The impact of physical rebound effects on the heat losses in a retrofitted dwelling

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SUMMARY:
In Flanders, as in many European regions, a calculation method has been developed in the framework of the EPBD-directive to evaluate the energy performance of newly erected dwellings. Although not intended to, this method is now more and more used to predict energy savings when retrofitting existing, badly insulated dwellings. In this calculation method the dwelling is considered as a single zone at a fixed indoor temperature of 18 °C. This paper investigates whether these assumptions are appropriate when calculating energy savings. On the one hand, although this indoor temperature gives a fairly good estimation for new dwellings, it cannot reflect the indoor climate in old, badly insulated dwellings where dwelling mean indoor temperatures can be considerably lower than 18 °C. Energy consumptions before retrofit are thus easily overestimated. On the other hand plays the physical rebound effect. When insulating the building envelope of a poorly insulated dwelling, the indoor temperature will rise, even if the heating pattern of the inhabitants remains unchanged. Using a fixed temperature for all insulation levels cannot incorporate this physical rebound, leading to inaccurate predictions of energy savings. In this paper the impact of a fixed indoor temperature of 18 °C on the net energy demand is analysed by simulations on an existing terraced house with different insulation levels. The comparison is made with a more realistic heating pattern where only part of the dwelling is heated intermittently. The simulations reveal a physical rebound and the need for a correlation between indoor temperature and insulation level.

1. Introduction

In the battle against the reduction of CO_2 emissions in the Flemish building stock, the focus has mainly been on new buildings. Since the growing rate of new buildings is decreasing and the building stock still consists of a large number of old and badly insulated buildings, a shift towards the energy efficient retrofit of these buildings is necessary. In order to take effective energy renovation measures, policy makers have to be able to rely on robust and reliable models that predict the energy savings potential of this part of the building stock. Due to their simplified assumptions and their widespread use, it is very tempting to use models that have been developed to evaluate the energy performance of buildings in a standardised way, mainly based on the standard EN ISO 13790. However, several monitoring projects have shown that real energy savings can be severely overestimated (Hong et al. (2006), Martin et al. (2006), Sanders et al. (2006)), raising the question whether these models are appropriate for predicting energy savings.

One of the elements often lacking in these models is the incorporation of the so-called *direct rebound* effect (Sorrell et al. (2009)). Explaining the economic mechanism behind this effect is fairly straightforward: when prices drop, demand rises. After an energy efficient renovation the marginal cost of space heating and hot water production lowers and thus, the inhabitants are likely to increase their comfort – especially in badly insulated dwellings with low comfort levels - by raising the set temperature, heating more rooms more often, taking more showers, ... This increased comfort level will reduce the potential energy savings as could be achieved by the energy efficiency improvements. This economic aspect of the direct rebound effect is already discussed in several studies (Greening et al. (2000), Sorrell et al. (2009)). However, the discrepancy between calculated and measured energy savings cannot be solely contributed to this economic mechanism.

Another explanation has to be found in simplifications made by the models used (Hens et al. (2010)). When looking at the situation in Flanders where the EPBD-regulation is implemented since 2006, the energy performance of dwellings is calculated in a standardised way by considering the dwelling as a single zone at a fixed temperature of 18 °C with preset infiltration and ventilation rates and with internal gains only in function of the protected volume (Anonymous (2005)). Besides the simplified assumptions concerning infiltration, ventilation, internal gains etc. it is found that the fixed indoor temperature of 18 °C is not a good approximation of reality.

Not only are measured dwelling averaged indoor temperatures lower than the assumed 18 °C (Janssens et al. (2006)), also the use itself of a single dwelling temperature applying for all insulation levels does not correspond with reality. After an energy efficient retrofit, an indoor temperature rise can occur, even when the heating pattern of the inhabitants has not changed. This is called the *physical rebound effect*. In reality, occupants tend to only heat their living rooms to an acceptable comfort temperature. Sleeping rooms, hallways, storage rooms etc. are generally not heated or are only kept at a minimum temperature. When improving the insulation quality of the building envelope (e.g. wall or loft insulation), the transmission heat losses decrease, not only in the heated zones but also in the unheated zones, leading to higher temperatures in the latter. In addition, occupants tend to only heat their homes at times of presence. Night setback is very common and the heating system is regularly turned down when the house is left during the day. A better insulation level leads to smaller temperature drops between two heating periods, resulting in higher time averaged temperatures. As a result, both dwelling and time averaged indoor temperatures increase after improvement of the insulation level.

