Goeltz (1985), Comparison of Actual Energy Saving with Audit Predictions for Homes in the North Central Region of the USA, **Building and**

Environment, 20 (1), pp. 1-6.

Iwashita, G. & H. Akasaka (1997), The Effect of Human Behaviour on Natural Ventilation Rate and Indoor Air Environment in Summer – a field study in southern Japan, **Energy and Buildings, 25**, pp. 195-205.

Jeeninga, H., M. Uyterlinde & J. Uitzinger (2001), E**nergieverbruik van energiezuinige woningen**, Report ECN & IVAM, ECN-C-01-072.

Karjalalainen, S. (2007), Gender Differences in Thermal Comfort and Use of Thermostats in Everyday Thermal Environments, **Building and Environment**, 42, pp. 1594-1603.

Lan, L., Z. Lian, W. Liu & Y. Liu (2008), Investigation of Gender Difference in Thermal Comfort for Chinese People, **European Journal of Applied Physiology**, 102 (4), p. 471.

Lenzuni, P., D. Freda & M. Del Guadio (2008), **Classification of Thermal Environments for Comfort Assessment**, The Annals of Occupational Hygiene doi:10.1093/annhyg/mep012.

Leth-Petersen S. & M. Togeby (2001), Demand for Space Heating in Apartment Blocks: measuring effect of policy measures aiming at reducing energy consumption, **Energy Economics, 23**, pp. 387-403.

Linden, A.L., A. Carlsson-Kanyama & B. Eriksson (2006), Efficient and Inefficient Aspects of Residential Energy Behaviour: What are the policy instruments for change?, **Energy Policy, 34**, pp. 1918-1927.

Lutzenhiser, L. (1992), A Question Of Control – Alternative Patterns Of Room Air- Conditioner Use, **Energy and Buildings, 18**, pp. 193-200.

Maier, T., M. Krzaczek & J. Tejchman (2009), Comparison of Physical Performances of the Ventilation Systems in Low-Energy Residential Houses, **Energy and Buildings, 41**, pp. 337-353.

Moujalled, B., R. Cantin & G. Guarracino (2008), Comparison of Thermal Comfort Algorithms in Naturally Ventilated Office Buildings, **Energy and Buildings, 40** (12), pp. 2215-2223.

NEN 5128: 2004, **Energy Performance of Residential functions and residential buildings: determination method**, ics 91.120.10, March.

Nevius, M.J. & S. Pigg (2000), Programmable Thermostats that Go Berserk? Taking a Social Perspective on Space Heating in Wisconsin, in: **ACEEE Summer Study in Energy Efficiency in Buildings.**

Nicol, J.F. & M.A. Humphreys (2009), New Standards for Comfort and Energy Use in Buildings, **Building Research & Information, 37** (1), pp. 68-73.

Papakostas, K.T. & B.A. Satiropoulos (1997), Occupational and Energy Behaviour Patterns in Greek Residences, **Energy and Buildings, 26**, pp. 207-213.

Schweiker, M. & M. Shukuya (2009), Comparison of Theoretical and Statistical Models of Air-Conditioning-Unit Usage Behaviour in a Residential Setting under Japanese Climatic Conditions, **Building and Environment, 44**, pp. 2137-2149.

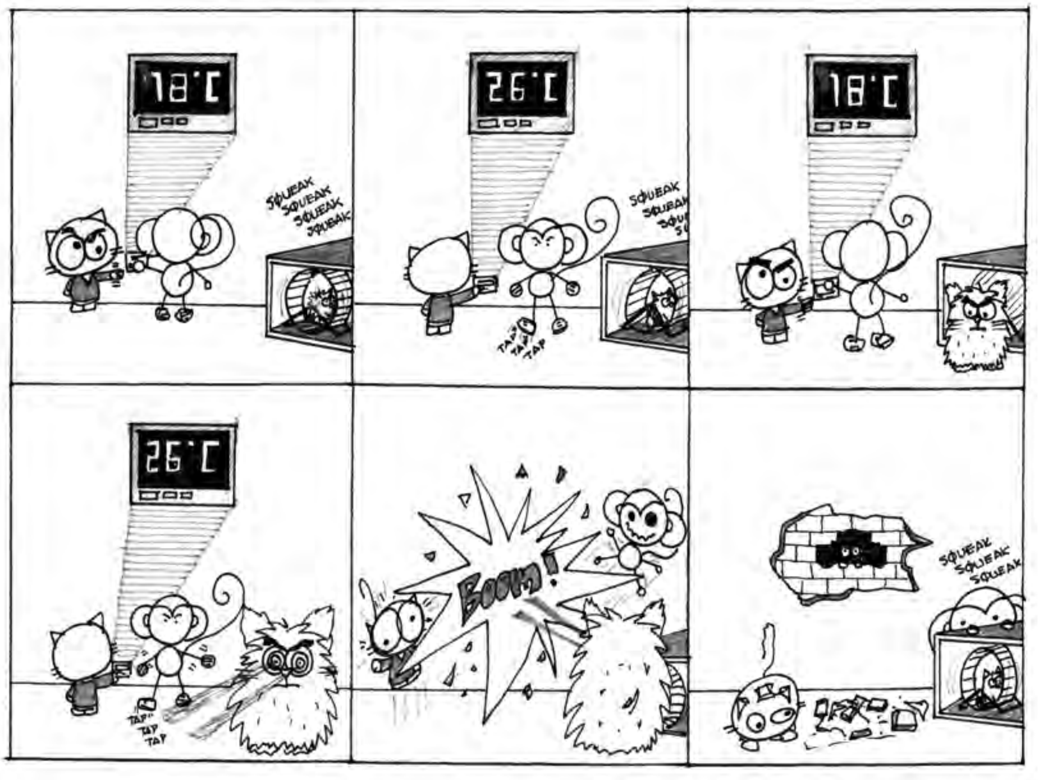
Shipworth, M., S.K. Firth, M.I. Gentry, A.J. Wright, D.T. Shipworth & K.J. Lomas (2010), Central heating thermostat settings and timing: building demographics, **Building Research & Information, 38**, pp. 50-69.

Thermal Comfort Chapter (2005), **Fundamentals volume of the ASHRAE Handbook**, ASHRAE, Inc., Atlanta, GA.

US Department of Energy (2002), **Whole-house ventilation systems**, http://www.southface.org/web/resources&services/publications/technical_bulletins/WHVS-Wholehouse_vent%2002-0778.pdf.

VROM, Dutch Ministry of Housing, **website: www.vrom.nl**, accessed July 2009.

Ye, X.J., Z.P. Zhou, Z.W. Lian, H.M. Liu, C.Z. Li & Y.M. Liu (2006), Field Study of a Thermal Environment and Adaptive Model in Shanghai, **Indoor Air, 16** (4), pp. 320-326.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5 Behavioural patterns related to energy consumption for heating

Abstract
The difference between the actual and predicted energy consumption for heating in residential buildings is thought to be partly attributable to the use of heating and ventilation systems. More reliable data on energy consumption could help in determining the actual energy performance of dwellings and in the search for the most adequate design for housing and home amenities. Further reductions on energy consumption might also be achieved if energy-saving policy programmes were geared to different household groups. The aim of this paper is to statistically determine behavioural patterns associated with the energy spent on heating in recently built housing and to identify household and building characteristics that could contribute to the development of energy-user profiles. This study had two outcomes: it identified behavioural patterns that can be used in energy calculations and it discerned household groups with different behaviours. Five underlying groups of behavioural variables were found: 'appliances and space', 'energy-intensive', 'ventilation', 'media' and 'temperature comfort', which were then used to define the behavioural patterns and the household characteristics for the user profiles. The behavioural patterns were 'spenders', 'affluent-cool', 'conscious-warm', 'comfort', and 'convenience'. The household groups were 'single/couples' 'high-income couples', 'families' and 'seniors'. These groups showed statistically significant differences in the scores for most of the behavioural factors. This study established clear relationships between occupant behaviour and household characteristics. However, it seems very difficult to establish relationships between behavioural patterns and household groups on the one hand and energy consumption on the other.

5.1 Introduction

In recent decades better thermal properties and installations have lowered the amount of energy required for space heating. Even so, various studies have signalled large differences in energy consumption in similar buildings (Jeeninga *et al.*, 2001; Branco *et al.*, 2004; Linden *et al.*, 2006; Haas *et al.*, 1998), thereby suggesting that occupant behaviour exerts a strong influence. The difference between the actual and predicted energy consumption in dwellings is believed to be caused by the actual quality of the construction, the actual efficiency of the systems and the actual use of home amenities (heating and ventilation systems).

More reliable data on energy consumption would help to determine the actual energy performance of dwellings. Simulation programmes use average occupant behaviour to predict the energy requirements of buildings but actual occupant behaviour may deliver a different set of figures. More information about the actual use of home amenities would help to determine the most adequate building design. Further reductions on energy consumption might also be achieved if energy-saving policy programmes were geared to different household groups (Raaij & Verhallen, 1983a; 1983b; Hamrin in Raaij & Verhallen, 1983b).

In the Netherlands various studies have been conducted with the aim of identifying behavioural patterns related to higher levels of energy consumption and to energy-saving attitudes (Raaij & Verhallen, 1983a; Poortinga *et al.*, 2005). Factors related to energy conservation have been identified as well as household characteristics related to higher levels of energy consumption through the use of heating and ventilation systems. However, studies have also shown that occupant behaviour is connected with certain types of building characteristics and heating and ventilation systems. A rebound effect in energy consumption has also been identified based on the finding that households in dwellings with improved thermal properties still opt for higher indoor temperatures (Hamrin in Raaij & Verhallen, 1983b; Hens, *et al.*, 2010). We found the same effect in Chapter 6.

We assume that behaviour in dwellings with improved thermal properties and automatic HVAC systems will be different from the behaviour in older dwellings and that the characteristics of households living in newer dwellings will be different from those of households living in older dwellings. Behavioural patterns in new dwellings might therefore be different from those determined for the total housing stock. The aim of this paper is to statistically determine behavioural patterns related to the energy consumption for space and water heating in recently built housing given that occupant behaviour is expected to be more visible in newer than in older dwellings. We also seek to ascertain the household and building characteristics that can be used in the construction of profiles for energy consumption in recently built housing.

5.2 State of the art

This section introduces a selection of studies on behavioural patterns and user profiles on energy consumption for space heating. User profiles have been defined with household characteristics (Groot *et al.*, 2008; Paauw *et al.*, 2009), lifestyle and behavioural patterns (Raaij & Verhallen., 1983a; Groot *et al.*, 2008; Paauw *et al.*, 2009; Assimakopoulos, 1992) and cognitive variables such as values, needs and attitudes (Poortinga *et al.*, 2005; Vringer & Blok, 2007). Some studies focus on either behavioural patterns or cognitive variables while others focus on both.

Cognitive variables refer to values, motivations, needs and attitudes (Assael, 1995; Ajzen, 1991). Some studies have successfully found relationships between cognitive variables and energy consumption. Raaij & Verhallen (1983a) found in the 1980s that 5% of the variation in energy consumption could be explained by energy-related attitudes that could be categorised under price, environment, energy concerns, health concerns and personal comfort.

More recently, a survey by Poortinga *et al.* (2005) among 455 households in the Netherlands investigated the acceptability of different energy-saving measures for different household characteristics. They found that different socio-demographic groups and people with different environmental concerns preferred different types of energy-saving measures. The average acceptability of energy-saving measures varied among people with different environmental concerns. Seniors, singles and low-income households were less willing to apply energy-saving measures at home.

Vringer (2007) studied the effect of values, motivation and perception of climate change on the energy consumption of different groups of Dutch households. He found no significant differences in the energy consumption of groups of households with different value patterns (taking account of the socio-economic status), though he did establish that families that were least motivated to save energy used 4% more energy. The households were grouped according to income, age, education and household size.

Behaviour regarding the use of home amenities has been more successfully linked to energy consumption. In a recent study by TNO-ECN (Groot *et al.*, 2008; Paauw *et al.*, 2009) five groups of households were studied on the basis of composition: single inhabitant, couple (<60), single-parent, family and seniors (>60). Four profiles were built on the basis of answers to questions about potential drivers of energy consumption in relation to income, environment and personal convenience: 'convenience/ease' (comfort is important, no interest in saving energy, money or the environment), 'conscious' (comfort is important, some environmental- and cost-awareness), 'costs' (awareness of energy costs and a concern to save money) and 'climate/environment' (concern for the environment). According to Groot *et al.* (2008), these groups had different drivers to engage in energy-saving behaviour.

Raaij & Verhallen (1983a) maintain that, in most households, energy behaviour is not a separate type of behaviour but is contingent on other behaviour associated with, for example, housework, childcare, and hobbies. They carried out a study in 145 households in the Netherlands in the early 1980s and defined five patterns of energy behaviour in relation to the use of heating systems and ventilation habits: conservers, spenders, cool, warm, and average. They found that the age of occupants in the 'warm' cluster was higher than in the other four, that the educational level of 'conservers' was higher than that of 'spenders', and that the household size of 'conservers' was smaller than the rest. They ascertained no differences for income and employment. The conclusion was that the household lifestyle influences energy-related attitudes and behaviour. Family size and composition, besides presence or absence at home, had a direct effect on behaviour and energy consumption.

The results of the study by Raaij & Verhallen (1983a) show similarities with this study and are therefore further addressed in the discussion.

This paper takes account only of behaviour defined as the use of heating and ventilation systems and other home amenities. Previous studies have already revealed a relationship between energy consumption and occupant behaviour (Branco *et al.*, 2004; Linden *et al.*, 2006; Haas *et al.*, 1998, Groot *et al.*, 2008; Leth-Petersen & Togeby, 2001; Andersen *et al.*, 2009; Papakostas & Satiropoulos, 2007). We found the same relationship in Chapter 4. Relationships between behavioural patterns and household and building characteristics have also been investigated with a view to building user profiles based on household types. The determination of household types would lead to more accurate estimates of the energy that could be saved by targeted measures and, at the same time, help energy companies to predict energy consumption. Relationships between energy consumption and household (Linden *et al.*, 2006; Raaij & Verhallen, 1983a; Andersen *et al.*, 2009; Papakostas & Satiropoulos, 2007; Sardianou, 2008; Schweiker & Shukuya, 2009; Lenzen *et al.*, 2006; Liao & Chang, 2002; Biesiot & Noorman, 1999; Vringer, 2005) and building characteristics (Andersen *et al.*, 2009; Papakostas & Satiropoulos, 2007; Sardianou, 2008; Hirst & Goeltz, 1985; Caldera *et al.*, 2008; Tiberiu *et al.*, 2008; Olofsson *et al.*, 2009; Sonderegger, 1977-78) have been previously identified in other research.

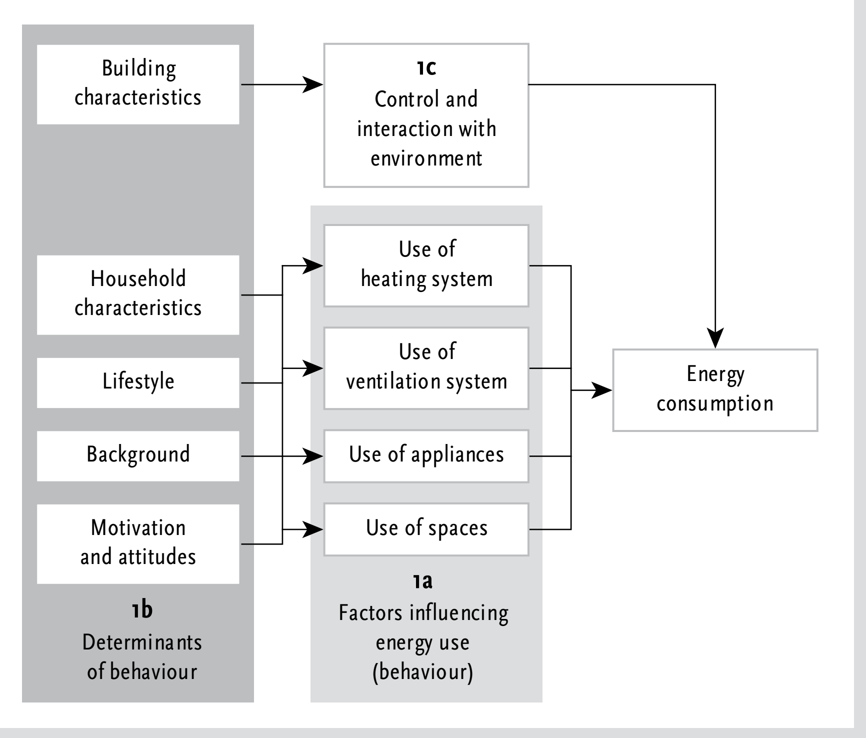
5.3 Methodology and data

5.3.1 Approach

Household characteristics and occupant behaviour were studied since both might prove relevant in the determination user profiles for energy use. A distinction has been made between behaviour and use (Kanis, 1998). Behaviour has been defined as all activities that people perform in the house, while use refers to the direct interaction between an occupant and an action to achieve a goal. In this study behaviour was defined as the use of space, systems and other amenities in the house that can influence the energy consumption for space and water heating. The framework, based on literature and preliminary studies, is shown in Figure 5.1. Household characteristics, lifestyle, background, motivation, values and attitudes (1b) determine behaviour (1a) which in turn influences energy consumption. Behaviour might also be influenced by the interaction between the user and the systems in the building (1c).

Statistical analyses were used in this study. As a first step, an analysis of the effect of occupant behaviour on energy consumption was carried out (Figure 5.2, a), since in other studies (Raaij & Verhallen, 1983a) the lack of correlation between the variables used and energy consumption caused limitations

Figure 5.1 Research framework



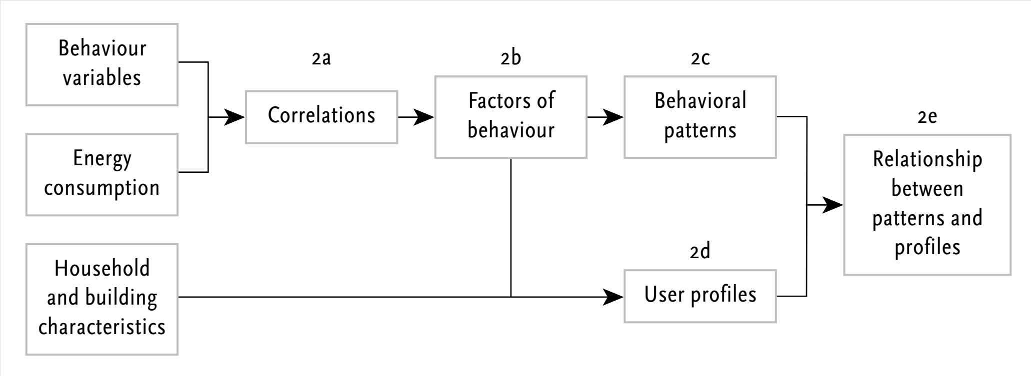
in the analysis.

Afterwards, exploratory factor analysis was carried out to determine the factors underlying behaviour (Figure 5.2, b). These factors can be understood as clusters of variables with relationships that point to hidden drivers of behaviour. For example, Raaij and Verhallen (1983a) found a relationship between a desire to save energy and less ventilation and heating.

In the third step the behavioural patterns were defined (Figure 5.2, c). Clustering procedures were used to determine user profiles. The behaviour factor scores (obtained in step 2) were dichotomised and the households were categorised according to their scores (below the mean = 0, above the mean = 1) for each factor. Because of the relatively small sample size, clusters were formed from groups that demonstrated behaviours with similar energy consequences (e.g. more hours with the radiator on and more hours with the thermostat on are both related to more energy consumption).

The fourth step consisted of defining user profiles. The behavioural factors (from step 2) were used in Pearson's correlations to determine their relationship with household and building characteristics (Figure 5.2, d). The households were then allocated to groups on the basis of the results. The last step was to determine the relationship between the behavioural patterns and the user profiles since they were obtained using different methods (Figure 5.2, e). Further, the relationship between patterns, profiles and energy consumption was determined.

Figure 5.2 Methodology



5.3.2 Research data

The statistical analyses were based on a household survey carried out by the OTB Research Institute. The aim of the OTB survey was to obtain detailed data on occupant behaviour and to pair it with data on building characteristics obtained from municipalities and architects' firms. The survey consisted of a paper questionnaire sent to all households in two previously selected districts in the Netherlands, both built after the introduction of the energy performance regulations in 1995. Consequently, the results of this study apply only to recently built housing. The districts were also selected to ensure that data could be collected about the building characteristics of the dwellings.

The survey was carried out simultaneously in the districts in autumn 2008. The questionnaire was sent to a total of 6,000 households in both districts and met with a response rate of 5% (313 usable cases). The low response rate was due to the length and detail of the questionnaire and to the sense of discomfort that respondents felt about providing personal information on their lifestyle and possessions. As only recently built housing was sampled, households with low income and low levels of education were underrepresented. The type of data that was collected is further explained in the following subsections.

5.3.3 Building characteristics

The studied districts were Leidsche Rijn in Utrecht and Wateringse Veld in The Hague. Both districts contain the type of housing that is representative for the Netherlands: detached, semi-detached, terraced and corner houses, maisonettes and flats. The dwellings in Wateringse Veld had individual central heating systems, while almost all the dwellings in the Leidsche Rijn sample had district heating (with four exceptions). The data on building characteristics were obtained from EPC files provided by municipalities and architects' firms. These data were matched with the survey responses.

There were three types of heating control in the sample: manual valves on radiators, manual thermostats and programmable thermostats. Dwell-

Table 5.1 Definition of household and building characteristics

Variable	Definition	Mean, SD		
Household size	Number of people living in the dwelling	M = 2.58		SD = 1.18
Heating area	Heating area of the dwelling in m²	M = 127.33		SD =36.02
Number of bedrooms	Number of bedrooms in the dwelling	M = 3		SD = 1
Variable	**Definition**		**N**	**%**
Presence of elderly	Presence of person > 65 years old	No	265	84.9
		Yes	47	15.1
Presence of children	Presence of child < 12 years old	No	231	74
		Yes	81	26
Presence at home	Presence at home (working at or in the home)	No	221	67.8
		Yes	100	32.2
Type of tenure (tenant)	Occupant is not owner of the dwelling	No	247	78.9
		Yes	66	21.1
Smoking at home	A member of the household smokes inside the dwelling	No	271	86.6
		Yes	42	13.4
Pets at home	Pets live in the dwelling	No	215	68.7
		Yes	98	31.3
High level of education	A member of household has high level of education (BSc, MSc, PhD, Post doc)	No	88	28.6
		Yes	220	71.4
High income	Annual household income is € 56,000 or more	No	175	59.7
		Yes	118	40.3
Presence of attic	There is an attic in the dwelling	No	185	59.1
		Yes	128	40.9
Multi-family house	The dwelling is a flat or maisonette	No	226	72.2
		Yes	87	27.8
Presence of programmable thermostat	There is an programmable thermostat in the dwelling	No	160	51.4
		Yes	151	48.6

ings which had manual valves on radiators in addition to a manual or programmable thermostat were categorised according to the type of thermostat. Only a few dwellings had balanced ventilation, and all others had mechanical exhaust ventilation, which is the representative situation in the Netherlands. In this paper, only the building characteristics with a strong influence on energy consumption are analysed (Chapters 2 and 3). Based on the results from previous chapters (2 and 3), the building characteristics that affected energy consumption were the dwelling size (which is related to heat-transfer surfaces and total heated area), the insulation level and the presence of a programmable thermostat. Dwelling size and programmable thermostats were related to higher energy consumption and insulation level was related to lower energy consumption. The variables used were: heating, number of bedrooms, presence of attic, type of dwelling and presence of programmable thermostat (see definitions in Table 5.1). Insulation was not taken into account since all the houses in the sample were well insulated.

Table 5.2 Definitions of occupant behaviour variables and correlations with energy consumption

Variable	Definition	Mean and SD	Correlation energy consumption (+)
Number of bedrooms used	Number of bedrooms used for sleeping, working or studying	M = 2.31 SD = 0.96	r = .267*** N = 233
Hours at highest temperature	Hours with the thermostat at the highest chosen temperature	M = 11 SD = 5	r = .180* N = 176
Hours radiator in living room	Hours with the radiator on in the living room	M = 16 SD = 9	r = .269*** N = 221
Hours radiator in bedroom	Hours with the radiator on in the bedrooms	M = 24 SD = 3	ρ = .205*** (-) N = 215
Hours radiator in bathroom	Hours with the radiator on in the bathroom	M = 12.71 SD = 11.5	ρ = .193*** (-) N = 176
Hours radiator in entrance	Hours with the radiator on in the entrance	M = 5.97 SD = 9.98	ρ = .174*** (-) N = 215
Hours windows open in living room	Hours with the windows open in the living room	M = 6 SD = 8	r = -.157* N = 233 (+)
Hours windows bedrooms	Hours with the windows open in bedrooms	M = 18 SD = 18	NS
Hours grilles in living room	Hours with the grilles open in the living room	M = 14 SD = 11	
Hours grilles in bedroom	Hours with the grilles open in the bedroom	M = 16 SD = 11	r = .254*** N = 194
Hours grilles in rest	Hours with the grilles open in the rest of the house	M = 5 SD = 10	

5.3.4 Household characteristics

The information gathered with the survey was related to socio-demographic variables and lifestyle. The analysis looked only at the household characteristics that had shown to influence energy consumption in previous studies: household size, presence of children and seniors, presence at home, education and income (for definitions see Table 5.1).

5.3.5 Occupant behaviour

The questionnaire used for the survey included questions on the use of heating and ventilation systems, showering and bathing frequency, and the use of heat-generating appliances. The occupants were asked to fill in tables, showing the use of home amenities and the time spent at home. Since the survey was carried out in autumn, they were asked about their behaviour during the previous winter considering no extreme weather conditions (too much wind, rain or cold).

The data from the survey took as far as possible the form of continuous var-

Variable	Definition	Mean and SD	Correlation energy consumption (+)
LOG showers	Log 10 of the sum of shower * minutes for the household	M = 1.67 SD = 0.30	NS
Use bath	Number of times that the bath is used per week	M = 1.35 SD = 0.61	ρ = .152* (-) N = 233
Halogen lamps in living room	Number of halogen lamps in the living room	M = 2.53 SD = 1.14	NS
Saving lamps in living room	Number of energy-saving bulbs in the living room	M = 0.80 SD = 0.79	NS
Hours electronics and computers in living room	Number of hours that electronics and computers are used in the living room	M = 2.48 SD = 1.12	ρ = .182** (-) N = 233
Standby electronics and computers in living room	Number of hours that electronics and computers are on stand-by in the living room	M = 0.91 SD = 0.74	NS
Dishwasher times per week	Number of times per week that the dishwasher is used	M = 1.37 SD = 1.15	ρ = .140* (-) N = 232
Dryer	Number of times per week that the dryer is used	M = 0.85 SD = 0.84	r = .171** N = 233
Laundry	Number of times per week that the washing-machine is used	M = 2.25 SD = 1.06	r = .177** N = 233
Laundry warm water	Number of times per week that the washing-machine is used with warm water (30°C)	M = 2.36 SD = 1.07	ρ = .123 (-) p = .06 N = 233

(-) Person's ρ is reported. For the correlation, the variables were used before being converted for normality.
(+) The variable used was the dichotomous: 'Window open in living room for few hours'.
* = p < .05, ** = p < .01, *** = p < .001

iables. All variables were checked for normality and outliers. A Kolmogorov-Smirnov test was performed to check for kurtosis, skewness and normality of distribution. The non-normal variables were checked for outliers. Since the outliers seemed to be accurate data, non-normal variables were either converted according to their shape with base 10 logarithm or square root (Field, 2005). The definitions for behaviour variables can be found in Table 5.2.

5.4 Results

The results are presented in five sections. The occupant behaviour affecting energy consumption for heating (5.4.1) is determined in Section 5.4.1. The second step is developed in Section 5.4.2. It consisted in determining the factors underlying behaviour with exploratory factor analysis. In the third step (5.4.3) we define the behavioural patterns. The fourth step is the analysis of household and building characteristics in relation to each factor in order to determine user profiles (5.4.4). Last, in Section 5.4.5 we analyse the relationship between the behavioural patterns, user profiles and energy consumption.

5.4.1 Effects of occupant behaviour on energy consumption

In this section, correlations analyses are carried out to determine the relationship between occupant behaviour and energy consumption for heating. The statistics are shown in Table 5.2.

The number of rooms in use turned out to be one of the most important variables determining energy consumption for space heating. The rooms considered were those used for sleeping, studying or working.

The heating systems considered were thermostats and radiators. The occupants were asked to report retrospectively the thermostat setting per hour and the hours that the radiators were kept open in each room. The obtained data formed the basis for a set of variables that took account of the highest chosen thermostat setting and the number of hours that it was retained. The 'thermostat setting' by itself did not show a statistically significant correlation with energy consumption since there was not much variation in the sample. This variable was therefore not taken into account for further analysis.

The respondents reported the setting of the mechanical ventilation system (mechanical exhaust or balanced) per hour and the hours with windows and grilles open in each room. However, only the use of windows and grilles was considered in this analysis, since most households reported that the mechanical ventilation was almost always off or at the lowest setting and since any relationship between energy consumption and use of mechanical ventilation systems was absent (Chapter 3).

The users reported the number and usual duration of showers taken by each family member per week. The duration in minutes of shower use (for the entire household) per week was divided by the household size. Users also reported the number of times per week that the bath was used. Although no correlation was found between the frequency of showers and energy consumption, this variable was still included in the analysis because it can help to identify trends in behaviour (Table 5.2).

Use of appliances, computers and electronics refers to the frequency of the use of heat-generating electronics and computers in the living room and the number of times per week that hot-water-consuming appliances such as washing-machines and dishwashers were used. No correlation was found between the use of halogen lamps, energy-saving bulbs, standby electronics and computers and energy consumption for heating. However, as in the case of showering frequency, these variables can point to trends that would otherwise be unidentifiable (e.g. greater use of energy-saving bulbs might indicate a positive attitude towards saving energy).

5.4.2 Factors underlying behaviour: exploratory factor analysis

Exploratory factor analysis was used to identify factors underlying occupant behaviour. Factor analysis describes the variability among variables in terms of factors, which can then help to determine related behaviours. The factors resulting from the analysis (groups of related variables) were further analysed in order to find hidden dimensions that could be understood as drivers of behaviour. According to (Field, 2005), a factor can be described in terms of the variables measured and the relative importance of these variables to that factor. The variables used for the exploratory factor analysis are shown in Table 5.2. The correlation of each variable with energy consumption is also shown in the table. Not all variables were correlated to energy consumption for space and water heating, but their inclusion in the analysis can shed light on underlying behaviours.

Twenty-one variables were used for the analysis. They were examined to ascertain whether factor analysis was suitable, taking account of the correlation between them. All variables correlated by at least .3 with other variables, thus suggesting reasonable factorability. Further analysis of the assumptions led to the conclusion that factor analysis including all variables was suitable. The initial Eigen values (degree of variation in the total sample accounted for by each factor) showed that the first factor explained 15.2% of the variance, the second 10.3%; the third 8.8%, the fourth 8.1%, and the fifth 5.9%. Factors 6 to 21 could explain less than 5% each. After examining the Eigen values in each of the resulting factors, the solution that included five factors and explained 48.4% of the variance was preferred. This decision was also based on the analysis of Eigen values on the scree plot. A final factor analysis test with the twenty-one variables was conducted with just the five factors. The factor loading matrix and communalities for this final solution are shown in Table 5.3. The first five columns show how much each variable contributes to each factor in the final solution. The sixth column contains the communalities, which are the common variance in one variable. The common variance is the variance shared with other variables.

