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Variations in Residential Space Heating Profiles At Room Level: the Influence of Building and System Characteristics

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Abstract

Theoretically estimated energy savings associated with better energy performance levels are rarely achieved in residential buildings. Part of this is explained by the higher indoor temperatures found at higher performance levels. Literature associates this temperature take-back with physical and behavioral causes: better insulated envelopes result in higher average indoor temperatures and inhabitants increase their comfort expectations and choose more demanding heating profiles in more efficient buildings. However, literature gives little to no proof for different heating profiles being linked to different energy performance levels.

To study possible changes in heating profiles and their causes, a statistical study was conducted on survey data and energy performance assessment data on more than 575 houses and their inhabitants: old, non-insulated houses, houses with standard performance levels and high-performance houses.

The study reveals significantly longer heating times in centrally heated houses compared to houses with de-centralized heating systems, but only in the bathrooms.

The number of heating hours in the living proved to be more strongly associated with the presence of a low temperature heating system or heat pump than with the presence of people. The number of heating hours was not associated with the calculated net space heating and only to a small extent with other technical and socio-demographic data. These findings indicate that more demanding heating profiles do occur in higher performance houses, but mainly as a result of the type of heating system (its control and response time) and less as a result of behavioral rebound induced by the lower cost per demand ratio.

Keywords – heating profiles; system control interaction; user behavior; rebound

1. Introduction

Temperature take-back causes real energy savings to be lower than theoretical savings calculated using simplified models. It refers to the higher average temperatures found in more energy efficient houses, temperature increases which are not taken into account by most simplified models [1,2]. One part of this temperature take-back, the physical part, refers to better insulation levels resulting in higher temperatures in unheated rooms and during switch-off periods [3]. Another part is often claimed to result from the rebound effect: higher energy efficiencies reduce heating costs and induce higher comfort expectations and more demanding heating profiles [4,5]. While higher average temperatures have been measured in better insulated houses, literature supplies little to no proof that this results in part from changes in heating profiles (set-point temperatures and heating times) due to behavioral rebound. However, most studies focus on living room heating profiles, while the largest average temperature differences between well and non-insulated houses are found in e.g. bedrooms and while studies suggest that shifts in heating profiles caused e.g. by shifting from de-centralized to centralized heating systems mainly occur in those secondary rooms [6].

To understand the causes of temperature take-back, additional studies should thus investigate changes in heating profiles (heating times and set-point temperatures instead of the resulting average temperatures) and they should consider all different room types (bedrooms, bathrooms, etc.). The study presented in this paper contributes to this research track by means of a statistical study on three datasets. These account for more than 575 houses that are representative for different building periods and energy performance levels. The data consists of self-reported heating profiles for all rooms, socio-demographic data, technical characteristics of the building and its systems and theoretical energy performance values.

2. Case-studies, data and method of analysis

Case-studies

The analyzed data originates from three complementary datasets. The first two datasets correspond to two different case-study neighborhoods, cs1 and cs2 [7,8]. All the houses within one neighborhood are built by the same architect and contractors, using the same type of systems and construction materials and thus reaching comparable performance levels that are representative for their respective building period. Most houses of cs1 and cs2 are terraced houses, a few are semi-detached houses. The 33 houses of cs1 are old houses from the 1960s with no insulation, mainly single glazing, no mechanical ventilation system and no central heating system. They have a gas heater in the living room and electric radiators in the bathrooms, in most bedrooms and in some kitchens. The 26 houses of cs2 are representative for the more modern standards from 2006: they are insulated, have a mechanical exhaust ventilation system and a central heating system with a gas boiler. Compared with cs1 and cs2, the third dataset (HPH) is much larger and less homogeneous. It contains data about 537 houses whose inhabitants responded to a survey of the Flemish Energy Agency (VEA) [9]. Similarly to cs2, the HPH-houses are modern houses built over the past 10 years, but they were built to higher performance standards. 83% of the HPH-houses have a mechanical, balanced ventilation system with heat recovery and 14% have a mechanical exhaust ventilation system. 33% have a heat pump and only 5 houses (1%) have no central heating, but local heaters. Compared with the old social houses of cs1, the new houses of cs2 and HPH are inhabited mainly by younger families whose heads of the family, on average, have higher education levels and fewer of them are unemployed or retired. While most inhabitants of cs1 are social renters, cs2 has a mix of private renters and owners and 99% of the houses of HPH are inhabited by their owners.

