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The co-heating test as a means to evaluate the efficiency of thermal retrofit measures applied on residential buildings

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ABSTRACT

In order to reduce the energy use of residential buildings, regional governments in Belgium established, amongst others, mandatory criteria for the energy performance to be achieved after retrofitting. However, due to construction deficiencies, deviating boundary conditions, and non-modeled physical phenomena and interactions, the actual energy performance may differ significantly from theoretical design value. Several studies indicate this as the performance gap. This paper focuses on analyzing the actual impact of the refurbishment measures applied to a single-family home in Belgium. Hereto, in-situ measurements assessing the building envelope's thermal performance, described by the overall heat loss coefficient HLC [W/K], are performed both before and after the retrofit. To analyze this HLC, a quasi-steady state test, the so-called co-heating test, has been performed before and after renovation of a single-family home in Belgium, renovated to the nearly Zero Energy Building (nZEB) level.
As a result, the HLC determined with linear regression and an Auto-Regressive model with eXogenous inputs (ARX) show similar estimates, except for a smaller confidence interval for the ARX. Furthermore, it is shown that data set lengths shorter than 10 days are quite sensitive to sample times. For our case study, the gap between the theoretical and measured HLC enlarges after retrofit. Finally, the influence of a unheated neighboring zone on the HLC is assessed.

KEYWORDS
Heat loss coefficient – In-situ measurement – Renovation – Residential buildings – Regression techniques

INTRODUCTION

Since households have a 25 % share in the total energy use in Europe (Eurostat 2017), and a large share of the buildings has a poor energy performance (Cyx et.a al 2011), there is a high need to renovate existing buildings in order to increase energy savings. However, several studies indicate discrepancies between the theoretical and the actual energy use after renovation, a phenomena most-commonly known as the 'performance gap'. (Hens 2007 & Bell 2010)

This paper aims to assess the building envelope performance and identify the performance gap before and after retrofit by evaluating the overall heat loss coefficient (HLC) using a co-heating test (Bauwens 2015). Three aspects of the HLC estimation are evaluated for a single-family, terraced house. First, different sample times and data set lengths are evaluated for HLC estimation with linear regression and ARX models. Secondly, the performance gap of the pre-retrofit and post-retrofit dwelling state is assessed. Thirdly, the influence of the garage as a neighboring unheated room is evaluated for the post-retrofit HLC.

The methodology section consists of three parts: first the test case is described, then the heat loss coefficient is calculated from theory and finally the two data assessment models for HLC identification are presented. The results section discusses the HLCs and the performance gap.

METHODOLOGY

Test case

The case study is a terraced dwelling in Belgium, which has been renovated in the framework of the 'Ecoren'-project, one of the Flemish pilot projects for renovation. The characteristics of this dwelling before and after renovation are presented in Table 1. The table distincts between the situation with and without the garage enclosed in the protected volume, which enables to evaluate the garage's influence on the HLC, since the walls between the dwelling and its garage are uninsulated. As the attic floor was already insulated before renovation, the attic is assumed to be a neighboring unheated zone. The envelope renovation was realised by replacing the outer cavity leaf of the original uninsulated wall by a prefabricated building component. The air permeability and the air change rate at 50 Pa shown in Table 1 represent the resulting values of the blower door tests performed according to NBN EN 13829:2001.

Table 1. Characteristics of the dwelling case

	Pre-retrofit With garage	Pre-retrofit Without garage	Post-retrofit With garage	Post-retrofit Without garage
Protected volume [m³]	467	408	467	408
Building envelope [m²]	261	261	261	261
Air permeability at 50 Pa V_{50} [m³/(hm²)]	18.11	9.03	24.49	21.63
Air change rate at 50 Pa n_{50} [1/h]	15.95	9.59	21.57	22.98

A quasi steady-state co-heating test, as elaborated by Bauwens (2015), was carried out on the last three dwelling scenarios in Table 1. The co-heating tests of the protected volume without garage enables to compare the HLC of the same volume before and after renovation, while the tests of the two different volumes of the post-retrofit state can be used to estimate the heat losses through the garage. Before renovation, the protected volume without garage was kept at a constant indoor temperature of 20 °C for a period of 34 days in January 2016. After renovation, in February 2018, the indoor set temperature was 22 °C. During the first 20 days the protected volume included the garage, and secondly for 14 days the garage was excluded from the protected volume by closing the door. During these co-heating tests, the heating power was monitored, together with the outdoor climate, and the indoor air temperatures (accuracy ± 0.4 °C) in all rooms of the protected volume and neighboring zones, i.e. the attic, the garage and the two neighboring dwellings. The mean indoor temperature of the tested volume, used to estimate the HLC, was calculated as the volume-weighted average temperature $T_{i,avg}$ of all rooms enclosed by the protected volume. Additionally, the heat flux in between the protected volume and neighboring zones was measured using Hukseflux HFP01 sensors (3 % accuracy).