Measuring this physical rebound effect by monitoring indoor temperatures before and after energy efficient refurbishments is difficult, since such monitored retrofit projects are quite scarce and if available, the measured data does not allow to make a distinction between the change in occupant behaviour and the physical rebound. Therefore, modelling the physical rebound is a better way for estimating the impact on the indoor temperature.

The aim of this paper is twofold. By simulating a realistic heating pattern in an existing terraced house, it is firstly shown how dwelling averaged indoor temperatures can easily deviate from the 18 °C as used in the Flanders Energy Building Performance Directive. Furthermore, these simulations depict how this more realistic heating pattern can lead to indoor temperatures that rise with increased insulation level – making it important to incorporate physical rebound when predicting energy savings.

2. Methodology

An existing terraced house is modelled as a multi-zone building in the dynamic simulation program TRNSYS. By varying the insulation thicknesses of the building envelope a set of cases with different insulation levels is obtained. For all of these, the net energy demand for space heating and indoor temperatures are calculated by whole year simulations with a time step of one hour. To do so, two main approaches are used: a reference calculation where the indoor temperature is fixed at 18 °C (based on the EPBD-regulation in Flanders) and an adjusted calculation where more realistic temperature settings are used (different time-schemes and temperature set-points for living, hall and sleeping zone). All other input parameters remain constant.

Hourly outside conditions are taken from the Meteonorm weather data file of Ukkel, Belgium. As an illustration, the monthly mean values of the external air temperature and the monthly aggregated total

(=diffuse + beam) solar radiation on a horizontal plane are given in Figure 1 and depict the moderate climate in Belgium.

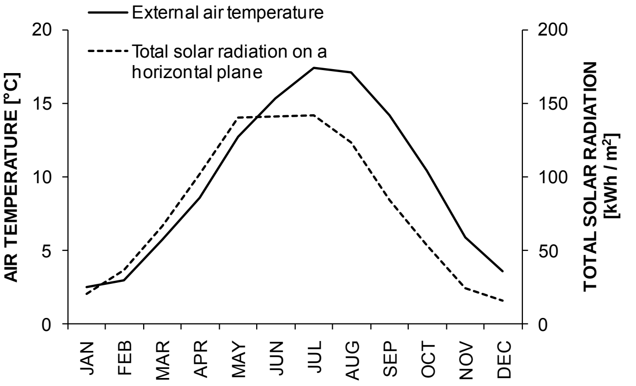


FIG 1. Monthly mean external air temperature and the monthly aggregated total solar radiation on a horizontal plane for Ukkel, Belgium (Meteonorm).

2.1 Case study

The terraced house was built in 1922 and consists of three stories and a basement. Floor plans are given in Figure 2. 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. The original building is not insulated. External walls consist of (from inside to outside) 0.015 m plaster finish, 0.30 m brick work and 0.02 m facade plastering. The floor above the basement is composed of (from top to bottom) tiles, 0.05 m sand bed and a bearing structure of brick vaults on iron beams. All internal floors and all flat and pitched roofs are built from wooden beams and wooden laths. Original windows have single glazing ($U_{glazing} = 5.68$ W/(m^2K), g-value = 0.855) in timber frames.

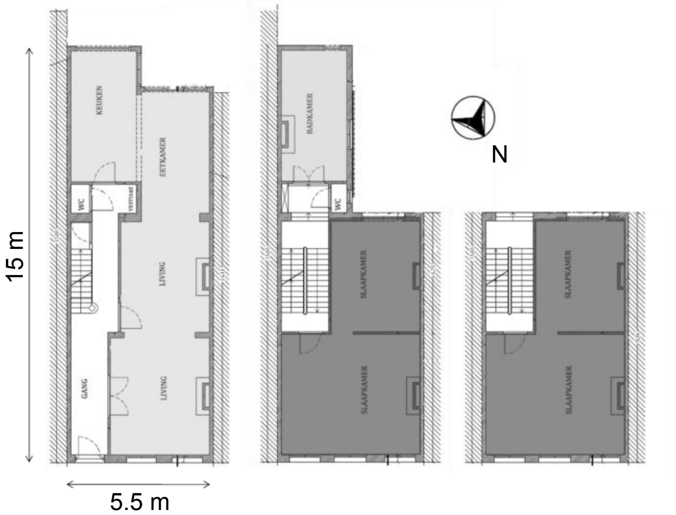


FIG 2. Floor plans of the three storey house with the ground floor (left), first floor (middle) and second floor (right). Light grey indicates ZONE I (living zone), dark grey ZONE II (sleeping zone) and white ZONE III (hallway). Basement floor is identical to ground floor.

