SIMULATING PHYSICAL REBOUND IN RETROFITTED DWELLINGS

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ABSTRACT

When predicting energy savings in existing dwellings, quasi steady-state calculation tools with fixed boundary conditions are often used. However, they may result in an overestimation of the energy savings. One of the reasons is the physical rebound effect that typically occurs when insulating the building envelope, a phenomenon seldom taken into account. Apart from the well-known behavioural rebound effect –when inhabitants offset part of the energy saving by increasing their comfort level– the physical rebound accounts for the fact that average indoor temperatures unintentionally rise after retrofit, even if the inhabitants do not change their heating pattern. This is due to the (unwanted) temperature rise in unheated zones and the lower temperature drop between two heating periods. Dwelling and time mean indoor temperatures are therefore higher after retrofit, leading to less energy savings than predicted with the simplified tools.

By using simulations it is possible to eliminate the behavioural rebound and focus on the physical rebound. Given a fictitious building stock, retrofit measures can be simulated and the impact on indoor temperature and energy demand can be analysed statistically. To do so, an existing dwelling is modelled in TRNSYS as a dynamic multi-zone building for which indoor temperatures and energy demands are calculated. To cover a sufficiently wide variation of building characteristics and building use, a pragmatic approach is used. Dwelling variants are generated by stepwise improving the insulation levels and a number of predetermined occupancy patterns are imposed to simulate differences in dwelling use (identical before and after retrofit).

As could be expected, the analysis shows that, even with the given variation of input parameters like temperature set points, heating patterns, ventilation/infiltration rates, a global correlation between indoor temperature and energetic quality exists. Good insulated dwellings give higher mean indoor temperatures than badly insulated dwellings. As a result, when insulating a dwelling in a retrofitting project, the indoor condition will change after retrofit, resulting in a physical rebound. When for comparison a fixed indoor temperature is assumed for the whole building stock –as is commonly done in many standard calculation tools, thereby neglecting physical rebound– the simulations show that the potential energy savings are easily overestimated.

INTRODUCTION

In the past, several energy efficient renovation projects have revealed that the predicted energy savings are not always achieved e.g. [1]. One of the reasons is the well-know (behavioural) rebound effect where inhabitants take back part of the energy saving in enhanced comfort by e.g. raising the thermostat setting. However, apart from the inhabitants, another ‘rebound’ can be detected. When the building envelope is insulated, the temperature in the unheated zones rises and the dwelling cools down less between two heating periods –

even if the inhabitants do not change their heating pattern. This effect leads to higher indoor temperatures after retrofit and is called the *physical rebound*. Since the indoor temperature has proven to be one of the main determinants in the energy consumption of dwellings, it is important to assess the size of this temperature rise and whether or not it is overruled by other factors when calculating energy savings.

In this paper, the physical rebound is investigated by dynamic simulations. Starting from a badly insulated case study, six new variants are modelled with increasing insulation level. The MonteCarlo technique is used to impose realistic occupancy patterns and the impact on net energy demand and indoor temperature is studied. The comparison is made with a commonly used calculation tool in Flanders, based on the EPBD-regulation [2], which does not incorporate this physical rebound.

METHOD

Building Model

An existing three storey terraced house is modelled in the dynamic building simulation program TRNSYS. The floor plan is given in Figure 1. The dwelling is divided in 3 thermal zones: living zone (kitchen, living room and bath room; 284 m^3), sleeping zone (310 m^3) and circulation zone (157 m^3). Each zone is considered as one node for which heat balances are solved every time step. Heat transfer between these zones is assumed to occur only by heat conduction through the internal walls and floors, thereby neglecting possible heat transfer via interzonal air flows.

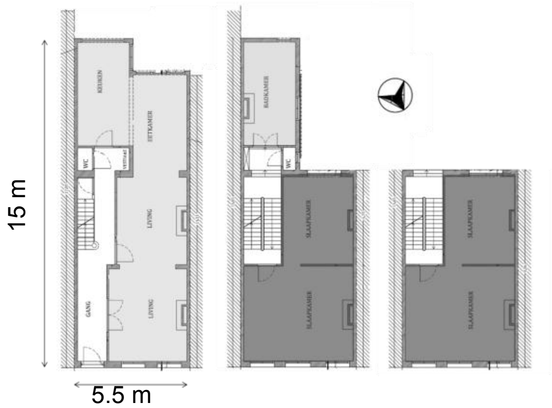

Figure 1: Floor plan of the three storey house with the ground floor (left), first floor (middle) and second floor (right). Light grey indicates the living zone, dark grey the sleeping zone and white the hallway. Basement floor is identical to ground floor.

