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

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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.

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 [1]. According to EuroAce [2] (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 [3–5].

The importance of building characteristics has been determined in diverse studies. Leth-Petersen and Togeby [6] 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 [4,7,8]. In the Netherlands, Beerepoot and Beerepoot [9] 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 [3,10], 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

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simulation, and can now be found in various handbooks (for example, [11–14]). 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 [4]. 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 will provide a literature survey which will determine the parameters used in the model, while Section 3 will present the analysis methods and data used. Section 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 5 will provide the conclusions of the study and make recommendations for further research.

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. [4], 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 [15,16], and on the utilisation of the dwelling's systems, such as interior temperature and ventilation rate [3]. For example, in this experimental study by Branco et al. [3], conducted over 3 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 [10], 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 and Goeltz [5] 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 [8]. The parameters influencing energy demand for space heating are: the thermal quality of the building, building type, occupant behaviour and climate. Table 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 sub-sections. More detailed results from international studies and their comparison with the results of this study can be found in the discussion section.

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 [17,18]. 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 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 2800 households in the Netherlands, Vringer [19] 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 and Noorman [20], 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 and Togeby [6] 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. Behaviour

Motivation is thought to have a great influence on the variation in energy consumption in different households [21,18]. There are differences in energy use that are not explained by occupant characteristics such as household size, level of education and age distribution [21]. Vringer et al. [21] 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 [4], 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, Lindén et al. [18] 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 2 °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. [4] 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 [4]. Indoor temperature is often different for different types of

Table 1
International references per type of study.

Building characteristics	
Urbanisation rate	Assimakopoulos [28] (Greece, empirical)
Vintage of building	Assimakopoulos [28] (Greece) Leth-Petersen and Togeby [6] (Denmark) Liao and Chang [17] (USA) Hirst and Goeltz [5] (USA, monitoring)
Design of dwelling	Assimakopoulos [28] (Greece) Leth-Petersen and Togeby [6] (Denmark) Haas et al. [4] (Australia) Liao and Chang [17] (USA) Sonderegger [30] (USA) Sardianou [31] (Greece) Lenzen et al. [32] (International) Schuler et al. [25] (Germany) Pachauri [26] (India)
Insulation	Assimakopoulos [28] (Greece) [4] (Australia) Sonderegger [30] (USA) Hirst and Goeltz [5] (USA, monitoring)
Heating systems	Leth-Petersen and Togeby [6] (Denmark) Hirst and Goeltz [5] (USA, monitoring)
Energy type	Leth-Petersen and Togeby [6] (Denmark)
Household characteristics	
Age respondent, household size, income	Liao and Chang [17] (USA) Assimakopoulos [28] (Greece) Jeeninga et al. [10] (the Netherlands) Vringer [19] (the Netherlands) Sardianou [31] (Greece) Lenzen et al. [32] (International) Schuler et al. [25] (Germany) Pachauri [26] (India) Hirst and Goeltz [5] (USA, monitoring) Biesiot and Noorman [20] (the Netherlands)
Ownership	Leth-Petersen and Togeby [6] (Denmark)
Behaviour	
Preferences in space heating	Leth-Petersen and Togeby [6] (Denmark) Haas et al. [4] (Australia) Linden et al. [18] (Sweden) Jeeninga et al. [10] (the Netherlands) Tommerup et al. [33] (Denmark, monitoring)
Presence at home and hot water use	Papakostas and Satiropoulos [8] (Greece)
Ventilation	Iwashita and Akasaka [23] (Japan, monitoring) Erhorn [24] (Germany, monitoring) [22] (UK, monitoring)
Values	Vringer et al. [21] (the Netherlands)

buildings and heating systems due to occupant preferences and consumer behaviour [6], which may also depend on the thermal quality of the building and the climate [4].

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 [22]. Some studies suggest that ventilation from windows accounts for a large percentage of the ventilation rate in occupied dwellings [23]. Iwashita and Akasaka [23] 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 [24] 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 1). The presence of people at home has also been found to influence energy use for space heating [8].

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 3 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. [25], 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 [26]. In addition, according to Freire et al. [27], 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 [28], 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.

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 [29]: 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.

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.

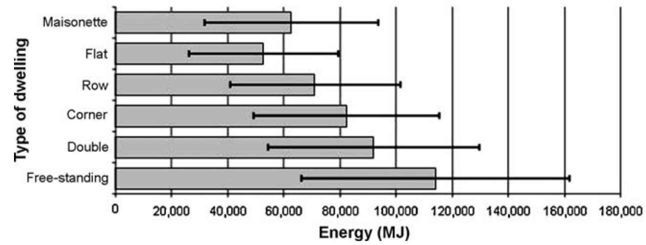

Fig. 1. Mean and standard deviation for energy use (MJ/year) per type of dwelling.

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.