Scores were created for each of the factors, based on the mean of the variables which have their primary loadings on each factor. These composite scores were named after the aspects that defined them: ‘use of appliances and space’, ‘energy-intensive’, ‘ventilation’, ‘media’, and ‘temperature comfort’.

The variable related to Factor 1 indicated a more intensive use of large appliance and spaces. The variables in Factor 2 were related to a more energy-intensive lifestyle. The fact that greater use of halogen lamps and less use of energy-saving bulbs are related to higher scores for this factor indicates less concern for saving energy. The variables in Factor 3 were related to ventilation. The fact that no other variable has a high loading in this factor and

Table 5.3 Factor loadings and communalities based on a principle components analysis for 21 variables of occupant behaviour (N = 235)

	Components					
	1	2	3	4	5	Communalities
Number of bedrooms used	.552			-.381		.462
(LOG) Dishwasher times per week	.725					.575
(LOG) Dryer	.562					.326
(LOG) Washing-machine	.869					.768
(LOG) Washing-machine warm water	.825					.693
(LOG) Halogen lamps in living room (main in other factor)	.406	.389		.442		.512
(SQRT) Hours radiator in living room		.462			.360	.377
(SQRT) Hours radiator in bedroom		.655				.529
(SQRT) Hours radiator in bathroom		.773				.639
(SQRT) Hours radiator in entrance		.632				.434
(LOG) Hours electronics and computers in living room		.310		.382	.364	.394
(LOG) Saving lamps		-.398			.416	.418
Hours grilles in living room			.855			.744
Hours grilles in bedroom			.842			.722
Hours grilles in rest			.586			.398
(LOG) Hours windows open in living room				.387		.308
(LOG) Showers				.650		.467
Use bath				-.490		.347
Hours highest temperature					.559	.324
(SQRT) Hours windows bedrooms					-.500	.321
(LOG) Standby electronics and computers					.589	.411

Rotation method: Varimax with Kaiser Normalization.
Factor loadings < .4 are suppressed.
The Kaiser-Meyer-Olkin measure of sampling adequacy was.644, above the recommended value of.6. The diagonals of the anti-image correlation matrix were all above.5, supporting the inclusion of each item in the factor analysis. Finally, the communalities were all above.3 (see column communalities), further confirming that each item shared some common variance with other items. Given these overall indicators, factor analysis was conducted with all 21 variables.

that loadings in these variables are not present in any other factor indicates that ventilation behaviour is almost independent of other types of behaviour. The variables in Factor 4 indicate a lifestyle with more use of media and modern technology. Use of more halogen lamps might also indicate less concern for energy saving. The relationship between the variables in Factor 5 seems to indicate a preference for a warm indoor environment, since thermostats and radiators are on for more hours and bedrooms are less ventilated. The relationship with use of more energy-saving bulbs indicates that this factor is determined by comfort rather than lack of energy-awareness (as in 'ener-

Table 5.4 Behavioural factors

Factor	Name of factor	Variables
Factor 1	Use of appliances and spaces	• Number of bedrooms used • Dishwasher times per week • Dryer • Washing-machine • Washing-machine warm water • Halogen lamps in living room
Factor 2	Energy-intensive	• Halogen lamps in living room • Hours radiator in living room • Hours radiator in bedroom • Hours radiator in bathroom • Hours radiator in entrance • Hours electronics and computers in living room • Fewer saving lamps
Factor 3	Ventilation	• Hours grilles in living room • Hours grilles in bedroom • Hours grilles in rest
Factor 4	Media	• Fewer number of bedrooms used • Halogen lamps in living room • Hours electronics and computers in living room • Hours windows open in living room • Showers • Less use bath
Factor 5	Temperature comfort	• Hours radiator in living room • Hours electronics and computers in living room • Saving lamps • Hours highest temperature • Fewer hours windows bedrooms • Standby electronics and computers

gy-intensive'). Furthermore, more extensive use of electronics and computers indicates a preference for personal convenience. Table 5.4 shows the variables defining each factor.

5.4.3 Behavioural patterns

To determine behavioural patterns the factor scores obtained in Section 4.2 were dichotomised into above and below the mean. The five dichotomous scores for each case (household) formed a string. After the cases had been categorised by string, fourteen categories were found (corresponding to the fourteen strings found in the sample) (see Table 5.5). Only fourteen strings emerged because of polarity in the scores for some factors: for example, households with high scores for 'temperature comfort' had low scores for 'ventilation' and households with high scores for 'media' had low scores for 'appliances and space'. This limited the number of possible string combinations (see Table 5.5).

As the sample was relatively small, the fourteen strings had to be clustered according to the effect that the behaviour variables in each factor (based on

Table 5.5 Definition of behavioural patterns: strings classification and number of cases (N) per string

High score for this factor equals:	Factor 1 Appliances and space *(More bedrooms used)*	Factor 2 Energy-intensive *(More intensive use of heating, less concern for saving energy)*	Factor 3 Ventilation *(More ventilation)*	Factor 4 Media *(More ventilation, fewer bedrooms used)*	Factor 5 Temperature comfort *(More intensive use of heating, more concern for saving energy)*	N
Spenders	1	1	1	0	0	22
	1	1	0	0	1	12
	1	1	0	0	0	8
Affluent-cool	1	0	1	0	0	28
	1	0	0	0	0	12
Conscious-warm	1	0	0	0	1	18
	0	0	0	1	1	24
	0	0	0	0	1	18
Comfort	0	1	1	1	0	16
	0	1	1	0	0	6
	0	1	0	1	0	19
	0	1	0	0	0	6
Convenience-cool	0	0	1	1	0	31
	0	0	0	1	0	15

the correlations in Table 5.1) had on energy consumption. In other words, factors that were positively related to variables that were positively related to energy consumption were clustered. For example, three strings were categorised under 'spenders'. The first contained 22 cases and consisted of households with high scores for 'appliances and space', 'energy-intensive' and 'ventilation'. The second contained 12 cases and consisted of households with higher scores for 'appliances and space', 'energy-intensive' and 'temperature comfort'. The third string contained 8 cases and consisted of households with high scores for 'appliances and space' and 'energy-intensive'. The fourteen strings were organised into five behavioural patterns:

1. Spenders: use of more space, more use of electronics, more hours of heating, more hours of ventilation, no energy-saving concerns;
2. Affluent-cool: use of more space, more hours of ventilation;
3. Conscious-warm: use of more space, more use of electronics, more hours of heating, fewer hours of ventilation, energy-saving concerns;
4. Comfort: more use of electronics, more hours of heating, more hours of ventilation;
5. Convenience-cool: more use of electronics, more hours of ventilation.

Table 5.5 shows the strings for each behavioural pattern. For classification purposes, priority was given to three factors that were more strongly associated with energy consumption: factor 1, which was related to more use of bedrooms and proved to be an important predictor of energy consumption; factor 2 which was related to more intensive use of the heating systems with less concern for saving energy; and factor 5 which was related to more intensive use of the heating system with more energy-saving concerns. The criteria for the classification can be seen in Table 5.5.

Table 5.6 Correlations between household and building characteristics and behavioural factors

	Factor 1 Appliances and space	Factor 2 Energy-intensive	Factor 3 Ventilation	Factor 4 Media	Factor 5 Temperature comfort
Household size	.583***	NS	NS	-.252***	.149*
Presence of elderly	-.324***	NS	NS	NS	NS
Presence of children	.474***	NS	NS	-.150*	NS
Presence at home	-.169**	NS	NS	NS	.189**
Type of tenure (tenant)	-.137*	-.199**	NS	.136*	NS
Smoking at home	NS	NS	NS	.191**	NS
Pets at home	.292***	NS	NS	NS	NS
High level of education	.159*	NS	NS	NS	NS
High income	.187**	.146*	NS	NS	NS
Heating area	.154*	NS	NS	-.161*	NS
Number of bedrooms	.346***	.164*	NS	-.218**	NS
Presence of attic	.176**	NS	NS	-.199**	NS
Multi-family house	-.315***	NS	.135*	.179**	NS
Presence of automatic thermostat	.179**	.246**	NS	NS	NS

* = p < .05, ** = p < .01, *** = p < .001

5.4.4 User profiles: household and building characteristics related to behavioural factors

The behavioural factors obtained in Section 4.2 were used in correlation tests to determine the household and building characteristics related to each factor. The ultimate aim was to define user profiles. An approximately normal distribution emerged for the composite score data, meaning that the new variables were well-suited for parametric statistical analyses (e.g. correlations, t-tests). There was a practical reason for exploring relationships between household types and behavioural factors (user profiles). Housing career studies have focused on relationships between dwelling type and household type. Energy predictions (i.e. with simulation programmes) are usually based on an average household, which might lead to wide differences between the actual and predicted energy consumption. More accurate predictions could be obtained by linking dwelling type with household type and household type with behavioural patterns.

Pearson's correlations were carried out (see Table 5.6 for statistics). The variables used were those created for each factor in Section 4.2, based on factor scores.

The results indicated that the households that scored high for 'appliances and space' were large young families living in large houses. The absence of people at home during the day and high levels of education and income might indicate a household with two breadwinners. These double-earner households, which usually comprise large families with children, tend to make more frequent use of heavy appliances such as dryers, dishwashers and washing-machines. Thus the first user profile was defined as 'family'.

The household variables related to 'energy-intensive' were 'type of tenure' and 'household income'. Number of bedrooms and an automatic thermostat were also positively correlated to a higher score for this factor. Households with high scores for this factor were home-owners with high incomes living in large houses. They tended to keep a warmer indoor environment and use more electronics and lighting. The negative correlation with energy-saving bulbs combined with high income seems to indicate a low concern for saving energy. The second user profile was defined as 'high-income household'.

No correlations were found between 'ventilation' and household characteristics, making it impossible to define the type of household with a high score for this factor. This indicates that a preference for a cool indoor environment is the main driver of behaviour in this group. No household group was therefore assigned to this factor.

Households with high scores for 'media' were small without children and with smokers at home. They also tended to be tenants in small multi-family dwellings. The user profile for this factor was defined as 'low-income household'.

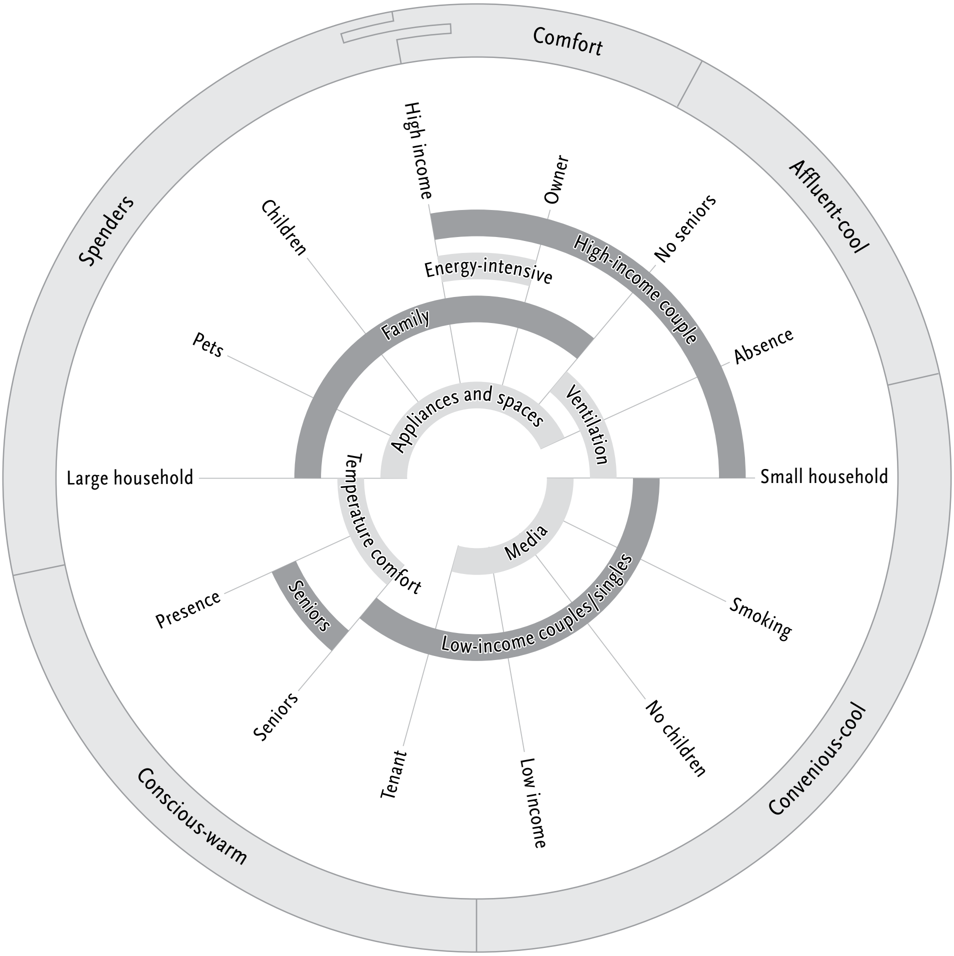
Although no correlation was found between building variables and 'temperature comfort', the household variables relating to 'temperature comfort' were considerable for households with somebody working at home. It seems, therefore, that the thermal properties of the building may have no influence on the preference for a warmer indoor environment. The household group assigned to this factor was therefore 'seniors' since this is the group spending more time at home.

5.4.5 Relationship between behavioural patterns and user profiles

Since the behavioural patterns and the user profiles were determined with different methods, in this section we explain the relationship between them. Figure 5.3 shows the relationship between the outcomes from the different steps of this analysis: behavioural factors, behavioural patterns and user profiles.

Firstly, the figure shows how the behavioural factors (see Section 5.4.2) are opposed to each other (see also Table 5.6). 'Appliances and space' is opposed to 'media' in household characteristics since the former relates to large households and the latter to small households. 'Temperature comfort' is opposed to 'media' for the same reason. 'Ventilation' did not correlate with household characteristics, but we assumed that it is opposed to 'temperature comfort'. 'Appliances and space' and 'energy-intensive' share 'type of ownership' as household characteristic. 'Appliances and space' and 'temperature

Figure 5.3 Relationships found between behavioural factors and household characteristics



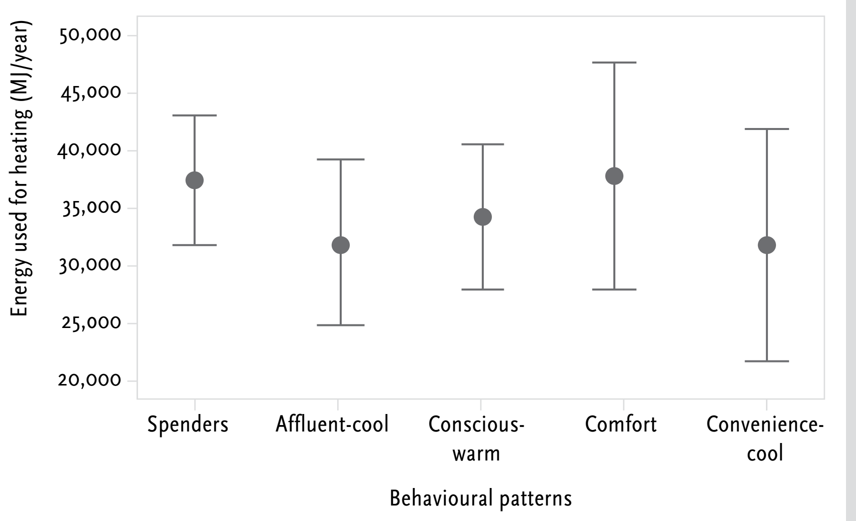
comfort' are opposed in terms of absence but are the same in household size.

The behavioural patterns can be seen in the outer circle of Figure 5.3. The pattern 'affluent-cool' corresponds to the 'ventilation' factor and the 'appliances and spaces' factor. The second pattern 'convenience-cool' corresponds with the factors 'ventilation' and 'media'. The third pattern 'conscious-warm' corresponds to the 'temperature comfort' factor. Last, the patterns 'spenders' and 'comfort' correspond to both 'family' and 'high income' profiles.

The user profiles are identified by the curved lines in the middle of Figure 5.3. The 'family' profile corresponds with 'spenders', 'comfort' and 'affluent cool' behavioural patterns. The 'seniors' profiles corresponds with the pattern 'conscious-warm'. The 'low-income' profile corresponds with the 'convenience-warm' and 'convenience-cool' patterns. The 'high-income' profiles corresponds to the patterns 'affluent-cool', 'comfort' and 'spenders'.

Identifying household characteristics would allow determining the associ-

Figure 5.4 Mean and 95% CI for (LOG) energy consumption in MJ per year per behavioural pattern



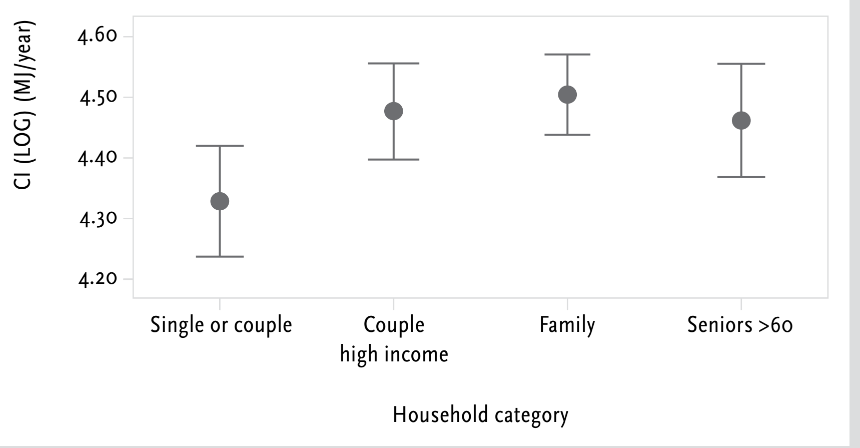
ated behavioural factors and behavioural patterns. For example, if a household turns out to belong to the 'spenders' profile, one may infer a high score for 'appliances and space' and 'temperature comfort', which indicates intensive use of appliances, bedrooms and heating systems and less ventilation.

5.4.6 Relationship between behavioural patterns, user profiles and energy use

As mentioned before, not all the variables used in factor analysis correlated with energy consumption (Table 5.2). Correlation tests were therefore used to determine the factors which were related to energy consumption. The results showed that energy consumption correlated only to 'appliances and space' [ρ=.152, $p<.05$, N=175], 'energy-intensive' [ρ=.153, $p<.05$, N=175] and 'media' [ρ=-.266, $p<.001$, N=175]. No differences were found for 'ventilation' or 'temperature comfort', probably because the correlation between the variables in these factors and energy consumption were too small (for example, though the correlation between energy consumption and ventilation with grilles was statistically significant, the effect was small). These factors do, however, show different drivers behind occupant behaviour and were used to define behavioural patterns.

A one-way ANOVA test was conducted to determine the differences in energy consumption per behavioural pattern. Indicative but non-statistically significant differences were found at $p<.05$ level. [$F(4,170)=1.296$, $p=.274$]. The differences were not statistically significant for two reasons: (1) some of the variables used were not related to energy consumption, and (2) the strong influence of outliers due to the small sample size. Although the patterns showed no statistically significant correlations with energy consumption (Figure 5.4), some displayed clear similarities with those found in other studies and there-

Figure 5.5 Mean and 95% confidence intervals for (LOG) energy consumption in MJ per year per household pattern



fore could be used in further research on user profiles. The similarities and differences are addressed in the discussion section.

Figure 5.5 shows the energy consumption per user profile. Singles/couples tended to use less energy than any other household type. This was related to a high score for 'media' and a low score for 'appliances and space'. The higher energy consumption in the other household types may be related to a different behaviour in each case. High-income couples tended to have a higher score for 'energy-intensive', families tended to have a higher score for 'appliances and space' and seniors tended to have a higher score for 'temperature comfort'. Even though we could not find energy correlations for all behavioural variables and profiles, we can conclude that households with higher scores for 'media' consume less energy than households with higher scores for the other behavioural factors.

5.5 Discussion and conclusions

The purpose of this study was to statistically determine behavioural patterns on the basis of occupant behaviour and to build user profiles based on the household and building characteristics related to these behavioural patterns. First, correlations tests between occupant behaviour variables and energy consumption were carried out as a basis for the exploratory factor analysis.

As a second step, five underlying groups of occupant behaviour variables were found: 'appliances and space', 'energy-intensive', 'ventilation', 'media' and 'temperature comfort'. As this study focused on recently built dwellings, trends discovered in other studies were not found in this study (for example, attitude to energy conservation was not found in this study due to the homogeneity of income and education level).

In the third step, behavioural patterns were formed using the household scores for each dichotomised behavioural factor variable. Five groups were identified: 'spenders', 'affluent-cool', 'conscious-warm', 'comfort', and 'convenience'.

The differences on energy consumption of the different behavioural patterns were only indicative. There were three explanations for the non-statistically significant results: (1) the variations in energy consumption that can be explained by occupant behaviour in new dwellings are smaller than in the total housing stock (see Appendix 3), (2) the relatively small sample size, and (3) not all the occupant behaviour variables were related to energy consumption. We also used variables that were not related to energy consumption in order to gain more information on the underlying behaviour.

The fourth step consisted in determining user profiles. Four profiles – seniors, families, singles/couples and high-income couples – were defined with the correlations between the resulting behavioural factors and the household and building characteristics. No statistically significant differences on energy use were found for the user profiles, however from the analysis we can conclude the type of behaviour observed in each profile. Singles/couples behaviour was less related to temperature comfort or intensive use of appliances and space. High-income couples were less concerned about saving energy and sought a more convenient use of the dwelling. Families needed more space and made more use of heavy appliances. Seniors clearly preferred more comfort given that they scored high for 'ventilation' and 'temperature comfort'. Energy consumption turned out to be lower in senior households and higher in family households.

Some similarities in behavioural patterns were found with the findings of Raaij and Verhallen (1983a) and Groot *et al.* (2008). Raaij and Verhallen (1983a) gathered their data through retrospective self-reports on occupant behaviour regarding thermostat settings and use of radiators, use of ventilation grilles, windows and mechanical ventilation systems. They found five behavioural patterns: 'conservers' (low temperature, low ventilation, higher education, small household size, working wife, less energy consumption), 'spenders' (high temperature, high ventilation, low education, more often at home, more energy consumption), 'cool' (low temperature, high ventilation, medium energy consumption, attitude does not explain energy consumption), 'warm' (high temperature, low ventilation, older people), and 'average'. Their analysis showed statistically significant differences in the energy consumption of the groups. In our study, we found behavioural patterns similar to 'cool', 'warm' and 'spenders'. We did not find patterns related to energy-saving efforts, but our pattern 'convenience' could be comparable, since it related to the factor 'media' which was defined by fewer bedrooms used and showers rather than baths. TNO (de Groot *et al.*, 2008; Paauw *et al.*, 2009) found four behavioural patterns: 'convenience', 'conscious', 'costs' and 'environment'. The similarities with results (de Groot *et al.*, 2008; Paauw *et al.*, 2009) lie in 'convenience/spender' and 'conscious/warm'. The 'costs' pattern was not found for the same reasons as 'conservers' in Raaij and Verhallen (1983a) was not found. The 'climate / environment' pattern was not found because this study did not take account of energy-saving attitudes.

The user profiles defined in our study correspond to those defined by TNO (de Groot *et al.*, 2008; Paauw *et al.*, 2009) which were: 'single', 'two adults below 60', 'single-parent families', 'two-parent families', and 'seniors above 60'. In our sample 'single-parent families' and 'two-parent families' were part of a single group because there were only a few 'one-parent families' among the households. In addition, 'two adults below 60' was split into high-income and low-income, because income turned out to be an important determinant of behaviour. Households in the 'low-income couples' category were merged with 'singles', since the range of income was similar and no notable differences in behaviour were found between 'singles' and 'low-income couples'.

5.6 Recommendations

This research had two outcomes: it identified behavioural patterns and user profiles with different behaviours. Behavioural variables for the use of home amenities can be used to develop behavioural profiles that can be applied in simulation programmes or energy-saving calculations by linking households with specific behaviour (more hours of ventilation, more use of energy-saving light bulbs). User profiles can be used to formulate targeted energy-saving policy for specific sectors of society. The recommendations in this section are derived from the results for household groups.

Previous studies have shown that thermostat type has a significant effect on energy consumption. Hamrin (in Raaij & Verhallen, 1983a) showed that active involvement in energy conservation (by controlling home amenities) leads to lower energy consumption. He also found that energy-conscious households conserve more energy with systems that require active involvement, while less energy-conscious households conserve more energy with systems that do not require active involvement. Thus the type of system should be matched to the lifestyle of the household.

Programmable thermostats are related to higher energy consumption since they are used to heat space that might be used, whereas manual thermostats are used to heat space that is used. The installation of thermostats according to household type could help to reduce the energy consumed for space heating. For example, temperature comfort was found to be important for seniors, who also spend more time at home and therefore keep the heating on for longer. Manual thermostats might reduce energy consumption in these small households, since it would mean that only the rooms that are in use would be heated. In the case of large households, living in larger dwellings, a manual thermostat in each room might be more convenient to heat only the needed space. However, active and younger households might be better off with programmable thermostats since they might be less willing to interact with the system.

Further research should look into the causes of behaviour. The behaviour considered in this study related to the use of systems and other home amenities. This research therefore focused on behaviour itself and not on the causes (cognitive variables). Though it showed that seniors prefer warmer temperatures, it found no relationship between household characteristics and ventilation behaviour. The study of cognitive variables could help to explain why some households prefer higher temperatures or more ventilation than others.

Factor analysis delivered interesting results in relation to the behavioural patterns and factors underlying occupant behaviour. The results were used to identify households and the related building characteristics, which then formed the basis of household profiles. However, no relationships were found between some household profiles and energy consumption or between behavioural patterns and energy consumption because of the addition of variables not related to energy use for heating. A larger sample size and the use of electricity data could enhance the probability of finding such relationships.

Acknowledgements

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References

Ajzen, I. (1991), The Theory of Planned Behaviour, **Organizational behaviour and human decision processes, 50**, pp. 179-211.

Andersen, R.V., J. Toftum, K.K. Andersen & B.W. Olessen (2009), Survey of Occupant Behaviour and Control of Indoor Environment in Danish Dwellings', **Energy and Buildings, 41**, pp. 11-16.

Assael, H. (1995), **Consumer Behaviour and Marketing Action**, Cincinnati, South-Western College Publishing.

Assimakopoulos, V. (1992), Residential Energy Demand Modelling in Developing Regions, The use of multivariate statistical techniques, **Energy Economics**, pp. 57-63.

Biesiot, W. & K.J. Noorman (1999), Energy Requirements of Household Consumption: a case study of Netherlands, **Ecological Economics**, 28, pp. 367-383.

Branco, G., B. Lachal, P. Gallinelli & W. Weber (2004), Expected versus Observed

Heat Consumption of a Low Energy Multifamily Complex in Switzerland based on Long-Term Experimental Data, **Energy and Buildings, 36**, pp. 543-555.

Caldera, M., S.P. Corgnati & M. Filippi (2008), Energy Demand for Space Heating through a Statistical Approach: application to residential buildings, **Energy & Buildings**, 40, pp. 1972-1983.

Field, A. (2005), **Discovering Statistics using SPS**, 2nd Edition, SAGE Publications, London.

Groot de, E., M. Spiekman & I. Opstelten (2008), **Dutch Research into User Behaviour in relation to Energy Consumption of Residences**, Proceedings PLEA Conference.

Haas, R., H. Auer & P. Biermayr (1998), The Impact of Consumer Behaviour on Residential Energy Demand for Space Heating, **Energy and Buildings, 27**, pp. 195-205.

Hamrin, J. (1983), Energy-Saving Homes: don't bet on technology alone, in: Van Raaij & Verhallen 1983a.

Hens, H., W. Parijs & M. Deurinck (2010), Energy Consumption for Heating and Rebound Effects, in: **Energy and Buildings, 42**, pp. 105-110.

Hirst, E. & R. Goeltz (1985), Comparison of Actual Energy Saving with Audit Predictions for Homes in the North Central Region of the USA, **Building and Environment, 20** (1), pp. 1-6.

Jeeninga, H., M. Uyterlinde & J. Uitzinger (2001), **Energieverbruik van energiezuinige woningen**, Report ECN & IVAM, ECN-C-01-072.

Kanis, H. (1998), Usage Centred Research for Everyday Product Design, **Applied Ergonomics, 1** (29), pp. 75-82.

Lenzen, M., M. Wier, C. Cohen, H. Hayami, S. Pachauri & R. Schaeffer (2006), A Comparative Multivariate Analysis of Household Energy Requirements in Australia, Brazil, Denmark, India and Japan, **Energy, 31**, pp. 181-207.

Leth-Petersen, S. & M. Togeby (2001), Demand for Space Heating in Apartment Blocks: measuring effect of policy measures aiming at reducing energy consumption, **Energy Economics, 23**, pp. 387-403.

Liao, H.C. & T.F. Chang (2002), Space-Heating and Water-Heating Energy Demands of the Aged in the U.S., **Energy Economics, 24**, pp. 267-284.

Linden, A.L., A. Carlsson-Kanyama & B. Eriksson (2006), Efficient and Inefficient Aspects of Residential Energy Behaviour: What are the policy instruments for change?', **Energy Policy, 34**, pp. 1918-1927.

Olofsson, T., S. Andersson & J.U. Sjogren (2009), Building Energy Parameter Investigations based on Multivariate Analysis, **Energy and Buildings, 41**, pp. 71-80.

Paauw, J., B. Roossien, M.B.C. Aries & O. Guerra Santin (2009), **Energy Pattern Generator – understanding the effect of user behaviour on energy systems**, Proceedings First European Conference on Energy Efficiency and Behaviour, 18-19 October, Maastricht, available at www.eceee.org/conference_proceedings/EE_and_Behaviour/2009.

Papakostas, K.T. & B.A. Satiropoulos (2007), Occupational and Energy Behaviour Patterns in Greek Residences, **Energy and Buildings, 26**, pp. 207-213.

Poortinga, W., L. Steg, C. Vlek & G. Wiersma (2005), Household Preferences for Energy-Saving Measures: a conjoint analysis', **Journal of Economic Psychology, 29**, pp. 49-64.

Raaij van, W.F. & T.M.M. Verhallen (1983a), Patterns of Residential Energy Behaviour, **Journal of Economic Psychology, 4**, pp. 85-106.

Raaij van, W.F. & T.M.M. Verhallen (1983b), A Behavioural Model of Residential Energy Consumption, **Journal of Economic Psychology, 3**, pp. 39-63.

Sardianou, E. (2008), Estimating Space Heating Determinants: an analysis of Greek households, **Energy and Buildings, 40**, pp. 1084-1093.

Schweiker, M. & M. Shukuya, Comparison of Theoretical and Statistical Models of Air-Conditioning-Unit Usage Behaviour in a Residential Setting under Japanese Climatic Conditions, **Building and Environment, 44**, pp. 2137-2149.

Sonderegger, R.C. (1977-78), Movers and Stayers: the resident's contribution to variation across houses in energy consumption for space heating, **Energy and Buildings, 1**, pp. 313-324.