The total heated volume V equals 751 m^3 while the heat loss surface A_T equals 312 m^2, leading to a compactness of $C = V/A_T = 2.41$ m. Outside and inside walls are heavy brick structures, while the internal floors are lightweight wooden structures. The least performing variant (mean U-value = 2.00 $W/(m^2K)$) is stepwise insulated in order to obtain 6 variants with increasing insulation levels – see Table 1.

Calculation methods

For each dwelling, two calculation methods are used to obtain the net energy demand and indoor temperatures. The first method is the reference method and treats the dwelling as a single zone at a fixed indoor temperature of 18 °C, as is done by a commonly used calculation tool in Flanders [2]. This temperature is lower than a typical thermostat set temperature in

Flat roof insulation – PU [m]	**0.05**	0.05	0.05	0.05	0.1	0.05	0.15
Pitched roof insulation –mineral wool [m]	**0.05**	0.05	0.1	0.1	0.15	0.15	0.3
Front facade (interior) – PU [m]	**0**	0.05	0.05	0.05	0.05	0.05	0.15
Back facade (exterior) – EPS [m]	**0**	0	0	0	0.1	0.05	0.15
Floor insulation (mineral wool) [m]	**0**	0	0.05	0.05	0	0.05	0.15
U-value glazing [W/(m^{2}K)]	**5.68**	5.68	5.68	2.83	2.83	1.3	0.86
g-value glazing [-]	**0.86**	0.86	0.86	0.76	0.76	0.62	0.60
Mean U-value [W/(m^{2}K)]	**2.00**	1.76	1.46	1.15	0.91	0.58	0.29

Table 1: Overview of the different insulation levels of the dwelling.

living rooms and therefore already incorporates some night setback and zonal heating. Since a fixed temperature is used for all insulation levels, physical rebound cannot be taken into account. The second method is a more realistic method and uses a multi-zone model of the dwelling. Different time schedules are then imposed to the different zones to simulate more realistic user behaviour (see further).

In order to compare the influence of these more realistic heating patterns, all other assumptions and boundary conditions are taken equal for both methods. For each building, the net energy demand for space heating and indoor temperatures are calculated for the month January. Hourly outside conditions are taken from the Meteonorm weather data file of Ukkel, Belgium. The internal gains and infiltration and ventilation rates are based on the legal energy performance calculation in Flanders [2]. The internal gains are only function of the heated volume, set constant throughout the year and uniformly distributed throughout the dwelling ($\Phi_{int} = 220 + 0.67\ V$ *[W]*). Infiltration rates are expressed as a function of the heated volume and the air change rate at 50 Pa, n_{50} ($\dot{V}_{inf} = 0.04\ n_{50}\ V$ [m^3/h]). The n_{50}–value is assumed to be 3 h^{-1} for all dwelling variants. In a similar way are the ventilation rates fixed ($\dot{V}_{vent} = (0.2 + 0.5\ exp(-V/500))\ m\ V$ [m^3/h], with m a constant depending on the type of ventilation system and its performance, taken equal to 1.5 by default). Both air rates are set constant throughout the simulation period. The air capacity of the zones is multiplied by 10 to incorporate the thermal capacity of furniture. For this analysis, only net energy demand for space heating is considered, so no heating system is modelled.

In reality, inhabitants alter the thermostat settings depending on their comfort feeling, which is a complex combination of physiological factors (activity level, clothing) and physical factors (air temperature, mean radiant temperature, relativity humidity, air velocity). An indicator for thermal comfort that is often used for practical purposes, is the operative temperature T_{op} which is defined as the average of the zone air temperature T_a and the zone area weighted surface temperature T_{surf}. Therefore, the desired set temperature T_{set} is considered to be equal to the operative temperature T_{op}.

Generating heating patterns with Monte-Carlo technique

To generate realistic heating patterns, a quasi-stochastic approach is used. Based on mainstream lifestyles (full-time out to work, halftime out to work, continuously home), a number of predetermined time schedules are modelled for each zone (Table 2). In the absence of reliable statistical data, probabilities of occurrence are arbitrary allocated to each of the schedules. For each zone, a random number between 0 and 1 is generated and used –in combination with the probabilities- to pick the corresponding time schedule. Similarly, the set temperature in the living zone is randomly picked from a uniform distribution between [19-23] °C and the set temperature of the sleeping rooms between [14-16] °C. Between two heating periods, the living zone is kept at a minimum temperature of [15-19] °C. The hallway is never heated. The first day of the simulation (January 1st) is randomly chosen between Monday till Sunday.

So for the more realistic method, every simulation starts with the previous Monte Carlo algorithm to determine a realistic heating pattern. For each dwelling variant, multiple simulations are carried out to reach convergence in the results. Based on [3], 100 simulation runs per dwelling are performed.

