Can DEAP help us to predict the energy demand and indoor temperature of homes before and after renovation ? A case study from Dublin

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ABSTRACT: Improving the energy efficiency of buildings via retrofitting is seen as one of the key mitigation measures to reducing the energy demand and carbon emissions of the built environment in Ireland. However, while energy efficiency retrofits for buildings are effective in theory, the energy savings estimated by statistical or engineering models can often be inaccurate. The Domestic Energy Assessment Procedure (DEAP) is the standard assessment procedure used for assessing the energy performance standard of residential buildings in Ireland. This paper examines the gas energy demand for space and water heating and the internal temperature profiles in contrast to DEAP estimates for a group of social housing units which were retrofitted to improve their energy performance standard. For the 16 households examined, theoretical energy demand was overestimated and theoretical average temperatures were underestimated on average. Based on the sample of houses in this study, the DEAP assumption of a 3°C temperature differential between the living area and the rest of the dwelling during heating hours is not representative of temperatures in actual buildings.

KEY WORDS: Energy Performance Gap; Energy Efficiency Retrofits; Indoor Temperature Profiles.

1 INTRODUCTION

Improving the energy efficiency of buildings via retrofitting is seen as one of the key mitigation measures to reducing the energy demand and carbon emissions of the built environment in Ireland [1]. However, while energy efficiency retrofits for buildings are effective in theory, the energy savings estimated by statistical or engineering models can often be inaccurate.

Several studies have reported the average energy saving deficits of studies to range from 14% to 98% [2]–[12]. Scheer et al. [2] found a shortfall in energy savings ranging from 28-44% for homes involved in the SEAI Better Energy Homes scheme which provides grants to Irish homeowners for energy efficiency retrofits.

Many studies have used engineering models which rely upon steady state/quasi steady state formulae to determine the theoretical space heating demand of a building. These models/formulae are representative of the formulae used for producing an energy performance certificate.

Of the reviewed studies involving the use of steady state/quasi-steady state models/formulae, reasons for the discrepancies in actual energy usage to theoretical energy usage of engineering energy demand models have been associated with technical building characteristics, energy usage practices and malfunctioning equipment. Studies have highlighted the quality of the energy audit [13], model [3], space heating system efficiency [12], air-tightness of buildings [11], [14], building fabric [4], [11], [12] and solar coefficient [12] as issues with the technical building characteristics of the engineering energy demand models.

Energy usage practices such as internal room temperatures [5], [8], [15], heating duration [16], space heating set point temperatures [12], [16], [17], multiple space heating systems contributions to heating load [5], [18], hot water heating practices [8], [17], [19], space heating return temperature, ventilation practices [15] and occupancy patterns [15], [20] have been also identified as reasons for the discrepancies. Reasons outside the control of both, such as malfunctioning space and water heating equipment [8], [11], [18], have also been identified.

In Ireland, an energy performance certificate for a residential building is known as a Building Energy Rating (BER) and is assessed using a standard assessment procedure referred to as Domestic Energy Assessment Procedure (DEAP). Studies have examined the differences in the assumptions used in DEAP to model the energy demand of houses in Ireland to what actually occurs in the monitored houses. An Irish study on the oil consumption of 145 houses pre-retrofit found that houses with a lower BER were poorer predictors of a household's oil consumption [5]. Based upon the post-retrofit data collected in this study, some of the main reasons for the differences in the theoretical and actual energy demand were believed to be due to the theoretical internal room temperatures of DEAP not being representative of the actual internal room temperatures and the underestimation of the usage of the secondary heating systems in the households.

Byrne et. al [21] examined the in-situ thermal resistances of the external wall and ceiling building elements of a detached house in Ireland. The study found that improvement in the thermal resistance of the ceiling and wall building elements following a retrofit were 75% and 60% lower than expected. Hunter et. al [22] examined differences in assumptions in DEAP to what actually occurred in a group of retrofitted houses regarding the hours of heating and indoor temperatures. The study found that DEAP overestimated heating schedules and room temperatures by up to 37% and 1°C, respectively.

This paper adds to the growing literature of studies examining the differences in assumptions used in DEAP to model the energy demand of houses in Ireland to what actually occurs in

Irish homes. The paper focuses on the gas energy demand for space and water heating and the internal temperature profiles of a group of social housing units which were retrofitted to improve their energy performance standard.