Tiberiu, C., J. Virgone and E. Blanco (2008), Development and Validation of Regression Models to Predict Monthly Heating Demand for Residential Buildings, **Energy and Buildings, 40**, pp. 1825-1832.

Vringer, C.R. (2005), **Analysis of the Requirements for Household Consumption**, Netherlands Environmental Assessment Agency, Bilthoven, thesis ISBN 90-6960-1303.

Vringer, K. & K. Blok (2007), Household Energy Requirement and Value Patterns, **Energy Policy, 35**, pp. 553-566.

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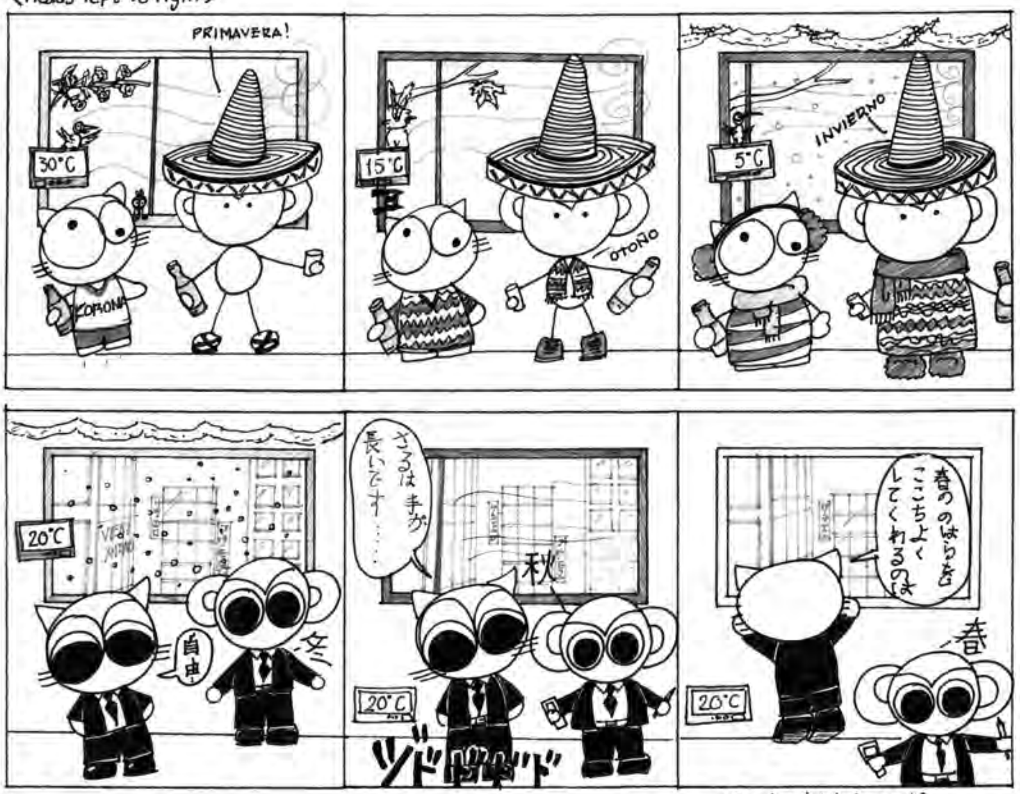

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6 Occupant behaviour in dwellings with improved thermal characteristics
Evidence of a rebound effect

Abstract
The energy required for space heating has been significantly reduced in recent decades by improved insulation and by more efficient heating and ventilation systems. Even so, wide variations in energy consumption can still be observed between similar dwellings and between actual and predicted levels. It is thought that these variations stem from differences in occupant behaviour, the structural quality of the building, and a rebound effect. This paper statistically examines differences in occupant behaviour in relation to the building characteristics of the housing stock in the Netherlands and explores the possible existence of a rebound effect on the consumption of energy for space heating. We found that although energy consumption is lower in recently built dwellings, analysis of the behaviour determinants indicates that occupants of newer dwellings and dwellings with better thermal properties tend to prefer higher indoor temperatures and to ventilate less than occupants of older dwellings. This finding might be related to a rebound effect on occupant behaviour in newer dwellings. However, the improvement of thermal properties and systems efficiency still lead to a reduction on energy consumption for heating.

6.1 Introduction

The energy required for space heating had has been significantly reduced in recent decades by improved insulation and by more efficient heating and ventilation systems. Though energy consumption has decreased, wide variations can still be observed between similar dwellings and between actual and predicted levels (Branco *et al.*, 2004; Haas *et al.*, 1998; Hirst & Goeltz, 1985). It is thought that these differences are to some extent related to differences in occupant behaviour.

Occupant behaviour and building characteristics are known determinants of the level of energy required for space heating in dwellings. But, whereas building characteristics can be directly influenced by regulations, occupant behaviour – which is determined by a whole string of variables including household characteristics, lifestyle, motivation and the interaction between the occupant and the dwelling – cannot be easily changed by external means.

System efficiency and the thermal properties of building elements have improved consistently in recent years; they create a better indoor environment and, at the same time, lower the energy consumption for space heating. Several studies have demonstrated that lower energy consumption is related to better insulation levels and HVAC systems (Hirst & Goeltz, 1985; Caldera *et al.*, 2008; Leth-Petersen & Togeby, 2001; Tiberiu *et al.*, 2008). However, others have found evidence of a rebound effect in better insulated dwellings (Haas *et al.*, 1998; Hens *et al.*, 2010; Brookes, 2000; Schipper & Grubb, 2007; Krewitt *et al.*, 2007). According to Herring & Sorrell (2009), since improvements on energy efficiency reduce the costs of energy services (e.g. gas for heating), the consumption of those services may be expected to increase. Rebound occurs when people compensate for efficiency improvements by increasing their spending (Hens *et al.*, 2010). It is therefore plausible that lower energy costs for heating are offset by a demand for more heating-related benefits (Hens *et al.*, 2010). A clearer understanding of the relationship between building characteristics and occupant behaviour could help to lower the influence of occupant behaviour on energy consumption and identify the factors behind the rebound effect.

Our previous research has focused on determining the effect of occupant behaviour on energy consumption in dwellings that were built after the introduction of the energy-performance regulations in the Netherlands. The type of temperature control and type of ventilation seemed to influence occupant behaviour in dwellings built after the introduction of the Dutch energy-performance regulations (Beerepoot & Beerepoot, 2007). This study showed that the behavioural patterns of users with programmable thermostats – which included higher settings and more hours of open radiators – could lead to higher energy consumption. Type of temperature control and ventilation also appeared to influence the use of mechanical ventilation. Households with a balanced ventilation system were more likely to keep the radiators on for longer and to turn off the heating during ventilation.

These preliminary studies on occupant behaviour in the Netherlands focused on houses built after the introduction of the energy-performance regulations and therefore did not take account of building characteristics such as natural ventilation and low insulation levels. Hence, assuming that wider variations exist in the building characteristics of the total housing stock, one can expect wider differences in occupant behaviour. Since new building stock is more homogeneous and more effects may be assumed to exist in a heterogeneous sample, this paper will explore differences in occupant behaviour in relation to building characteristics in the entire Dutch housing stock. It will also investigate the existence of a rebound effect on the energy used for space heating.

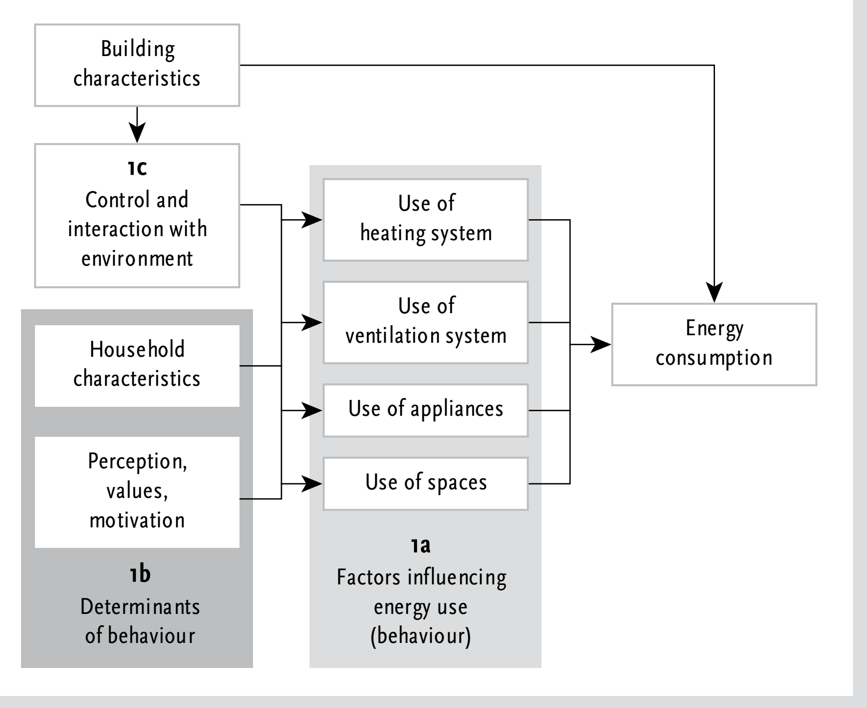
6.2 Effect of occupant behaviour and building characteristics on energy consumption

Several international studies have addressed the importance of the influence of building characteristics and occupant behaviour on levels of energy consumption in housing. Authors agree that better thermal properties and system efficiency in dwellings built after the introduction of energy-performance regulations have helped to significantly reduce the amount of energy used for space heating (Leth-Petersen & Togeby, 2001; Beerepoot & Beerepoot, 2007; Jeeninga *et al.*, 2001). Additionally, international studies have identified a relationship between energy consumption and certain building characteristics, such as year of construction, the shape and size of the building, thermal properties and type of heating system (Hirst & Goeltz, 1985; Caldera *et al.*, 2008; Leth-Petersen & Togeby, 2001; Tiberiu *et al.*, 2008; Olofsson *et al.*, 2009; Sardianou, 2008; Sonderegger, 1977-78). All confirm that newer, better insulated buildings with more efficient systems are related to lower energy requirements for space heating. The size and shape of the dwelling (though considered less often) also seem to have an effect on energy consumption (Andersen *et al.*, 2009). We concluded the same in Chapter 2.

Considerable variations in energy consumption have been found in buildings with the same physical characteristics. These variations are partly attributed to differences in occupancy patterns (Branco *et al.*, 2004; Haas *et al.* 1998; Leth-Petersen & Togeby, 2001; Jeeninga *et al.*, 2001; Andersen *et al.*, 2009; Groot *et al.*, 2008; Linden *et al.*, 2006; Papakostas & Satiropoulos, 2007), which are determined by household characteristics, lifestyle, cognitive variables and perception of comfort (Andersen *et al.*, 2009; Poortinga *et al.*, 2005; Vringer & Blok, 2007; Schweiker & Shukuya, 2009). The relationship between the amount of energy used for heating and household characteristics such as age, composition and size has been extensively studied internationally (Leth-Petersen & Togeby, 2001; Sardianou, 2008; Andersen *et al.*, 2009; Groot *et al.*, 2008; Linden *et al.*, 2006; Schweiker & Shukuya, 2009; Lenzen *et al.*, 2006; Liao & Chang, 2002; Biesiot & Noorman, 1999; Vringer, 2005). Other studies have looked at the effect of household motivation, attitudes and values (Linden *et al.*, 2006; Poortinga *et al.*, 2005; Vringer & Blok, 2007; Schweiker & Shukuya, 2009; Raaij & Verhallen, 1983), although these have been more difficult to relate to energy use. In addition, authors agree, that the way in which the occupant controls the heating and ventilation systems is an important factor.

Our previous study of 313 households in the Netherlands showed that, in dwellings built after the introduction of energy performance regulations in 1995, 18.6% of the variation in energy consumption for space heating can be explained by building characteristics (Chapter 3) and 11.9% by occupant behaviour (Chapter 4). The building characteristics in this study were derived from the Dutch energy-performance regulations, namely: U-values, surface of facades, living area and the efficiency of heating and ventilation systems. The occupant behaviour was related to the use of the heating and ventilation system. In a previous study encompassing the entire Dutch housing stock, the variation explained by building characteristics was far higher at 42% (Chapter 2), since there is a larger variety of buildings' characteristics in the housing

Figure 6.1 Research framework: relation between energy consumption, building characteristics and occupant behaviour

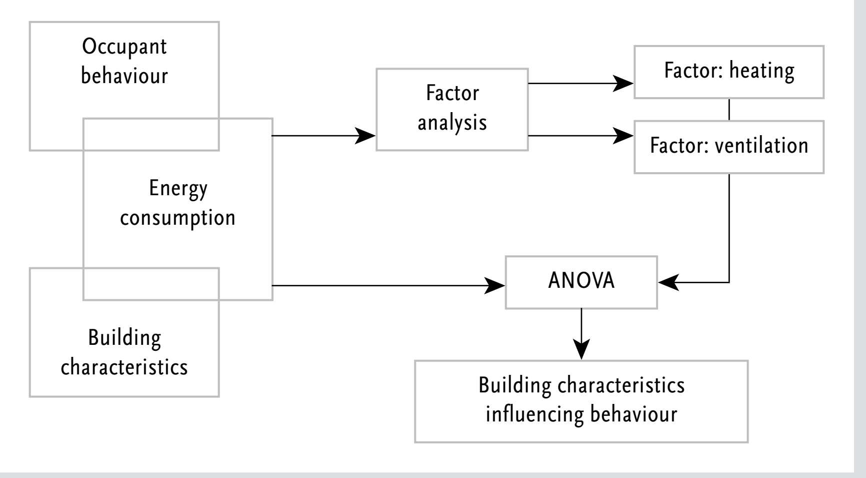


stock. This variation was explained with variables related to type of dwelling, insulation in different building components, and the presence of a garage, open kitchen and attic. In the same study, only 4.2% of the variation in energy consumption was explained by household characteristics and occupant behaviour. This low percentage was attributed to the limited number of variables for occupant behaviour, due to the set-up of the survey.

6.3 Data and methodology

Based on literature, Figure 6.1 shows the relationship between energy consumption, building characteristics and occupant behaviour. Energy for space heating is directly influenced by the use of the heating system (i.e. the temperature chosen by the occupants or the hours that the system is kept on), the use of the ventilation system (i.e. hours of ventilation), use of appliances (i.e. intensity in the use of heat-generating appliances) and the use of space (i.e. number of rooms used, presence of people). In the context of this study these variables fall under behaviour (1a). Behaviour may be affected or determined by several factors, such as building characteristics, household characteristics, perceptions (Assael, 1995) and values, and beliefs and attitudes (Ajzen, 1991) (1b). These are referred to as determinants of behaviour. Building characteristics also affect energy consumption via the thermal properties and the interaction between the user and the building system (1c). Research on

Figure 6.2 Research methodology



occupant behaviour in relation to energy consumption should look at the potential effects of both building characteristics and household characteristics.

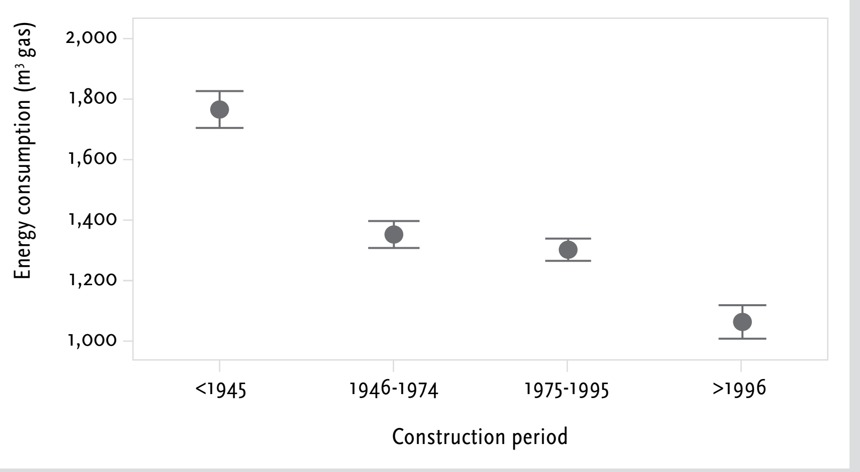
First, an analysis on the influence of building characteristics and occupant behaviour in energy consumption in the existing housing stock and in newer housing was carried out (see Figure 6.2). Pearson's correlation and regression analysis were used for continuous variables (i.e. surfaces, hours, temperature) with the aim of estimating the strength and trend of the relationship between variables. Independent-samples T-test and one-way ANOVA tests were used to determine differences in energy consumption for categorical variables (i.e. dwelling type and ventilation systems). The analysis is followed by a brief comparison with the situation in new housing taken from Chapter 3 and 4.

Statistical analyses were performed with the WoON database. The WoON survey, which was carried out in 2005 by the Dutch Ministry of Housing (VROM, 2009), comprised two questionnaires for occupants, a building inspection and data on energy consumption from energy providers. The sample consists of 4,724 random cases in the Netherlands. Building characteristics were obtained from the inspections while the questionnaires provided information on household characteristics and self-reported use of heating and ventilation systems. More detailed information on the variables can be found in the corresponding sections below.

To determine the relationship between occupant behaviour and building characteristics, Factor Analysis was applied to identify the main components of behaviour, thus reducing the number of variables and facilitating the subsequent analysis. According to (Filed, 2005), a factor can be described in terms of the measured variables and their relative importance for that factor. These factors are later used as dependent variables to determine differences in occupant behaviour in dwellings with different building characteristics.

The factors (expressing behaviour) obtained with the Factor Analysis were used as the dependent variables in the subsequent tests. One-way ANOVAs and factorial ANOVAs were used to identify the building characteristics that affect behaviour. The one-way ANOVAs aimed to identify differences in occu-

Figure 6.3 Energy consumption for space and water heating per construction period (mean and 95% confident interval)



pant behaviour in dwellings with different characteristics while the factorial ANOVAs were used to test the behavioural effects of the interaction between different building characteristics.

6.4 Results

6.4.1 Variations in energy consumption in dwellings built in different construction periods

This section explores the effect of building characteristics and occupant behaviour on energy consumption in the total building stock. First, the building periods were defined according to important changes in building trends in the Netherlands: 1975, the introduction of energy requirements in Dutch building regulations; 1995, the introduction of Dutch energy-performance regulations. Figure 6.3 shows the mean energy consumption and 95% confidence intervals for each construction period. Energy consumption is lower in newer dwellings. Interestingly, the confidence interval is much greater in newly built stock than in older stock. A one-way ANOVA test revealed statistically significant differences between dwellings built before 1945, dwellings built between 1946 and 1974, and dwellings built after 1996 (for statistics see Table 6.2). Earlier construction periods do not necessarily imply lower energy efficiency. The dwellings may, after all, have been refurbished. The relationship between construction period and other building characteristics is therefore further analysed in following sections.

Table 6.1 Descriptive statistics and definitions of building characteristics variables

Variable	Definition	Mean	SD
Number of bedrooms	Number of bedrooms in the dwelling	4.19	1.39
(LOG) Heat transfer surface	Sum of exterior surfaces of the dwelling in square metres (ground floor multiplied by a factor .7 to weight for difference in temperature between ground and air) (m^2)	2.06	0.23
(LOG) Living area	Area of the heated space in the dwelling (m^2)	2.02	0.23
Non-insulated open surface	Sum of surfaces of non-insulated doors, panels and windows (m^2)	8.42	8.81
Insulated open surface	Sum of surfaces of double or insulated doors, panels and windows (m^2)	21.52	12.27
Variable	**Definition**	**N**	**%**
Ventilation system	Natural	552	12
	Local ventilator	2199	47.6
	Mechanical exhaust and balanced	1865	40.4
Temperature control	Manual valves in radiators	199	4.2
	Manual thermostat	2577	54.6
	Programmable thermostat	1581	33.5
	None	362	7.7
Construction period	< 1945	1001	21.2
	1946-1975	1550	32.8
	1976-1995	1587	33.6
	> 1996	586	12.4

6.4.2 Effect of building characteristics on energy consumption: do better thermal properties and systems efficiency lead to reductions in energy consumption?

In this section we analyse the possible existence of a rebound effect on energy consumption. We part from the assumption that better thermal properties, improved systems efficiency and better methods of temperature and ventilation control would lead to a decrease on energy consumption. The characteristics in question are: insulation level, useful living area, dwelling type, construction period, type of ventilation and type of temperature control. Table 6.1 shows definitions and descriptive statistics of the variables.

Medium positive correlations were found between energy consumption and thermal properties (Table 6.2). These findings suggest that energy consumption increases with the size of the dwelling, but decreases in dwellings with more insulation.

Independent samples t-test showed that statistically, energy consumption was significantly higher in dwellings with local ventilator than in those with other types of ventilation (natural, mechanical and balanced) (Table 6.2). Further factorial ANOVA showed that dwellings with local ventilation consume

Table 6.2 Relationship between building characteristics and energy consumption for the total housing stock and housing built after 1995: statistics of Pearson's correlations and ANOVAs

Variable	WoON housing stock		Comparison with
Number of bedrooms	r = .443***	n = 4646	r = .311*** (OTB) r = .344*** (WoON)
(LOG) Living area	r = .381***	n = 4646	r = .262*** (OTB) r= .270*** (WoON)
(LOG) Heat transfer surface	r = .547***	n = 4646	r = .366*** (OTB) r = .450*** (WoON)
Non-insulated open surface	r = .166***	n = 4303	r = .144** (WoON)
Insulated open surface	r = -.166***	n = 4481	r = .345*** (WoON)
Ventilation system	F(2,1451.19) = 190.294*** (+)		t(216) = 2.962** (OTB) t(585) = 1.298 (NS) (WoON)
	Natural	M = 31.02 (13.49)	
	Local	M = 38.95 (11.8)	
	Mechanical	M = 32.41(11.36)	
Type of temperature control	F(3,609.24) = 170.668*** (+)		F(2,236) = 3.380* (OTB) F(3,559) = 3.794** (WoON)
	Programmable	M = 39.67 (10.76)	
	Manual	M = 34.24 (11.77)	
	None	M = 33.09 (11.73)	
	Manual valves in radiators	M = 18.65 (12.30)	
Construction period	F(3,2036.58) = 96.45*** (+)		
	< 1945	M = 40.34 (11.71)	
	1946-1974	M = 34.39 (13.93)	
	1975-1995	M = 34.69 (10.90)	
	> 1996	M = 31.45 (9.47)	

Dependent variable: (SQRT) Energy consumption for heating (m^3/year).
* = p < .05, ** = p < .01 and *** = p < .001
(+) Welch statistic is reported. This statistic is an alternative to F-ratio derived to be robust when homogeneity of variance has been violated (Field, 2005).

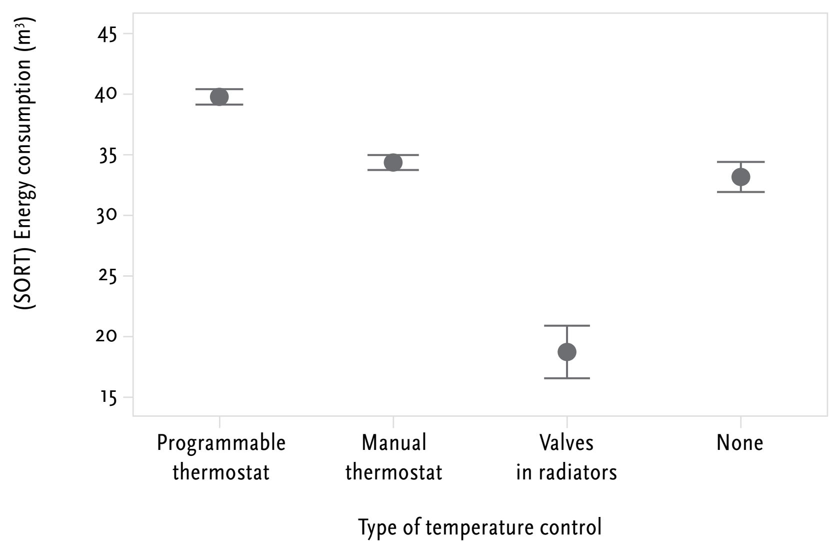
more energy because only few were built in the most recent period and therefore have less insulation and less efficient systems.

A significant difference in energy consumption was also found for different types of temperature control. Programmable thermostats are associated with more energy consumption, followed by manual thermostats and no central temperature control, and finally by manual valves in radiator (Table 6.2, Figure 6.4).

From this section, we can conclude that better thermal properties and systems efficiency seem to reduce energy consumption. However, the presence of better systems control (temperature and ventilation control) does not reduce energy consumption. Mechanical and balanced ventilation were not related to lower energy use. Dwellings with thermostats actually consume more energy that dwellings without thermostat.

Table 6.2 also shows the results from Chapters 3 and 4, in which similar tests were conducted on recently built dwellings in the Netherlands (after

Figure 6.4 Energy consumption per type of temperature control (mean and 95% confident interval)



1995) via the WoON survey and the OTB survey. The OTB survey was carried out in 2008 and contained 313 dwellings built after 1995. The correlations for the total building stock may be greater than the correlations for new housing because there were more building characteristics for older housing than for new housing. The only exception in these findings is 'insulation open surface', which has a medium-size positive correlation in new dwellings and a small negative correlation in the older stock. This is because all new dwellings are insulated and therefore 'insulated open surfaces' correlates to larger dwellings, which consume more energy. In the older housing stock the correlation between 'insulated open surfaces' and energy consumption is negative because in this case, it is a matter of insulation level, since not all dwellings have insulation.

To further determine the effect of different building characteristics on energy consumption, factorial ANOVA tests were used to determine the effects cause by combination of building characteristics. Dwellings with more insulation consume less energy as it would be expected. However, in dwellings built in the last period (after 1996), energy consumption was almost the same for both insulation levels. Multi-family homes built after 1996 consume more energy than those built before 1995 [$F(2,4461)=30.347$, $p<.001$]. This leads to think on a rebound effect caused by the improvement of the thermal quality of the building and the socio-economical situation of the occupants. Other studies already concluded that a rebound effect could be more important in low-income households (Herring & Sorrell, 2009). In dwellings with higher levels of insulation, more energy is used in dwellings with mechanical ventilation than in dwellings with natural ventilation, which refutes the expectation that airtight housing consumes less energy [$F(2,4536)=7.733$, $p<.001$].

The results seem to indicate that dwellings with more modern technology consume more energy for heating. This finding could stem from a rebound effect or be tied in with the structural quality of the building. However, this could also be explained by differences between the actual structural quality of the building and the theoretical efficiency of systems (Elkhuizen *et al.*, 2006; Nieman, 2007).

6.4.3 Effect of occupant behaviour on energy consumption: determining the main factors of occupant behaviour

This section analyses the effect of occupant behaviour on energy consumption in the existing stock. The behaviour relates to the use of heating and ventilation systems. The heating behaviour covers the thermostat settings during the day, evening, night and weekend expressed as standard deviations from the mean. Two variables for each time of the day were found in the database, one expressed in Celsius degrees and the other in settings from 1 to 5. To enable all the cases to be included in the analysis, both variables were converted into standard deviations from the mean and then merged.

Ventilation behaviour refers to the number of hours of ventilation per room (living room, kitchen, bedroom, and bathroom) and includes all types of ventilation. There were three ventilation variables in the database: grilles, windows and mechanical systems. As a result of the mixed combinations of ventilation type per dwelling, all cases had at least one missing value in one variable. To cover all cases, a new variable was formed by aggregating the three types of ventilation. Since all variables were reported in hours, the type of ventilation with more hours was taken into account. For example, in a case with three hours of window ventilation and one of mechanical ventilation, the new variable would be 'three hours of ventilation'. This aggregation therefore omits the least used ventilation type on a case-by-case basis. No account could be taken of the sum of the variables as this would have created problems of normality. Since the purpose is to determine the effect of behaviour and not to calculate the real energy performance, the omission of the real ventilation rate should not pose a problem. Descriptive statistics are shown in Table 6.3.

Factor analysis was used to identify the factors underlying occupant behaviour and to reduce the number of variables. The variables for the factor analysis were temperature settings during the day, evening, night and weekend (in SD from the mean) and variables for the number of hours of ventilation per room (as explained in Section 6.4.3). The descriptive statistics for occupant behaviour variables are shown in Table 6.4.

First, the eight behavioural variables were examined to determine whether factor analysis was suitable for this analysis with regard to correlation between variables. All eight variables correlated at least .3 with at least

Table 6.3 Descriptive statistics for ventilation behaviour variables

	WoON total stock	
Variables	**Mean**	**SD**
(SQRT) Hours of ventilation in living room/day	1.27	1.53
(SQRT) Hours of ventilation in kitchen/day	1.37	1.62
(SQRT) Hours of ventilation in bedrooms/day	2.69	1.53
(SQRT) Hours of ventilation in bathroom/day	1.56	1.81

Table 6.4 Relationship between occupant behaviour and energy consumption for the total housing stock and housing built after 1995: statistics of Pearson's correlations

Variables	WoON total stock		WoON new housing	
Temperature during the day (in SD)	NS		NS	
Temperature during the evening (in SD)	NS		NS	
Temperature during the night (in SD)	r = .091 ***	n = 3621	r = .163*	n = 557
Temperature during the weekend (in SD)	NS		NS	
(SQRT) Hours of ventilation in living room/day	r = -.052***	n = 4541	NS	
(SQRT) Hours of ventilation in kitchen/day	r = -.067***	n = 4539	NS	
(SQRT) Hours of ventilation in bedrooms/day	r = .033*	n = 4573	NS	
(SQRT) Hours of ventilation in bathroom/day	r = .108***	n = 4551	r = .120**	n = 557

* = p < .05, ** = p < .01 and *** = p < .001

one other item, suggesting reasonable factorability. Further analysis of the assumptions led to the conclusion that factor analysis was suitable including all eight variables. Eight factors (clusters of correlated variables) were identified. These initial Eigen values showed that the first factor explained 26% of the variance, the second explained 24%, the third explained 11%, the fourth and fifth explained 9%, the sixth explained 8%, and the seventh and eighth factors had Eigen values of 5%. The Eigen values were examined and the solution that included two factors and explained 50% of the variance was selected because of its theoretical underpinning (clear division between heating and ventilation behaviour) and the 'levelling off' of Eigen values on the scree plot after two factors. The first factor is related to heating behaviour and the second to ventilation behaviour. A final factor analysis of the eight variables was conducted with the two factor solution (heating behaviour and ventilation behaviour). The factor loading matrix and communalities for this solution are shown in Table 6.5. The first two columns show the contribution of each variable to each factor in the solution. The third column contains the communalities, which are the common variance in one variable. The common variance is the variance shared with other variables.

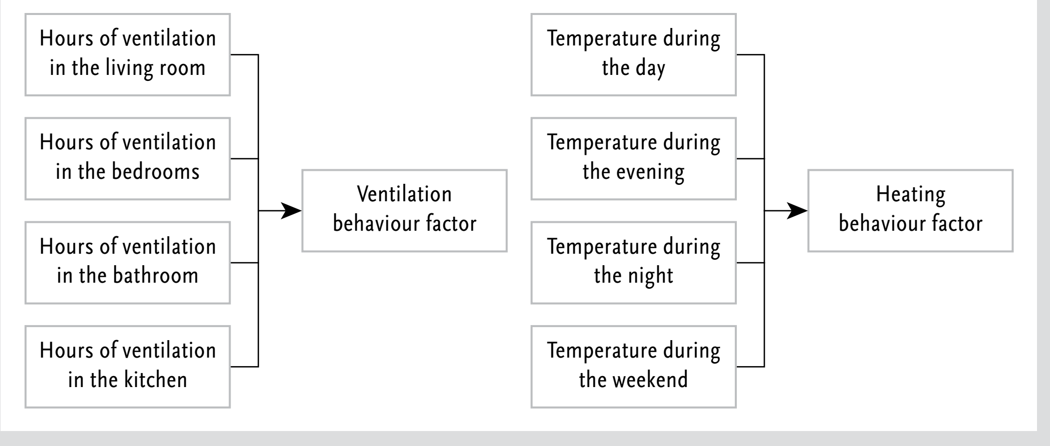
Figure 6.5 shows the relationship between the eight original variables used in the factor analysis, and the two resulting factors. The variables related to ventilation are part of the 'ventilation behaviour' factor; while the variables related to the use of the heating system are part of the 'heating behaviour' factor.