Possible insulation measures of the building envelope are summarised in Table 1. All of these retrofit measures are combined with each other to form a set of 864 retrofitted dwellings. Since all dwellings have the same geometry and compactness, the insulation quality can be characterized by the mean U-value [W/(m^2K)]. The U-values vary from 0.28 W/(m^2K) to 1.83 W/(m^2K), with 0.66 W/(m^2K) representing the legal requirements in Flanders for this given dwelling geometry. Since retrofitting a dwelling without insulating the roof is highly unlikely, variants without roof insulation are not considered.

TABLE 1. Possible retrofit measures

	Material	**Thicknesses [m]**
Insulation flat roof	PU	0.10 / 0.20
Insulation pitched roof	Mineral wool	0.10 / 0.20 / 0.30
Interior insulation street-side facade	PU	0 / 0.05 / 0.10 / 0.15
Exterior insulation back-side facade	EPS	0 / 0.05 / 0.10 / 0.20
Insulation floor above basement	Mineral wool	0 / 0.05 / 0.10
	Frame	**Glazing**
Windows	Timber Frames	U = 5.68 W/(m^{2}K), g = 0.855
	Aluminium, thermally insulated	U = 2.83 W/(m^{2}K), g = 0.755
	Aluminium, thermally insulated	U = 0.86 W/(m^{2}K), g = 0.598

2.2 Two calculation methods

2.2.1 Reference calculation, based on the Flemish energy performance calculation

According to the EPB-legislation in Flanders, the dwelling is treated as a single zone at a fixed indoor temperature of 18 °C. This temperature is lower than a typical thermostat set temperature in living rooms and therefore already incorporates some night setback and zonal heating. Internal gains are only function of the heated volume, are set constant throughout the year and are uniformly distributed throughout the dwelling ($\Phi_{int} = 220 + 0.67\,V = 723$ W). Infiltration rates are expressed as a function of the heated volume and the air change rate at 50 Pa, n_{50} ($\dot{V}_{inf} = 0.04\,n_{50}\,V = 30$ m^3/h, with n_{50} assumed equal to 1 h^{-1}). In a similar way are the ventilation rates fixed ($\dot{V}_{vent} = (0.2 + 0.5\exp(-V/500))\,m\,V = 351$ 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 year.

2.2.2 Adjusted calculation, with realistic heating demand pattern

To account for the spatial variation in heating demand, the single-zone dwelling model is divided in 3 thermal zones: living rooms and kitchen at the ground floor and the adjacent bath room at the first floor (zone I, $V_I = 284$ m^3), sleeping rooms at the first and second floor (zone II, $V_{II} = 310$ m^3) and the hallway at to the 3 stories (zone III, $V_{III} = 157$ m^3). 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. Internal gains and infiltration and ventilation rates are adopted from the reference calculation method and remain constant throughout the year.

Given this adapted calculation procedure, it is possible to impose heating patterns that differ in time and space, thereby modelling more realistic building usage. A realistic heating pattern is given in Table 2, representing for example a single family with both parents working fulltime. Air temperatures of $T_{set} = 21$ °C and $T_{min} = 16$ °C are assumed for this analysis.

3. Results

The reference calculation (fixed indoor temperature of 18 °C) and the adjusted calculation (heating pattern Table 2 with a set temperature $T_{set} = 21$ °C and setback temperature $T_{min} = 16$ °C) are imposed to all dwellings. To visualize the influence of the external temperature, the data is analysed according to the assessment method as found in Janssens et al. (2006). Per zone, every daily mean value is sorted according to the external temperature, using intervals of 1 °C. Averaging the values per interval leads to a mean value per zone for a specific external temperature. When this is done for the same zone of all 864 dwellings, every interval contains 864 values from which mean, minimum and maximum

TABLE 2. Example of a realistic heating pattern: timetable and demand temperatures

		ZONE I Living area	ZONE II Sleeping area	ZONE III Hallway
WEEK	0 – 6h	T_{min}	T_{min}	-
	6h – 9h	T_{set}	-	-
	9h – 16h	T_{min}	-	-
	16h – 22h	T_{set}	-	-
	22h – 0h	T_{min}	T_{min}	-
WEEKEND	0 – 7h	T_{min}	T_{min}	-
	7h – 22h	T_{set}	-	-
	22h – 0h	T_{min}	T_{min}	-

values can be derived. The outside temperature of the three former days is incorporated by using a reference external temperature $T_{e,ref}$ as described in van der Linden et al. (2006):

$$T_{e,ref} = \frac{T_{e,0} + 0.8T_{e,-1} + 0.4T_{e,-2} + 0.2T_{e,-3}}{2.4}\ [°C] \tag{1}$$

with $T_{e,n}$ the arithmetic average of the minimal and maximal external temperature of day n. Following this method, the daily mean indoor temperatures of the zones and total dwelling are given in Figure 2. The minimum and maximum values correspond to the least and best insulated dwelling. The dwelling averaged temperature is the volume weighted mean of all zone temperatures.