Available Data and Statistical Analysis

This paper does not report all findings from the study. It focuses on the analysis of the number of heating hours reported by the inhabitants for different room types for an average week-day in winter. It does not discuss all room types, but focuses on the living rooms, bedrooms, bathrooms and circulation areas (entryway and hallways). These showed the largest variability and proved to be very good indicators for other room types [8].

Compared to the data about cs1 and cs2, the larger number of cases included in the HPH-dataset and the larger variation of the technical and socio-demographic parameters within that dataset allow a more thorough statistical analysis. The statistical tests analyze the associations between the heating hours and the technical and socio-demographic parameters. Those parameters consist of ventilation and heating system characteristics, characteristics of the building envelope, household income levels and presence of the inhabitants. The technical parameters (average U-values, type of systems, theoretical energy performance levels…) were obtained from the official energy performance certificates stored in the governmental EPB-database and verified based on surveys of the inhabitants. These surveys also provided the self-reported socio-demographic and behavioral data (number of inhabitants, age, income levels, presence…).

When analyzing most of these parameters, the parametric assumptions of the most standard statistical tests could not be met. Therefore, the statistical analyses are based on non-parametric tests: Kendall tau-b (τ_b) associations, Mann-Whitney U-tests (U) as well as odds ratios (OR). 95%-confidence intervals (95% CI) were calculated based on bias-corrected and accelerated bootstrapping (BCa).

3. Results

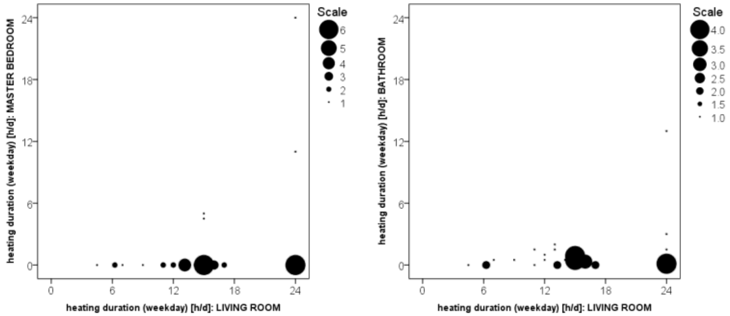
Differences in heating profiles between rooms in old, standard and high performance houses

Fig. 1(a), Fig. 2(a) and Fig. 3(a) compare the daily number of heating hours in the bedrooms (ordinates) with the daily number of heating hours in the living rooms (abscissae) of the corresponding houses for the old neighborhood (cs1), the recent neighborhood (cs2) and the set of high performance houses (HPH), respectively. The sizes of the binned dots indicate the number of households that they represent. Because of the different sample sizes, these dots are scaled in each chart separately to be representative of the percentages within each dataset. The fact that all bedrooms in the recent houses of cs2 had a radiator while this was not the case for a few houses of the old houses of cs1 did not result in the bedrooms being heated by many more households in cs2, as can be seen by most dots forming almost horizontal line at the bottom of the chart: only 8 of the 26 households (31%) of cs2 heated at least one bedroom. However, 6 of the 8 households heating their bedrooms did so for as long as they were heating their living room, as indicated by the dots on the diagonal line. The bedroom heating profiles of HPH are very similar to those of cs2, except for the fact that more households heat their bedrooms (approximately 50%), but this difference was not found to be statistically significant. The fact that many households of HPH heated their living room 24 hours per day and that many of them also heat their bedrooms for as many hours as their living room (Table 1) results in almost one in every five households in HPH heating their bedrooms for 24 hours per day, while only one household did so in cs1 and not one household in cs2.

Fig. 1(b), Fig. 2(b) and Fig. 3(b) make a similar comparison with the living room, but considering the bathrooms instead of the bedrooms. For cs1 (Fig. 1(b)), the use of the decentralized, electric heaters in the bathrooms resembles the use of the decentralized, electric heaters in the bedrooms: both are used intermittently for very brief durations. On the opposite, the centrally heated houses of cs2 (Fig. 2(b)) and HPH (Fig. 3(b)) show heating hours in the bathrooms that are more similar to the higher number of heating hours in their living rooms. Only 35% of those households living in those modern, centrally heated houses switch the heating of the bathrooms off locally for at least some period of time while they continue to heat the living area.