Table 6.5 Factor analysis: factor loadings and communalities based on a principle components analysis with Oblimin rotation for eight occupant behaviour variables

Variables	Factors: Factor 1 Heating behaviour	Factors: Factor 2 Ventilation behaviour	Communalities
Setting weekend (in SD from the mean)	.821		.675
Setting evening (in SD from the mean)	.740		.548
Setting day (in SD from the mean)	.739		.547
Setting night (in SD from the mean)	.520		.271
(SQRT) Hours ventilation in kitchen/day		.774	.599
(SQRT) Hours ventilation in living room/day		.747	.560
(SQRT) Hours ventilation in bedroom/day		.649	.422
(SQRT) Hours ventilation in bathroom/day		.616	.385

Rotation method: Oblimin with Kaiser Normalization.
Factor loadings < .4 are suppressed.
N = 2779

Figure 6.5 Results from factor analysis: relationship between behavioural factors and the eight original variables



Composite scores were created for each of the two factors, based on the mean of the items which had their primary loadings on each factor. These composite scores were saved as two new variables: heating behaviour and ventilation behaviour. Higher scores indicated more intensive use of the system. In heating behaviour a higher score is related to above-average thermostat settings (since the original variables were expressed in standard deviations from the mean). In ventilation behaviour a higher score relates to more hours of ventilation. From now on, these variables are referred to as heating behaviour and ventilation behaviour. An approximately normal distribution was observed for the composite score data, meaning that the new variables were well suited for parametric statistical analyses (e.g. correlations). In the following section, these variables are used in multivariate statistical analyses to determine differences in behaviour in relation to building characteristics.

6.4.4 Effect of building characteristics on heating behaviour

The relationships between occupant behaviour and building characteristics were analysed by applying the new variables obtained in Section 6.4.3 (heating behaviour and ventilation behaviour). The building characteristics were: type of ventilation system and temperature control; thermal properties (insulation and type of dwelling); and building period. One-way ANOVA tests were used to determine behavioural differences in groups of dwellings with different building characteristics. Table 6.1 shows the categories for each building characteristic variable.

The results of one-way ANOVA tests showed that all buildings characteristics have an effect on heating behaviour (for statistics see Table 6.6). The heating behaviour factor score turned out to be lower in dwellings built before 1945, followed by dwellings built in the periods 1946-1974 and 1975-1995. A higher factor score was recorded for dwellings built after 1996. This indicates a preference for higher temperatures in newer dwellings despite better thermal properties.

A similar trend emerged for dwellings with higher insulation levels. These turned out to have a higher score for heating behaviour than dwellings with lower insulation levels.

We already know from the results in Section 6.3 that better insulated dwellings and more recently built dwellings consume less energy for heating than older dwellings and dwellings with less insulation. Hence, what appears to be a rebound effect on behaviour does not necessarily imply a rebound effect on energy consumption. It does suggest, however, that some of the potential benefits of insulation are being counteracted by behaviour and this may partly explain why energy savings are lower than the savings predicted by models that do not take account of the change in temperature preferences (Gommans, 2008).

Multi-family dwellings have higher scores for heating behaviour than single-family dwellings. Multi-family dwellings have less area to heat and less heat-loss area; therefore, the occupants might be choosing higher temperatures. This explains the higher energy consumption in multi-family dwellings seen in Subsection 6.4.2.

Type of ventilation system seems to have an effect on heating behaviour. Heating behaviour scores are lower for naturally ventilated dwellings than for other dwellings, though the latter are usually older and therefore have less optimal thermal properties than newer dwellings. These results relate to

Table 6.6 Relationship between heating behaviour and building characteristics: statistics of results of ANOVA and t-tests

Groups	Statistics for ANOVAs and t-tests	Mean (SD)	
Construction period	F(3,1663.53) = 15.690***	< 1945	M = -.15 (1.02)
		1946-1975	M = -.004 (1.06)
		1976-1995	M = .04 (0.89)
		> 1996	M = .17 (1.04)
Dwelling type	t(1821.19) = -3.136**	Multi-family	M = .08 (1.18)
		Single-family	M = -.04 (.89)
Insulation level	t(3913) = -2.926**	> 50	M = .04 (.97)
		< 50	M = -.05 (1.03)
Ventilation system	F(2,1210.65) = 7.610*** (+)	Natural ventilation	M = -.07 (1.31)
		Local ventilator	M = -.03 (.91)
		Mechanical ventilation	M = .06 (1.01)
Type of temperature control	F(3,494.89) = 5.945*** (+)	None	M = .16 (1.32)
		Radiator taps	M = .36 (1.13)
		Manual thermostat	M = -.07 (1.03)
		Automatic thermostat	M = .04 (.82)

* = p < .05, ** = p < .01 and *** = p < .001
(+) Welch statistic is reported. Welch statistic is an alternative to F-ratio derived to be robust when homogeneity of variance has been violated (Field, 2005).

research on adaptive thermal control in office buildings (Ye *et al.*, 2006) and show that, in winter, much lower temperatures are accepted in naturally ventilated offices than in mechanically ventilated offices.

Dwellings with thermostats (manual or programmable) have lower scores for heating behaviour than dwellings with no temperature control or with manual valves in radiators (i.e. no feedback). This finding is in stark contrast with the finding that dwellings with thermostats consume more energy. This might be explained by results from previous research (Chapter 4), which showed that households with a thermostat keep radiators on for more hours than households without thermostat. Also, when it comes to energy consumption, the number of hours with the heating system on is more significant than the thermostat setting. However, the number of hours with the heating system on was not in the WoON database that was used for this study thus this could not be verified. Households without thermostats are less aware of the indoor temperature and may therefore be choosing higher settings, but as fewer radiators are turned on and for fewer hours, the energy consumption is lower.

The effect of these building characteristics varies when combined with other building characteristics (e.g. more efficient systems and thermal properties might be more common in newer dwellings). Interactions were analysed with Factorial ANOVA (statistics shown in Table 6.6). The results revealed higher heating behaviour scores in dwellings with thermostats built after 1996,

Table 6.7 Relationship between ventilation behaviour and building characteristics: statistics of results of ANOVA and t-tests

Groups	Statistics for ANOVAs and t-tests		Mean (SD)	
Construction period	F(3,1913.32)	= 6.459***	< 1945	M = -.13 (.92)
			1946-1975	M = .05 (.97)
			1976-1995	M = .08 (1.04)
			> 1996	M = -.12 (1.06)
Dwelling type	t(4303)	= 4.687***	Multi-family house	M = -.10 (.98)
			Single-family house	M = .06 (1.00)
Ventilation system	F(2,1410.63)	= 3.713* (+)	Natural ventilation	M = .12 (1.06)
			Local ventilator	M = -.02 (.95)
			Mechanical ventilation	M = -.01 (1.04)

* = p < .05, ** = p < .01 and *** = p < .001
(+) Welch statistic is reported. Welch statistic is an alternative to F-ratio derived to be robust when homogeneity of variance has been violated (Field, 2005).

although the differences were not statistically significant at a level of p< .05. Heating behaviour scores are higher in homes with more insulation – except in the case of naturally ventilated houses which confirms with the finding that occupants in offices with natural ventilation tend to accept lower temperatures in winter [F=6.339, p<.01].

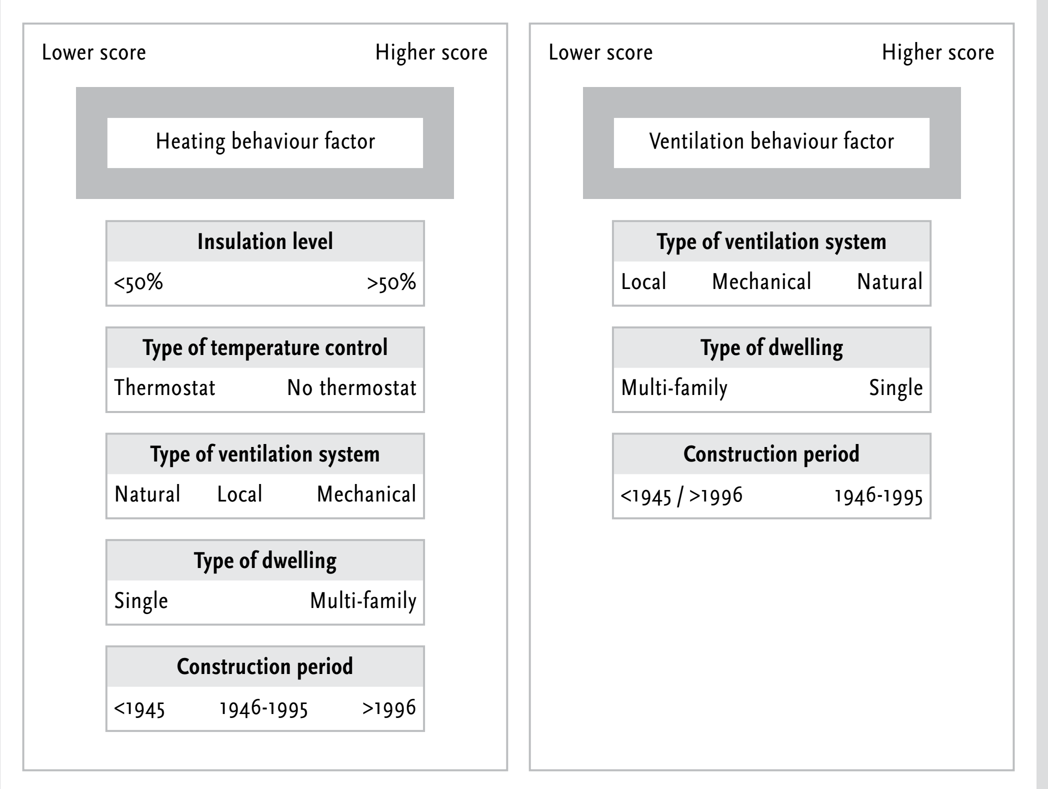
6.4.5 Effect of building characteristics on ventilation behaviour

Results of one-way ANOVA tests showed that ventilation behaviour is affected by construction period, type of dwelling and type of ventilation system (for statistics see Table 6.7). Dwellings built before 1945 and after 1996 show a lower score for ventilation behaviour than dwellings built in other periods. Lower levels of ventilation in older houses might be related to the fact that the dwellings are not airtight and therefore need less 'active' ventilation (open windows, grilles and switched-on ventilation system). Lower levels of ventilation in newer houses might be due to sub-optimal use of the mechanical ventilation system. In Chapter 4 it is shown that almost all the households in the sample kept the mechanical ventilation system either off at all times or at the lowest setting.

The ventilation factor score in multi-family dwellings turned out to be lower than in single-family dwellings. This might be related to behavioural differences between single occupants or couples and larger households. These results are in accordance with (Wouters & de Baets, 1986), who found differences in ventilation for multi- and single-family housing.

The ventilation score for dwellings with natural ventilation differed from the score for dwellings with local ventilator and those with mechanical ventilation. Dwellings with natural ventilation had higher scores than other dwellings. Results of Factorial ANOVA tests showed that, in dwellings built after 1996 and before 1945, the ventilation behaviour score was lower in homes

Figure 6.6 Relationship between behavioural factors and building characteristics



with a thermostat [$F=2.775$, $p<.05$].

Figure 6.6 shows the relationship between building characteristics and behaviour. A higher score for heating behaviour implies above-average thermostat settings. A higher score for ventilation behaviour implies more hours of ventilation. Each building characteristic is shown in the (heating and ventilation) behaviour factor scales. Higher 'heating behaviour' factor scores were related to multi-family dwellings houses built after 1996 with higher insulation level, no thermostat, and mechanical ventilation systems. Higher 'ventilation behaviour' scores were seen in single-family dwellings built after 1945 and before 1996 with natural ventilation.

6.5 Discussion and conclusions

The aim of this paper was to determine differences in the behaviour of occupants of dwellings with different building characteristics and to ascertain the possible existence of a rebound effect on the consumption of energy for space heating.

6.5.1 Rebound effect on energy consumption in the Dutch residential stock

The periods were defined according to important changes in the energy regulations in the Netherlands. Energy consumption was significantly lower for dwellings built in the most recent construction periods.

The correlations with energy consumption in the total housing stock seem to be larger than for recently built housing, which is explained by more types of building characteristics in the older housing. When comparing both samples (recently built dwellings versus all dwellings) we can find comparable results in heating, only temperature by night showed a significant effect. For ventilation the results are different since there are larger variations on type of ventilation systems in the building stock (i.e. natural ventilation and local ventilators).

The building characteristics associated with an increase in energy consumption were low insulation levels, the presence of thermostats, and local ventilation. Insulation and thermal properties are related to lower energy consumption, as it was expected. However, more advanced control of heating and ventilation systems did not show to decrease energy consumption.

Analysis of energy consumption and type of temperature control indicates that dwellings with thermostats consume more energy than dwellings without thermostats. Mechanical and balanced ventilation systems did not show a reduction on energy consumption in comparison to naturally ventilated houses. Our previous study (Chapter 3) in dwellings built after 1996 showed that the use of thermostats was related to higher energy consumption. In addition, no statistical significant differences were found on the energy use for different types of ventilation systems.

6.5.2 Differences in behaviour determined by building characteristics

Analysis of the relationships between these characteristics and heating behaviour (factor score) suggested that households living in dwellings with better thermal properties prefer above-average indoor temperatures, although this did not necessarily go hand in hand with higher energy consumption.

Type of temperature control seemed to have contrary effects, since thermostats appeared to be related to higher energy consumption but to lower scores for heating behaviour (i.e. below-average settings). Previous studies have indicated that energy consumption is more affected by hours of use than by thermostat settings. This finding could not be further tested since the required data were not in the database. It should therefore be tested in further studies in which the heating behaviour score relates not only to thermostat settings but also to hours of use. There seems therefore to be evidence of a rebound effect on behaviour, but not on energy consumption. Another possibility is that higher settings could be compensating for air leaks caused by poor construction.

Occupant behaviour does appear to have a significant effect, given the higher temperature settings in dwellings with better thermal properties and better temperature control. This conclusion is confirmed by other international studies (Haas *et al.*, 1998; Hens *et al.*, 2010; Brookes, 2000; Schipper & Grubb, 2000; Krewitt & Sorrell, 2009). According to Hens *et al.*, (2010), temperature in daytime and in bedrooms and the mean indoor temperature are connected with direct rebound.

Ventilation behaviour seems to be affected by the type of ventilation system, type of dwelling and construction period. Households in dwellings with natural ventilation tend to ventilate more than households in other dwellings. Scores for ventilation behaviour are higher in single-family dwellings than in multi-family dwellings, probably because of the relationship between occupancy patterns and household composition. Dwellings built before 1946 and after 1996 tend to be ventilated for fewer hours than dwellings from other periods. This finding could be related to higher levels of infiltration in older dwellings and the sub-optimal use of mechanical exhaust and balance ventilation systems in newer dwellings. When combined with lower infiltration in newer dwellings, sub-optimal use of mechanical ventilations systems could result in poorer indoor air quality.

This study sought to understand the differences on behaviour in the housing stock and explored the possible existence of a rebound effect on the consumption of energy for space heating. A more intensive use of the heating system and preferences for less ventilation were found for households living in recently built housing. As households living in newer dwellings might differ from those living in older dwellings, the occupant behaviour associated to lower ventilation rates and higher temperature settings might be therefore, related to household characteristics. Results from previous studies on occupant behaviour in recently built housing showed that a more intensive use of the heating systems was related to lifestyle of households (e.g. households where somebody stays at home kept the thermostat on for longer time) (Chapter 4). Yet, the heating behaviour variables used in this study were related to thermostat settings, which pointed at preferences for a warmer indoor environment.

6.6 Recommendations

Factor analysis was used to reduce the number of behaviour variables and to facilitate the analysis. Heating and ventilation variables were applied but as the data at our disposal was limited, we were unable to analyse all the factors that determine energy consumption. Results from Chapter 4 showed that the number of hours that the heating system and radiators are turned on is more important than the temperature setting, but these sort of data were not available in the database owing to the large sample size. In addition, ventilation variables – windows, grilles and mechanical ventilation systems – had to be aggregated into one single variable per room because at least one type of ventilation was missing in each case. This simplification may not have serious consequences, given that the aim of this study is to seek relationships between behaviour and building characteristics. Other studies provide more information on the relationships between occupant behaviour and energy consumption. These simplified variables are used solely as a proxy for behaviour and not to predict energy consumption.

The results pointed at a rebound effect on heating behaviour. The type of temperature control could help to reduce this effect, since it seems that households with more information about indoor temperature set the thermostat at below-average levels. In addition, it seems that programmable thermostats are related to more hours of use and that energy consumption might therefore be reduced by a switch to manual thermostats.

The results point to inefficient use of mechanical ventilation systems. Low levels of ventilation and low infiltration rates can adversely affect indoor air quality. Further research is needed to determine whether to give occupants more information on the correct use of ventilation systems or whether to develop better systems or interfaces between system and user.

Energy consumption seems to be lower in dwellings built more recently. However, further analysis of the behaviour determinants showed that occupants of newer dwellings and dwellings with better thermal properties tend to prefer higher indoor temperatures and fewer hours of ventilation. Further research should aim to determine the role of household characteristics in heating and ventilation preferences.

References

Ajzen, I. (1991), The theory of planned behaviour, **Organizational behaviour and human decision processes, 50**, pp. 179-211.

Andersen, R.V., J. Toftum, K.K. Andersen & B.W. Olessen (2009), Survey of occupant behaviour and control of indoor environment in Danish dwellings', **Energy and Buildings**, 41, pp. 11-16.

Assael, H. (1995), **Consumer behaviour and marketing action**, Cincinnati, South-Western College Publishing.

Beerepoot, M. & N. Beerepoot (2007), Government regulations as an impetus for innovations, Evidence for energy performance regulation in the Dutch residential building sector, **Energy Policy, 35**, pp. 4812-4825.

Biesiot, W. & K.J. Noorman (1999), Energy requirements of household consumption: a case study of Netherlands, **Ecological Economics, 28**, pp. 367-383.

Branco, G., B. Lachal, P. Gallinelli & W. Weber (2004), Expected versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data, **Energy and Buildings, 36**, pp. 543-555.

Brookes, L. (2000), Energy efficiency fallacies revisited, **Energy Policy, 28**, pp. 355-366.

Caldera, M., S.P. Corgnati & M. Filippi (2008), Energy demand for space heating through a statistical approach: application to residential buildings, **Energy and Buildings, 40**, pp. 1972-1983.

Elkhuizen, P.A., J.E. Scholten, E.G. Rooijakkers, J. de Knegt & L. Deutz (2006), **Kwaliteitsborging van installaties – Evaluatie van bestaande instrumenten en een visie voor toekomst**, Report TNO bouw/Halmos for SenterNovem.

Field, A. (2005), **Discovering statistics using SPSS**, 2nd Edition, London, SAGE Publications.

Gommans, L.J. (2008), **Energy performance of energy conscious buildings: between design and reality**, proceedings PLEA 2008, 25th Conference on Passive and Low Energy Architecture, Dublin, 22-24th.

Groot, E. de, M. Spiekman & I. Opstelten (2008), **Dutch research into user behaviour in relation to energy use of residences**, proceedings PLEA Conference.

Haas, R., H. Auer & P. Biermayr (1998), The impact of consumer behaviour on residential energy demand for space heating, **Energy and Buildings, 27**, pp. 195-205.

Hens, H., W. Parijs & M. Deurinck (2010), Energy Consumption for heating and rebound effects, **Energy and Buildings, 42**, pp. 105-110.

Herring, H. & S. Sorrell (2009), **Energy efficiency and sustainable consumption, The rebound effect**, Energy, Climate and the Environment series, Palgrave Macmillan, UK.

Hirst, E. & R. Goeltz (1985), Comparison of actual energy saving with audit predictions for homes in the north central region of the USA, **Building and Environment, 20** (1), pp. 1-6.

Jeeninga, H., M. Uyterlinde & J. Uitzinger (2001), **Energieverbruik van energiezuinige woningen**, Report ECN & IVAM, ECN-C-01-072.

Krewitt, W., S. Simon, W. Graus, S. Teske, A. Zervos & O. Schafer (2007), The 2oC scenario -A sustainable world energy perspective, **Energy Policy, 35**, pp. 4969-4980.

Lenzen, M., M. Wier, C. Cohen, H. Hayami, S. Pachauri & R. Schaeffer (2006), A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan, **Energy, 31**, pp. 181-207.

Leth-Petersen, S. & M. Togeby (2001), Demand for space heating in apartment blocks: measuring effect of policy measures aiming at reducing energy consumption, **Energy Economics, 23**, pp. 387-403.

Liao, H.C. & T.F. Chang (2002), Space-heating and water-heating energy demands of the aged in the U.S., **Energy Economics, 24**, pp. 267-284.

Linden, A.L., Carlsson-Kanyama & B. Eriksson (2006), Efficient and inefficient aspects of residential energy behaviour: What are the policy instruments for change?, **Energy Policy, 34**, pp. 1918-1927.

Milne, G. & B. Boardman (2000), Making cold homes warmer: the effect of energy efficiency improvements in low-income homes, **Energy Policy, 28**, pp. 411-424.

Nieman (2007), **Eindrapportage woonkwaliteit binnenmilieu in nieuwbouwwoning**, Report Wu060315aaA4.PK, VROM Inspectie Regio Oost, Arnhem.

Olofsson, T., S. Andersson & J.U. Sjogren (2009), Building energy parameter investigations based on multivariate analysis, **Energy and Buildings, 41**, pp. 71-80.

Papakostas, K.T. & B.A. Satiropoulos (2007), Occupational and energy behaviour patterns in Greek residences, **Energy and Buildings, 26,** pp. 207-213.

Poortinga, W., L. Steg, C. Vlek & G. Wiersma (2005), Household preferences for energy saving measures: a conjoint analysis, **Journal of Economic Psychology, 29**, pp. 49-64.

Raaij, W.F. & T.M.M. Verhallen (1983), Patterns of residential energy behaviour, **Journal of Economic Psychology, 4**, pp. 85-106.

Sardianou, E. (2008), Estimating space heating determinants: an analysis of Greek households, **Energy and Buildings, 40**, pp. 1084-1093.

Schipper, L. & M. Grubb (2000), On the rebound? Feedback between energy intensities and energy uses in IEA countries, **Energy Policy, 28**, pp. 367-388

Schweiker, M. & M. Shukuya (2009), Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions, **Building and Environment, 44**, pp. 2137-2149.

Sonderegger, R.C. (1977-78), Movers and stayers: the resident's contribution to variation across houses in energy consumption for space heating, **Energy and Buildings, 1**, pp. 313-324.

Tiberiu, C., J. Virgone & E. Blanco (2008), Development and validation of regression models to predict monthly heating demand for residential buildings, **Energy and Buildings, 40**, pp. 1825-1832.

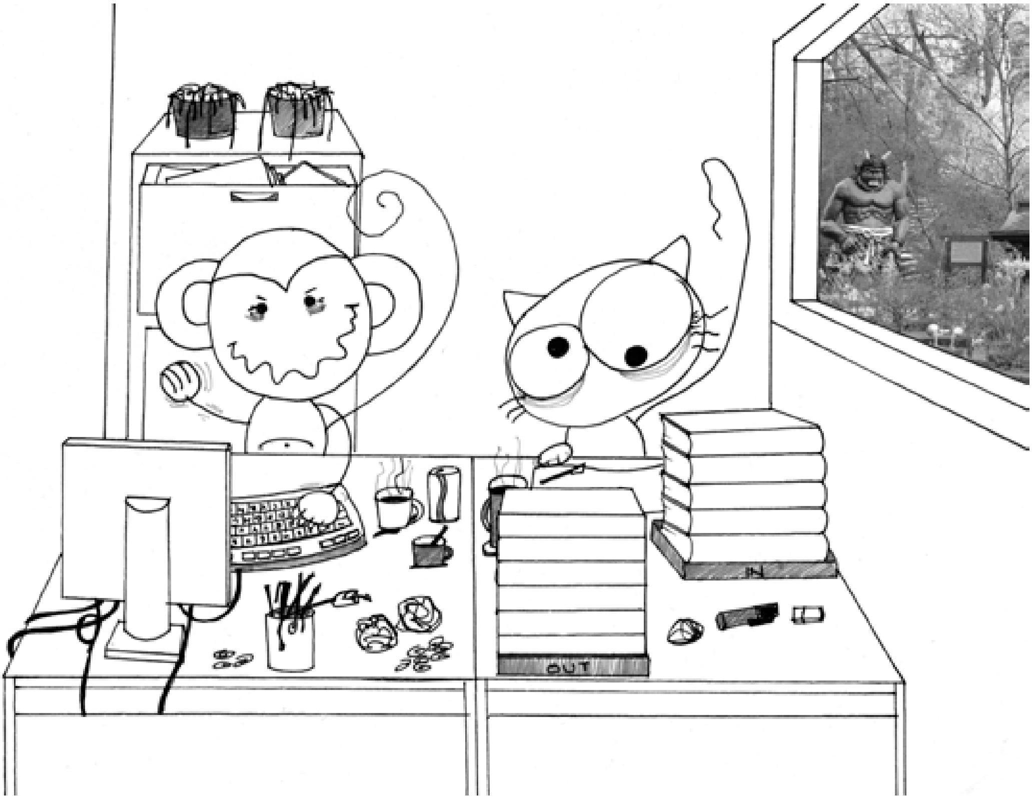
Vringer, C.R. (2005), **Analysis of the requirements for household consumption**, Netherlands environmental assessment agency, Bilthoven, thesis, ISBN 90-6960-1303.

Vringer, K. & K. Blok (2007), Household energy requirement and value patterns, **Energy Policy, 35**, pp. 553-566.

VROM (2009), Dutch Ministry of Housing, Website: **www.vrom.nl**, accessed July.

Wouters, P. & D. de Baets (1986), **A detailed statistical analysis of window use and its effect on the ventilation rate in 2400 Belgian Social Houses**, 7th AIC Conference, pp. 33-53.

Ye, X.J., Z.P. Zhou, Z.W. Lian, H.M. Liu, C.Z. Li & Y.M. Liu (2006), Field study of a thermal environment and adaptive model in Shanghai, **Indoor Air, 16** (4), pp. 320-326.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7 Conclusions and recommendations

7.1 Introduction

This research sought to provide insight into the role of energy performance regulations and occupant behaviour in actual energy consumption of space and water heating in residential stock. Actual energy consumption was analysed in dwellings built after the introduction of energy performance regulations in the Netherlands. The objective was to determine whether further tightening of Dutch energy performance regulations could be used to further decrease energy consumption and to gain insight into household and building characteristics that determine occupant behaviour and its effect on actual energy consumption for heating.

Figure 1.4 shows the relationships studied. The relationship between energy performance coefficient (EPC) and energy consumption was investigated first and this was followed by the relationship between energy consumption and occupant behaviour. The analysis of occupant behaviour determinants included looking at the effect of building characteristics and household characteristics on the use of heating and ventilation systems; these were used to determine behavioural patterns of occupant behaviour related to energy consumption for heating. Differences between recently built housing (after 1995, when energy performance regulations were introduced) and the total housing stock were also analysed to determine the effect of energy performance regulations on actual energy consumption.

Statistical analyses determined the relationships between building characteristics, occupant behaviour and energy consumption for heating. These provided correlations between variables that pointed at factors having a direct or indirect influence on energy consumption.

Three sources of data were used: the OTB database, and the KWR and WoON databases from the Dutch Ministry of Housing. The OTB database consists of a household survey and data collected from the legal document containing the EPC calculation of the buildings. The survey was conducted in dwellings built after 1995 and the introduction of energy performance regulations. The aim was to collect data on the EPC level and detailed self-reported occupant behaviour. The WoON database consisted of two surveys and a building inspection carried out by the Dutch Ministry of Housing. WoON was used to: (1) validate the OTB database with a random nationwide sample, and (2) to analyse the situation in the total housing stock. The KWR database, predecessor of WoON, was used for an exploratory analysis of building characteristics, household characteristics and occupant behaviour predicting energy consumption in the total housing stock.

The first part of the study (Chapter 2) used the KWR database to analyse the relative influence of building and household characteristics and occupant behaviour in energy consumption in the total housing stock. A regression model determined percentages for variation in energy consumption. Comparison with a second regression model and analysis of partial correlations pointed to interactions among the three types of variables: building characteristics, occupant behaviour and household characteristics; this established the relationships further studied in subsequent parts of the research.

Energy performance regulations introduced in 1995 made it compulsory to comply with the EPC level in new buildings. The EPC calculation takes account of thermal properties and systems efficiency of buildings. To determine the effect of this regulation on actual energy consumption in dwellings built after 1995, differences on energy consumption between groups of dwellings were categorised according to their EPC level (Chapter 3).

The Chapter 2 results showed a small percentage of variation in energy consumption explained by occupant behaviour and household characteristics (4.2%). Since the variables in the KWR database related to occupant behaviour were not considered optimal for regression analysis, using a more appropriate set of variables would improve the analysis. Therefore, in Chapter 4, the effect of occupant behaviour in energy consumption was studied with the OTB database. In addition, the determinants of occupant behaviour with a large effect on energy consumption were studied to further determine the relationships found in Chapter 2 between building characteristics, household characteristics and occupant behaviour.

With relationships found between energy consumption and occupant behaviour, further analysis of behaviour was carried out in Chapter 5. Factor analysis was used to determine behavioural patterns to find the household and building characteristics useful for building user profiles for heating energy consumption in recently built housing.

The introduction of energy performance regulations not only had a direct effect on energy consumption for heating (Chapter 3), it was thought to have an indirect effect as well due to the effect of building characteristics on occupant behaviour. Since recently built dwellings have better thermal properties, households might be opting for different indoor conditions, identified as some causes of a rebound effect on energy consumption. Rebound occurs when people compensate for efficiency improvements by increasing their spending. It is therefore possible that lower energy costs for heating are offset by a demand for more thermal comfort. In addition, the occupants' interaction with more advanced heating and ventilation systems is also thought to have an effect on occupant behaviour and therefore on energy consumption. The effects and determinants of occupant behaviour in recently built dwellings were analysed in Chapters 4 and 5.

Chapter 6 dealt with the building characteristics affecting occupant behaviour in the total housing stock, and sought indications of a rebound effect in energy consumption. More insight into the differences of occupant behaviour in recently built housing and the total housing stock provided another perspective on the effect of energy performance regulations on actual energy consumption.

The objective of this research was to determine the effect of occupant behaviour and energy performance regulations on energy consumption for heating. Three research questions were defined. The first was related to the effect of energy performance regulations on actual energy consumption for heating. The second was related to the effect and determinants of occupant behaviour. The third referred to differences in energy consumption and behaviour observed in recently built housing in comparison to the total housing stock.