Theoretical heat loss coefficient

The HLC, composed by ventilation heat losses H_v and transmission heat losses H_{tr}, is calculated using equation (3) based on the approach of Bauwens (2015):

$$HLC = H_v + H_{tr} \tag{3}$$

With $H_v = c_a \rho_a n_{actual} V_i$ & $H_{tr} = \sum_{j=1}^{c} U_j A_j$

First, for ventilation heat losses H_v the following parameters are used: specific heat capacity of air c_a ($Jkg^{-1}K^{-1}$), air density ρ_a (kg/m^3), actual air change rate per hour n_{actual} (1/h), and the net air volume V_i enclosed by the building envelope (m^3). The actual air change rate per hour is estimated by dividing the air change rate at 50 Pa by 20 (Kronvall 1978) or by a tracer gas test.

Second, H_{tr} is calculated using the thermal transmittance U ($Wm^{-2}K^{-1}$) and the surface area A (m^2) of all building envelope components. As the original U-values cannot be identified exactly, H_{tr} is defined as a range to incorporate uncertainties. Therefore, for the original dwelling the thermal resistances of the building components are based on the national standard NBN B 62-002 2008, while for the renovated state an accuracy band of ± 5 % was set to the designed H_{tr}-value. In these H_{tr}-calculations, an equivalent, increased thermal resistance is determined for the floor addressed to the unheated attic following the national standard. (NBN B 62-002 2008).

Table 2 shows the resulting HLC calculated with equation (3) and the intermediate results of the actual air change rates n_{actual} and the heat losses H_v and H_{tr}. First, for all dwelling states n_{actual}-values in Table 2 were calculated from the n_{50}-values divided by 20. Additionally a tracer gas test was carried out for the full protected volume of the renovated dwelling, which resulted in a n_{actual}-value of 0.31 using the decay regression method (Sherman 1990). This is about three times lower than the resulting value based on the n_{50}-value, which was 1.08 1/h (Table 2). Therefore, the ventilation heat losses H_v of the post-retrofit dwelling are given as a range, of which the minimum is based on the tracer gas test and the maximum is based on the n_{50}-values. Finally, the resulting values of the HLC indicate an influence of 26 % to 31 % of excluding the garage from the pre-retrofit dwelling and 6 % to 10 % for the post-retrofit dwelling.

Table 2. Theoretic overall heat loss coefficient and its components

	Pre-retrofit With garage	Pre-retrofit Without garage	Post-retrofit With garage	Post-retrofit Without garage
Actual air change rate n_{actual} [1/h]	0.80	0.48	1.08	1.15
Ventilation heat loss H_v [W/K]	83	41	32 – 112	32 – 99
Transmission heat loss H_t [W/K]	310 – 366	260 – 314	114 – 126	105 – 116
HLC [W/K]	**393 – 449**	**301 – 355**	**146 – 238**	**137 – 215**

Data assessment models

In this work, the HLC is estimated using both a linear regression model and an Auto-Regressive model with eXogenous inputs (ARX). Using linear regression, the HLC can be estimated from equation (1) as the regression parameter ω_i, following the recommendations of Bauwens (2015):

$$\phi_h^h - \phi_{tr}^n = \omega_i T_{i,avg} + \omega_e T_e + \omega_{sol} I_{sol} + \epsilon \quad (1)$$

with ϕ_h^h the heating power, ϕ_{tr}^n the heat losses towards the neighboring zones, T_i the volume-weighted average of the indoor temperature, T_e the outdoor temperature, I_{sol} the global horizontal solar radiation, ϵ the residuals and ω_x the estimated regression parameters. Note that the intercept of equation (1) is equal to zero. The heat losses ϕ_{tr}^n, calculated from the heat flux signals, depend on the two tested volumes. When the garage is included in the protected volume, ϕ_{tr}^n consists only of the heat losses towards the neighboring dwellings, else the heat losses towards the garage are also accounted for.

The research of Bauwens (2015) assessed that one disadvantage of the linear regression model is that it tends to underestimate the confidence interval, and that the result is often less robust.