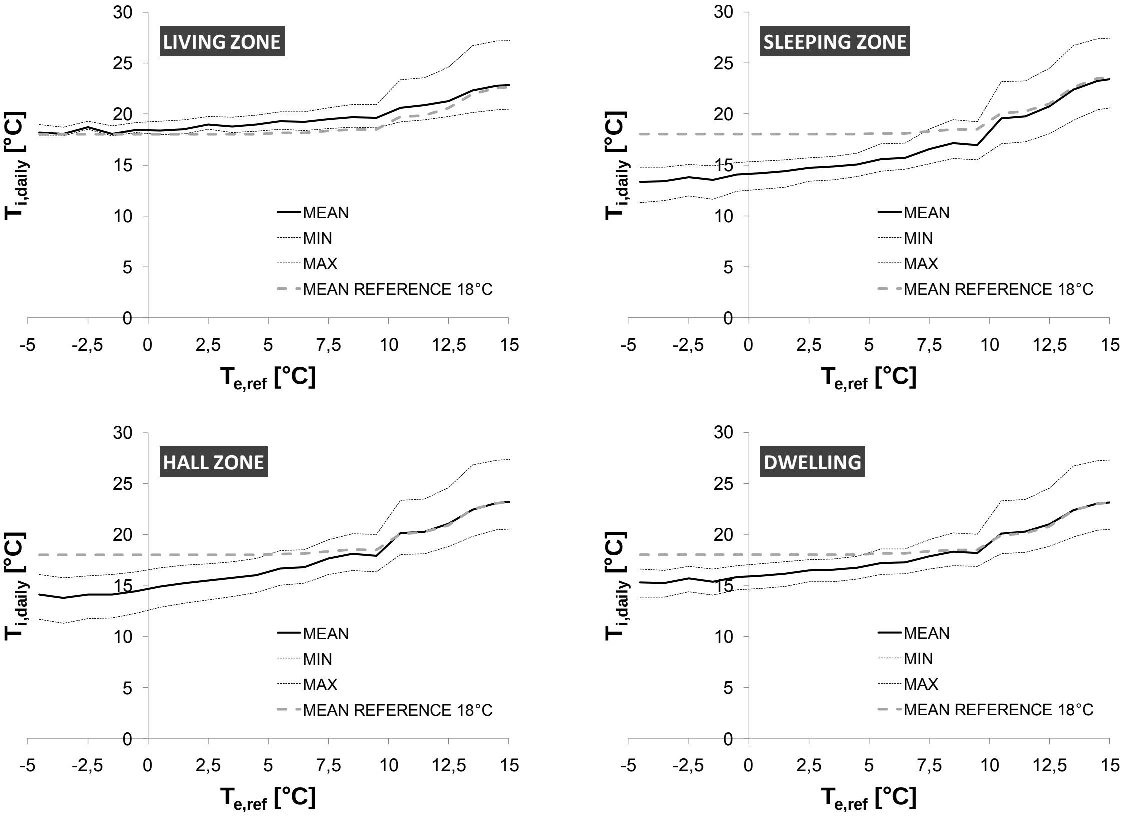
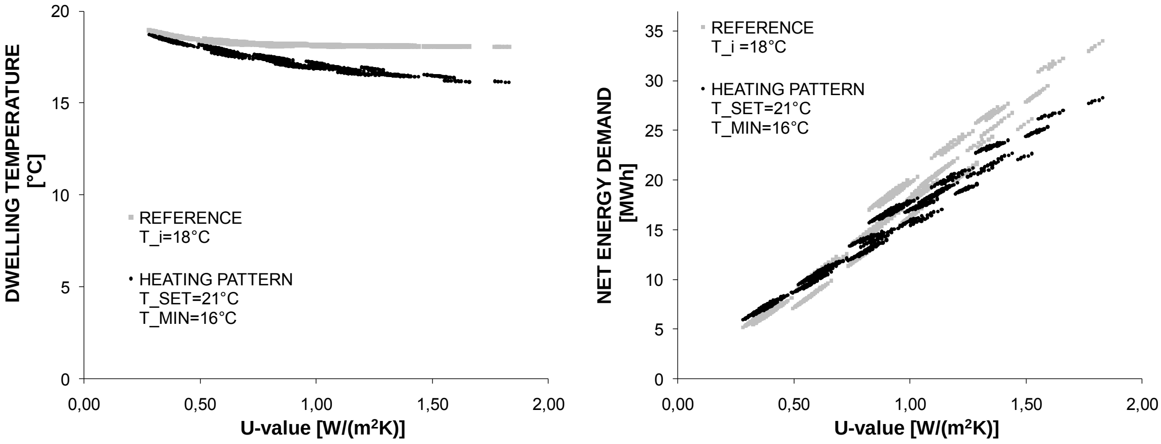