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 Fig. 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. Fig. 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.

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 Fig. 3, detached dwellings in general have a higher energy use than all other dwellings, followed by double dwellings, 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,

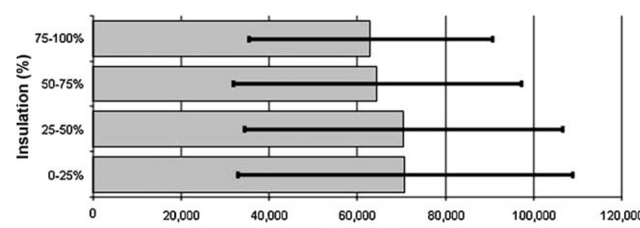

Fig. 2. Mean and standard deviation for energy use (MJ/year) per insulation degree category.

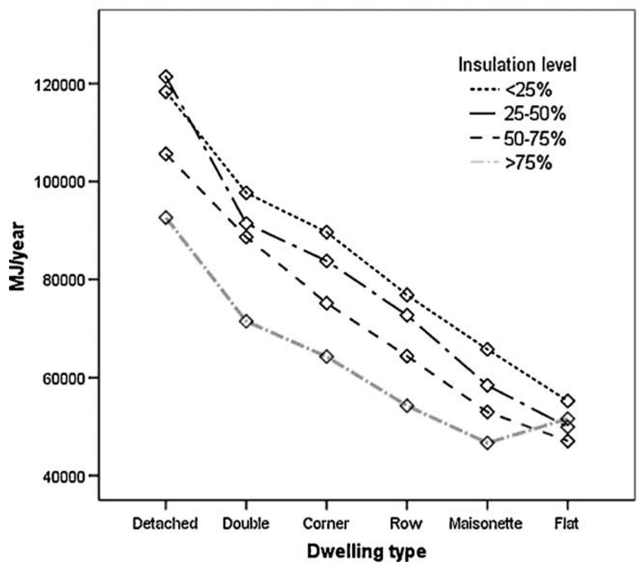

Fig. 3. Mean energy use per type of dwelling and insulation level.

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 Fig. 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 shows the number of cases and percentage of the sample for each type of dwelling and insulation level.

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
Number of cases and percentage of cases for dichotomous variables.

	Number of cases	Percentage
Type of dwelling: maisonette	1,634	11.0%
Type of dwelling: flat	5,583	37.6%
Type of dwelling: row	3,718	25.0%
Type of dwelling: double	1,014	6.8%
Type of dwelling: corner	1,766	11.9%
Insulation of facade	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%

Table 3
Mean and standard deviation for continuous variables.

	Mean	Standard deviation
Energy for space and water heating (MJ)	69,345.30	36,247.55
(LOG) useful living area (m2)	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	17
Household size	2.13	1.18
Income (in euros)	23,866.71	16,496.91

Table 3 presents the variable means and standard deviations. The number and percentages of cases for dichotomous and dummy variables are shown in Table 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 (Model 1), 37.9% ($R_1^2 = 0.379$) of the variability in energy use is accounted for by building characteristics. An additional 3.8% ($R_2^2 = 0.038$) is accounted for by the type of dwelling. The addition of behavioural predictors caused the variation to increase by 4.2% ($R_3^2 = 0.043$).

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 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.

Table 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 facade	−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%)			
Maisonette	−32,400.93	1,210.10	−.280***
Flat	−25,891.05	1,192.08	−.346***
Row dwelling	−25,437.80	1,031.46	−.304***
Double dwelling	−11,594.73	1,175.94	−.081***
Corner dwelling	−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	.094	.015	.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.
*** <0.001.

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).

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

4.3.2. 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 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.

4.3.3. 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.

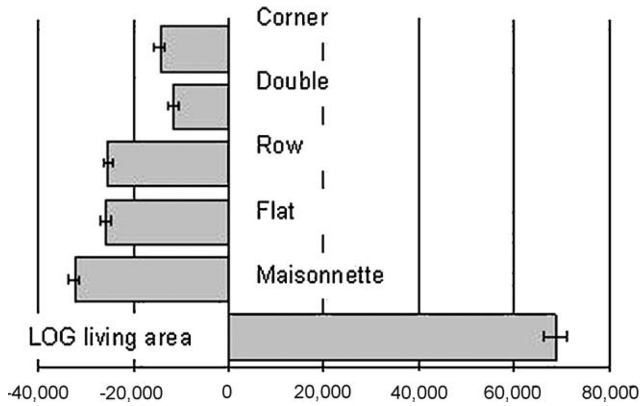

Fig. 4. Energy saved or spent for an increase of one unit in LOG living area, and by type of dwelling in comparison to detached dwellings.

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. Fig. 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 Fig. 4, more energy use is expected for each one-unit step of LOG living area in a dwelling.