The ARX model however, leads to a more reliable confidence interval. Therefore, the second model used is the ARX model, represented by a similar equation as the linear regression model:

$$\Phi(B)\,[\phi_h^h - \phi_{tr}^n] = \omega_i(B)T_{i,avg,j} + \omega_e(B)T_{e,j} + \omega_{sol}(B)\,I_{sol} + \epsilon_j \quad (2)$$

However, in this model backshift operators are applied to the inputs and output of the model ($\Phi(B), \omega_i(B), \omega_e(B), \omega_{sol}(B)$), each of them being a polynomial of a different order. (Madsen et al. 2015) The overall HLC is now estimated as $\frac{\omega_i(1)}{\Phi(1)}$. The order of each backshift operator is determined by backward elimination: a 12-order model is reduced eliminating insignificant high-order parameters stepwise.

Following the statistical guidelines from IEA EBC Annex 58 (Madsen et al. 2015), the models are validated performing different tests: (1) testing for white noise residuals by autocorrelation plots or cumulative periodograms, (2) testing for uncorrelated inputs by cross-correlation functions between the residuals and their inputs, but also in between the inputs (3) testing for high parameter significance, and (4) testing for similar results using different data subsets and sample times. This fourth test is quite important, since the results of both models might be variating for different data subsets and sample times. Since cross-correlations might be affected by autocorrelations, an ARIMA(1,1,0) model is used to pre-whiten the inputs. (Bauwens 2015)

RESULTS

HLC estimation using linear regression models

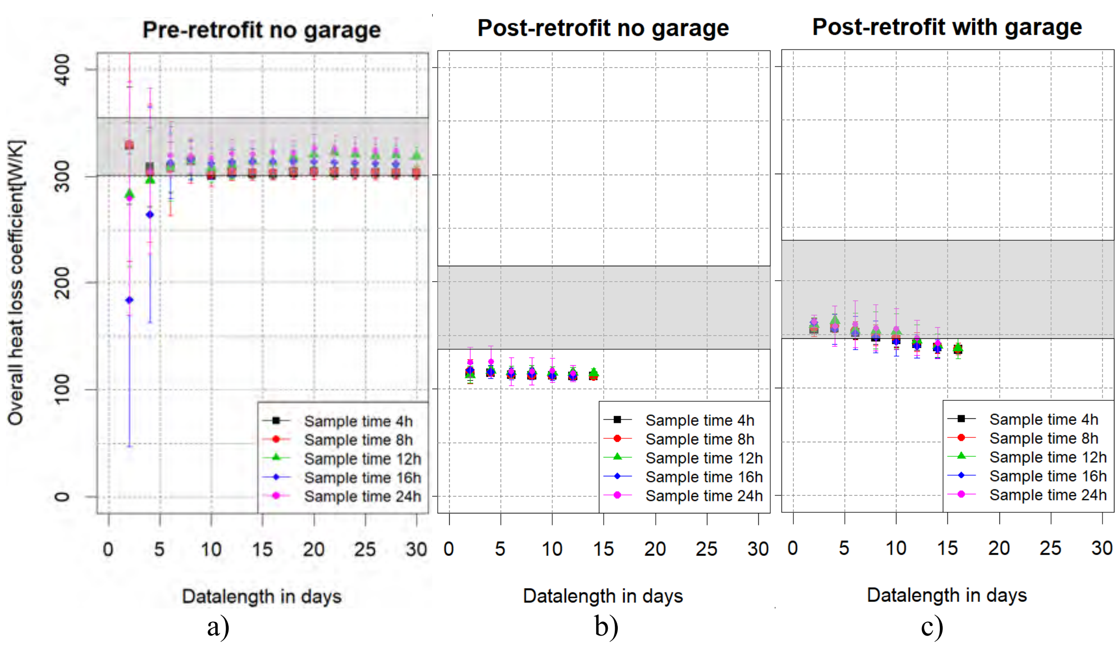

Figure 1. HLC estimated by linear regression a) pre-retrofit state without the garage enclosed in the tested volume, b) post-retrofit without garage, c) post-retrofit with garage.

Figure 1 shows the resulting overall heat loss coefficients and the related confidence intervals (2 times the standard deviation, 2σ), estimated by linear regression using different sample times and data set lengths. The grey band presents the theoretical HLC (Table 2). For the original dwelling (pre-retrofit Figure 1.a) the estimated overall heat loss coefficient (HLC_{estim}) in general corresponds to the theoretical value (HLC_{theo}). The HLC_{estim} values for data set lengths of more than ten days are quite similar. The sample time, however, seems to influence the estimates: for small sample times (4h and 8h) HLC_{estim} is ca. 10 % lower than for large sample times (24 h). Validation plots in Figure 2.a and 2.b show that the estimates of larger sample times are more reliable, although these results are less robust (i.e. more susceptible to the input) since less data points are involved. Therefore, a 12h sample time was selected to compare the linear regression model to the ARX model (further in Table 3), being more reliable than short sample times and more robust than long sample times. (see Figure 2.c)

For the post-retrofit dwelling scenarios, the gap between HLC_{estim} and HLC_{theo} has increased: HLC_{estim} is now lower than HLC_{theo}, although this discrepancy diminishes if the garage is enclosed in the protected volume (Figure 1.b and 1.c). Next, compared to the pre-retrofit state, the influence of sample time has decreased: HLC_{estim} of the first post-retrofit state is quite constant for a dataset length of more than ten days. The results for the second post-retrofit state, however, are more scattered and also less reliable (Figure 1.d and 1.e).