2 METHOD

The theoretical energy demand for each of the case study buildings was calculated using the quasi-steady state formulae of DEAP detailed in Section 2.1. The theoretical energy demand was calculated for three months pre- and post-retrofit. The theoretical energy demand and indoor temperatures were compared to gas usage and indoor temperature data collected from a group of social housing units discussed in Section 2.3 with the data collection and screening procedure discussed in Section 2.2.

2.1 Quasi-Steady State Formulae

DEAP is based on the European Standard IS EN 13790:2004 [23] and draws heavily on the UK's Standard Assessment Procedure (SAP) [24]. DEAP is similar to other European standard assessment procedures as it includes an analysis of the buildings (i) form, (ii) thermal, solar and daylight properties of the building envelope, (iii) air permeability, (iv) space, water heating and ventilation systems, (v) fixed lighting and (vi) fuel and renewable energy sources. Using these variables together with a standardised heating schedule and monthly climatic conditions, the energy required to maintain an average internal temperature on a monthly basis is calculated. DEAP assumes that the heating season is from October to May. The space heat in DEAP is determined by the energy required to maintain a single-zone average temperature during a given period of time [25]. The energy demand (ED) for space heating for a given period of time is calculated as follows:

$$ED = \frac{(Q - UEG)\ Days\ 24}{\mu A_f 1000} \tag{1}$$

where Q is the rate of heat loss, UEG is the useful energy gains experienced by the house from solar energy gains through windows in addition to internal gains from appliances, occupants and space heating, Days is the number of days during the time period, A_f is the total floor area (m^2) of the dwelling, and μ is the efficiency (%) of the primary heating system. The coefficient 24 (h/day) within Eq. 1 is to convert the rate of fuel consumption into the rate of fuel consumed per day (W/m^2/day), while the coefficient 1000 is to convert the fuel consumed to (kWh/m^2/day). The rate of heat loss Q is calculated as follows:

$$Q = \left(\sum U_i A_i + 0.33NV\right)\Delta T \tag{2}$$

where U_i is the thermal transmittance ($W/K/m^2$) of the building fabric, A_i is the surface area (m^2) of the building fabric, N is the background air infiltration rate (air changes/h) and V is the internal dwelling volume (m^3). The background air infiltration rate, N, is a combination of the infiltration rate due to openings (chimneys, vents etc.) and the structural air tightness of the building. ΔT is the difference between the average internal and external temperature. The sum of the fabric and ventilation heat loss of a building is referred to as the heat loss coefficient.

During weekdays and weekends, the space heating is assumed to operate from 7am to 9am and 5pm to 11pm [25]. The required internal temperatures during the two heating periods are 21°C for the living area and 18°C for the rest of the dwelling. The average temperature during the heating periods is calculated based on the required temperature of the living area and the rest of the dwelling weighted by their respective floor areas. The required energy to achieve the average temperature is divided between the primary and secondary heating system.

2.2 Data collection and screening

There were four main forms of data collection during the pre-retrofit and post-retrofit monitoring phases including (i) surveys on the physical characteristics of the buildings, (ii) installation of temperature, relative humidity and electricity consumption data-logging instrumentation, (iii) monthly readings of electricity and gas meters and (iv) pre-retrofit and post-retrofit participant surveys. At least four temperature and relative humidity data loggers were installed in each of the houses. Six months of pre-retrofit data is available and 15 months post-retrofit. The six pre-retrofit months of data comprises of four heating season months (Feb-May) and two non-heating season months (June-July). For the purposes of this paper, data collected from Mar-May in 2015 (pre-retrofit) and in 2016 (post-retrofit) were utilised. Further information on the surveys is available in a study examining how the energy cultures of the householders shaped the household energy demand of the case study houses [26].

Four or five rooms had temperature and relative humidity data loggers installed. Lascar EL-USB-2+ acted as the temperature and relative humidity data loggers. The data loggers have an accuracy of ±0.45°C for temperature and ±2.05% for relative humidity. These data loggers were unobtrusive and recorded data at one-hour intervals pre-retrofit and 15-minute intervals post retrofit. The internal environment data loggers were installed at heights ranging from 0.5m to 2m. The height installation depended on both the available surfaces in a house and the householders. In some instances, householders did not want the data loggers to be installed on walls in case the paint on the wall or wallpaper was damaged when removing the data logger. For other houses, data loggers had to be installed at heights to avoid children moving the data loggers.