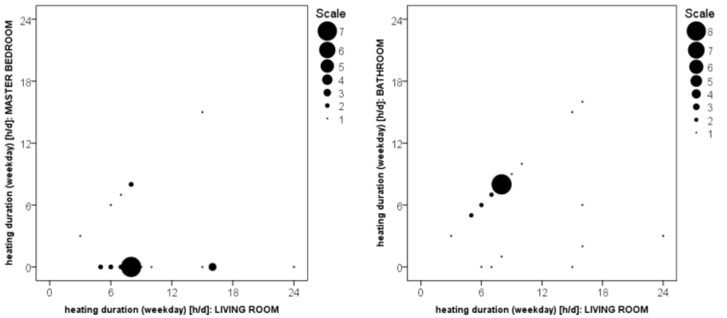
The charts for the circulation areas were comparable to those for the bedrooms, except that there was an even more clear separation into two groups: households that do not heat their circulation area (horizontal line) and households that heat their circulation area for as many hours as the living room (diagonal). Compared to e.g. the bedrooms and especially the bathrooms, only very few circulation areas (4,9%) did not fit in one of these two groups (Table 1).

Similar values as for the circulation area were found in the toilets and the washing or storage rooms. Additional analyses showed that the heating profiles in those three room types were usually identical, forming a cluster of comparably heated rooms. This was also the case for the living rooms and kitchens, and for the master and children bedrooms, but the heating profiles in the bathrooms could not be assimilated with the heating profiles of any other room type. This is illustrated by the percentage of rooms being heated for more, the same or less hours than the living rooms, or not being heated at all (Table 1). This differentiation between room types was further strengthened by the difference in self-reported set-point temperatures with, compared to the living rooms, lower values being reported for the circulation areas and bedrooms and higher values being reported for the bathrooms [8].



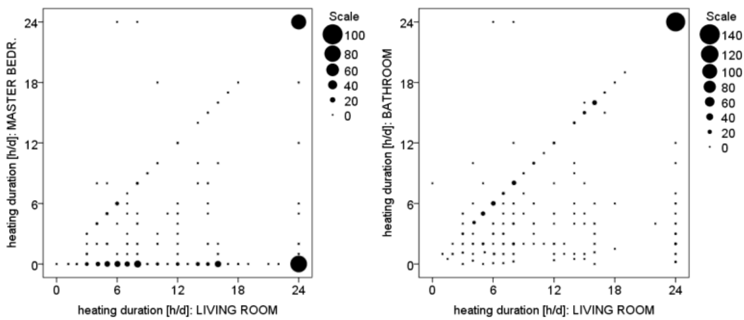
(a) (b)

Fig. 1: daily heating hours: bedrooms (a) and bathrooms (b) of cs1 vs. living rooms



(a) (b)

Fig. 2: daily heating hours: bedrooms (a) and bathrooms (b) of cs2 vs. living rooms



(a) (b)

Fig. 3: daily heating hours: bedrooms (a) and bathrooms (b) of HPH vs. living rooms

Table 1: heating durations per room: HPH

	Heated?	If heated:			
		Heating time compared to living r.			
	YES	N	less	equal	more
living r.	100%	499	0.0%	100.0%	0.0%
kitchen	99%	486	0.8%	98.4%	0.8%
circulation area	64%	298	6.0%	92.3%	1.7%
washing r./stor.	45%	206	9.2%	90.3%	0.5%
toilet	50%	233	5.6%	92.7%	1.7%
bathroom	98%	478	34.9%	63.0%	2.1%
children bedr.	50%	222	37.8%	59.0%	3.2%
master bedr.	42%	195	32.8%	64.6%	2.6%

Determinants of the heating profiles

As stated in literature [1,6], the presence of a central heating system can explain the fact that more demanding heating profiles are found in the bathrooms of the centrally heated houses (cs2 and HPH), being heated for as many hours as the living room. However, the remaining variations in heating profiles and the larger number of households in HPH that heat their living room 24h/d (34% in HPH compared to 1/26 in cs2) are not yet explained. This section studies these differences statistically, first focusing on the link between heating profiles and the individual user and building related parameters before also considering the resulting theoretical energy use.