FIG 2. The daily mean zone and dwelling temperatures in function of the reference external temperature when the heating pattern from Table 2 is imposed with T_{set} = 21 °C/ T_{min} = 16 °C. The mean value of the reference situation with a constant indoor temperature of 18 °C is also shown.

Given the imposed heating pattern of Table 2, the temperatures in the living zone correspond best to those of the reference calculation: both are relatively independent from outside temperatures lower than 10 °C and only little variation occurs for different insulation levels. While the living temperatures of the least insulated dwelling vary around the reference 18 °C, temperatures in the best insulated dwelling are somewhat higher. For the latter, the temperature drop between two heating periods is very small, leading to average temperatures closer to the set-point of 21 °C. In the sleeping and hall zone however, strong correlation can be found with the external temperature: daily mean temperatures easily drop below 15 °C for external temperatures under 0 °C. Now the band width around the mean value is quite large, depicting how a better insulation level impacts the temperature in unheated zones through lower transmission heat losses and higher utilization of solar gains. As a result, dwelling temperatures clearly depend on both outside temperature and insulation level and moreover, do not attain the 18 °C as assumed in the reference method.

The heating season and dwelling averaged indoor temperature and the heating season net energy demand for space heating are given in Figure 3 as a function of the mean U-value of the dwelling. In Belgium the heating season can be defined from October to April.



a) b)

FIG 3. Reference calculation with indoor temperature 18 °C (grey) versus adjusted calculation with heating pattern from Table 2 with T_{set} = 21 °C/ T_{min} = 16 °C (black): heating season mean dwelling indoor air temperature (a) and heating season net energy demand for space heating (b).

In Figure 3a the impact of the heating pattern on the dwelling temperature is clearly visible. The simplified reference gives, as expected, temperatures almost independent of insulation level, while the more realistic settings show a clear correlation with insulation level. High U-values give dwelling temperatures around 16 °C, much lower than the 18 °C assumed in the reference calculation. When looking at better insulated dwellings with U-values around the legally required value of 0.66 W/(m^{2}K), both methods give quite similar temperatures. For the very low U-values the heating season indoor temperatures rise above 18 °C, even for the reference calculation. Due to the enhanced insulation level of these dwellings the heating season is much shorter than the period used in the calculation (from October to April) and temperatures at the beginning and end of this period can be higher due to the better utilization of solar gains. One can clearly see the physical rebound effect when applying a realistic heating pattern: indoor temperatures increase with improved U-values. This implies that, when calculating energy savings with a single zone model, the indoor boundary condition before retrofit should be different from that after retrofit. The evidence for this is found in the corresponding net energy demands of Figure 3b. With a mean U-value of 1.8 W/(m^{2}K) the net energy demand evaluated with the reference calculation is about 20 % higher than that evaluated with the more realistic heating pattern. Since all other parameters are equal, this large difference can only be explained by the lower indoor temperatures for the latter. Again, when going to better insulated variants that fulfill the legal requirements in Flanders, both methods give similar results. This indicates that the 18°C of the reference method –which was originally developed for newly built, well insulated houses– is indeed a good assumption for these dwellings. For the extremely well insulated dwellings the situation reverses. For the case considered, simulations with 18 °C give slightly lower energy demands than with the realistic heating pattern.