Despite a researcher installing the data loggers, internal environment data for some individual rooms in a number of houses were missing for data analysis. The amount of missing data varied from case to case. Reasons for the missing data included (i) loss of the data logging instrumentation by the householder, (ii) loss of battery power in the data logging instrumentation, (iii) full capacity of the data logger's internal memory, (iv) malfunction of data logging instrumentation, (v) data loggers placed together, (vi) data loggers moved or stored in press and (vii) data loggers in direct sunlight. All the temperature data collected from the data loggers for each room were plotted for qualitative analysis to identify any errors or anomalies. Reasons identified for exclusion of data included (i) data logger moved near heat source or window and (ii) temperature profile of room significantly different to other rooms of house with no logical explanation.

For the purposes of this paper, temperature data had to be available for either the kitchen or living room and at least one of the bedrooms for the household to be included in the analysis. The same rooms also had to be available for the pre- and post-retrofit period. Due to this screening procedure, data from 16 of the 23 houses were available for processing. Although temperature data were available in 15-minute intervals post retrofit, hourly temperature values were processed for comparison of the pre- and post-retrofit periods.

Three months (March, April and May) of monitored pre- and post-retrofit gas usage and indoor temperature data were compared to the theoretical assumptions and results of DEAP. To improve the direct comparison of the results, the external temperature and global radiation values from Dublin Airport [27] were used when assessing the theoretical gas demand and internal temperatures for the 3 months pre- and post-retrofit. Dublin Airport is located within an 11 km radius of the case study buildings.

The daily global radiation on surfaces for the given time periods were determined from hourly direct solar radiation, isotropic diffuse radiation, and isotropic ground reflectance radiation values. The hourly direct solar radiation, isotropic diffuse radiation and isotropic ground reflectance radiation values for eight orientations were calculated using a given surface tilt angle, hourly surface azimuth angle relative to the sun [28] and hourly direct solar radiation and diffuse radiation collected at Dublin Airport [27].

2.3 Case Study

There were five main types of houses within this study, as defined by construction year and terrace position (figure in brackets indicates the number of houses in each category): 1994 mid-terrace (2), 1994 end-terrace (6), 2000 mid-terrace (4), 2000 end-terrace (2) and 2000 semi-detached (2). As the end-terrace and semi-detached houses constructed in 2000 had the same technical characteristics, they are referred to as end-terrace houses for the remainder of the paper. The houses constructed in 1994 and 2000 had heated floor areas of 78m^2 and 87m^2, respectively. Each house has a downstairs kitchen and living room, 3 bedrooms upstairs (front bedroom, back bedroom and box bedroom) and an upstairs bathroom.

Each of the houses received a package of thermal fabric and heating system energy efficiency retrofit measures. The thermal fabric energy efficiency measures included pumped cavity wall insulation, attic insulation, double-glazed uPVC-framed windows, uPVC-framed front door, and uPVC-framed back patio doors. The U-values of the building elements pre- and post-retrofit are given in Table 1. The building element U-values were calculated based on ISO 6946:2007 [29]. The pre-retrofit layers of the building elements were identified in a pre-retrofit survey. Product data sheets on the retrofit measures were sourced from the architectural firm overseeing the project [30]. The thermal properties of the layers for the building elements were sourced from product information data sheets and the Irish energy performance building regulations [31].

The main space heating systems in all the Dublin residences comprised of a gas boiler feeding a central heating system with radiators in each of the rooms of the house. The main domestic hot water (DHW) heating system for the houses was also the gas boiler in combination with a DHW storage tank. The original boiler installed in the 1994 house had an efficiency of 78%. The original boiler in the 2000 house had an efficiency of 77%. The main space and water heating system in each house was replaced with a high energy efficiency gas boiler and hot water tank. Following the retrofit works, all houses had a gas boiler with an efficiency of 92%.

For comparing the theoretical and actual gas demand results, it was not feasible to disaggregate the actual gas demand into space and domestic hot water (DHW) heating requirements. Therefore, a theoretical estimate of gas demand for DHW was added to the space heating demand estimates. DEAP estimates the theoretical energy demand for DHW taking account of heating demand, storage and distribution losses, efficiency of the heating system and the water usage per person per day. The theoretical energy demand for DHW was estimated based on the version of DEAP (when it was known as the Dwelling Energy Assessment Procedure) published in 2012 [32]. The following version, published in Q3 2019 [25], provides a more detailed procedure for assessing the theoretical DHW energy demand. Some of the information required for the new procedure was not collected during the building inspections in 2015 and 2016.