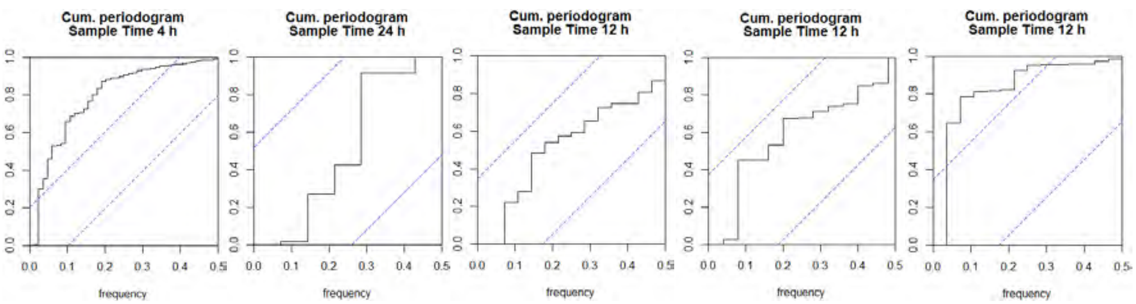

Figure 2. Validation plots of the linear regression model of a 14 day data set, first for the pre-retrofit dwelling scenario for a sample time of a) 4 h b) 24 h and c) 12 h, second for the post-retrofit dwelling scenario for a sample time of 12 h d) without garage and e) with garage

Performance analysis using different models

The dynamic ARX model was the second model from which the HLC was estimated. Since this model type can incorporate dynamic effects like the influence of solar radiation and thermal inertia of a building, the sample time can be reduced considerably. Out of four sample time models – 15, 30, 60 or 120 minutes – a 30 minute model was selected as the most reliable, based on the validation plots. The resulting HLC_{estim} for this model are compared to the theoretical values and the estimates of the linear regression model in Table 3. This table shows quite similar estimates of the HLC for both models, but with smaller confidence intervals for the ARX model.

Table 3. HLC values and confidence intervals (± 2σ) using the different models, for a 14 days dataset length. Linear regression: 12 hours sample time. ARX model: 30 minutes sample time.

Dwelling state	Theoretical HLC_{theo} [W/K]	Linear regression HLC_{estim} [W/K]	ARX HLC_{estim} [W/K]
Pre-retrofit no garage	301 ~ 335	313 ± 12.31	308 ± 6.68
Post-retrofit no garage	137 ~ 215	115 ± 4.61	115 ± 3.66
Post-retrofit with garage	146 ~ 238	139 ± 11.04	142 ± 10.21

As a result, table 3 shows a quite small performance gap for the pre-retrofit state, since HLC_{estim} is identified in the range of HLC_{theo}. Conversely, the HLC_{estim}-value for the first post-retrofit dwelling scenario deviates ca. 20 % from the theoretical lower boundary. However, the discrepancy decreases for the second post-retrofit scenario to ca. 5 %, although here a larger confidence interval was found. Altogether, the measured HLC increases by 20 % if the garage is included in the protected volume, which is higher than the theoretical influence (10 %).

CONCLUSIONS

In this paper, the building envelope performance of a terraced single-family dwelling was assessed before and after renovation by means of the overall heat loss coefficient (HLC), identified from co-heating tests. First, for linear regression analysis, the estimated HLC is quite constant for a data set length of more than 10 days, although the pre-retrofit results are varying with about 10 % for different sample times. Using ARX models results in similar estimates albeit with a smaller confidence interval. Hence, a co-heating test of 10 days should suffice to estimate a quite reliable HLC of a dwelling. Second, the measured HLC corresponds quite well to the theoretical HLC for the original dwelling state, but deviates ca. 20 % for the post-retrofit dwelling state without garage. Third, the garage's influence on the HLC is theoretically lower (10 %) than was measured (20 %), indicating the need for further assessment on the influence of an unheated neighboring zone on a dwelling's HLC.

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