The following sections present the conclusions and recommendations drawn from this analytical research. Sections 7.3 to 7.5 present the conclusions of each research question. Section 7.6 presents the discussion. Recommendations for policy, practice and further research are presented in Sections 7.7 to 7.9.

7.2 Effect of energy performance regulations on actual energy consumption

Q1.1 What is the effect of a tighter EPC value on energy consumption for heating?

The energy performance regulation is an instrument aimed at reducing building-related energy consumption. The energy performance coefficient has been tightened three times in the past. Dwellings with a lower EPC are expected to have lower energy consumption than dwellings with a higher EPC. The EPC is calculated by normalising the predicted energy consumption with a standard value taking into account the 'total heated area' and the 'heat-transfer surface' of the dwelling. The predicted energy consumption used in the EPC is the sum of the energy required for space and water heating, cooling, ventilation and lighting and also considers the energy efficiency of systems. The energy required for space heating also takes account of the thermal properties of the building. The calculation makes assumptions about heating system use (see Appendix 1) with reference to thermostat settings at various times of the day.

Actual energy consumption for heating was not statistically significantly different in dwellings with various EPC values, even when the actual energy consumption was normalised per 'square meter heated area'. Therefore, a statistically significant reduction in energy consumption is not seen in dwellings with more stringent EPC levels. However, a statistically significant difference was found between dwellings built before and after the introduction of the EPC, indicating that the EPC has helped to reduce energy consumption since its introduction.

Comparable results using the WoON database provided validation. The

WoON database does not contain the EPC value of dwellings but a comparable indicator, the Energy Index. Results showed that Energy Index was not correlated with the actual energy consumption for heating.

Although lower EPC values are not related to statistically significant lower energy consumption, the predicted energy consumption for heating correlated to actual energy consumption for heating, indicating that dwellings with increased thermal properties consume less energy.

Q1.2 What is the difference between actual and predicted energy consumption?

With findings of a medium correlation between actual and predicted energy consumption for heating, it is remarkable that no statistically significant differences were found with the EPC values. The lack of statistically significant differences is thought to be related to an effect caused by the normalisation factor for building size or because energy requirements for water heating, lighting and ventilators, which are more dependent on occupant behaviour than on building characteristics, are not estimated correctly. Further tests established that 'total expected energy consumption' ($Q_{pres;tot}$) showed the same correlation with actual energy consumption for heating than 'expected energy consumption for heating' ($Q_{pres;\ verw+tap}$), thus ruling out an effect caused by the energy requirements for lighting, ventilators and auxiliary energy for space heating. The lack of statistically significant differences in the EPC levels might thus be caused by the normalisation factor.

In most cases, actual energy consumption for heating was lower than expected, underlying the importance of occupant behaviour on energy consumption. These differences may arise if the calculation applies excessive energy requirements for occupant comfort or if small households live in large dwellings and therefore use less energy than anticipated. Therefore, the standard household behaviour used in the EPC might be far from reality (see EPC calculation detailed in Appendix 1). For example, the EPC calculation assumes that between 9 a.m. and 5 p.m. temperature is kept at 19^{0}C, assuming somebody is at home. However, the OTB sample showed statistically significant differences in energy consumption between households with people absent and present at home.

Q1.3 Which building characteristics in the EPC have statistically a major influence on energy consumption for space heating?

The analysis of the building characteristics included in the EPC calculation was aimed at further determining the differences between actual and expected energy consumption, and to study the building characteristics that have a major effect on energy consumption. According to the results, thermal properties seemed better at decreasing energy consumption than increasing efficiency of ventilation and heating systems. Medium-sized correlations were found between energy consumption and thermal properties, and small or not statistically significant correlations were found with the type of heating and ventilation systems.

A regression analysis showed that 18-22% of the variation on energy consumption in recently built housing can be explained with the building characteristics used to calculate the EPC level. A 78-82% variation in energy consumption is therefore unaccounted for, explaining the large difference between expected and actual energy consumption, the barely medium-size correlation, and the lack of statistically significant differences in energy consumption for dwellings with different EPC values.

Jeeninga *et al.*, (2001) and Uitzinger (2004) found similar results for the effects of building characteristics, although the regression model (Uitzinger, 2004) claimed to predict 70% of the variation, contradicting other literature sources.

Two factors seem to explain the rest of the variation in energy consumption: actual quality of construction (e.g. actual thermal properties and systems efficiency) and actual occupant behaviour. Studies have shown that buildings are constructed differently than specified in official documents (i.e. EPC document) and HVAC services run under very different conditions than is assumed on paper. A report by Nieman (2007) showed that in a sample of 154 dwellings, 25% did not meet EPC requirements, and in 50% of the dwellings, the construction was not in accordance with data used to calculate the EPC. Gommans (2008) monitored the energy performances of energy efficient buildings for 17 years. In his study 40% of solar boilers appeared to function poorly, while only 25% of the heat pumps reached the expected efficiency. This was essentially due to construction faults, lack of control and lack of continuous monitoring.

Differences between the building characteristics specified in the EPC calculations and the actual building characteristics could partly justify the percentage of variance that has not been explained. Such differences might also explain the absence of correlation between the EPC and actual energy consumption.

The fact that actual energy consumption for heating is lower than expected apparently contradicts the assumption that actual building characteristics are different from those described in the EPC document (therefore implying poor construction of buildings). However, the lower actual energy consumption is caused by the calculation method assuming high levels of comfort and usage of systems, as well as the use of average indoor and outdoor temperatures. Actual energy consumption is therefore only lower than expected if average occupant behaviour is taken into account as in the EPC calculations. A more accurate calculation method (such as an energy simulation model) would probably also show a large difference between the modelled energy consumption and the expected energy consumption in the EPC document.

7.3 Effect and determinants of occupant behaviour in actual energy consumption for heating

Q2.1 What is the effect of occupant behaviour on energy consumption from a statistical perspective?
Analysis of the effect of building characteristics on energy consumption in recently built housing showed that a large percentage of variation in energy consumption is unaccounted for. Occupant behaviour is thought to play an important role in this variation.

Statistical analysis in Chapter 4 showed that the number of hours a heating system was turned on at the highest chosen setting appeared to have a stronger effect on energy consumption than the highest chosen setting as such. Small variations in the setting in new houses are probably because of the similar thermal properties of all new houses. 'Open radiators' in more rooms was found to have a significant effect on energy consumption.

Low correlations were found between energy consumption and the use of a mechanical ventilation system since most households kept the mechanical ventilation system off or at the lowest level. Window and grille ventilation seemed to have a stronger effect on energy consumption than a mechanical ventilation system.

Occupant behaviour was found to explain 12% of the variation in energy consumption for heating in recently built housing. This percentage was explained with four variables: 'windows open in living room', 'hours at highest chosen temperature', 'hours with radiators open' and 'hours with grilles open'.

The results seem in accordance with other studies finding important correlations between energy consumption and heating system use (Jeeninga *et al.*, 2001; Haas *et al.*, 1998; Linden *et al.*, 2006; Hirst & Goeltz, 1985). Similar to the results of the OTB survey, the Jeeninga *et al.* results (2001) indicate that most Dutch households (73%) keep indoor temperature at 18-20^{0}C.

Thermostat use emerged as an important factor related to occupant behaviour: households with a programmable thermostat were associated with higher temperature settings during the night in the WoON sample, and with more hours with radiators on in the OTB sample. Nevius & Pigg (2000) found that households with programmable thermostats reported slightly higher settings than households with manual thermostats, although the differences were not statistically significant. Similar results were obtained in the WoON survey, where statistically significant differences had a small effect. Shipworth *et al.* (2010) found that thermostat use did not reduce average maximum temperatures or hours of use. Although households with programmable thermostats were found to use heating for 0.4 hours a day longer than households with manual thermostats, the differences were not statistically significant. Shipworth *et al.* (2010) also found that households without thermostatic control set the temperature 0.6^{0}C lower than households with thermostatic control, though again the difference was not statistically significant.

Q2.2 What are the determinants of occupant behaviour that have an effect on energy consumption?

In Chapter 2 correlations between occupant behaviour, household and building characteristics were found. Therefore Chapter 4 studied building characteristics and household characteristics related to occupant behaviour. The building characteristics analysed were the type of temperature control and type of ventilation since occupants interact with these systems. Other building characteristics such as thermal properties were not considered because these are relatively constant in recently built housing. A relation between occupant behaviour, its determinants and their effect on energy consumption is shown in Figure 1.6.

Both type of temperature control and type of mechanical ventilation seemed to have an effect on the use of heating and ventilation systems. Households with manual thermostats and mechanical exhaust ventilation have more energy-conserving behaviour than households with programmable thermostats and balanced ventilation systems.

Jeeninga *et al.* (2001) found that the type of thermostat had no influence on the preferred setting. However, in the OTB sample a relationship between type of thermostat and the hours that radiators were on was found while in the WoON sample a relationship between type of temperature control and the temperature at night was found. Differences might have risen from the type of variables used (hours of thermostat use instead of temperature settings). However, results from Jeeninga *et al.* (2001) also point to a relationship between a manual thermostat and energy-saving behaviour. Authors distinguish between heating spaces when these are used (usually present in dwellings with programmable thermostat), independently of whether they are actually used and the heating of spaces actually in use (usually present in dwellings with manual thermostat). Chapter 4 results indicate that personal heating is less energy intensive than heating spaces.

In relation to the effect of household characteristics on energy consumption, the presence of elderly persons in the household proved to be a determining factor in both heating system and ventilation use. A more intensive use of the heating system and less ventilation was associated with seniors. The presence of seniors might be closely related to hours spent at home.

The presence of children also had a significant effect on ventilation use. Other household characteristics related to a more intensive use of the heating system were average education levels (in comparison to high education levels) and having previously lived in a single-family dwelling.

Q2.3 What are the main patterns of occupant behaviour?

In Chapter 3 large differences between actual and expected energy consumption for heating were found. Expected energy consumption was found to be statistically significantly higher than actual energy consumption for heating. The low percentage of energy consumption explained for building characteristics was thought to be caused by the effect of actual building characteristics, and by actual occupant behaviour. The standard occupant behaviour taken into account in the EPC calculation might be causing a big difference between actual and expected energy consumption, since this could be far from actual behaviour. Therefore, this research also sought to (1) determine behavioural patterns and (2) define building characteristics and household characteristics to be taken into account in user profiles for energy consumption.

This study identified five underlying groups of behavioural factors in occupant behaviour: 'appliances and space', 'energy intensive', 'ventilation', 'media' and 'temperature comfort'. The 'appliances and space' factor was related to more use of spaces and large appliances (i.e. laundry machine, dryer, dish washer). The 'energy intensive' factor was related to behaviour leading to more use of energy, for example more intensive use of the heating system. 'Ventilation' referred to more hours of ventilation. The fourth factor, 'media' was related to behaviour seen in young households, for example using showers instead of baths, more use of electronics and computers, less use of spaces and more ventilation. The final factor, 'temperature comfort' was related to preferences for a warmer indoor environment and less ventilation.

Five patterns were identified in relation to the factors: (1) spenders, (2) affluent-cool, (3) conscious-warm, (4) comfort and (5) convenience-cool. The behavioural patterns were developed to be used in simulation programmes or energy savings calculations by linking households types with specific behaviour (more hours of ventilation, more use of energy-saving lamps). Though only indicative differences in energy consumption were found between the groups, results showed that 'convenience-cool' is related to lower energy consumption than other behaviour patterns, while 'spenders' is related to higher energy consumption than the other groups.

Other Dutch studies have found similar patterns. Raaij & Verhallen (1983) gathered data through retrospective self-reporting on 17 variables of occupant behaviour including: thermostat settings and use of radiators; use of ventilation grilles, windows and mechanical ventilation system; and closing of curtains. They found five behavioural patterns: 'conservers' (low temperature, low ventilation, higher education, small household size, working wife, less energy consumption), 'spenders' (high temperature, high ventilation, low education, more often home, more energy consumption), 'cool' (low temperature, high ventilation, medium energy consumption, attitude does not explain energy consumption), 'warm' (high temperature, low ventilation, older people), and 'average'. Their analysis showed statistically significant differences in energy consumption between groups. This study found patterns similar to 'cool', 'warm' and 'spenders' but did not find patterns related to efforts to save energy ('conservers'). 'Convenience' could be comparable, since this related to 'media' defined as less bedrooms used and using showers instead of baths.

Groot *et al.* (2008) found four behaviour groups: 'convenience', 'conscious', 'costs' and 'environment'. This study showed similarities with the TNO study on 'convenience/spender' and 'conscious/warm'. The pattern 'costs' was not found because low income and low education are less common household types in the sample (recently built dwellings). 'Climate/environment' was not found because this study did not take into account environment and energy-saving related attitudes.

Q2.4 Which household categories show significant differences in energy-related behaviour?

Correlations between resulting behaviour factors and households and building characteristics were used to define household groups as: 'seniors', 'families', 'singles/couples' and 'high-income couples'. Household groups with different behaviour can be used to create policies for energy saving aimed at specific sectors of society. Families, seniors and high-income couples showed indicatively higher energy consumption (not statistically significant). The higher energy consumption in these three household groups has various reasons. Families showed higher energy consumption because of a high score for 'space and appliances'; seniors because of a high score in 'temperature comfort'; and high-income couples scored highly in 'energy intensive'.

Both household and building characteristics were found important in identifying differences in behaviour patterns related to energy consumption. Knowing the type, size of a dwelling and HVAC systems, in addition to main household characteristics such as household size, age, background and lifestyle (hours at home) made it possible to identify behaviour patterns related to household groups.

No differences in energy consumption were found for different behavioural patterns and household groups due to the use of variables uncorrelated with energy consumption. However, the addition of behaviour variables related to use of appliances, electronics, computers and lighting provided information on relationships that could have not been found otherwise. For example, the relation between the use of energy-saving lamps and warmer indoor environment pointed to a preference for temperature comfort but with concern for saving energy in comparison to patterns where high heating systems use was correlated to more use of normal lighting. Use of variables not statistically correlated to energy consumption for heating made it hard to correlate the patterns and the household groups with energy consumption. However, they provided more information in order to define underlying behaviour factors. Using both energy consumption for heating and electricity to build profiles could help overcome this problem.

7.4 Determinants of energy consumption in recently built housing in comparison to the complete housing stock

Q3.1 Which building characteristics have the strongest influence on energy consumption in the total housing stock?
Determining the effect of building characteristics and occupant behaviour in the total housing stock gave a different perspective to the research problem. Other studies have found a rebound effect in dwellings with improved thermal properties. Investigating the differences between recently built housing and the total housing stock can help to further understand the role of the energy performance regulation in energy reductions.

The statistical analysis (regression) in Chapter 2 showed that household characteristics and behaviour significantly affect energy consumption (4.2% of variation in energy consumption for heating), but building characteristics still determine a larger part of the energy consumption in a dwelling (42% of variation in energy consumption for heating). In newly built dwellings this was 12% and 18-22% respectively. Therefore, in the total housing stock, building characteristics (thermal properties) still seem to be more important than household characteristics or behaviour.

The most important building characteristics affecting energy consumption are related to the size of dwelling and insulation level. Energy consumption also tends to decrease in newer buildings (except in the most recent period, this is not statistically significant) and in non-detached dwellings, while the presence of a thermostat, garage, shed and basement tend to increase energy consumption.

Q3.2 What is the relative importance of occupant behaviour and building characteristics on energy consumption in the total building stock?
Occupant behaviour seems to be not as important as building characteristics (since these determine only 4.2% of the variation) in determining energy consumption; however behaviour is highly dependent on building characteristics. For example the thermostat presence and dwelling type might have larger effects on energy consumption, as shown by a second regression model (see Chapter 2). Comparison with a second model showed that occupant behaviour is determined by the type of dwelling and HVAC systems and specially by dwelling size and type of thermostat; therefore, the effect of occupant characteristics such as income or household size might be larger than expected,

since these are important in determining the type of dwelling.

The household characteristics affecting energy consumption are the continuous presence of people at home, the number of heated rooms and temperature settings. Age of the respondent, household size and income also have a positive correlation with energy consumption for heating.

Occupant behaviour is in some cases as important as thermal properties: an increase of one degree Celsius on thermostat settings has a comparable effect on heating energy as roof insulation or a household income increase of 10,000 euros per year. Heating an extra bedroom has a comparable effect on heating energy as the presence of double glazing.

The small percentage of variation in energy consumption explained by household characteristics and occupant behaviour might be caused by a small number of behaviour variables present in the database and because these variables might not be in the right form to be used in a regression analysis. A larger percentage of the explained variation was found in recently built housing using the OTB database, which contained more detailed data. This shows the importance of collecting and registering data in the right form.

Q3.3 What are the differences in energy consumption between housing built after 1995 and the total housing stock?

Energy performance regulations seem to have been successful in decreasing energy consumption for heating, since the better thermal properties of the dwellings have had a positive effect; this is corroborated by the larger variation explained by building characteristics and occupant behaviour in the total housing stock in comparison to recently built housing.

Comparison of the regression analysis results (Chapter 3) with the regression analysis described in Appendix 2 showed more energy consumption variation in both building characteristics and occupant behaviour in total housing stock than in recently built housing. In the latter 19% to 23% of the variation on energy can be explained by building characteristics (OTB survey and WoON database), while in the total housing stock, buildings' characteristics can explain 34% with the same variables (WoON database) (see Appendix 2).

Using the OTB database, Chapter 4 showed that occupant behaviour explained 12% of the variation on energy consumption for heating in recently built housing. The same analysis with the WoON database could explain only 3.2% of the same behavioural variables. However, the WoON survey does not contain sufficiently detailed data to be comparable with the OTB results. Regression analysis of the total housing stock with the WoON database showed an increase to 9.4% as compared to 3.2% in recently built housing (see Appendix 2) as the explanation for consumption of heating energy, pointing to a larger effect of occupant behaviour in the total housing stock than in recently built housing.

In a regression model compiled by Schuler *et al.* (2000), building characteristics were found to predict from 11.7 to 14.9% of the variation. Other studies including broader selection of building characteristics, occupant behaviour and household characteristics in the total housing stock seem to predict more variation in energy consumption: Sonderegger 86% (1977-1978), Ledelmeijer & Grieken 50% (2005) and Pachauri 61-66% (2004).

In addition, the variation in energy consumption in recently built housing is more related to lifestyle (presence at home) and dwelling size (number of bedrooms) than to ventilation (hours of ventilation) or temperature (temperature setting), though this might be because there is a more homogeneous set of household types in the recently built housing sample than in the total housing stock sample.

Q3.4 What are the differences in behaviour determined by building characteristics in the total housing stock?
Energy consumption for heating was significantly lower in housing built in more recent construction periods. A slight increase in energy consumption was observed in the period after 2000 in comparison to 1997-1998 and 1998-1999. However, this was not statistically significant.

Building characteristics such as insulation and thermal properties were related to a decrease in energy consumption, but analysis of the relationships between these and heating behaviour (factor score) indicated that households living in dwellings with better thermal properties prefer higher than average indoor temperatures. Although this does not affect energy consumption, it might hinder the positive effects of better thermal properties and energy performance regulations.

Type of temperature control seemed to have contrary effects, since the presence of thermostats is related to higher energy consumption but to a lower heating behaviour score (i.e. the heating system is set at a lower than average temperature). Nevertheless Chapter 4's results indicated that 'hours' and not 'setting' affects energy consumption, although this could not be further tested since the database used (WoON) did not contain this data.

7.5 Data collection: limitations and recommendations

This study was partly aimed at studying the relationship between building characteristics, occupant behaviour and household characteristics. Given the large number of activities considered as aspects of behaviour, and the extensive number of factors that might have an effect on it, statistical analyses seemed to be the right option to analyse these relationships. A large sample was needed to carry out the statistical analysis; therefore choices were made with regard to data collection that might have consequences on the generalisation of the results.

First, since the study was focused on energy performance regulations, the sample had to contain cases of dwellings built after their introduction in 1995. To facilitate this, districts in the Netherlands built after 1995 were chosen. This also facilitated the data collection about the EPC level, since only two municipalities had to be visited to obtain the EPC documents. Furthermore, since the EPC documents often refer to groups of houses, it was not necessary to check individual documents per dwelling. This choice did not ensure a random sample.

The household characteristics of the OTB sample compared to the WoON sample consisted on higher education and income. Higher income is however determined by the type of neighbourhood and therefore becomes a characteristic of recently built housing.

Higher education could mean that the respondents had a higher than average concern for the environment. However no statistical significant differences were found between education and energy use, and although lower education was correlated to more hours using the heating system, this was actually caused by the hours spent at home. Previous analyses with the KWR database (Chapter 2) had already shown that energy consumption is not affected by education level.

To solve these problems, the results were compared with a random nationwide database. However, results of the analyses on energy consumption and behaviour showed similar results in the samples. Therefore, we concluded that the OTB sample could be generalised to recently built housing in the Netherlands in similar housing districts.

Previous studies have addressed the problem of differences between actual characteristics of dwellings and the building characteristics written in the calculation document. In this study, we assumed these would be the same, since buildings are supposed to be constructed according to the specifications in the document; these being part of the building permit procedures. Inspection of the buildings was not undertaken because the building characteristics defined in the document were needed to assess the role of the regulations on energy consumption. In addition, collecting data on actual building characteristics would have been prohibitive in costs and time.

Second, to collect data on behaviour, we decided to use a written questionnaire for the detailed amount of data needed. A format similar to the one used by the Dutch Ministry of Housing for the WoON survey was used, therefore allowing comparability between the databases. Retrospective questions might not be as accurate as real-time data (such as diaries); however, there is some doubt as to the accuracy of diaries. The measurement of real parameters and settings in the dwelling is considered better for obtaining high quality data; however, the costs and time involved are also excessive.

Although data collection methods for occupant behaviour were similar for the OTB and WoON surveys, differences were found in the data entered in the databases, which meant that the results on occupant behaviour were not entirely comparable and highlighted the importance of data processing. The WoON variables included average temperature settings in four specific periods: day, evening, night and weekends. For the OTB study, we decided to use the highest and lowest chosen temperature instead of average setting because this was more accurate. The OTB database also introduced the number of hours temperature was kept at its highest and lowest settings. The variables in the OTB database showed a stronger correlation with energy consumption than the variables in the WoON database. This was probably due to data loss during the averaging of values in the WoON database. The size of the WoON sample (more than 4,500 cases) might have led to the use of variables that contained far less data than the data originally collected in the survey.

Accurate relationships in energy consumption cannot be found without detailed data. However, too much or too detailed data is sometimes difficult to process and might therefore compromise the quality of the data in databases, since important information could be lost. Data collection should focus on aspects of behaviour that tend to vary widely across the population and that seem to have a stronger influence on energy consumption. Therefore a literature study is important before setting out on data collection. This research analysed the KWR database as a first step in order to find the most important data to be obtained for the study. This proved to be effective since it determined only the most necessary variables for inclusion in the OTB database.

The results showed a large unexplained share of variance in energy consumption, which could be related to differences between the building characteristics as defined in the EPC document and actual building characteristics, but also to the quality of the data. However, similar results have been found in other studies, indicating that the sample size may not be a problem.

7.6 Recommendations

From this research, two types of general conclusions can be drawn. The first type refers to the EPC calculation method and its effect on energy consumption for heating; the second type is concerned with occupant behaviour.

Although lower energy consumption is not seen in dwellings with lower EPC values, there is a relationship between better thermal properties and less energy use. However, the actual energy consumption is lower than expected. Moreover, the analysis showed that only a small percentage of the variation in energy consumption could be explained by building characteristics included in the EPC calculation and occupant behaviour, leading to the conclusion that the unaccounted percentage could be due to the actual quality of the construction (i.e. the real thermal properties of the dwelling).

It was also concluded that the relationship between the EPC value and energy consumption could be improved with more accurate standardized occupant behaviour. The occupant behaviour leading to large variations in energy consumption was mainly related to household characteristics or lifestyle aspects that are difficult to modify (i.e. hours spent at home). However, it was shown that although energy consumption is lower in dwellings built after 1995, the heating behaviour in these dwellings is more intensive.

In Subsection 7.6.1, recommendations for policy are drawn from the conclusions on the EPC calculation. These are considered to be easily implemented into energy performance regulations. The energy performance of a building is calculated taking into account a standardized behaviour. Behaviour can only be indirectly influenced by energy performance regulations through the type of control of heating and ventilation systems. Policies to influence occupant behaviour to decrease energy consumption fall within the scope of behavioural studies, and therefore are not part of this study. However, being aware of the behaviour of the occupants of buildings can help to predict more accurately energy savings and energy performance.

In this study we concluded that one of the most important factors of behaviour influencing energy consumption for heating is the presence of people at home, since they keep the heating system on for a longer time. Nevertheless, an attempt to reduce the hours of heating system use (e.g. by increasing energy prices) might have negative consequences on the comfort of these households. Therefore, policies to reduce energy consumption for heating should consider the comfort and behaviour of different types of households. Subsection 7.6.2 deals with recommendations for practice drawn from important findings regarding the role of occupant behaviour on energy consumption.

7.6.1 Recommendations for policy

Since 2006 the Energy Performance Building Directive (EPBD) requires all EU member states to implement performance-based energy requirements and label certification schemes aiming at lowering the energy consumed for heating, cooling, ventilation, lighting and domestic hot water.

In the Netherlands energy performance regulations have been in use for fifteen years. Therefore, the results from this research can be helpful for implementing energy performance regulations in other countries. Moreover, the Netherlands is currently developing the EPG, which will replace the EPN. The EPG includes calculation methods for new and existing buildings, and for residential and utility buildings. For the development of the EPG, the formulas used for the EPC are in revision.

Improving the thermal quality seemed more effective at decreasing energy consumption than improvements in the efficiency of heating and ventilation systems, since statistically significant correlations with energy consumption were found for thermal quality but these were very small or not significant for type of systems. However, not all types of heating and ventilation systems were included in the sample. In the energy performance regulations, the designer may decide on which aspect to focus, which might undermine the effect of the regulations. More emphasis on the importance of thermal properties in comparison to systems efficiency could further decrease energy consumption.

The EPC value is expected to decrease the overall building-related energy consumption; therefore calculations take account of the energy required for water heating, lighting and ventilation. However these calculations are mainly based on the size of the dwelling since standard values for occupant-related parameters are used (e.g. indoor temperature, presence at home and use of ventilators). Consequently, actual energy consumption differs statistically from expected energy consumption for heating and is lower than calculated. Taking into account in the calculations more accurate standard occupant behaviour could improve the energy consumption predictions. Further, an evaluation tool for the energy performance of a building (obtained in the EPC calculation) could be used to guarantee better energy predictions. Accurate user profiles for energy use could be used as a part of the evaluation tool. Although accurate energy prediction is not the aim of the EPC, a better estimation of the actual energy performance and the actual energy savings expected from the introduction or tightening of building regulations, could be achieved.

A large difference was found between actual and expected energy consumption for heating, pointing partly at differences between the building characteristics defined in the EPC document and the actual quality of the construction. The measurement and control of infiltration values and insulation levels after construction of the building might lead to large energy savings since the construction quality might have a large effect on the energy consumption.

A missed opportunity for reducing energy consumption for heating in new dwellings is related to dwelling size and type of dwelling, but regulations on building size are more difficult to establish. The EPC currently corrects for dwelling size. A small dwelling will always consume less energy for heating than a large dwelling with the same thermal properties and systems efficiency. However, a review on the EPC calculation should consider dwelling size in order not to penalise small dwellings, since excessive cost would be expected for flats to reach the compulsory EPC level (Jeeninga & Kets, 2004). For example, EPC levels could be less stringent in smaller dwellings or flats than in larger dwellings.

7.6.2 Recommendations for practice

Less energy is consumed in housing built after 1995 in comparison to the total housing stock but a more intensive use of the heating system was found in these. This factor might be reducing the effectiveness of energy performance regulations. The development of more energy-friendly types of temperature control and ventilation systems is important.

As indicated before, installation of manual thermostats instead of programmable thermostats might have a positive effect on the reduction in energy consumption for heating. Households in dwellings with programmable thermostats take less deliberate actions and leave the control to the thermostat, which is insufficient when the time spent at home varies too much, or when interaction with other systems take place (e.g. during ventilation periods). This gives an opportunity for improvement, for example by installing manual thermostats per room. This would help to maintain a desired temperature per room leaving sufficient interaction with the thermostat to achieve deliberate heating only when needed. Another possibility would be to develop a type of automatic thermostat that reacts to presence sensors instead of pre-programmed timetables. Moreover, giving immediate feedback to users on the impact of their choices in the use of the heating system might help to reduce energy consumption, for example, feedback on the effects of having the radiators on at entrances and in corridors, choosing higher temperatures, or leaving the heating on during the night.

The use of ventilation systems in recently built dwellings seems not to be as intended. Providing better instructions and feedback to users could help more efficient use of systems. Development of less noisy mechanical ventilation systems is also of great importance since this is the main reason for turning the system down or off.

7.6.3 Recommendations for further research

This section gives recommendations for further research regarding suggestions drawn from the framework and the delimitation of the research.

Determinants of behaviour

Further research should be aimed at the causes of occupant behaviour (cognitive variables). The behaviour taken into account in this study is defined as use of systems and other provisions in the dwelling. Therefore this research focused on behaviour itself and not on its causes. Although this study showed for example that seniors prefer warmer temperatures, a relation between household characteristics and ventilation behaviour was not found. The study of cognitive variables could explain why some households prefer higher temperatures or more ventilation than others.

Factor analysis showed interesting results in relation to behaviour patterns and factors underlying occupant behaviour. The results were used to identify households and their related building characteristics to determine household profiles. However, no relationships between household profiles and behaviour patterns and energy consumption were found. A larger sample size or the addition of electricity consumption could increase these relationships. Analysis of total housing stock could lead to different results due to a greater variety of household and building characteristics affecting behaviour.

This research used self-reported occupant behaviour in retrospective. Thus there might be large differences with actual use of dwelling provisions. More research into these differences should be carried out in the future.

Electricity consumption

This study focused on the effect of energy performance regulations on energy use for space and water heating. The exclusion of electricity consumption was because even when the Dutch energy performance regulations include the energy used for ventilators and lighting, these make use of standardized values and are therefore merely based on the floor area of the building. In addition, the use of electricity for appliances and electronics are not building-related.

The energy use for appliances, electronics and lighting is known to have increased in recent years. The effect of occupant behaviour and household characteristics on electricity consumption is believed to be higher than on space heating. Further research is therefore needed in this area in order to decrease the environmental burden caused by occupant behaviour in residential buildings.

7.7 Closing remarks

The indoor environment of a dwelling is an important factor determining the quality of life of its inhabitants. Providing a safe and healthy environment is an objective of architects and urban designers. However, our society cannot afford to maintain current trends in over-consumption of resources. Housing should be made not only healthy and comfortable but sustainable as well; energy efficiency is now one of the main goals of building regulations.

Energy efficient buildings will not achieve their expected effects if user behaviour is not taken into account. Occupants' decisions on how they use building provisions have an important effect on the efficiency of the building. That occupants understanding the effect of their decisions is crucial to achieving the expected energy performance of a building.

Summary

Actual energy consumption in dwellings

The effect of energy performance regulations and occupational behaviour

Olivia Guerra Santín

Many governments have introduced regulations to make buildings more energy-efficient. Policies and research on energy conservation in buildings are geared primarily to saving energy through technical measures relating to the building envelope and the heating and ventilation installations.