Based on the simulations from Figure 3, one can see how the slope of the reference calculation is steeper than that of the adjusted calculation. Although the simulations are based on simplifications concerning internal gains, ventilation and infiltration rates etc., this difference in slope gives an insight in how incorrect predictions are easily made. Consider the case study dwelling with a U-value before retrofit of 1.83 W/(m^{2}K) (10 cm flat and pitched roof insulation; single glazing) and a U-value after retrofit of 0.62 W/(m^{2}K) (10 cm flat roof and 20 cm pitched roof insulation; 10 cm wall insulation (interior and exterior); 5 cm floor insulation; double glazing $U_{glazing}$ = 2.83 W/(m^{2}K)). Figure 4 shows the initial points before retrofit and the end points after retrofit for both calculation methods.

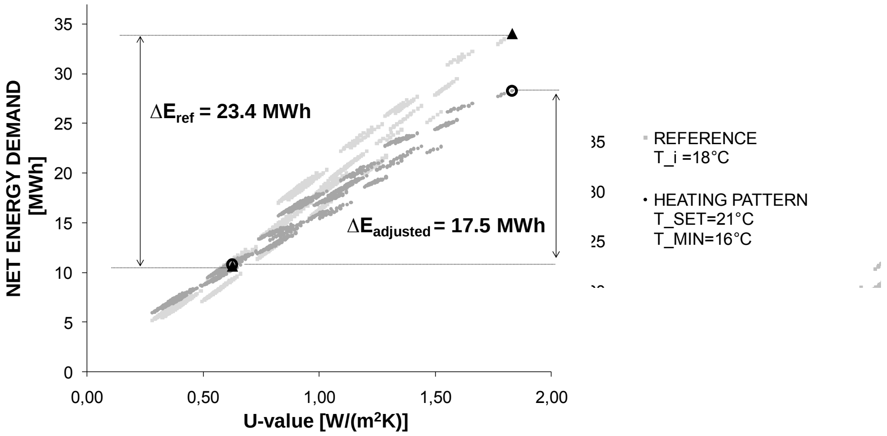


FIG 4. The reduction in net energy demand for space heating when the dwelling is retrofitted from an initial U-value of 1.83 W/(m^{2}K) to a U-value of 0.62 W/(m^{2}K), calculated with a fixed indoor temperature of 18 °C (ΔE_{ref}) and with the more realistic heating pattern ($\Delta E_{adjusted}$).

When calculated with the reference method, the heating season net energy demand for space heating equals 34 MWh before retrofit and 10.6 MWh after retrofit. When calculated with the adjusted calculation method, initial demand is only 28.3 MWh decreasing to 10.8 MWh after retrofit. The relative reduction in energy demand equals 69% for the reference and 62% for the adjusted method. In absolute terms, the difference between the two methods is much more pronounced. The reference calculation gives a net reduction of 23.4 MWh compared to 17.5 MWh for the adjusted calculation. This means that, if the reference calculation is used, the net decrease in energy demand can be overestimated by (23.4-17.5)/17.5 x 100% = 34%. Even though this analysis concerns only net energy demand, it is clear that the impact on calculated savings of end energy consumption can be important.

As already mentioned, general assumptions have been made in the simulations. In reality, infiltration rates often decrease after retrofit (air-tight window frames), ventilation rates might increase due to the introduction of mechanical exhaust or balanced ventilation systems, internal gains are seldom distributed uniformly, the type of heat emission system might influence the comfort level in the indoor environment leading to a different demand temperature than assumed, ... Furthermore, these simulations are performed for one predetermined heating pattern in a specific case study with a fixed geometry and orientation. Large variations are possible for all of these parameters. An extensive sensitivity analysis will be performed to reveal the impact on the results. Although a first comparison of the calculated indoor temperatures with temperatures from monitored projects already gives good correspondence, further validation with reality is needed to confirm the conclusions.

4. Conclusions

The implementation of the EPBD-directive in Flanders lead to the development of a calculation tool to determine the energy performance of newly built well insulated dwellings. Nowadays this tool is more and more used as a prediction tool for energy savings in existing dwellings. In this tool the dwelling is considered as a single zone at a fixed indoor temperature of 18 °C, which proved to be a fairly good approximation in well insulated dwellings. For badly insulated dwellings this is not the case.

In this paper the impact of the single zone assumption is analysed by simulations on an existing dwelling. By varying the insulation thicknesses it is made clear how the dwelling indoor temperature can deviate from the generally assumed 18 °C when a more realistic heating pattern (zonal and intermittent heating) is imposed – especially in badly insulated dwellings. The physical rebound is revealed and the impact on net energy demand assessed. Based on the simulations, a single zone model can only be used for calculating energy savings if a correlation is provided between insulation level and indoor temperature. Further research is needed on how this correlation should be described.

5. Acknowledgements

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