A solid fuel open fire, multi-fuel stove, gas fire or electric fire act as a secondary heating system in the living room in the homes, but were rarely used. Therefore, when assessing the theoretical gas demand and internal temperatures, it was assumed the gas boiler provided all the space heating requirements of the buildings.

Table 1. Pre-retrofit (PRE) and post-retrofit (POST) U-values (W/m^{2}K) of the building elements.

Building Element	Construction Year	PRE U-Value	POST U-Value
External Wall	1994	0.59/1.62*	0.59/1.32*
External Wall	2000	0.46	0.33
Roof	1994, 2000	0.39	0.11
Windows	1994, 2000	3.1	1.5
Doors	1994, 2000	3.0	1.5

*section of the exterior wall on the ground floor adjacent to the living room is constructed with cavity wall construction with brickwork acting as the external layer

3 RESULTS

Pre-retrofit, the 16 households included in the analysis had an average theoretical energy demand of 25 kWh/m^2, 15 kWh/m^2 and 13 kWh/m^2 during March, April and May, respectively. However, the theoretical energy demand overestimated the actual energy demand of the households. The average actual energy demand during March, April and May was 11 kWh/m^2, 9 kWh/m^2 and 5 kWh/m^2, respectively. All 16 households consumed less energy over the three month period compared to the DEAP estimates.

Post-retrofit, the average theoretical energy demand of March, April and May reduced to 8 kWh/m^2, 7 kWh/m^2 and 4 kWh/m^2. The gap between the theoretical and actual energy demand reduced post-retrofit. Actual energy demand was 7 kWh/m^2, 6 kWh/m^2 and 3 kWh/m^2. All but six of the households consumed less energy over the three month period compared to the DEAP estimates. Overall, while the total gas demand during March, April and May dropped by 118 kWh/m^2 following the retrofit, only 25% of the estimated energy savings were achieved.

Based on the large overestimates of the theoretical energy demand, it may be assumed that the householders were living in very cold houses. Prior to the retrofit works, many householders complained of heat loss, uncomfortably cool indoor temperatures, excess drafts entering via badly sealed windows and doors, condensation on windows and mould growth around window framing and junctions of walls and ceilings. However, the average 24hr temperature profiles of the households included in this study suggest many householders were living in what many perceive to be appropriate indoor temperatures.

For this group of households, the kitchen is considered the living area. 11 of the 16 households had temperature data available for the living area. Figure 1 and Figure 2 give the pre-retrofit average 24hr temperature profiles of the living area and rest of the dwelling of the households during March.

DEAP assumes the space heating operates from 7am to 9am and 5pm to 11pm and the required internal temperatures during the heating periods are 21°C for the living area and 18°C for the rest of the dwelling. These periods and temperatures are highlighted in Figure 1 and Figure 2.

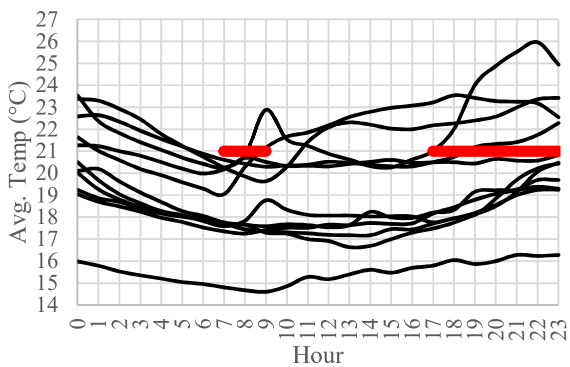

Figure 1. Pre-retrofit measured average 24hr living area temperature profile of the 11 households during March (red line indicates the default average temperature assumed in DEAP).