Remark that this working method has no ambition to cover all possible heating scenarios or to obtain a reproduction of real-life inhabitants heating their homes. It is a pragmatic method of modelling more realistic behaviour in order to reveal the impact and spread on calculated energy savings.

	L1	L2	L3	L4	S1	S2	S3	H1
00:00 – 06:00	--	--	--	--	X	X	X	
06:00 – 09:00	X	X	X	X			X	
09:00 – 12:30	--	X	--	X				
12:30 – 17:00	--	--	X	X				
17:00 – 22:30	X	X	X	X		X		
22:30 – 00:00	--	--	--	--	X	X	X	
PROBABILITY	0.5	0.125	0.125	0.25	0.33	0.33	0.33	1

Table 2: Overview of the different deterministic time schedules in the living zone (L), sleeping zone (S) en hallway (H) All days of the week are identical except for the living zone, where during the weekend L4 is always used. 'X' = set temperature, '--' = minimum temperature.

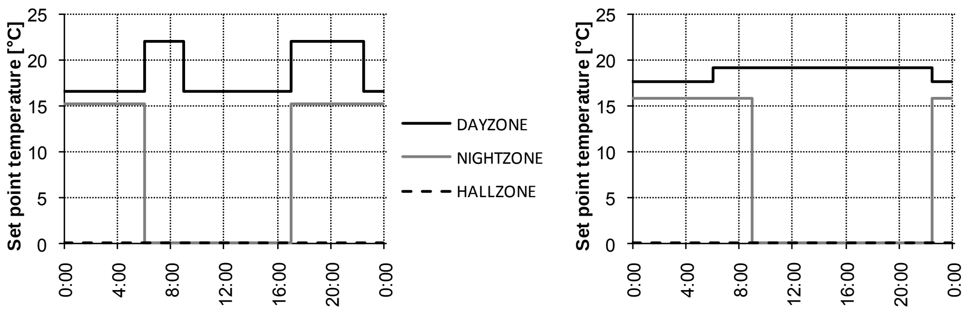

Figure 2: Example of two stochastic heating patterns, based on the predetermined time schedules of Table 2.

RESULTS

The zone volume weighted operative dwelling temperature and the dwelling net energy demand, respectively averaged and summed over the month January, are given in Figure 3 as a function of the mean U-value. The reference method –which treats the dwelling as 1 zone at a temperature of 18°C– gives one deterministic value per dwelling, while the quasi-stochastic method gives 100 values per dwelling (of which only the average, minimum and maximum values and 25% and 75%-quartiles values are shown).

When looking at the operative temperatures, one can clearly see the physical rebound: even with identical distribution of heating patterns, the dwelling temperature is not a constant but a function of the insulation level. For the badly insulated dwellings (U-value > 1.5 $W/(m^2K)$), indoor temperatures vary around 16°C, much lower than 18°C of the reference. Since the

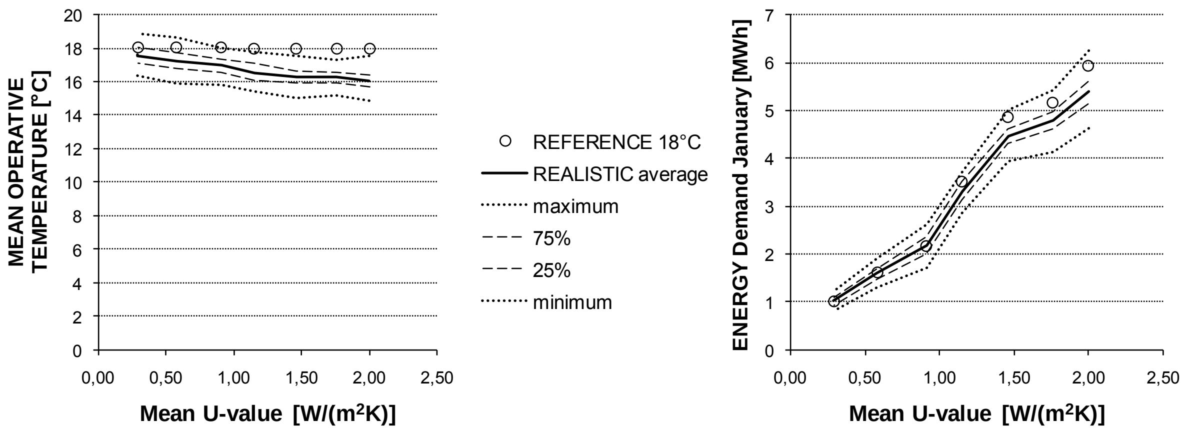

Figure 3: The zone weighted operative dwelling temperature (left) and the total energy demand (right) for the month January in function of the mean thermal transmittance U_m of the dwelling variant.

bandwidth nearly interferes with the 18°C-line, the 18° is probably too high to correctly assess energy consumption for existing, poorly insulated dwellings. This is also reflected in the total energy demand where, although the reference method is within the bandwidth of the realistic method, the 18°C still gives slightly higher energy demands. For the badly insulated dwellings the reference method gives energy demands that are almost 10% higher than the mean energy demands of the realistic method. For the best insulated dwelling however, temperatures vary around 18°C and the net energy demand of both methods corresponds very well.