Since 2006 the Energy Performance Building Directive (EPBD) has required all EU member states to enhance their building regulations by implementing performance-based energy requirements and by introducing energy-label certification schemes in buildings. In the Netherlands, the energy-efficiency requirement is based on the energy performance coefficient (EPC), a non-dimensional figure that expresses the energy efficiency of a building.

The aim of energy performance regulations is to ease the environmental burden imposed by the energy consumed in the built environment. However, the energy savings from space heating might fall short of expectations. The effectiveness of energy regulations needs to be verified in order to discern whether more energy savings will be generated by tighter regulations. It is thought that occupant behaviour, the actual quality of the construction, and rebound effects might be undermining the effect of the regulations.

The aim of this research is to provide insight into the effect of energy performance regulations on the energy consumption for space heating and to clarify the role of occupant behaviour in determining this effectiveness. This will enable us to establish whether tighter energy performance regulations are required and to identify the factors (building characteristics) that could be causing households to consume more energy.

Research methods

This research sought to draw conclusions on the determinants of energy consumption at macro-level in order to analyse the effects of national energy regulations. The study at macro level was necessary because of the large number of variables that influence energy consumption.

Statistical analyses were therefore used to determine the factors that influence energy consumption for heating. The analyses carried out in this research were exploratory in nature. The objective was to deliver relationships between different variables (occupant behaviour, household characteristics and building characteristics) which would then deepen the understanding of the relative influence and interaction between the variables and pave the way for energy-consumption predictions for certain groups.

Thanks to the use of standardisations in statistical methods (i.e. standard deviations) statistical analysis also enabled us to systematically compare

recently built housing with the total housing stock and also made comparisons possible with other research and databases. This study made use of multivariate statistical analyses.

Different methods were applied depending on the research questions. Regression analyses were used to carry out energy predictions in order to identify the building and household characteristics that have an effect on energy use. Based on the results from the regression analyses, more specific analyses of the building characteristics and occupant behaviour influencing energy consumption were carried out with a view to determining the effects of the energy performance regulations on actual energy consumption. ANOVA tests were used to identify differences in behaviour and energy consumption across different groups. In order to further analyse the effect of behaviour on energy consumption, exploratory factor analysis was used to determine behavioural patterns. To conclude, an analysis of the possible existence of a rebound effect in recently built dwellings was carried out making use of Factorial ANOVAs.

The statistical analysis required detailed data on occupant behaviour, building characteristics and household characteristics. Four types of data were used: data on building characteristics; demographic data on household characteristics; data on occupant behaviour; and data on the actual energy consumption for space and water heating.

The data were obtained from three sources. The main source was the OTB database carried out as part of this study. The other sources were two databases of the Dutch Ministry of Housing derived from household energy surveys in the Netherlands in 2000 and 2005.

Effect of energy performance regulations on actual energy consumption

Effect of EPC value on energy consumption for heating

The energy performance regulation is an instrument for reducing building-related energy consumption. In the Netherlands, the energy performance coefficient has been tightened three times in the past. The energy consumption in dwellings with a lower EPC is expected to be lower than the energy consumption in dwellings with a higher EPC. The EPC is calculated by normalising the predicted energy consumption per building size by applying a standard value. The predicted energy consumption in the EPC is the sum of the energy required for space and water heating, cooling, ventilation and lighting. The energy efficiency of systems is also taken into consideration. The EPC calculation makes assumptions about thermostat settings at various times of the day. The energy required for space heating also takes account of the thermal properties of the building.

Our results showed that actual energy consumption for heating was not statistically significantly lower in dwellings with stricter EPC values. However, substantial differences that were found between dwellings built before and after the introduction of the EPC indicate that, since its introduction, the EPC has helped to reduce energy consumption.

Although lower EPC values are not related to statistically significant lower energy consumption, the predicted energy consumption for heating did correlate to the actual energy consumption for heating, indicating that dwellings with increased thermal properties consume less energy.

Difference between actual and predicted energy consumption

Given that a medium correlation was found between actual and predicted energy consumption for heating, it is remarkable that no statistically significant differences were found for the EPC values. This might conceivably be due to an effect triggered by the normalisation factor for building size or to incorrect estimation of energy requirements for water heating, lighting and ventilators, which are more dependent on occupant behaviour than on building characteristics. Further tests established that 'total expected energy consumption' showed the same correlation with actual energy consumption for heating than 'expected energy consumption for heating', thus ruling out an effect caused by the energy requirements for lighting, ventilators and auxiliary energy for space heating. The absence of statistically significant differences in the EPC levels might therefore be caused by the normalisation factor.

In most cases, actual energy consumption for heating was lower than expected, again underlying the importance of the effect of occupant behaviour on energy consumption. These differences may appear if the calculation applies excessive energy requirements for occupant comfort or if small households live in large dwellings and therefore use less energy than anticipated. Hence, the standard household behaviour used in the EPC might be far from reality.

The influence of building characteristics in the EPC on energy consumption for space heating

Analysis of the building characteristics included in the EPC calculation aimed to further determine the differences between actual and expected energy consumption and to identify the building characteristics that have a major effect on energy consumption. According to the results, thermal properties seemed to be more effective than more efficient ventilation and heating systems in lowering energy consumption. Medium-sized correlations were found between energy consumption and thermal properties and small or non-statistically significant correlations were found for the type of heating and ventilation system.

A regression analysis showed that 18-22% of the variation in energy consumption in recently built housing can be explained with the building characteristics that are used for the EPC. A 78-82% variation in energy consumption is therefore unaccounted for, explaining the wide difference between expected and actual energy consumption, the barely medium-size correlation, and the absence of statistically significant differences in energy consumption for dwellings with different EPC values.

Two factors seem to explain the remaining variation in energy consumption: actual quality of construction (e.g. actual thermal properties and system efficiency) and actual occupant behaviour. Studies have shown that buildings are constructed differently than specified in official documents (i.e. EPC document) and HVAC services run under very different conditions than is assumed on paper.

The fact that actual energy consumption for heating is lower than expected apparently contradicts the assumption that the actual building characteristics are different from those described in the EPC document (therefore implying poor construction practices). However, the lower actual energy consumption is caused by the fact that the calculation method assumes high levels of comfort and system usage as well as average indoor and outdoor temperatures. A more accurate calculation method (such as an energy simulation model) would probably also show a wide difference between the modelled energy consumption and the expected energy consumption in the EPC document.

Effect and determinants of occupant behaviour on actual energy consumption for heating

Effect of occupant behaviour on energy consumption

Statistical analyses showed that the number of hours a heating system was turned on at the highest chosen setting appeared to have a stronger effect on energy consumption than the highest chosen setting as such. Minor variations in the setting in new dwellings are probably due to the similar thermal properties of all new houses. The number of hours that radiators were open also turned out to have a significant effect on energy consumption.

Low correlations were found between energy consumption and the use of a mechanical ventilation system since most households kept the mechanical ventilation system off or at the lowest level. Window and grille ventilation seemed to have a stronger effect on energy consumption than mechanical ventilation.

Thermostat use emerged as an important factor in occupant behaviour: households with a programmable thermostat were associated with higher temperature settings during the night and with more hours with the radiators on.

Determinants of occupant behaviour that have an effect on energy consumption

The interaction of the occupant with the dwelling is thought to have an effect on occupant behaviour. The building characteristics and household characteristics related to occupant behaviour were therefore analysed. The building characteristics were the type of temperature control and type of ventilation since occupants interact with these systems.

Both type of temperature control and type of mechanical ventilation seem to have an effect on the use of heating and ventilation systems. Households with manual thermostats and mechanical exhaust ventilation display more energy-conserving behaviour than households with programmable thermostats and balanced ventilation systems. Results also showed that personal heating (heating space that is in use) is less energy-intensive than space heating (heating space whether it is used or not).

Analysis of the effect of household characteristics on occupant behaviour revealed that the presence of elderly persons in the household proved to be a determining factor in both heating system and ventilation use. More intensive use of the heating system and less ventilation was associated with seniors. The presence of seniors might be closely related to hours spent at home.

The presence of children also had a significant effect on ventilation use. Other household characteristics related to a more intensive use of the heating system were average education levels (compared with high education levels) and having previously lived in a single-family dwelling.

Main patterns of occupant behaviour

The standard occupant behaviour applied in the EPC calculation might be responsible for the wide difference between actual and expected energy consumption, since it could be far from actual behaviour. This research therefore also sought to (1) determine behavioural patterns and (2) define building characteristics and household characteristics for user profiles on energy consumption.

This study identified five underlying groups of behavioural factors in occupant behaviour: 'appliances and space', 'energy-intensive', 'ventilation', 'media' and 'temperature comfort'. 'Appliances and space' was related to more use of space and heavy appliances (e.g. washing machine, dryer, dish washer). 'Energy-intensive' was related to behaviour leading to more use of energy, such as more intensive use of the heating system. 'Ventilation' referred to more hours of ventilation. The fourth factor 'media' related to behaviour seen in young households, for example, taking showers instead of baths, more use of electronics and computers, less use of space and more ventilation. The final factor 'temperature comfort' related to preferences for a warmer indoor environment and less ventilation.

Five patterns were identified for the five factors: (1) spenders, (2) affluent-cool, (3) conscious-warm, (4) comfort and (5) convenience-cool. The behavioural patterns were developed for use in simulation programmes or energy-savings calculations by linking household types with specific behaviour (more hours of ventilation, more use of energy-saving light bulbs). Though only indicative differences in energy consumption were found between the groups, results indicated that 'convenience-cool' was more strongly related to lower energy consumption than the other behaviour patterns, while 'spenders' is more strongly related to higher energy consumption than the other behaviour patterns.

Household categories showing significant differences in energy-related behaviour
Correlations between the behaviour factors and households and building characteristics were used to split the household groups into: 'seniors', 'families', 'singles/couples' and 'high-income couples'. Household groups with different behaviour patterns can be useful in the formulation of energy-saving policies that target specific sectors of society. Indicatively higher energy consumption (not statistically significant) was found for families, seniors and high-income couples. The higher energy consumption in these three household groups has various reasons. The higher energy consumption by families stemmed from a high score for 'space and appliances'. In the case of seniors it was caused by a high score for 'temperature comfort' and in the case of high-income couples by a high score for 'energy-intensive'.

Both household and building characteristics proved important in identifying differences in behaviour patterns related to energy consumption. Information on the type and size of a dwelling and HVAC systems combined with information on the main household characteristics such as household size, age, background and lifestyle (hours at home) made it possible to identify behaviour patterns for the household groups.

Determinants of energy consumption in recently built housing in comparison with the complete housing stock

Building characteristics having the strongest influence on energy consumption in the total housing stock
Determining the effect of building characteristics and occupant behaviour in the total housing stock placed the research question in a different perspective. Other studies have ascertained a rebound effect in dwellings with improved thermal properties. An investigation of the differences between recently built housing and the total housing stock would shed more light on the role of the energy performance regulations in lowering energy consumption. The results showed that, in the total housing stock, building characteristics (thermal properties) still seem to be more important than household characteristics or behaviour.

The most important building characteristics affecting energy consumption are related to the size of dwelling and insulation level. Energy consumption also tends to be lower in newer buildings and in non-detached dwellings, while the presence of a thermostat, garage, shed and basement tend to increase energy consumption.

Relative importance of occupant behaviour and building characteristics on energy consumption in the total building stock

Occupant behaviour seems to be less important than building characteristics in determining energy consumption; however, occupant behaviour is highly dependent on building characteristics. It is determined by the dwelling type and HVAC systems and especially by the dwelling size and type of thermostat; therefore, the effect of occupant characteristics such as income or household size might be greater than expected, since these are important in determining the type of dwelling.

Energy performance regulations seem to have been successful in lowering energy consumption for heating, since better thermal properties in dwellings have had a positive effect; this is corroborated by the larger variation explained by building characteristics and occupant behaviour in the total housing stock compared with recently built housing.

Differences in behaviour determined by building characteristics in the total housing stock

Building characteristics such as insulation and thermal properties were related to a decrease in energy consumption, but analysis of the relationships between these characteristics and heating behaviour indicated that households living in dwellings with better thermal properties prefer higher indoor temperatures. Although this does not affect energy consumption, it might limit the positive effects of better thermal properties and energy performance regulations.

Type of temperature control seemed to have contrary effects, since the presence of thermostats is related to higher energy consumption but to a lower heating behaviour score (i.e. the heating system is set at a lower than average temperature). Nevertheless, results indicated that it is ‘hours’ rather than ‘setting’ that affects energy consumption.

Final conclusion

Two types of general conclusions can be drawn from this research. The first concerns the EPC calculation method and its effect on energy consumption for heating; the second concerns occupant behaviour.

Although lower energy consumption is not observed in dwellings with lower EPC values, a relationship does exist between better thermal properties and lower energy consumption. However, the actual energy consumption is lower than estimated. Moreover, the analysis showed that only a small percentage of the variation in energy consumption could be explained by the building characteristics in the EPC calculation and occupant behaviour, leading to the conclusion that the unaccounted percentage could be due to the actual quality of the construction (i.e. the real thermal properties of the dwelling).

The improvement of energy efficiency in buildings is important to decrease energy consumption. This is especially important in the building stock, since new buildings are designed to have a good energy performance. However, it has been shown that occupant behaviour could undermine the positive effects of energy performance regulations.

It was also concluded that the relationship between the EPC value and energy consumption could be improved with more accurate standardised occupant behaviour. The occupant behaviour that led to wide variations in energy consumption was related mainly to household characteristics or lifestyle aspects that are difficult to modify (i.e. hours spent at home).

Influencing behaviour as a method to decrease energy consumption presents an opportunity in energy efficient dwellings (i.e. recently built dwellings). Targeting the right groups in policies is however necessary to succeed, and therefore more knowledge in the causes of behaviour (cognitive variables) is needed.

It is necessary to make a distinction between household characteristics, and cognitive variables (preferences, attitudes). All these factors have an effect on energy use, but the possibility of influencing them are different. Household characteristics and often lifestyle cannot be externally influenced. There are more possibilities in influencing cognitive variables with the right methods. For further research, a clear distinction should be made between these types of variables.

Both factors, building characteristics and occupant behaviour, are important in the bid to decrease energy consumption for heating in residential buildings. The application of the right method would depend on the particular situation.

Samenvatting
Feitelijk energiegebruik van woningen
Het effect van energieprestatieregelgeving and bewonersgedrag

Olivia Guerra Santín

Een groot aantal overheden heeft regelgeving uitgevaardigd om gebouwen energie-efficiënter te maken. Het beleid en het onderzoek naar energiebehoud in gebouwen is er voornamelijk op gericht energie te besparen door middel van technische maatregelen met betrekking tot de gebouwschil en de verwarmings- en ventilatie-installaties.

In 2006 is de EPBD (Energy Performance Building Directive) van kracht geworden. Deze Europese richtlijn verplicht alle lidstaten maatregelen met betrekking tot energieprestaties voor gebouwen te implementeren en energieprestatiecertificaten af te geven. Daartoe is in Nederland de Beoordelingsrichtlijn (BRL 9500) ontwikkeld. De energieprestatiecoëfficiënt (EPC) voor nieuwbouwwoningen is een niet-dimensionaal getal waarin de energie-efficientie van een gebouw wordt uitgedrukt.

Het doel van de regelgeving is het energieverbruik in gebouwen terug te dringen en daarmee het milieu zoveel mogelijk te ontzien. Op het gebied van verwarming zal de energiereductie wellicht niet worden gehaald. De effectiviteit van energiewetgeving zal moeten worden gecontroleerd om vast te kunnen stellen of meer energiebesparingen en dus strengere wetgeving nodig zijn. Het gedrag van bewoners, de kwaliteit van het gebouw en eventuele terugslageffecten kunnen een negatief effect hebben op de effectiviteit van regelgeving.

Het doel van dit onderzoek is inzicht te verschaffen in de effectiviteit van energieprestatieregelgeving op het energieverbruik voor het verwarmen van woonruimten en de rol van bewoners in het bepalen van die effectiviteit. Aan de hand daarvan hopen we te kunnen vaststellen in hoeverre strengere regelgeving nodig is. Ook willen we graag weten welke factoren (bouwkenmerken) ertoe leiden dat huishoudens meer energie gebruiken.

Onderzoeksmethoden

Het doel van dit onderzoek was om conclusies te kunnen trekken over de determinanten van energieconsumptie op macroniveau, om daarmee de effecten van nationale energieregelgeving te kunnen analyseren. Het was noodzakelijk om het onderzoek op macroniveau uit te voeren in verband met het grote aantal variabelen dat van invloed is op de energieconsumptie.

Om de factoren die van invloed zijn op de energieconsumptie met betrekking tot verwarming te kunnen bepalen, werd dan ook gebruikgemaakt van statistische analyses. De analyses die in dit onderzoek werden uitgevoerd waren verkennend van aard. Het doel was om verbanden tussen verschillende variabelen (gedrag van bewoners, kenmerken van huishoudens en woningen) te vinden die meer inzicht zouden kunnen bieden in de relatieve wederzijdse beïnvloeding en de interactie tussen variabelen, en die voorspellingen op het gebied van energieconsumptie voor verschillende groepen mogelijk zouden maken.

Effect van energieprestatieregelgeving op het feitelijke energieverbruik

Het effect van de EPC-waarde op het energieverbruik voor verwarming

De energieprestatieregelgeving is een instrument waarmee het energieverbruik met betrekking tot gebouwen kan worden teruggedrongen. De energieprestatiecoëfficiënt is in het verleden in Nederland al drie keer aangescherpt. Van woningen met een lagere EPC wordt een lager energieverbruik verwacht dan van woningen met een hoge EPC. De EPC wordt berekend met behulp van een gestandaardiseerde gebouwengrootte, het verwachte energieverbruik volgens een standaardwaarde ten opzichte van de totaal te verwarmen ruimte en het warmtereflectie-oppervlak van de woning. Het verwachte energieverbruik binnen de EPC is de som van de vereiste energie voor de verwarming van de ruimte en van water, van koeling, ventilatie en verlichting. Bovendien wordt de energie-efficiëntie van installaties in aanmerking genomen, wordt bij de berekening rekening gehouden met de thermostaatinstellingen gedurende de dag en worden de thermische eigenschappen van een gebouw meegenomen in de berekening van de energie die benodigd is voor het verwarmen van ruimten.

Uit onze resultaten blijkt dat het feitelijke energieverbruik voor verwarming statistisch niet significant lager uitvalt in woningen met strenge EPC-waarden. Wel werden aanzienlijke verschillen vastgesteld tussen woningen gebouwd voor en na de invoering van de EPC. Daaruit blijkt dat de EPC een rol heeft gespeeld bij het terugdringen van het energieverbruik.

Hoewel lagere EPC-waarden statistisch gezien niet tot een significant lager energieverbruik leidden, kwam het verwachte verbruik overeen met het feitelijke verwarmingsverbruik. Daaruit blijkt dat in woningen met verbeterde thermische eigenschappen minder energie wordt verbruikt.

Het verschil tussen het verwachte en feitelijke energieverbruik

Met een gemiddelde correlatie tussen verwacht en feitelijk energieverbruik voor verwarming is het opmerkelijk dat geen statistisch significante verschillen met de EPC-waarden konden worden vastgesteld. Het gebrek aan statistisch significante verschillen zou iets te maken kunnen hebben met de standaardisatiefactor voor de grootte van gebouwen. Aan de andere kant is het ook mogelijk dat de energievereisten voor de verwarming van water, voor verlichting en ventilatie (die meer afhankelijk zijn van bewonersgedrag dan de eigenschappen van een gebouw) niet helemaal correct worden ingeschat. Uit testen blijkt dat het 'totaal verwachte energieverbruik' dezelfde correlatie met het feitelijke verbruik vertoonde als het 'verwachte verbruik voor verwarming'. Dat betekent dat de energievereisten voor verlichting, ventilatie en bijkomende energie voor het verwarmen van ruimten geen factoren van belang zijn. Daarom kan worden geconcludeerd dat het gebrek aan statistisch significante verschillen in de EPC-waarden veroorzaakt wordt door de standaardisatiefactor.

In de meeste gevallen viel het feitelijke energieverbruik voor verwarming lager uit dan verwacht. Daarmee werd het belang van het bewonersgedrag ten opzichte van energieverbruik nog eens onderstreept. Deze verschillen kunnen zich voordoen als binnen de berekening buitensporig veel ruimte wordt gelaten voor de energievereisten ten aanzien van het comfort van de bewoners, of als er sprake is van kleine gezinnen in grote woningen en er dus minder energie wordt verbruikt dan verwacht. Om die redenen kan het standaardgedrag van huishoudens zoals binnen de EPC is vastgesteld, aanzienlijk van de werkelijkheid verschillen.

De eigenschappen van gebouwen binnen de EPC die van invloed zijn op het energieverbruik voor de verwarming van ruimten

De analyse van de eigenschappen van gebouwen zoals deze in de EPC-berekening worden meegenomen, dienen voor een verdere vaststelling van de verschillen tussen het verwachte en het feitelijke energieverbruik. Verder hoopt men dat de analyse een beter inzicht verschaft in de eigenschappen van gebouwen voor zover die van invloed zijn op het energieverbruik. De resultaten wijzen erop dat de thermische eigenschappen wel bijdragen aan een lager energieverbruik maar minder aan efficiëntere ventilatie- en verwarmingsinstallaties. Er kon een gemiddelde correlatie worden vastgesteld tussen energieverbruik en thermische eigenschappen, terwijl kleine en niet statistisch significante correlaties werden vastgesteld met betrekking tot het type verwarming en ventilatie.

Uit een regressieanalyse bleek dat 18 tot 22% van de variatie in energieverbruik in recentelijk gebouwde woningen kan worden verklaard aan de hand van de bouwkenmerken die worden gebruikt om het EPC-niveau te berekenen. Voor de resterende variatie van 78 tot 82% in energieverbruik is daarmee geen verklaring gevonden. Dat verklaart echter wel het grote verschil tussen verwacht en feitelijk energieverbruik, de nauwelijks gemiddelde correlatie en het gebrek aan statistisch significante verschillen in energieverbruik voor woningen met verschillende EPC-waarden.

Toch zijn er voor de resterende variatie in energieverbruik twee factoren aan te wijzen: de feitelijke kwaliteit van de gebouwen (bijvoorbeeld de huidige thermische eigenschappen en de efficiëntie van de gebruikte installaties) en het gedrag van de huidige bewoners. Onderzoek wijst uit dat woningbouw vaak anders verloopt dan in officiële documenten is vastgelegd (bijvoorbeeld een EPC-document) en dat de werking van verwarming, ventilatie en airconditioning (HVAC) vaak afwijkt van de specificaties op papier.

Dat het feitelijke energieverbruik lager uitvalt dan verwacht, is in tegenspraak met de veronderstelling dat bouwkenmerken afwijken van het EPC-document (wat met zich mee zou brengen dat de constructie van gebouwen te wensen overlaat). Het lagere feitelijke energieverbruik wordt echter veroorzaakt door de berekeningsmethode, waarin een hoog niveau van comfort en gebruik van installaties is verdisconteerd, alsmede het gebruik van gemiddelde binnen- en buitentemperaturen. Een nauwkeurigere berekeningsmethode (zoals een energiesimulatiemodel) zou waarschijnlijk ook een groot verschil aan het licht brengen tussen het energieverbruik binnen het model en het verwachte energieverbruik in het EPC-document.

Effecten en beslissende factoren in bewonersgedrag ten aanzien van het feitelijke energieverbruik voor verwarming

Het effect van bewonersgedrag op het energieverbruik

Uit statistische analyse blijkt dat het aantal uren dat een verwarming op de hoogste stand staat van meer invloed op het energieverbruik is dan de hoogst gekozen stand. Kleine variaties in de verwarmingsstand in nieuwe huizen worden waarschijnlijk veroorzaakt door vergelijkbare thermische eigenschappen van alle nieuwe huizen. Het aantal uren dat radiatoren worden gebruikt, was ook significant van invloed op het energieverbruik.

Lage correlaties werden aangetroffen tussen het energieverbruik en het gebruik van een mechanische ventilatie omdat deze in de meeste huishoudens uit of op de laagste stand wordt gelaten. Raam- en roosterventilatie leek sterker van invloed op het energieverbruik dan een mechanisch ventilatiesysteem.

Het thermostaatgebruik trad naar voren als een belangrijke factor in het bewonersgedrag: huishoudens met een programmeerbare thermostaat lieten ’s nachts een hogere temperatuurinstelling zien met langer ingeschakelde radiatoren.

Factoren van bewonersgedrag die van invloed zijn op het energieverbruik

De interactie van bewoners met hun woning is vermoedelijk van invloed op het bewonersgedrag. De bouwkenmerken en eigenschappen van het huishouden met betrekking tot het bewonersgedrag zijn daarom tot het onderwerp van onderzoek gemaakt. De geanalyseerde bouwkenmerken waren het type temperatuurregeling en het type ventilatie, omdat er sprake is van interactie tussen deze systemen en de bewoners.

Zowel het type temperatuurregeling als het type mechanische ventilatie leek van invloed te zijn op het gebruik van verwarming en ventilatiesysteem. Huishoudens met handmatige thermostaten en mechanische uitlaatventilatie gaan zuiniger met hun energie om dan huishoudens met programmeerbare thermostaten en uitgebalanceerde ventilatiesystemen. De resultaten wezen er ook op dat persoonlijke verwarming (van alleen de ruimten die in gebruik zijn) minder energie verbruikt dan het verwarmen van alle ruimten (of deze nu wel of niet in gebruik zijn).

Met betrekking tot de invloed van de eigenschappen van het huishouden op het gedrag van de bewoners bleek de aanwezigheid van ouderen in het huishouden een bepalende in zowel het gebruik van de verwarming als de ventilatie. Een intensiever gebruik van de verwarming en een lager gebruik van de ventilatie werd geassocieerd met ouderen. De aanwezigheid van ouderen kan ook sterk verband houden met het aantal uren dat thuis wordt doorgebracht.

Ook de aanwezigheid van kinderen was significant van invloed op het ventilatiegebruik. Andere huishoudelijke kenmerken die verband houden met een intensiever gebruik van de verwarming zijn een gemiddeld opleidingsniveau van de bewoners (in vergelijking met een hoog opleidingsniveau) en of men eerder in een eengezinswoning heeft gewoond.

De voornaamste patronen van bewonersgedrag

Het standaardgedrag van bewoners zoals dat wordt meegenomen in de EPC-berekening kan een groot verschil veroorzaken tussen het verwachte en feitelijke energieverbruik omdat dit sterk kan afwijken van het feitelijke bewonersgedrag. Daarom is binnen dit onderzoek ook getracht om (1) gedragspatronen vast te stellen en (2) eigenschappen en kenmerken van gebouwen en huishoudens vast te leggen, zodat daarmee rekening kan worden gehouden bij het opstellen van gebruikersprofielen voor energieverbruik.

In het kader van het onderzoek zijn vijf onderliggende groepen van gedragsfactoren vastgelegd: ‘apparatuur en ruimte’, ‘energie-intensief’, ‘ventilatie’, ‘media’ en ‘temperatuur en comfort’. De factor ‘apparatuur en ruimte’ houdt verband met een intensiever gebruik van ruimten en witgoedapparatuur (zoals wasmachines, drogers en vaatwasmachines). De factor ‘energie-intensief’ houdt verband met gedrag dat leidt tot een intensiever gebruik van energie, bijvoorbeeld een hogere stand van de verwarming. ‘Ventilatie’ verwijst naar een intensiever gebruik van de ventilatie. De vierde factor, ‘media’, gaat over het gedrag in jonge huishoudens, bijvoorbeeld over het gebruik van de douche in plaats van het bad, een intensiever gebruik van elektronica en computers, minder gebruik van ruimten en meer ventilatie. De laatste factor, ‘temperatuur en comfort’ houdt verband met de voorkeur voor een warmer huis en minder ventilatie.

Met betrekking tot bovenstaande factoren werden ook vijf patronen vastgesteld: (1) grootverbruikers, (2) welvarend-koel, (3) bewust-warm, (4) comfort en (5) gemak-koel. De gedragspatronen zijn ontwikkeld voor gebruik in simulatieprogramma’s of berekeningen met het oog op energiebesparing. Huishoudens worden gekoppeld aan specifieke gedragspatronen (meer ventilatieuren, meer gebruik van spaarlampen enz.). Hoewel er geen zeer betekenisvolle verschillen konden worden vastgesteld in het energieverbruik van de diverse groepen, bleek uit de resultaten toch dat ‘gemak-koel’ kon worden gerelateerd aan een lager energieverbruik dan de andere gedragspatronen, terwijl voor 'grootverbruikers' een hoger energieverbruik opging dan voor de andere groepen.

Huishoudenscategorieën met significante verschillen in energiegerelateerd gedrag
Correlaties tussen gedragsfactoren en huishoudens en bouwkenmerken zijn gebruikt om verschillende huishoudensgroepen vast te stellen: 'senioren', 'gezinnen', 'alleenstaanden/stellen' en 'veelverdieners/stellen'. Huishoudensgroepen met verschillende gedragspatronen kunnen worden gebruikt om richtlijnen voor een zuiniger energieverbruik op te stellen voor specifieke sectoren van de samenleving. Gezinnen, senioren en veelverdienende stellen lieten een enigszins hoger energieverbruik zien (hoewel niet statistisch significant). Aan het hogere energieverbruik van deze drie huishoudensgroepen liggen diverse redenen ten grondslag. Gezinnen lieten een hoger energieverbruik zien door een hoge score op 'ruimte en apparatuur', senioren door een hoge score in 'temperatuur en comfort' en veelverdienende stellen scoorden hoog op 'energie-intensief'.

Zowel de huishoudens- als bouwkenmerken bleken van belang in het vaststellen van verschillen in gedragspatronen met betrekking tot energieverbruik. Als het type en de grootte van een woning, alsmede de gebruikte HVAC-installaties bekend zijn, en tevens de huishoudenskenmerken zoals omvang, leeftijd, achtergrond, en levensstijl (thuis doorgebrachte uren) zijn vastgesteld, kunnen gedragspatronen worden afgezet tegen huishoudensgroepen.

Factoren die het energieverbruik bepalen in recentelijk gebouwde woningen ten opzichte van het totale woningaanbod

Bouwkenmerken met de sterkste invloed op het energieverbruik in het totale woningaanbod
Het vaststellen van de bouwkenmerken en het bewonersgedrag in het totale woningaanbod bood een ander perspectief op het onderzoeksprobleem. Uit andere onderzoeken is een terugslageffect gebleken voor woningen met verbeterde thermische eigenschappen. Het onderzoek naar de verschillen tussen recentelijk gebouwde woningen ten opzichte van het totale woningaanbod kan inzicht verschaffen in de rol van energieprestatieregelgeving met betrekking tot het terugdringen van energieverbruik. Het totale woningaanbod, de bouwkenmerken (zoals thermische eigenschappen) lijken van groter belang dan huishoudenskenmerken en bewonersgedrag, zo blijkt uit de resultaten.

De bouwkenmerken die het meest van invloed zijn op het energieverbruik houden verband met de grootte van de woning en de mate van isolatie. Het energieverbruik daalt doorgaans ook in nieuwere gebouwen en vrijstaande huizen, terwijl de aanwezigheid van een thermostaat, garage, schuur en kelder doorgaans leiden tot een hoger energieverbruik.