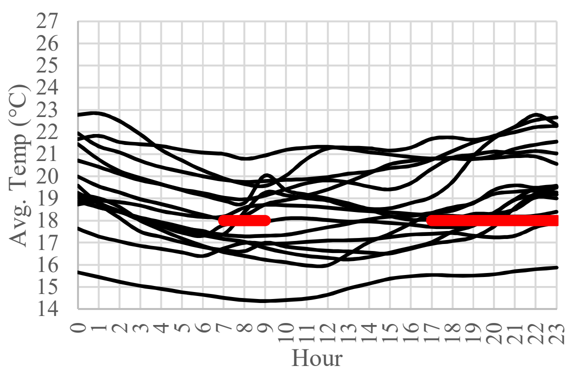

Figure 2. Pre-retrofit measured average 24hr rest of the dwelling temperature profile of the 16 households during March (red line indicates the default average temperature assumed in DEAP).

While all but four of the households have temperatures below the 21°C level assumed by DEAP in the living area during the heating periods, all but five of the households have temperatures above 18°C in the rest of the dwelling during the heating hours. During the three month pre-retrofit period, the 11 households with temperature data available in the living area had an average temperature of 20.0°C during the heating hour periods assumed in DEAP. Following the retrofit, the average temperature in the living area of the 11 households increased to 20.6°C. For the rest of the dwelling, the average temperature increased by 0.9°C to 20.3°C following the retrofit. Based on the sample of houses, assuming a temperature differential of 3°C between the living area and the rest of the dwelling during heating hours is not representative of temperatures in actual buildings.

The energy performance gap (EPG) is a metric used when comparing the actual energy consumption of a building as a proportion of the theoretical energy demand [33]. Table 2 gives the pre-retrofit EPG of each of the 16 households included in the study for March, April and May. Also included in Table 2 is the average (Avg.) and coefficient of variation (V). The case study numbers are the numbers applied to the case study houses in [26]. A negative EPG means the household consumed less energy than theoretically expected. Table 2 also includes the temperature performance gap (TPG). DEAP estimates the average indoor temperature of a building to calculate the rate of heat loss, Q, for a given period of time. The TPG compares the actual average temperature of a building as a proportion of the theoretical average temperature. The results of Table 2 show that even when the theoretical average temperatures were similar to the actual average temperatures, households still had significant EPGs. TPGs of ± 5% across the three months had corresponding EPGs of -67% on average.

Overall, theoretical energy demand was overestimated and theoretical average temperatures were underestimated. Households had an average EPG across the three months of -53% with a TPG of 7%. Following the retrofit, the average TPG increased, while the EPG decreased. Households had an average EPG of -18% post-retrofit and an average TPG of 15%.

Based on Eq.1, factors impacting the energy demand for space heating are the efficiency of the heating system, the useful energy gains, the floor area and the rate of heat loss, Q. The rate of heat loss, Q, is impacted by the heat loss coefficient (HLC) and the differential between the indoor and external temperature. Assuming the useful energy gains, heating system efficiency, monitored average indoor temperatures, external temperature data from Dublin Airport and steady state formulae are accurate, the HLC values required for the households to demand the actual energy consumption were estimated. The average, minimum and maximum estimated pre- and post-retrofit HLC for Mar, Apr and May are given Table 3 and Table 4. The theoretical HLC values, which are the sum of the fabric and ventilation heat loss of a building and remain constant, are also given.

As can be seen in Table 3 and Table 4, the average theoretical HLC values are higher pre- and post-retrofit. The estimated average HLC values for the month of May are lowest pre- and post-retrofit. The lower estimated HLC values for the May period may partially be explained by the fact that in the estimation of the HLC, it is assumed that heating occurs every day during the May period. In reality, this may not have occurred as May is the final month of the Irish heating season. Therefore, assuming a higher number of days where heating occurred resulted in a lower HLC.

Table 2. Pre-retrofit energy performance gap (EPG) and temperature performance gap (TPG) of households for March, April and May.