Fig. 5 shows the energy prediction for a dwelling, based on the presence of a building characteristic or behaviour. For example, when an open kitchen is present, a reduction of 1700 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.

Fig. 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, 1000 MJ/year more energy will be used.

Figs. 4–6 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 4000 MJ/year, while having double glazing decreases energy use by 5000 MJ/year.

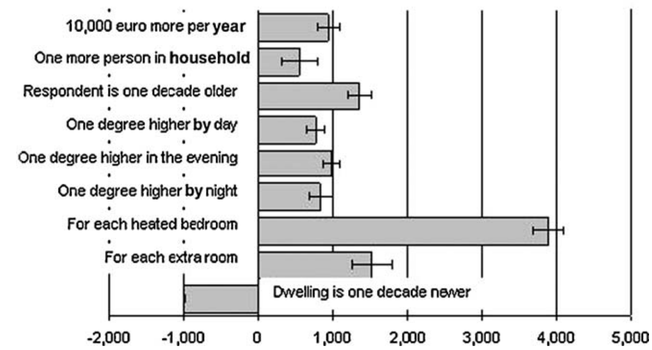

Fig. 6. Energy saved or spent for an increase of one unit in a continuous variable.

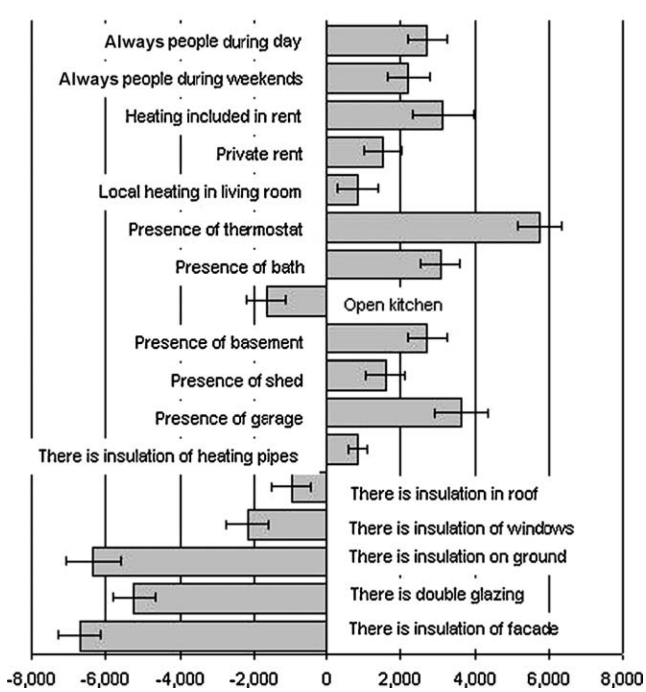

Fig. 5. Energy saved or spent when a variable is present, in comparison to cases when the variable is not present.

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), ΔR^2 = .225 for the second step (building characteristics), and ΔR^2 = .033 for the third step (dwelling type). Table 5 compares the Beta values of the original model to a model with only building characteristics and Table 6 compares the regression model with a model with only behaviour and occupant variables. The differences between the main model and the model

Table 5
Comparison of Beta values of regression model with behaviour model.

	Beta second model	Beta model building
Dwelling characteristics		
LOG living area	.321***	.352***
Construction year	−.082***	−.065***
Insulation of facade	−.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		
Maisonette	−.280***	−.295***
Flat	−.346***	−.352***
Row dwelling	−.304***	−.316***
Double dwelling	−.081***	−.082***
Corner dwelling	−.129***	−.134***

Dependent variable: energy for heating MJ.
** <0.01.
*** <0.001.

Table 6
Comparison of Beta values of regression model with building model.

	Beta second model	Beta model behaviour
Household characteristics and 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.
*** <0.001.

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.

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 [30] 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. [25] 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 [26] 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 and Goeltz [5] 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 and Togeby [6] in Denmark and Liao and Chang [17] in the USA.

In studies by Haas et al. [4] in Australia and Sardianou [31] 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. [32] 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 [4]. 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 [31] found that dwelling size is a factor influencing energy use, while Sonderegger [30] 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. [4] 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 [10] involving 180 households, showed that differences in heating demand is mainly determined by set-point heating temperature. In an empirical study in Sweden, Lindén et al. [18] found that preferences for indoor temperature are contributing factors for energy requirements. Calculations by Tommerup et al. [33] 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 [10,18].

Income was found to be positively correlated to energy use, similar to the results of Biesiot and Noorman [20], who found an almost linear relationship between expenditure and energy requirements for direct and indirect energy needs in the Netherlands. Vringer [19] 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. [7], 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 [31] found that the age of the respondent, household size and ownership were influencing factors on space heating demand. Liao and Chang [17] found that rented houses, the age of the respondent and the household size were positively correlated with more energy use. Lenzen et al. [32] 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 [4], 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.

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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