Het relatieve belang van bewonersgedrag en bouwkenmerken ten opzichte van energieverbruik in het totale woningaanbod
Het gedrag van bewoners lijkt van minder belang dan bouwkenmerken bij het vaststellen van energieverbruik; aan de andere kant is het bewonersgedrag weer sterk afhankelijk van de bouwkenmerken. Het bewonersgedrag wordt bepaald door het woningtype en de geïnstalleerde HVAC-installaties, en vooral door de grootte van de woning en het type thermostaat; mede daarom kan de invloed van bewonerskenmerken zoals het inkomen of de grootte van het huishouden zwaarder wegen dan verwacht, omdat deze factoren weer een grote rol spelen bij het vaststellen van het woningtype.

De energieprestatieregelgeving lijkt zijn vruchten te hebben afgeworpen met betrekking tot verwarming omdat de verbeterde thermische eigenschappen van woningen een positief effect hebben; dit wordt bevestigd door de grotere variatie aan bouwkenmerken en bewonersgedrag binnen het totale woningaanbod in vergelijking met recentelijk gebouwde woningen.

Verschillen in gedrag zoals bepaald door bouwkenmerken in het totale woningaanbod
Bouwkenmerken zoals isolatie en thermische eigenschappen houden verband met een lager energieverbruik, maar uit een analyse van de relatie tussen deze en het verwarmingsgedrag blijkt dat huishoudens in woningen met betere thermische eigenschappen de voorkeur geven aan hogere binnentemperaturen. Dit is weliswaar niet direct van invloed op het energieverbruik maar staat wel de positieve effecten van betere thermische eigenschappen en energieprestatieregelgeving in de weg.

Het type temperatuurbeheersing leek een tegengesteld effect te hebben omdat de aanwezigheid van een thermostaat verband houdt met een hoger energieverbruik maar tegelijkertijd met een lagere score voor verwarmingsgedrag (met andere woorden, de verwarming wordt op een lagere gemiddelde temperatuur ingesteld). Uit de resultaten blijkt echter dat het niet de instelling maar de uren zijn die van invloed zijn op het energieverbruik.

Conclusie
Uit het onderzoek kunnen twee algemene conclusies worden getrokken. De eerste conclusie betreft de voor de EPC gebruikte berekeningsmethode en het effect daarvan op het energieverbruik voor verwarming; de tweede conclusie betreft het bewonersgedrag.

Hoewel in woningen met lagere EPC-waarden geen lager energieverbruik kan worden geconstateerd, bestaat er een relatie tussen betere thermische eigenschappen en een verminderd gebruik van energie. Het feitelijke energieverbruik is echter lager dan verwacht. Uit de analyse bleek zelfs dat slechts een klein percentage van de variatie in energieverbruik kon worden verklaard door de in de EPC-berekening opgenomen bouwkenmerken en het bewonersgedrag. Dat heeft geleid tot de conclusie dat het resterende percentage kan worden verklaard door de feitelijke kwaliteit van de gebouwen (met andere woorden, de echte thermische eigenschappen van de woningen).

Het verbeteren van de energie-efficiëntie van woningen is een belangrijk middel om de energieconsumptie te verminderen. Dit geldt vooral voor de bestaande woningvoorraad, aangezien een goede energieprestatie tegenwoordig al in het ontwerp van nieuwe gebouwen wordt meegenomen. Het is echter ook aangetoond dat het gedrag van bewoners de positieve effecten van energieprestatieregelgeving kan ondermijnen.

De tweede conclusie was dat de relatie tussen de EPC-waarde en het energieverbruik zou kunnen worden verbeterd door een nauwkeurigere vaststelling van het standaardgedrag van bewoners. Het bewonersgedrag leidt tot sterke variaties in het energieverbruik en houdt voornamelijk verband met de huishoudenskenmerken of de levensstijl van de bewoners. Deze zijn moeilijk aan te passen (bijvoorbeeld het aantal uren dat thuis wordt doorgebracht).

Het beïnvloeden van gedrag om energieconsumptie te verminderen kan dus besparingen opleveren in energie-efficiënte (nieuwbouw)woningen. Het is hierbij echter van groot belang dat beleid gericht is op de juiste doelgroepen; hiervoor is meer inzicht nodig in de oorzaken van gedrag (cognitieve variabelen).

Er moet een onderscheid gemaakt worden tussen de kenmerken van huishoudens en cognitieve variabelen (voorkeuren, attitude). Beide soorten factoren zijn van invloed op het gebruik van energie, maar de mogelijkheden om ze te beïnvloeden zijn verschillend. De kenmerken van huishoudens en vaak ook leefstijl kunnen niet van buitenaf worden beïnvloed. Het beïnvloeden van cognitieve variabelen biedt meer mogelijkheden, mits de juiste methodes worden ingezet. In verder onderzoek zou er een duidelijk onderscheid gemaakt moeten worden tussen deze soorten variabelen.

Beide soorten factoren – de kenmerken van woningen en het gedrag van bewoners – zijn van belang bij het zoeken naar maatregelen om de energieconsumptie met betrekking tot verwarming van woningen te verminderen. De juiste aanpak moet voor elke situatie apart bekeken worden.

Appendix 1 EPC calculation

Source: NEN 5128: 2004. Energy Performance of Residential functions and residential buildings: determination method, ics 91.120.10, March 2004.

The EPC is calculated with the following formula:

$$EPC = \frac{Q_{pres;tot}}{[330 \text{ x } A_{g;verwz}] + [65 \text{ x } A_{verlies}]} \text{ x } \frac{1}{C_{EPC}}$$

where,

$Q_{pres;tot}$ is the primary energy consumption in MJ, determined by eq. 2
$A_{g;verwz}$ is the useful surface of the heated zones of the building in m^2
$A_{verlies}$ is the heat-transfer surface of the building in m^2
C_{EPC} is the correction factor for changes in the methodology

The required energy (MJ) is calculated with the following formula:

$$Q_{pres;tot} = Q_{prim;verw} + Q_{prim;hulp;verw} + Q_{prim;tap} + Q_{prim;vent} + Q_{prim;vl} \quad (2)$$

where,

$Q_{prim;verw}$ is the primary energy consumption for space heating in the building
$Q_{prim;hulp;verw}$ is the primary auxiliary energy consumption for space heating
$Q_{prim;tap}$ is the primary energy consumption for water heating
$Q_{prim;vent}$ is the primary energy consumption for ventilators
$Q_{prim;vl}$ is the primary energy consumption for lighting

To determine the heat-transfer surface of the building, the surfaces are multiplied by a reduction factor determined by the type of space limiting with the surface. For an outdoor wall the factor is 1; for a floor the factor is 0.7 to account for the fact that the average ground temperature is higher than the outdoor average air temperature during the heating season.

The primary energy consumption for space heating is calculated by dividing the energy needed for space heating by the efficiency of the installations. The energy needed for space heating is determined by subtracting the effective heat gain from the heat loss.

Heat loss takes account of the transmission and ventilation losses. It considers the difference between the average indoor (18^0C) and average outdoor (5^0C) temperature multiplied by the number of days in mega seconds (212 days). The considered indoor temperatures in Celsius degrees are:

- 7-17 hrs = 19 (living area all week and sleeping area on weekends), 16 (sleeping area on weekdays)
- 17-23 hrs = 21 (living area all week and sleeping area on weekends), 16 (sleeping area on weekdays)
- 23-7 hrs (thermostat setting) = 16 (living area all week and sleeping area on weekends), 14 (sleeping area on weekdays).

Heat gains take account of solar gains and internal heat gains. Solar gains are determined on the basis of orientation, reduction factors for shadows, solar entry factors and surface. Heat gains are calculated by multiplying the total heated area by 110, which is calculated by multiplying the average heat-gain (6.0 W/m^2) by the value of the length of the considered period (212 days) in mega seconds.

The primary energy consumption for heating water is determined by the gross energy requirement minus the yearly input of solar energy (in the case of a solar boiler) and divided by the efficiency of the tap water system. The gross energy requirement is calculated with the gross energy in the bathroom and sinks divided by the efficiency of the systems.

The primary energy consumption for ventilators is determined by the energy consumption of the ventilator divided by the efficiency of the electricity. The calculation assumes that mechanical ventilators are constantly working.

The primary energy consumption for lighting is determined by multiplying the heated area of the dwelling by a factor of 22 and dividing it by the efficiency of the electricity. The factor 22 is obtained by multiplying the electricity needed for lighting 1 m^2 of the surface (6.0 kWh/m^2/year) by 3.6, which is the conversion from kWh to MJ).

Appendix 2 OTB Survey questionnaire

This appendix contains a condensed version of the questionnaire's survey in the original Dutch and a translation to English. Only the questions relevant to this thesis are presented.

Note: In the original questionnaire, space for answers was given for up to 7 persons and 5 rooms.

HOUSEHOLD CHARACTERISTICS

HOUSEHOLD

We would like to know some facts about your household. Fill in the following table, start with yourself (respondent) and continue with the rest of your family.

1. What is the year of birth and the gender of you and your relatives/housemates?

↓ Mark the persons of your household here	Year of birth	Gender (M/F)
☒ Respondent		
☐ Person 2etc		

Remember the order you gave your family members above, and use this order along the rest of the questionnaire.

2. Was there change in the composition of your household, by e.g. childbirth or living in lodging, in the past year?
   ☐ Yes, explanation:
   ☐ No

MAIN OCCUPATION

3. What is the main occupation of the household members? Mark the category of the main occupation of each family member. Multiple marks per person are possible.

	Main occupation (Tick where appropriate)				
	Works outside the home	Works at home	Household activities	Pupil/Student	Other
☒ Respondent					
☐ Person 2etc					

4. In general, how many hours do you (and your family members) work or study outside the house?

	Hours a week outside work and/or study (excluding travelling time)
☒ Respondent	
☐ Person 2etc	

BACKGROUND

5. Did someone of your household ever lived outside the Netherlands? If so; for how long, and where? If there were multiple periods outside the Netherlands, please add up the total years.

	Lives in the Netherlands since (fill in the year)	Total number of years residential outside the Netherlands	Country (with multiple countries, the country where one lived the longest time)
☒ Respondent			
☐ Person 2etc			

6. Mark the highest level of education programme for every household member, including current education and not completed education.

	None	Elementary school	Low vocational training (LBO/VMBO)	MAVO	HAVO	VWO	Middle vocational training (MBO)	High vocational training (HBO/Bachelor)	University (Masters/WO)	Postgraduate (WO+)	Other, viz:
☒ Respondent											
☐ Person 2etc											

DWELLING CONDITIONS

CURRENT DWELLING

7. In what type of dwelling do you live?
   - ☐ Apartment; Pleas answer this next question →
   - ☐ Maisonette (apartment with two floors); Answer this→
   - ☐ Corner house (house in the corner of the block)
   - ☐ Row house (sharing both walls with other houses)
   - ☐ Semi-detached house (sharing a wall with a house)
   - ☐ Detached house (no houses next to it)

If you are living in an apartment or maisonette, pleas mark in this figure how your dwelling is located.
E.g. At ground floor with neighbours at one side is E, at the top floor with at both sides neighbours is B, and so on.

A ☐	B ☐	A ☐
C ☐	D ☐	C ☐
E ☐	F ☐	E ☐

8. For how many years have you been living in this house?
   - ☐ Less than 1 year
   - ☐ ______ years

9. Do you rent or own your dwelling? And what are the living expenses every month?
   - ☐ Rental home: what is the monthly rent?
     - ☐ Less than € 300,-
     - ☐ Between € 300,- and € 500,-
     - ☐ Between € 500,- and € 700,-
     - ☐ Between € 700,- and € 900,-
     - ☐ More than € 900,-

Rental home: Is water included in the rent?	☐ Yes	☐ No
Rental home: Is heating included in the rent?	☐ Yes	☐ No
Rental home: Is electricity included in the rent?	☐ Yes	☐ No

   - ☐ Owner-occupied home: what is the gross monthly mortgage?
     - ☐ Less than € 300,-
     - ☐ Between € 300,- and € 500,-
     - ☐ Between € 500,- and € 700,-
     - ☐ Between € 700,- and € 900,-
     - ☐ Between € 900,- and € 1100,-
     - ☐ Between € 1100,- and € 1300,-
     - ☐ More than € 1300,-

PREVIOUS DWELLING

10. Before moving to this house, in what type of house you were living? Multiple answers possible, e.g. when you and your partner did not cohabited before the current house.
    - ☐ Apartment
    - ☐ Maisonette (apartment with two floors)
    - ☐ Corner house (house in the corner of the block)
    - ☐ Row house (sharing both walls with other houses)
    - ☐ Semi-detached house (sharing a wall with a house)
    - ☐ Detached house (no houses next to it)

PRESENCE AT HOME

Here we are going to ask about the use of de different rooms in your dwelling. Similar dwellings are being used in different ways by different occupants, and that is why we would like you to fill in the table below, marking how you are using your rooms.

11. Mark how you use your rooms, multiple marks per room are possible.

↓ Here you mark which rooms exist in your dwelling.	Baby's bedroom	Nursery	Bedroom	Hobby room	Study	Guest room	Living room	Storage
☐ Living room								
☐ Attic								
☐ Bedroom 1etc								

Remember the order you gave your rooms, and use this along the rest of the questionnaire. (E.g. did you fill in that Bedroom 2 is used as a study this will be your study along the whole questionnaire)

12. What kind of kitchen do you have?
- ☐ An open kitchen
- ☐ A closed kitchen

Fill in tables 13 and 15 according to the example below; example A:

This respondent leaves home at 8:30 o'clock, takes lunch at home between 12:00 and 14:00, than collects the children of school and arrives with them (persons 3 and 4) at home at 15:30 o'clock. Person 2 leaves every morning at 8:00 and returns home at 18:00. Person 3 leaves home at 8:30 o'clock, and returns at 15:30.

	01:00	*02:00*	*03:00*	*04:00*	*05:00*	*06:00*	*07:00*	*08:00*	*09:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*	*17:00*	*18:00*	*19:00*	*20:00*	*21:00*	*22:00*	*23:00*	*00:00*	*01:00*
☒ *Respondent*	X	X	X	X	X	X	X	/				X	X		/	X	X	X	X	X	X	X	X	X	
☒ *Person 2*	X	X	X	X	X	X	X											X	X	X	X	X	X	X	

Fill in tables 14 and 16 according to the example below; example B:

In general there are 2 persons in the kitchen between 7:00 and 8:00, 1 person is in the bathroom, and 1 in Bedroom 1. In general 3 people have breakfast in the kitchen between 8:00 and 8:30 ... Diner is at 18:00 o'clock with 4 people in the Living room, and one stays here until the children leave for bed at 21:00. Than there are 2 persons in the Living room, and they go to bed at 23:00 o'clock (Bedroom 1).

	01:00	*02:00*	*03:00*	*04:00*	*05:00*	*06:00*	*07:00*	*08:00*	*09:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*	*17:00*	*18:00*	*19:00*	*20:00*	*21:00*	*22:00*	*23:00*	*00:00*	*01:00*
☒ *Living room*												1	1			3	2	4	4	4	2	2			
☒ *(Open) kitchen*							2	3									1								

We would like to know how much family members are at home during the **WINTER** and in which room they generally stay. Please fill this in as accurate as possible at the next page.

Weekdays in the WINTER

13. Mark from when till when your family members are generally at home at **weekdays**, see example A.

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☒ Respondent																									
☐ Person 2etc																									

14. Mark from when till when, and how much, family members stay generally in the specified rooms at **weekdays**, see example B at the previous page.

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Living room																									
☐ (Open) Kitchen																									
☐ Bathroom																									
☐ Attic																									
☐ Bedroom 1etc																									

ENERGY

With these important questions the energy efficiency of your dwelling is being evaluated.

ELECTRICITY

17. Do you have an overview of your consumption of electricity?
☐ No. Please make an estimation as accurate as possible.
☐ Yes; How much electricity (in kWh) did you consume according to this last overview?

☐ Double rate	Low rate (rate or meter 1)	______	kWh
	High rate (rate or meter 2)	______	kWh
☐ Single rate	Electricity:	______	kWh

18. From when till when is the period of this overview? (day/month/year)
From: ___ / ___ / ___ Till: ___ / ___ / ___

19. In the above mentioned period, was there a long time no one at home, e.g. because of holidays?
______ weeks nobody was at home.

20. The company that supplies your electricity is: ______

21. Do you check your use of electricity by taking the meter reading frequently?
☐ No
☐ Yes. Please send copies of this in the return envelope?

22. Do you own solar panels (PV cells for electricity production)?
☐ No
☐ Yes; ______ m^2 PV cells

GAS

23. Do you have an overview of your gas consumption?
☐ No, I do not use gas. Continue with question 28, below.
☐ No. Please make an estimation as accurate as possible.
☐ Yes; How much gas (in m^3) did you consume according to this last overview?
Gas consumption: ______ m^3

24. From when till when is the period of this overview? (day/month/year)
From: ___ / ___ / ___ Till: ___ / ___ / ___

25. The company that supplies your gas is: ______

26. Do you check your consumption of gas by taking the meter reading frequently?
☐ No
☐ Yes; Please send copies of this in the return envelope?

27. Do you own solar collectors (a solar boiler for hot water)?
☐ No
☐ Yes; ______ m^2

HEAT SUPPLY

28. Do you have an overview of your heat supply?
☐ No, I am not connected to heat supply. Continue with question 31, at the next page.
☐ No. Please make an estimation as accurate as possible.

☐ Yes; How much heat was supplied to you according to this last overview?
Heat supply: ______ GJ / kWh (circle the correct unit)

29. From when till when is the period of this overview? (day/month/year)
From: __ / __ / __ Till: __ / __ / __

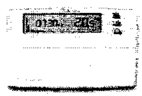
30. The company that supplies your heat is: ______

HEATING

We are interested in the way you use your heating system during the **WINTER** months. Consider a winter day not very warm or cold, in the last winter the temperature was 5°C on an average day.

TEMPERATURE REGULATION

31. Mark how you control the **central** temperature at home:

☐	With radiator taps	
☐	Manual thermostat	
☐	Automatic thermostat	
☐	No thermostat. Continue with question 33, at page 9.	

ADJUST TEMPERATURE

If you are not able to adjust the temperature because you do not have a thermostat, please continue with question 33 at page 9.
We would like to know when you adjust the central thermostat a regular day during the **winter**. See example below.

EXAMPLE*: When they get up out of bed at 7:00 the thermostat is set at 20°C, when they leave home it is adjusted to 15 degrees at 8:30. About 13:00 o'clock the thermostat is set again at 20°C, and at 22:00 it is adjusted to 15. This happens every weekday, except at Fridays.*
In the weekend the thermostat will be set at 20°C an hour later, and at 22:00 again adjusted to 15°C.

	01:00	*02:00*	*03:00*	*04:00*	*05:00*	*06:00*	*07:00*	*08:00*	*09:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*	*17:00*	*18:00*	*19:00*	*20:00*	*21:00*	*22:00*	*23:00*	*00:00*	*01:00*	*Same as previous day*
Monday	*15*	*15*	*15*	*15*	*15*	*15*	***20***	***20***	*15*	*15*	*15*	*15*	***20***	***20***	***20***	***20***	***20***	***20***	***20***	***20***	***20***	*15*	*15*	*15*	*15*	☐

32. Fill in how and when the thermostat in your house is adjusted:

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	Same as previous day
Monday																										☐
Tuesday / etc																										☐

RADIATOR USE

33. What settings are available at your radiators? (e.g. 0/1/2/3/4/5, of on/of)
______

Weekdays
We would like to know when you turn on/of your radiators in different rooms on **weekdays**. At general when is the radiator turned on in the specified room? Use the settings as given in the previous question (nr. 33). For the settings on/of, write ++ for 'on', and write 0 for 'of'. If your radiators do not have any indications than write down ++ for open (turned on), + for half open, and 0 for closed (turned of).

34. Where and when do you turn on the radiator(s) on **weekdays**?

	Radiator(s) present	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Living room																										
☐ (Open) Kitchen																										
☐ Bathroom																										
☐ Attic																										
☐ Bedroom 1 etc																										
☐ Entrance																										

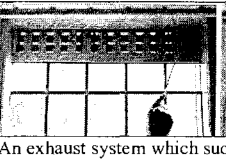
VENTILATION

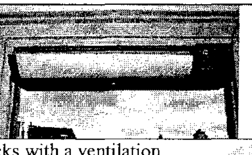
Ventilation at home occurs by windows, grilles and ventilators. With ventilators one speaks of mechanical ventilation. There are two kinds of mechanical ventilation: With balance ventilation both input and output of the air occur mechanical. If only the output/exhaust of air is mechanical one speaks of mechanical exhaust ventilation, with this the input of air occurs by natural way (e.g. grids). Natural ventilation is possible by means of windows or grids.

37. Mark what kind of ventilation is present at your **current dwelling**. Multiple marks are possible.

☐ Windows without grilles

☐ Grilles



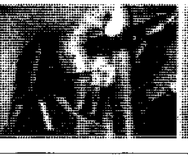


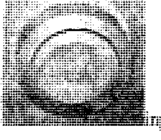
☐ Mechanical exhaust ventilation

An exhaust system which sucks with a ventilation motor via air pipes and exhaust valves air out of the kitchen, the bathroom and the toilet. Most of the times there are grids in the windows. The device as shown under 'balance ventilation' is NOT present.

exhaust valve

☐ Balance ventilation





input valve

Sometimes hidden in a closet:

☐ I don't know

38. What kind of ventilation was present in your **previous dwelling**?
☐ Windows without grilles
☐ Grilles
☐ Natural pipes in kitchen and sanitary rooms
☐ Bathroom ventilator (possible connection with lightning)
☐ Mechanical exhaust ventilation
☐ Balance ventilation
☐ Other, viz: ____
☐ I don't know

Now will follow some questions about the use of the windows during the winter (average temperature of about 5 °C, not to much wind, no rain, no snow). Where and when do you open and close your windows on an average day during the **WINTER**?

If you use doors for ventilation (like doors to the garden or balcony) please consider these doors as windows.

41. Where and when do you open your windows in the **WINTER**? Mark with a cross if the windows are open.

		01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Living room																										
☐ (Open) Kitchen																										
☐ Bathroom																										
☐ Attic																										
☐ Bedroom 1 etc																										
☐ Entrance																										

43. If there is nobody at home, does this change the number of windows opened during the **WINTER**?
- ☐ Yes, I will close all windows
- ☐ Yes, I will close some windows
- ☐ Yes, I will open some windows
- ☐ No, it stays the same

44. If the heating is turned on, does this change the number of windows opened?
- ☐ Yes, I will close all windows
- ☐ Yes, I will close some windows
- ☐ Yes, I will open some windows
- ☐ No, it stays the same

45. Does weather circumstances (snow, rain, wind) change the number of windows opened?
- ☐ Yes, I will close all windows
- ☐ Yes, I will close some windows
- ☐ Yes, I will open some windows
- ☐ No, it stays the same

GRILLES

Now some questions about the use of grilles (attached to windows) will follow.
If you do not own these kinds of ventilation grilles, please continue with question 54, page 15.

50. Why do you open the grilles? Multiple marks possible.
- ☐ To get fresh air
- ☐ Cooling down (adjust temperature)
- ☐ To remove condensation
- ☐ To dissipate dirty air (e.g. smoke, cooking smells)
- ☐ Other reason, viz: ______________

51. Why do you close the grilles? Multiple marks possible.
- ☐ Against draft
- ☐ Against the cold (adjust temperature)
- ☐ To block sounds from outside
- ☐ Because of the sounds of the grid
- ☐ To block smells from outside
- ☐ Because of the smells of the grid
- ☐ For safety reasons
- ☐ Other reason, viz: ______________

52. Where and when do you open the grilles at a normal day during the **WINTER**? Consider last winter (average temperature of 5 °C, not much wind, no rain, no snow).
Mark with a cross when the grilles are open.

	Number of grids in room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Living room																										
☐ (Open) Kitchen																										
☐ Bathroom																										
☐ Attic																										
☐ Bedroom 1 etc																										
☐ Entrance																										

MECHANICAL VENTILATION (exhausts ventilation and balance ventilation)

Do you not own mechanical ventilation, or is it impossible for you to adjust this, please continue with question 62, at page 17.

54. Why do you turn up your ventilation system? Multiple marks possible.
☐ To get fresh air
☐ Cooling down (adjust temperature)
☐ To remove condensation
☐ To dissipate dirty air (e.g. smoke, cooking smells)
☐ Other reason, viz: ________

55. Why do you turn down your ventilation system? Multiple marks possible.
☐ Because of the sounds of the system
☐ Because of the smells of the system
☐ Other reason, viz: ________

We would like to know in what way you use the mechanical ventilation during the WINTER (consider last winter, with an average temperature of 5 °C, not to much wind, no rain, no snow). With this question think about what you did last winter with the mechanical ventilation system while you were cooking diner, went to be, get up in the morning, and so on.

59. Fill in at what time, and to what setting, you adjusted the ventilation in the **WINTER** in the table below. (With settings like 'high' and 'low' use the first letters; H and L):

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
Settings on weekdays																									
Settings on weekends																									

(possible) comments: ________

HOUSEHOLD APPLIANCES

We would like to know more about the use of appliances. This is important to know because some appliances will heat up during use, and with that it influences the temperature in your dwelling.

APPLIANCES INVENTORY

62. Mark which and how much of the following appliances is present at your home, and how many hours a day **OR** a week these appliances are turned on. Count the total amount of hours. ***E.g.**: you have two TV's, one is turned on 21 hours a week, the other 3 hours a week, totally this is 24 hours a week.*

Appliance	Number	Minutes a day turned on (total)	Hours a week turned on (total)	Mark if this appliance is used in the living room/open kitchen.
Television set				
Computer monitor				
Computer and/or laptop				

Video game console				
Stereo and/or radio				
Home Cinema set				
Wireless internet				
DVD player				
Wireless home phone				
Dishwasher				
Washing machine				
Drier				

CHARGERS

63. How many appliances with chargers or batteries do you charge regularly at home? Consider mobile phones, cameras, laptops, loose batteries, and so on.
I own ____ appliances with chargers, and in total I charge ____ hours a week appliances with chargers. Count all the hours of all the chargers together!

HOUSEHOLD APPLIANCES
Of some of the household appliances there is more information needed.

66. If you own a **dishwasher**, what is its energy label? ____
What is the content in covers of your dishwasher? ____
And how often do you use your dishwasher every week? ____ times a week.

67. If you own a **washing machine**, what is its energy label? ____
And how often do you do your laundry every week? ____ washings a week.
At what temperature you usually do your laundry?

	Number of washings a week
cold	
30°C	
40°C	
50°C	
60°C	
90°C	

68. If you own a **drier**, what is its energy label? ____
And how often do you dry a load every week? ____ loads a week.
How much time (in minutes) does it take in general before your clothing is dry?
(on average for one drying load) ____ minutes.

LIGHTING

69. How much low-energy light bulbs are being used in your living room?
____ low-energy light bulb in the living room

70. How much normal light bulbs or halogen lights are being used in your living room?
____ normal or halogen light bulbs in the living room

71. How much electronic/electric appliances are in stand-by in the living room?
____ appliances in stand-by in the living room

SANITARY

SHOWER AND BATH

72. How many showers and baths are present in your house?
____ shower(s)
____ bath(s)

SHOWER

73. Write down per person how many showers are taken in your house and how much time these showers take approximately:

	Number of showers taken a week	Number of minutes a shower takes
☒ Respondent		
☐ Person 2 etc		

BATH

74. Write down per person how many baths one takes a week:

	Number of baths taken a week
☒ Respondent	
☐ Person 2 etc	

OTHER

PETS

The keeping of pets can correlate with the ventilation needs and the temperature at a dwelling.

75. If you own pets, how many and what kind of pet(s) do you own? And where are these pets in general accommodated? Multiple answers are possible.

		Accommodation		
	Number	Inside, whole house	Inside, part of the house	Outside
Dog				
Cat				
Other, viz:				

SMOKING

77. Does someone smoke in the household?

☐ Yes, namely: ______ (fill in which one, respondent/person…)
☐ No

78. Does someone in your household smoke inside the house?

☐ Yes; What and how much?
- ____ cigarettes a day.
- ____ cigars a day.
- ____ pipe a day.
- ____ a day other smoking materials, namely: ______

☐ No

HEALTH

79. How is your health and that of your family members?
Mark how everyone is doing in general.

	Very good	Good	Mediocre	Bad	I don't know
☒ Respondent					
☐ Person 2 etc					

80a. Mark if someone has one of the following complaints in the last year:
Mark if this complaint is decreasing considerable during long stays outside the house, like when one is on holidays.

	Allergies (pets, dust)	Stuffed up or runny nose	Common cold	Wheezy breathing	Tightness of the chest	Shortness of breath	Asthma-attacks	Hay fever	Sore throat	Weary or runny eyes
☒ Respondent										
☐ Person 2 etc										

INCOME

If we know your income we might make a correlation between income and energy consumption.

81. What is the total gross income of your **whole** household per year?

☐ Minimum;	less than € 9500,-
☐ Below average;	between € 9500,- and € 28500,-
☐ Average;	between € 28500,- and € 34000,-
☐ Between 1 and 2 times average;	between € 34000,- and € 56000,-
☐ 2 times average or more;	more than € 56000,-

GEGEVENS HUISHOUDEN

HUISHOUDEN

We willen graag de samenstelling van uw huishouden weten. Vul onderstaande tabel in, begin met uzelf (respondent) en ga door met de rest van uw gezin.

1. Wat is het geboortejaar en geslacht van de bewoners van het huis?

↓ Kruis hier alle personen in uw huishouden aan	Geboortejaar	Geslacht (M/V)
☒ Respondent		
☐ Persoon 2		

Onthoud bovenstaande volgorde die u uw gezinsleden heeft gegeven en gebruik dezelfde volgorde in de rest van de vragenlijst.

2. Was er het afgelopen jaar verandering in de samenstelling van uw huishouden, bv door geboorte of een kind dat op kamers is gaan wonen?
☐ Ja, uitleg:
☐ Nee

BELANGRIJKSTE BEZIGHEID

3. Waar zijn de leden van het huishouden voornamelijk mee bezig? Kruis aan in welke categorie de belangrijkste bezigheid van elk gezinslid valt. Meerdere kruisjes per persoon zijn mogelijk.

	Belangrijkste bezigheid (aankruisen)				
	Werkt buitenshuis	Thuiswerk	Huishouden	Scholier/ Student	Anders
☒ Respondent					
☐ Persoon 2					

4. Hoeveel uur per week werkt of studeert u (en uw gezinsleden) over het algemeen buitenshuis?

	Uren per week buitenshuis werken en/of studeren (exclusief reistijd)
☒ Respondent	
☐ Persoon 2	

ACHTERGROND

5. Heeft er iemand van uw huishouden buiten Nederland gewoond? Zo ja; voor hoe lang, en waar? Tel het totaal aantal jaren op bij meerdere periodes buiten Nederland woonachtig.