The results of Figure 3 are based on the assumption that all other boundary conditions are constant for both methods e.g. internal gains, infiltration/ventilation rates. However, as well as with heating patterns, large variations exist in these parameters. In order to see whether their variability and uncertainty overrule the detected physical rebound, the above method is entirely repeated, but now the following parameters are allowed to vary as well within the same Monte Carlo algorithm: the previously defined internal gains Φ_{int}, the infiltration rates $\dot{V}_{inf}$ and the ventilation rates $\dot{V}_{vent}$ are randomly chosen between -10% until +10% of their reference value. Although a correlation might exist between mean U-value and these parameters (e.g. infiltration rates: new, well insulated buildings tend to be more airtight), all parameters are considered uncorrelated here. These simulations are performed for both the reference method and the more realistic method. Figure 4 shows the average, minimum and maximum values. The dwelling temperatures are not shown since these temperatures were found to be nearly affected by the additional stochastic parameters.

Figure 4 shows that adding uncertainty on internal gains, infiltration and ventilation rates, does not increase the uncertainty on the output of the Monte Carlo simulations: the bandwidth for the advanced calculation method remains almost the same. This suggests that the overall uncertainty is dominated by the variation in indoor temperature and heating pattern –a sensitivity analysis should quantify the separate effects. The bandwidth of the reference method entirely stays within the minimum and maximum values of the advanced method. Still, for the badly insulated variants, the reference method gives consistently higher energy demands than the realistic method. So, even with the additional uncertainty and for existing, poorly insulated dwellings, it is clear that energy demands calculated with a fixed inside temperature of 18°C are probably an overestimation.

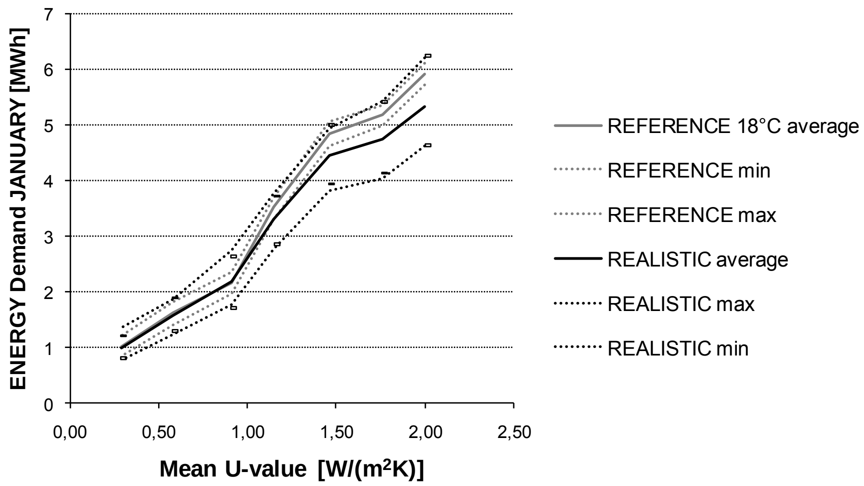

Figure 4: The total energy demand for the month January in function of the mean thermal transmittance U_m of the dwelling variant; the infiltration and ventilation rates and internal gains vary randomly between -10% until +10% of their reference value – the separate points depict the minimum and maximum values from the realistic method as shown in Figure 3.

DISCUSSION & CONCLUSION

The above analysis shows that, when heating patterns are randomly chosen between 'realistic' options, the physical rebound is clear: dwelling temperatures rise when insulation is added to the building envelope. The mean dwelling temperature increased from 16°C to 18°C when the mean U-value decreased from 2 W/(m^{2}K) to 0.3 W/(m^{2}K). This impacts the predicted energy demand, since calculating the energy demand with an inside temperature of 18°C for the initial, badly insulated dwelling, leads to a mean overestimation of about 10% for the presented case. This is of particular interest when the single-zone methodology of the EPBD-regulation is used for prediction energy savings of a building stock. Here, a consistent overestimation of initial energy consumption of 10% might lead to an important overestimation of potential energy savings and thus, the economical benefits of renovation measures. Nevertheless, due to their ease of use and limited calculation time, single zone models might still be of valuable use, but to attain more reliable results, it is suggested to make the indoor temperature a function of the insulation level.

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