Statistical tests proved that the number of heating hours during an average week-day was associated with the presence of people during the different week-days. For example, a median of 16 hours was reported by the households having someone staying at home on Monday compared with 9 hours for the households with no-one at home (Table 2). Significant but weaker associations were also found between this presence data and the heating hours in the other rooms because those heating hours are also associated with the heating hours of the living room while those rooms are not heated by all households (Table 1).

There was no significant difference between the heating profiles found in the houses with different types of ventilation systems (e.g. exhaust systems versus balanced systems with heat recovery), but the heating profiles proved to be associated with the characteristics of the heating system. A higher number of heating hours was found for houses with a heat-pump and for houses with lower return-water temperatures being reported in the EPB-assessment (Table 2). Systems were considered as ‘low temperature’ (LT) if the reported return-water temperature was equal or lower to 45°C. This is the default value for surface heating (floor, ceiling and wall heating) defined in the Flemish EPB-method. By consequence, a significant correlation was found between the number of heating hours of the living room and the reported efficiency of the space heating generation system (τ = .289, 95%CI [.222;.354], N=471, p < .001)(Table 3). There was a significant association between having an LT-system and having a heat-pump (N = 405, OR = 2.90, 95%CI [1.72; 4.89], p < .001), but factorial analyses showed that both heat-pumps and LT-systems were separately associated with a higher number of heating hours. Combining all cases with a LT-system or a heat-pump results in a subsample with a drastically higher number of households heating their living room and kitchen for 24 hours per day, independently of someone being at home during day-time or not. In fact, a higher number of heating hours in the living room is associated more strongly with the presence of a low-temperature heating system or a heat-pump than with the fact that someone stays at home (Table 2). This is illustrated by Fig. 4, showing the subsample without heat-pump or LT-system and the subsample with one of both, respectively. Their sub-groups with no one at home on Monday (left side of the figures) have a higher percentage of houses heated for less than half a day compared to the subsample with someone staying at home (right side of the figures). However, the average difference between the two groups is much smaller for the sub-sample with a heat-pump or a LT-system because more than 50% of those households leave their heating system on 24 hours per day. In addition to their association with more heating hours, heat pumps and LT systems were also associated with higher odds of heating other rooms than the living room and the kitchen. However, those associations were small (e.g. for heat pumps vs. circulation area: N = 453, OR = 3.33, 95%CI [1.811 4.95], p<.001; for heat pumps vs. bedrooms: N = 464, OR = 1.50, 95%CI [1.33, 3.13], p=.001).

Table 2: associations (Mann-Whitney U-test) between the number of heating hours in the living room [h] on the one hand, and, on the other hand, the presence of someone at home on Monday, of a low temperature heating system (LT), of a heat pump (HP)

	N	NO		YES		U	z	p
		Mdn	Av	Mdn	Av			
	[-]	[h]	[h]	[h]	[h]	[-]	[-]	[-]
Monday	499	9.0	13.2	16.0	15.9	20906	-3.829	< .001
LT	416	9.5	12.1	16.0	15.9	14532	-4.836	< .001
HP	452	9.0	12.1	24.0	19.7	9073	-8.179	< .001
LT or HP	459	8.0	11.2	24.0	17.4	14910	-8.214	< .001

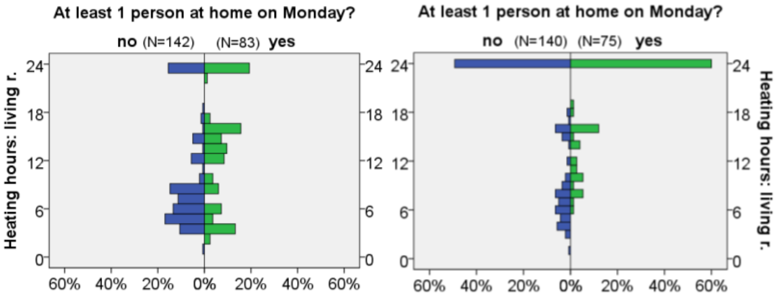


Fig. 4: heating hours of the living rooms vs. someone being at home on Mondays: houses without (left N=233) vs. with (right, N=229) a heat pump or a low temperature heating system

The characteristics of the construction and the income level of the households were also significantly associated with the heating profiles. For example, more heating hours were found in larger houses (volume and floor area), houses of a less compact typology (e.g detached), with more glazing or with better insulation levels and if inhabited by a households with a higher income level (Table 3). While having low p-values, these associations were small (see τ-values). Furthermore, associations are no proof of causal relations and they might be indirect. In fact, these different construction parameters were also significantly associated one to the other. Furthermore, larger houses, more glazing and less compact typologies were also associated with better efficiencies of the heating system ànd with higher income levels. While the association between higher income levels and *more* heating hours is small, this association is noteworthy considering that higher income levels were also associated with a *smaller* probability of someone being at home on week-days (except on Wednesdays).