	Woont in Nederland sinds (vul jaartal in)	Totaal aantal jaren buiten Nederland gewoond	Land (bij meerdere landen, het land waar men het langst woonde)
☒ Respondent			
☐ Persoon 2			

6. Kruis aan wat de hoogst genoten opleiding van iedereen in uw huishouden is, inclusief huidige opleiding en niet afgemaakte opleiding.

	geen	Lager onderwijs	Lager beroepsonderwijs (LBO/VMBO)	MAVO	HAVO	VWO	Middelbaar beroepsonderwijs (MBO)	Hoger beroepsonderwijs (HBO/Bachelor)	Universitair (Masters/WO)	Postdoctoraal (WO+)	Anders, nl:
☒ Respondent											
☐ Persoon 2											

WOONOMSTANDIGHEDEN

HUIDIGE WONING

7. In wat voor soort huis woont u?
   - ☐ Appartement; Vul de vraag hiernaast in →
   - ☐ Maisonnette (appartement met twee woonlagen); →
   - ☐ Hoekhuis (huis op de hoek van een rij)
   - ☐ Rijtjeshuis (aan beide kanten muren delen met andere huizen)
   - ☐ Twee onder één kap woning (met een ander huis een muur delen)
   - ☐ Vrijstaand huis (geen huizen direct tegen huis aan)

Wanneer u in een appartement of maisonnette woont, kruis in de figuur hieronder aan hoe uw huis is gesitueerd.
Bijv. op begane grond aan één kant buren is E, op de bovenste verdieping aan beide kanten buren is B, etc.

A ☐	B ☐	A ☐
C ☐	D ☐	C ☐
E ☐	F ☐	E ☐

8. Hoe lang woont u in deze woning?
   - ☐ Minder dan 1 jaar
   - ☐ ____ jaar

9. Huurt of koopt u de woning? En wat zijn de woonlasten per maand?

☐ Huurwoning: wat betaalt u aan huur?
- ☐ Minder dan € 300,-
- ☐ Tussen € 300,- en € 500,-
- ☐ Tussen € 500,- en € 700,-
- ☐ Tussen € 700,- en € 900,-
- ☐ Meer dan € 900,-

Huurwoning: Is water inbegrepen in de huur?	☐ Ja	☐ Nee
Huurwoning: Zit verwarming in de huur?	☐ Ja	☐ Nee
Huurwoning: Zit elektriciteit in de huur?	☐ Ja	☐ Nee

☐ Koopwoning: wat is de bruto hypotheek?
- ☐ Minder dan € 300,-
- ☐ Tussen € 300,- en € 500,-
- ☐ Tussen € 500,- en € 700,-
- ☐ Tussen € 700,- en € 900,-
- ☐ Tussen € 900,- en € 1100,-
- ☐ Tussen € 1100,- en € 1300,-
- ☐ Meer dan € 1300,-

VORIGE WONING

10. In wat voor type huis woonde u voordat u hier kwam wonen? Meerdere antwoorden mogelijk, bv wanneer u en uw partner hiervoor niet samenwoonden.
    - ☐ Appartement
    - ☐ Maisonnette (appartement met twee woonlagen)
    - ☐ Hoekhuis (huis op de hoek van een rij)
    - ☐ Rijtjeshuis (aan beide kanten muren delen met andere huizen)
    - ☐ Twee onder één kap woning (met een ander huis een muur delen)
    - ☐ Vrijstaand huis (geen huizen direct tegen huis aan)

AANWEZIGHEID IN HUIS

Hier wordt gevraagd naar het gebruik van de verschillende ruimtes in uw woning. Soortgelijke woningen worden op verschillende manieren gebruikt door verschillende bewoners, en daarom willen we graag dat u aangeeft hoe u de kamers gebruikt in onderstaande tabel.

11. Kruis aan hoe u uw kamers gebruikt. Meerdere kruisjes per kamer zijn mogelijk.

Kruis hier aan welke kamers in uw huis aanwezig zijn.	Babykamer	Kinderkamer	Slaapkamer	Hobby kamer	Werkkamer	Logeerkamer	Woonkamer	Opslagruimte
☐ Woonkamer								
☐ Zolder								
☐ Slaapkamer 1								

Onthoud bovenstaande volgorde bij het invullen van de rest van de vragenlijst. (Heeft u bv ingevuld dat Slaapkamer 2 de werkkamer is, dan zal dit in rest van de vragenlijst altijd de werkkamer zijn.)

12. Wat voor ecn keuken heeft u?
☐ Een open keuken
☐ Een gesloten keuken

Vul tabellen 13 en 15 in volgens onderstaand voorbeeld; voorbeeld A:
Onderstaande respondent gaat om 8:30 van huis, luncht thuis tussen 12:00 en 14:00, haalt vervolgens de kinderen van school en komt om 15:30 thuis met de kinderen (personen 3 en 4). Persoon 2 vertrekt om 8:00 van huis en komt om 18:00 weer thuis. Persoon 3 gaat om 8:30 van huis en komt om 15:30 thuis.

	01:00	*02:00*	*03:00*	*04:00*	*05:00*	*06:00*	*07:00*	*08:00*	*09:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*	*17:00*	*18:00*	*19:00*	*20:00*	*21:00*	*22:00*	*23:00*	*00:00*	*01:00*
☒ *Respondent*		X	X	X	X	X	X	X	/				X	X		/	X	X	X	X	X	X	X	X	X
☒ *Persoon 2*		X	X	X	X	X	X	X											X	X	X	X	X	X	X

Vul tabellen 14en 16 in volgens onderstaand voorbeeld; voorbeeld B:
Tussen 7:00 en 8:00 zijn er meestal 2 mensen in de keuken, 1 persoon in de badkamer, en 1 in Slaapkamer 1. Tussen 8:00 en 8:30 eten 3 mensen ontbijt in de keuken ... Men eet om 18:00 met 4 mensen in de woonkamer, en men blijft hier totdat om 21:00 de kinderen naar bed gaan. Dan verblijven er 2 mensen in de woonkamer, en zij gaan om 23:00 uur naar bed (Slaapkamer 1).

	01:00	*02:00*	*03:00*	*04:00*	*05:00*	*06:00*	*07:00*	*08:00*	*09:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*	*17:00*	*18:00*	*19:00*	*20:00*	*21:00*	*22:00*	*23:00*	*00:00*	*01:00*
☒ *Woonkamer*													1	1			3	2	4	4	4	2	2		
☒ *(Open) keuken*								2	3									1							

We willen graag weten hoeveel personen gebruikelijk thuis zijn in de **WINTER** en in welke ruimte zij dan meestal verblijven. Vul dit zo goed mogelijk in op de volgende bladzijde.
Doordeweeks in de WINTER

13. Geef aan van wanneer tot wanneer uw familie thuis is op **doordeweekse dagen**, zie voorbeeld A.

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☒ Respondent																									
☐ Persoon 2																									

14. Geef aan wanneer, en hoeveel personen, in de aangegeven kamers verblijven op **doordeweekse dagen**, zie voorbeeld B op de vorige pagina.

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00

☐ Woonkamer	
☐ (Open) Keuken	
☐ Badkamer	
☐ Zolder	
☐ Slaapkamer 1	

ENERGIE

Dit zijn belangrijke vragen omdat hiermee de energie efficiëntie van de woning wordt geëvalueerd.

ELEKTRICITEIT

17. Heeft u een overzicht van uw elektriciteitsverbruik?
☐ Nee. Geef hieronder een zo goed mogelijke schatting.
☐ Ja; Hoeveel elektriciteit (in kWh) heeft u gebruikt volgens uw laatste overzicht?

☐ Dubbeltarief	Laagtarief (tarief of meter 1)	______	kWh
	Hoogtarief (tarief of meter 2)	______	kWh
☐ Enkeltarief	Elektriciteit:	______	kWh

18. Van wanneer tot wanneer was de periode van dit overzicht? (dag/maand/jaar)
Van: ___ / ___ / ___ Tot: ___ / ___ / ___

19. Hoe lang is er in bovenstaande periode niemand in huis geweest, bv vanwege vakantie?
______ weken was er niemand in huis.

20. Het bedrijf dat elektriciteit bij u levert is: ______

21. Controleert u zelf uw elektriciteitsgebruik door regelmatig de meterstanden bij te houden?
☐ Nee
☐ Ja. Kunt u hier kopieën van meesturen in de retourenveloppe?

22. Heeft u zonnepanelen (PV cellenvoor elektriciteitsproductie)?
☐ Nee
☐ Ja; ______ m^2 PV cellen

GAS

23. Heeft u een overzicht van uw gasverbruik?
☐ Nee, ik gebruik geen gas. Ga door naar vraag 28, hieronder.
☐ Nee. Geef hieronder een zo goed mogelijke schatting.
☐ Ja; Hoeveel gas (in m^3) heeft u gebruikt volgens uw laatste overzicht?
Gasgebruik: ______ m^3

24. Van wanneer tot wanneer was de periode van dit overzicht? (dag/maand/jaar)
Van: ___ / ___ / ___ Tot: ___ / ___ / ___

25. Het bedrijf dat gas bij u levert is: ______

26. Controleert u zelf uw gasgebruik door regelmatig de meterstanden bij te houden?
☐ Nee
☐ Ja; Kunt u hier kopieën van meesturen in de retourenveloppe?

27. Heeft u zonnecollectoren (een zonneboiler voor warm water)?
☐ Nee
☐ Ja; ______ m^2

WARMTE LEVERING

28. Heeft u een overzicht van uw warmtelevering?
☐ Nee, ik ben niet aangesloten op warmtelevering. Ga door naar vraag 31, op de volgende pagina.
☐ Nee. Geef hieronder een zo goed mogelijke schatting.
☐ Ja; Hoeveel warmte heeft u gebruikt volgens uw laatste overzicht?
Verwarminggebruik: ______ GJ / kWh (omcirkel de eenheid)

29. Van wanneer tot wanneer was de periode van dit overzicht? (dag/maand/jaar)
Van: ___ / ___ / ___ Tot: ___ / ___ / ___

30. Het bedrijf dat warmte bij u levert is: ___

VERWARMING

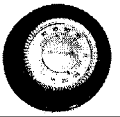
We zijn geïnteresseerd in de manier waarop u uw verwarmingsysteem gebruik tijdens de **WINTER** maanden. Denk aan een winterdag die niet heel warm of heel koud is, bijvoorbeeld in de laatste winter was het gemiddeld 5°C.

TEMPERATUUR REGELING

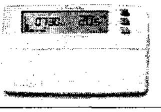
31. Kruis hieronder aan hoe u de **centrale** temperatuur in huis regelt:

☐ Met radiatorkranen

☐ Handmatige thermostaat



☐ Automatische thermostaat



☐ Geen thermostaat. Ga naar vraag 33, op pagina 9.

INSTELLEN TEMPERATUUR

Als u de temperatuur niet kunt instellen omdat u geen thermostaat heeft, ga dan naar vraag 33 op pagina 9.

We willen graag weten wanneer u de centrale thermostaat hoger en lager zet op een gebruikelijke dag in de **winter**. Zie hieronder een voorbeeld.

***VOORBEELD**: Wanneer men om 7:00 uur op staat wordt de thermostaat op 20°C gezet, dan gaat deze op 15 graden als men om 8:30 van huis gaat. Rond 13:00 uur stelt men de temperatuur weer in op 20°C. Om 22:00 uur gaat de thermostaat op 15 graden. Dit gaat zo elke doordeweekse dag, behalve vrijdag.*
In het weekend gaat de thermostaat een uur later op 20°C, en wordt om 22:00 uur weer op 15°C gezet.

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	*Zelfde als vorige dag*
Maandag	15	15	15	15	15	15	20	20	15	15	15	15	20	20	20	20	20	20	20	20	20	15	15	15	15	☐

32. Vul hieronder in hoe bij u de thermostaat wordt ingesteld:

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	Zelfde als vorige dag
Maandag																										☐
Dinsdag																										☐

RADIATOR GEBRUIK

33. Op welke standen kunt u uw radiatoren instellen? (bv 0/1/2/3/4/5, of aan/uit)
___

We willen graag weten wanneer u de radiatoren aan en uit zet in de verschillende ruimtes op **doordeweekse dagen**. Wanneer is de radiator gebruikelijk aan in de gegeven ruimtes? Gebruik de aanduiding zoals opgegeven in de vorige vraag (nr. 33). Gebruik bij standen aan/uit de aanduidingen ++ voor aan en 0 voor uit. Indien uw radiatoren geen aanduidingen hebben noteer dan ++ voor open, + voor halfopen en 0 voor dicht.

34. Waar en wanneer zet u de radiator(en) op **doordeweekse** dagen aan?

	Radiator(en) aanwezig	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Woonkamer																										
☐ (Open) Keuken																										
☐ Badkamer																										
☐ Zolder																										
☐ Slaapkamer 1																										
☐ Entree																										

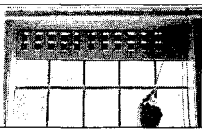
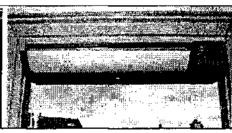
VENTILATIE

Ventilatie in huis vindt plaats via ramen, roosters en ventilatoren. Bij ventilatoren spreekt men over mechanische ventilatie. Er bestaan twee soorten mechanische ventilatie: Bij balansventilatie gebeurt zowel de toevoer als de afvoer van lucht mechanisch. Wanneer alleen de afvoer van lucht mechanisch gebeurt, spreekt men van mechanische afvoerventilatie, hierbij wordt via een natuurlijke weg (bv een rooster) lucht toegevoerd. Natuurlijke ventilatie kan door middel van ramen of roosters.

37. Kruis hieronder aan wat voor soort ventilatie in uw **huidige woning** aanwezig is. Meerdere antwoorden zijn mogelijk.

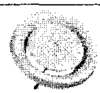
☐ Ramen zonder roosters

☐ Roosters

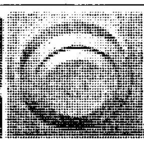
☐ Mechanische afvoerventilatie

Een afzuigsysteem zuigt met een ventilatormotor via luchtkanalen en afzuigventielen lucht weg uit de keuken, de badkamer en het toilet. Er zitten meestal roosters in de ramen. Het apparaat zoals onder 'balansventilatie' is dan NIET aanwezig.



afzuigventiel

☐ Balansventilatie

nblaasventiel

Soms verstopt in een kast:

☐ Weet ik niet

38. Wat voor soort ventilatie was in uw **vorige woning** aanwezig?
☐ Ramen zonder roosters
☐ Roosters
☐ Natuurlijk werkende kanalen in keuken en sanitairruimtes
☐ Badkamerventilator (evt. schakeling met verlichting)
☐ Mechanische afvoerventilatie
☐ Balansventilatie
☐ Anders, nl:
☐ Weet ik niet

RAMEN

39. Waarvoor opent u meestal de ramen? (Meerdere antwoorden mogelijk).
☐ Voor de frisse lucht

☐ Verkoeling (temperatuur regelen)
☐ Om condensatie te verwijderen
☐ Om vieze lucht (bv. rook, kookluchten) te verdrijven
☐ Andere reden, nl:

40. Waarvoor sluit u meestal de ramen? (Meerdere antwoorden mogelijk).
☐ Tegen de tocht
☐ Tegen de kou (temperatuur regelen)
☐ Om geluid van buiten tegen te houden
☐ Om vieze lucht van buiten tegen te houden
☐ Om veiligheidsredenen
☐ Andere reden, nl:

Nu volgen er vragen over het gebruik van ramen in de winter (gemiddelde temperatuur van ongeveer 5 °C, niet veel wind, geen regen, geen sneeuw). Waar en wanneer zet u de ramen open (en dicht) op een gemiddelde **WINTER** dag?

Als u voor ventilatie deuren gebruikt (zoals tuindeuren, of balkondeuren) beschouw deze dan als ramen.

41. Waar en wanneer zet u de ramen open in de **WINTER**? Zet een kruis wanneer de ramen open zijn.

		01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Woonkamer																										
☐ (Open) Keuken																										
☐ Badkamer																										
☐ Zolder																										
☐ Slaapkamer 1																										
☐ Entree																										

42. Als de ramen open staan, hoe staan de ramen normaal gesproken open in de **WINTER**?

	Aantal ramen in kamer	Aantal ramen open	Aantal ramen op een kier
☐ Woonkamer			
☐ (Open) Keuken			
☐ Badkamer			
☐ Zolder			
☐ Slaapkamer 1			
☐ Entree			

43. Als er niemand thuis is, verandert dat het aantal open ramen in de **WINTER**?
☐ Ja, ik doe alle ramen dicht
☐ Ja, ik doe een paar ramen dicht
☐ Ja, ik doe een paar ramen extra open
☐ Nee, het blijft gelijk

44. Als de verwarming aan is, verandert dan het aantal open ramen?
☐ Ja, ik doe alle ramen dicht
☐ Ja, ik doe een paar ramen dicht
☐ Ja, ik doe een paar ramen extra open
☐ Nee, het blijft gelijk

45. Verandert het aantal open ramen bij andere weersomstandigheden (sneeuw, regen, wind)?
☐ Ja, ik doe alle ramen dicht
☐ Ja, ik doe een paar ramen dicht
☐ Ja, ik doe een paar ramen extra open
☐ Nee, het blijft gelijk

ROOSTERS
Nu volgen er vragen over het gebruik van de roosters aan het raam.

Als u niet van soortgelijke ventilatieroosters in huis heeft, ga dan naar vraag 54, op pagina 15.

50. Waarvoor opent u de roosters? Meerdere antwoorden mogelijk.
- ☐ Voor de frisse lucht
- ☐ Verkoeling (temperatuur regelen)
- ☐ Om condensatie te verwijderen
- ☐ Om vieze lucht (bv. rook, kookluchten) te verdrijven
- ☐ Andere reden, nl: ______

51. Waarvoor sluit u de roosters? Meerdere antwoorden mogelijk.
- ☐ Tegen de tocht
- ☐ Tegen de kou (temperatuur regelen)
- ☐ Om geluid van buiten tegen te houden
- ☐ Vanwege het geluid van het rooster
- ☐ Om vieze lucht van buiten tegen te houden
- ☐ Vanwege de vieze lucht van het rooster
- ☐ Veiligheid
- ☐ Andere reden, nl: ______

52. Waar en wanneer zet u de roosters open op een reguliere **WINTER** dag? Denk hierbij aan de laatste winter (gemiddelde temperatuur van 5 °C, niet veel wind, geen regen, geen sneeuw).
Zet een kruis wanneer de roosters open zijn.

	Aantal roosters in kamer	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
☐ Woonkamer																										
☐ (Open) Keuken																										
☐ Badkamer																										
☐ Zolder																										
☐ Slaapkamer 1																										
☐ Entree																										

MECHANISCHE VENTILATIE (afvoerventilatie en balansventilatie)

Heeft u geen mechanische ventilatie, of kunt u deze niet instellen, ga dan naar vraag 62, op pag. 17.

54. Waarvoor zet u het ventilatiesysteem hoger? Meerdere antwoorden mogelijk.
- ☐ Voor de frisse lucht
- ☐ Verkoeling (temperatuur regelen)
- ☐ Om condensatie te verwijderen
- ☐ Om vieze lucht (bv. rook, kookluchten) te verdrijven
- ☐ Andere reden, nl: ______

55. Waarvoor zet u het ventilatiesysteem lager? Meerdere antwoorden mogelijk.
- ☐ Vanwege het geluid van het systeem
- ☐ Vanwege vieze lucht van het systeem
- ☐ Andere reden, nl: ______

56. Hoeveel standen heeft uw systeem? (bv 2 standen, of 3 standen) ______

57. Welke aanduiding heeft uw systeem? (bv 0/1, of 1/2/3, of hoog/laag) ______

58. Trekt u wel eens de stekker uit het systeem?
- ☐ Ja, namelijk ______ dagen per jaar
- ☐ Nee

We willen graag weten op welke manier u de mechanische ventilatie gebruikt tijdens de WINTER (denk aan vorige winter, met een gemiddelde temperatuur van 5 °C, niet veel wind, geen regen, geen sneeuw). Denk bij het antwoorden van deze vraag aan wat u afgelopen winter deed met de mechanische ventilatie wanneer u eten kookte, naar bed ging, weer opstond, etc.

59. Vul in onderstaande tabel in op welke tijd, en naar welke stand, u de ventilatie in de **WINTER** instelt. (Gebruik bij standen zoals 'hoog' en 'laag' alleen de eerste letters; H en L):

	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00
Stand doordeweeks																									
Stand in het weekend																									

Evt. opmerkingen:

HUISHOUDELIJKE APPARATEN

We willen graag meer weten over het gebruik van apparaten. Dit is belangrijk om te weten omdat sommige apparaten warm worden en daarmee de temperatuur in uw huis beïnvloeden.

APPARATEN INVENTARIS

62. Geef hieronder aan welke van de volgende apparaten u heeft, hoeveel u er heeft, en hoeveel uur per dag **OF** per week deze apparaten totaal aan staan. Tel hierbij de uren op. ***BV:*** *u heeft twee televisies, de ene staat 21 uur per week aan, de ander 3 uur per week, dan komt het totaal op 24 uur per week.*

Apparaat	Aantal	Minuten per dag aan (totaal)	Uren per week aan (totaal)	Kruis aan of dit apparaat in woonkamer/open keuken wordt gebruikt.
Televisie				
Computer monitor				
Computer en/of laptop				
Video game console				
Stereo en/of radio				
Home Cinema set				
Draadloos internet				
DVD speler				
Draadloze huis telefoon				
Vaatwasser				
Wasmachine				
Droger				

OPLADERS

63. Hoeveel apparaten met accu of batterij laadt u regelmatig thuis op? Denk hierbij aan mobiele telefoons, camera's, laptops, losse batterijen, etc.
Ik heb ___ apparaten met accu's, en totaal laad ik ___ uur per week apparaten met accu's op. Tel alle uren van alle opladers bij elkaar op!

HUISHOUDELIJKE APPARATEN

Van een aantal huishoudelijke apparaten is meer informatie nodig.

66. Indien u een **vaatwasser** heeft, wat is het energielabel hiervan? ___
En hoe vaak gebruikt u uw vaatwasser per week? ___ keer per week.

67. Indien u een **wasmachine** heeft, wat is het energielabel? ___
En hoeveel ladingen wast u met uw wasmachine per week? ___ wassen per week.
Op welke temperatuur wast u meestal?

	Aantal wasbeurten per week
koud	
30°C	
40°C	
50°C	
60°C	

90°C	

68. Indien u een **droger** heeft, wat is het energielabel hiervan?
En hoeveel ladingen droogt u met uw droger per week? ladingen per week.
Hoeveel tijd (in minuten) kost het normaal gesproken voor uw kleding droog is?
(gemiddeld voor één droogbeurt) minuten.

VERLICHTING

69. Hoeveel spaarlampen of tl-buizen worden er in de woonkamer gebruikt?
spaarlampen in de woonkamer

70. Hoeveel normale gloeilampen of halogeen lampen worden in de woonkamer gebruikt?
gloeilampen/halogeen lampen in de woonkamer

71. Hoeveel elektronische/elektrische apparaten staan er stand-by in de woonkamer?
apparaten op stand-by in de woonkamer

SANITAIR

DOUCHE EN BAD

72. Hoeveel douches en baden zijn aanwezig in uw huis?
douche(s)
bad(en)

DOUCHE

73. Noteer hieronder per persoon hoeveel douches er in uw huis worden genomen per week, en hoe lang deze douchebeurten ongeveer duren:

	Aantal douches per week	Aantal minuten per douche
☒ Respondent		
☐ Persoon 2		

BAD

74. Noteer hieronder per persoon noteren hoe vaak men per week een bad neemt:

	Aantal badbeurten per week
☒ Respondent	
☐ Persoon 2	

OVERIG

HUISDIEREN

Het bezitten van huisdieren kan een relatie hebben met de ventilatiebehoefte en de temperatuur in huis.

75. Indien u huisdieren heeft, hoeveel en wat voor huisdier(en) heeft u? En waar verblijven deze dieren meestal? Meerdere antwoorden zijn mogelijk.

		Verblijfplaats		
	Aantal	Binnenshuis, het hele huis door	Binnen, maar in een bepaald deel	Buitenshuis
Hond				
Kat				
Anders, nl:				

ROKEN

77. Rookt er iemand uit uw huishouden?
☐ Ja, namelijk: (vul in welke persoon, respondent/persoon…)
☐ Nee

sigaretten per dag.
sigaren per dag.
pijp per dag.
per dag aan andere rookwaren, namelijk:

☐ Nee

GEZONDHEID

79. Hoe is het met de gezondheid van u en uw gezin gesteld?
Kruis aan hoe het over het algemeen met alle gezinsleden van het huishouden is.

	Zeer goed	Goed	Middelmatig	Slecht	Weet niet
☒ Respondent					
☐ Persoon 2					

80a.Kruis aan of er iemand in huis het laatste jaar de volgende klachten heeft gehad:
Geef daarbij ook aan of de klachten afnemen tijdens langdurig verblijf buitenshuis, zoals bijvoorbeeld tijdens een vakantie.

	Allergie (dieren, stof)	Verstopte neus of loopneus	Verkoudheid	Een piepende ademhaling	Benauwdheid	Kortademigheid	Astma-aanvallen	Hooikoorts	Keelpijn	Vermoeide of tranende ogen
☒ Respondent										
☐ Persoon 2										

INKOMEN

Wanneer wij uw inkomen weten kunnen wij misschien een relatie leggen tussen inkomen en energieconsumptie.

81. Wat is het totale bruto inkomen van uw **totale** huishouden per jaar?

☐ Minimum;	minder dan € 9500,-
☐ Beneden modaal;	tussen € 9500,- en € 28500,-
☐ Modaal;	tussen € 28500,- en € 34000,-
☐ Tussen 1 en 2 keer modaal;	tussen € 34000,- en € 56000,-
☐ 2 keer modaal of meer;	meer dan € 56000,-

Appendix 3 Regression analyses (complete sample in the WoON database)

Building characteristics in the total housing stock

A regression analysis was carried out to determine the variation on energy use that can be explained by building characteristics in the total housing stock. The variables added to the model were: 'number of bedrooms', '(LOG) loss surface', '(LOG) non-insulated open surface', and '(LOG) living area'. The regression model can explain 33.6% of the variation on energy used (Table A3.1). Analysis of assumptions showed that the model was fairly accurate. In Chapter 3 the results showed that the variation in new housing that can be explained with building characteristics is from 18.6 (OTB survey) to 22.8 (WoON new housing) with the variables '(LOG) heat transfer surface' and 'number of rooms'. The increased percentage points out a larger influence of different building characteristics on energy use, given a larger variety of them.

Occupant behaviour in the total housing stock

To determine the amount on the variation on energy used that can be explained by behaviour, regression analysis was carried out. The regression was carried out with the statistically significant variables: '(SQRT) rooms with radiator always on', 'temperature in living room', and 'ventilation via windows in living room'. The model explains 9.4% of the variation on energy use in dwellings (Table A3.2). The results from Chapter 4 showed that the proportion of variation explained with occupant behaviour in new housing is from 3.2% (WoON new housing) to 11.9% (OTB survey). This means an increase from 3.2 to 9.4% on the variation in the WoON survey from new to existing housing respectively. The larger percentage explained with the OTB survey was caused by the fact that more detailed data was found in the database, such as the hours with heating and radiators on, which were found to be more significant than the temperature level.

The increased on the variation explained and on the variables related to energy use (ventilation) indicated a large influence of occupant behaviour in existing dwellings, which implies a good opportunity to reduce energy use by modifying behaviour through policies aimed at a more efficient use of heating and ventilation systems.

Table A3.1 B, Standard error of B and Beta of regression model for the building stock

	B	Std. Error B	Beta
(Constant)	-25.249	1.752	
Number of bedrooms	1.366	.151	.151***
(LOG) Heat transfer surface	23.489	.872	.431***
(LOG) Non-insulated open surface	2.232	.361	.078***
(LOG) Living area	2.517	.877	.046*

Dependent variable: (LOG) Energy for space and water heating in MJ.
R^2 = .336, * = p < .05, ** = p < .01 and *** = p < .001

Table A3.2 B, Standard error of B and Beta of regression model with behaviour variables

	B	Std. Error B	Beta
(Constant)	27.544	1.315	
(SQRT) Rooms with radiator on	2.921	.342	.237***
Temperature thermostat in living room	.326	.087	.104***
Ventilation via windows in living room	-2.177	.601	-.097***

Dependent variable: (LOG) Energy for space and water heating in MJ.
R^2 = .094, * = p < .05, ** = p < .01 and *** = p < .001

Curriculum vitae

Olivia Guerra Santín was born in Toluca, México in 1980. She studied architecture in the Faculty of Architecture and Design of the Universidad Autónoma del Estado de Mexico from 1997 to 2002. After concluding her studies, she moved to the Netherlands to obtain a masters degree in Urban Environmental Management at the University of Wageningen, which she received in 2006. She wrote her MSc thesis on sustainable building in Mexico. From 2005 she carried out an internship at the OTB Research Institute for the Built Environment at Delft University of Technology in the topic “health in the Life Cycle Assessment of buildings”. Olivia continued to do research at the OTB from 2006 to 2010. In 2010 she concluded her PhD research on the topics of energy consumption, occupant behaviour and building regulations.

Sustainable Urban Areas

1. Beerepoot, Milou, **Renewable energy in energy performance regulations. A challenge for European member states in implementing the Energy Performance Building Directive**
2004/202 pages/ISBN 90-407-2534-9 (978-90-407-2534-0)

2. Boon, Claudia and Minna Sunikka, **Introduction to sustainable urban renewal. CO_2 reduction and the use of performance agreements: experience from The Netherlands**
2004/153 pages/ISBN 90-407-2535-7 (978-90-407-2535-7)

3. Jonge, Tim de, **Cost effectiveness of sustainable housing investments**
2005/196 pages/ISBN 90-407-2578-0 (978-90-407-2578-4)

4. Klunder, Gerda, **Sustainable solutions for Dutch housing. Reducing the environmental impact of new and existing houses**
2005/163 pages/ISBN 90-407-2584-5 (978-407-2584-5)

5. Bots, Pieter, Ellen van Bueren, Ernst ten Heuvelhof and Igor Mayer, **Communicative tools in sustainable urban planning and building**
2005/100 pages/ISBN 90-407-2595-0 (978-90-407-2595-1)

6. Kleinhans, R.J., **Sociale implicaties van herstructurering en herhuisvesting**
2005/371 pages/ISBN 90-407-2598-5 (978-90-407-2598-2)

7. Kauko, Tom, **Comparing spatial features of urban housing markets. Recent evidence of submarket formation in metropolitan Helsinki and Amsterdam**
2005/163 pages/ISBN 90-407-2618-3 (978-90-407-2618-7)

8. Kauko, Tom, **Between East and West. Housing markets, property prices and locational preferences in Budapest from a comparative perspective**
2006/142 pages/ISBN 1-58603-679-3 (978-1-58603-679-9)

9. Sunikka, Minna Marjaana, **Policies for improving energy efficiency in the European housing stock**
2006/251 pages/ISBN 1-58603-649-1 (978-1-58603-649-2)

10. Hasselaar, Evert, **Health performance of housing. Indicators and tools**

2006/298 pages/ISBN 1-58603-689-0 (978-1-58603-689-8)

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Residential buildings have continuously improved in energy efficiency, partly as a consequence of the introduction of energy regulations in many countries. Although better thermal properties and systems efficiency have lowered energy consumption for space heating in recent decades, substantial differences in energy consumption in similar dwellings are still being observed. These differences in consumption are thought to be caused by differences in occupancy patterns, by quality of construction and by rebound effects.
This research addresses the effect of energy performance regulations and occupant behaviour on energy consumption for space and water heating in dwellings built after the introduction of the energy performance regulations in the Netherlands. The results of this research show that improving the energy efficiency of buildings alone is not enough to decrease that energy consumption. The large differences found in the use of dwellings indicate that, especially in energy efficient houses, occupant behaviour provides an opportunity for further reductions in the energy consumption for space heating which could boost the efforts to conserve energy worldwide.

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