	EPG (%)			TPG (%)		
Case	Mar	Apr	May	Mar	Apr	May
1	-74	-60	-81	3	9	11
4	-53	-35	-69	18	12	10
5	-58	-58	-69	1	4	2
6	-62	-52	-83	3	5	6
7	-35	-30	-76	14	14	12
8	-35	-51	-67	14	12	7
10	-20	-17	-46	22	24	20
11	-18	4	-32	20	17	15
13	-68	-66	-91	1	2	1
14	-74	-70	-71	-4	1	0
15	-49	-47	-61	-3	3	2
16	-51	-31	-37	8	10	11
17	-83	-78	-79	-14	-6	-3
19	-73	-55	-86	1	-1	3
22	-66	-58	-76	0	1	1
23	4	20	-7	16	15	17
Avg.	-51	-43	-64	6	8	7
V	-0.5	-0.6	-0.4	1.6	1.0	0.9

Table 3. Average, minimum and maximum theoretical and estimated HLC values (W/K) pre-retrofit

	Theoretical	Estimated		
		Mar	Apr	May
Avg.	196	99	111	75
Min.	177	65	81	45
Max.	207	165	181	133

Table 4. Average, minimum and maximum theoretical and estimated HLC values (W/K) post-retrofit

	Theoretical	Estimated		
		Mar	Apr	May
Avg.	151	92	82	63
Min.	134	61	62	42
Max.	167	125	108	79

The average theoretical HLC reduced by 45 W/K following the retrofit. The average estimated HLC reduced by 7 W/K to 29 W/K depending on the month following the retrofit, which suggests that the building fabric improvements were not as effective as theoretically expected. This supports the findings of Byrne et. al [21] who found that improvement in the thermal resistance of the ceiling and wall building elements of a detached house in Ireland following a retrofit were 75% and 60% lower than expected.

Additionally, the differences between the theoretical and estimated HLC values ranged from 85 W/K to 121 W/K pre-retrofit and 59 W/K to 88 W/K post-retrofit. While the differences between the theoretical and estimated HLC values may not be as high as the results suggest due to the assumptions made in their calculation, it is expected that the theoretical HLC values are overestimated to some degree. Theoretical HLC values are expected to be overestimated as of the 48 EPG and corresponding TPG values given in Table 2, 38 overestimated the energy demand while also underestimating the average indoor temperature. Thus, in 38 instances, households were achieving higher indoor temperatures using less gas than theoretically expected. Post retrofit, in 32 instances, households were achieving higher indoor temperatures using less gas than theoretically expected.

4 CONCLUSION

This paper presents differences between the theoretical and actual energy demand and average temperatures of 16 households pre- and post-retrofit. The theoretical energy demand and average temperature values were calculated using the steady state formulae used in DEAP. DEAP is the standard assessment procedure for producing energy performance certificates for residential buildings in Ireland.

Energy performance certificates are seen as a tool for providing clear and reliable information to homeowners and tenants to compare and assess the energy performance of buildings [34], encourage owners to invest in improving the energy efficiency of the building through the provision of cost effect retrofit measures [34] and assist governments in developing policies to achieve national energy reduction targets in the building sector [35].

However, based on the findings of this paper and the other studies examining the accuracy of energy demand predictions using steady/quasi steady state formulae discussed in Section 1, energy demand predictions using steady/quasi steady state formulae should be met with some pessimism.

For the 16 households examined in this paper, theoretical energy demand was overestimated and theoretical average temperatures were underestimated. Households had an average EPG across the three months of -53% with a TPG of 7%. Following the retrofit, the average TPG increased, while the EPG decreased. Households had an average EPG of -18% post-retrofit and an average TPG of 15%. Overall, while the annual gas usage demand dropped by 118kWh/m^2 following the retrofit, only 25% of the estimated energy savings were achieved. The high number of instances where households were achieving higher indoor temperatures using less gas than theoretically expected suggests the HLC of the building was overestimated. In calculating the theoretical HLC in this paper, default U-values for the ground floor from DEAP had to be assumed pre- and post-retrofit as no other information was available. Furthermore, default U-values had to be used for the windows and doors pre-retrofit in addition to the structural air-tightness of buildings.

Ahern et al. [36] argued for default U-values to be updated as the pessimistic default values are higher than the performance in reality. This is leading to inaccurate modelling of energy demand in residential buildings which in turn is causing homeowners to be misinformed on the energy demand of their home and the potential impact of investing in energy efficiency retrofits. Byrne et. al [21] found that improvement in the thermal resistance of the ceiling and wall building elements following a retrofit were lower than expected despite not using default U-values from DEAP. Further study is required to assess the thermal performance of building elements and infiltration rates and their role in causing the energy performance gap between theoretical and actual energy demand.

Finally, based on the sample of houses in this study, the DEAP assumption of a 3°C temperature differential between the living area and the rest of the dwelling during heating hours is not representative of temperatures in actual buildings.

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