This maze of correlations between system characteristics, building characteristics and income levels made it impossible to determine with absolute certainty if one of the reported parameters is more directly associated with the heating profiles than the other. The heating system characteristics were more strongly associated with the heating profiles than were all other parameters (Table 3), which did not show graphs differentiating heating profiles as strongly as Fig. 4. This suggests that those system characteristics are probably the most important parameters worth investigating for explaining the associations with the heating profiles. A series of factorial Spearman correlation analyses correcting for one parameter and testing the others never made the associations of those other parameters with the heating profiles become not significant. The higher influence of the heating system characteristics appears corroborated by the fact that houses with a lower theoretical primary energy use for space heating (normalized per floor area) showed more demanding heating profiles (Table 3), while the theoretical net energy use for space heating was not found to be associated with the heating profiles ($p > .200$ for $N > 280$), even though these net and primary energy demands were very strongly correlated (N = 295, τ = .641, 95%CI [.726, .833], p<.001). This can be explained by the fact that the largest association with the heating profiles on component level was found with regard to the space heating system, which differentiates to a large extent the net demand from the primary demand. Furthermore, the association between the heating profiles and the average U-value was lower and the presence of a ventilation system with heat recovery, strongly influencing the theoretical net energy use, was not found to be associated with the heating profiles.

Table 3: associations between the heating hours of the living room on the one hand and, on the other, construction and system characteristics and household income levels.(typology: 1=terraced, 2=semi-detached, 3=detached)

HEATING HOURS, LIVING R.	τ	95% CI	N	p
generation efficiency	.289	[.222, .354]	471	< .001
typology	.185	[.107, .258]	434	< .001
volume	.134	[.074, .190]	499	< .001
floor area	.092	[.032, .150]	499	.004
window area/floor area	.139	[.076, .199]	499	< .001
average U-value	-.075	[-.141, -.011]	499	.022
average U-value,opaque	-.140	[-.207, -.077]	499	< .001
income level	.107	[.029, .180]	390	.005
Qheat,prim	-.068	[-.137, .001]	468	.037
Qheat,prim/floor area	-.146	[-.214, -.085]	468	< .001

4. Conclusions and discussion

The difference in heating hours found in the bathrooms of the recent, houses compared to the old houses corroborates the findings from literature about changes in heating profiles caused by shifting from de-centralized to centralized heating system. The strong match between the number of heating hours in the bathrooms and the living rooms in many of the centrally heated houses, notwithstanding the lower presence in bathrooms, suggests that at least part of this shift in heating profile does not result from economically induced behavioral rebound, but from a behavioral response to a different type of system and control: letting the central thermostat control the heating time is the most easy way of heating the bathroom.

The higher number of heating hours found in the high performance houses proved to be strongly associated with the presence of heat pumps and low temperature heating system and it was associated less with other parameters influencing the energy efficiency of the house (e.g. ventilation systems and insulation levels) or with the income level of the household.

This also questions whether economically induced behavioral rebound is the most important explanation for these more demanding heating profiles. Other, more probable hypotheses can be made based on the lower temperature of those heating systems and their often bigger latency: leaving the heating on 24h/d could be a necessary answer to the slower response of these systems or it could also be caused by the fact that there is no hot surface (e.g. radiator) making the people aware of the energy use caused by leaving the heating on. Testing these hypotheses would require further research, trying to understand *why* different heating profiles occur.

Therefore, the fact that behavioral rebound might play a lesser role in the total temperature take-back than is often argued does not mean that considering user behavior becomes less important. On the contrary, the findings show that user behavior should be understood and taken into account more thoroughly when designing systems (e.g. making a de-centralized control and use more easy) and when calculating potential savings (e.g. considering shifts in heating profiles caused by design choices with a differentiation based on the type of rooms, going further than simple single or 2-zone models).

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