Assessment of the heat loss coefficient of a renovated historical dwelling using a co-heating test

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Abstract. Twelve quasi-identical almshouses with an architectural-historic value were renovated, because of their high energy use, poor indoor comfort and numerous moisture problems. Aerogel plaster was applied for the hygrothermal upgrade of the uninsulated brick walls, while limiting the reduction of living space in these very small houses and keeping the monumental character of the facades in their original state. Several quality assurance tests were executed to evaluate the quality of the renovation of the building envelope and to compare the results with the initial theoretical design calculations. It appeared that the existing materials performed considerably better than the assumed conservative default values. On the other hand, the newly installed insulation materials performed somewhat less than declared, for example due to on-site processing. This resulted in a strong overestimation of the improvement in thermal performance by the renovation works. Field measurements of the existing situation can help to close this gap.

1. Introduction
As about 36% of the current greenhouse gas emissions in the EU originate from buildings and 85-95% of today’s buildings will still be in use in 2050, the renovation of existing buildings has a key role to play in the European Green Deal. The so-called ‘Renovation Wave for Europe’ initiative aims to at least double the annual energy renovation rate in the next ten years. This goal will be crucial, since around 75% of the current stock in Europe is energy inefficient [1], including historic buildings built before 1945 which represent around 23% of the total stock [2]. In certain countries, like the UK, Belgium, Denmark and Slovenia [3], this share rises to even more than 30%. Consequently, there is a large potential for improving these existing buildings, both in terms of energy efficiency and thermal comfort.

When carrying out an (extensive) energy renovation, the involved parties often are interested in how far the thermal quality of the building envelope’s constituent components actually have improved. By relying on measured rather than theoretical values, a major source of uncertainty in the assessment of the thermal quality of building envelopes can be eliminated [4]. However, since a properly implemented energy renovation usually not only brings a (significant) reduction in energy use, but also leads to an increase in thermal comfort, it is difficult to evaluate this improvement of the envelope purely on the basis of energy use data. This study aims to evaluate the actual energy performance of the building envelope based on field measurements and compare it to the theoretical design calculations.
2. Case study
In the framework of the Flemish Living Lab Projects [5], twelve quasi-identical almshouses of a small residential quarter in the historic city center of Bruges (Belgium) were deeply renovated between 2017-2020. These terraced houses were constructed in 1908. Besides a social-cultural value, this former almshouse complex also has an artistic and architectural-historic value. Consequently, it is protected as a monument. However, because of the high energy use, the poor indoor comfort and the numerous moisture problems in the dwellings, a renovation was needed.

Every entity is very small with an average total floor area of only 52 m². The ground floor consists of a living room in the main building and a kitchen and toilet in the lower extension. The open staircase in the living room leads to a corridor on the first floor, through which the bathroom and the only bedroom are accessible. The main building has a steep dual-pitched roof; the L-shaped extension has a low mono-pitched roof. The facade of the main building of one dwelling is shown in figure 1 (b).

2.1. Renovation plan
The existing houses were hardly insulated, so they had a great energy saving potential. It was the ambition to improve the building envelope in such a way that a low-temperature heating system with a central ground source heat pump would be possible. Furthermore, an improved indoor environment and a reduction in energy demand by at least 35% was aimed for. An important boundary condition for the design of the renovation was the requirement to preserve the monumental character of the façades. Exterior insulation was therefore not an option. However, the space available for interior insulation was also very limited. Consequently, a balance had to be found between improving the hygrothermal performance of the building envelope, limiting the reduction of living space and properly respecting the historical heritage.

Therefore innovative insulation materials with a very limited spatial impact were used. Vacuum insulated panels of 2 cm were installed on the concrete floor slab. In order to prevent the risk of mold problems, the renovation plan provided that the original plaster was replaced by a layer of 1.5 cm aerogel plaster on the interior side of the massive, one-and-half brick walls. The single-glazed wooden windows were replaced by thin double glass ($U_\text{T} = 2.0 \text{Wm}^{-2}\text{K}^{-1}$) in a wooden frame. The existing double glazed windows remained untouched. The old mineral wool of 8 cm between the rafters of the pitched roof was removed and replaced by new rock wool blankets of 16 cm.

2.2. Quality assurance tests
To get a better idea of the actual improvement as a result of the renovation, several quality assurance tests were executed. Before the construction works started, a blower door test was performed in two existing dwellings, following EN ISO 9972:2015, and the thermal performance of the outer wall of one house was evaluated with a heat flux measurement based on the instructions in ISO 9869-1:2014. During the construction works six samples of aerogel plaster were made by a craftsman on site, in order to determine the thermal conductivity of this material. The method as described in the Belgian standard NBN B 62-201:1977 was followed, using a guarded hot plate (GHP) test in a two-plate setup.

After the completion of the renovation the focus of all tests was on one house, which is considered representative of the majority of dwellings. A co-heating test was carried out in this house for 21 days, starting from 17 December 2018. During this test the indoor environment was kept at a constant temperature using electrical convector. Several fans were installed to keep the temperature in the dwelling as uniformly as possible and to avoid stratification. Sensors registered the temperature in all rooms. The balanced mechanical ventilation system was turned off and all vents were sealed, to disregard the heat losses through the deliberately created openings. During the co-heating test, flux plates and thermocouples were attached to an exterior wall and two party walls. A schematic of the test setup is shown in figure 2. Since the permanent heating system was switched on a few days prior to setting up the co-heating test, a stable indoor temperature was already achieved after 3 days. Just before the start of the test a blower door test was performed.
3. **Evaluation of the building envelope**

During the design phase of the project, simple heat loss calculations were used to quantify the reduction target in energy demand. These initial calculations were based on default values and material properties as defined in the Flemish energy performance regulations [6] (“dsg.”). During the renovation process, the calculations were refined with in situ measurements and empirical data on properties in order to make a good estimate of the theoretically expected value (“exp”).

Special attention was given to the determination of the confidence intervals (CI) to better map the probable distribution of the results. All mentioned uncertainties in this paper consider a CI of 95%. The uncertainty of theoretical values is calculated by simply adding the various errors, in order to gain insight in the maximum range on these values. The uncertainties of empirical values for independent variables are determined using the root of the sum of the squares.

3.1. **Aerogel plaster**

Since around 44% of the heat loss area of the studied almshouse consists of exterior wall that is insulated with aerogel plaster, this material plays a key role in whether or not the objective of reducing the energy demand by 35% is met. Therefore, the thermal properties of the aerogel plaster is studied more closely using a GHP test. After 20 days in a drying oven, two square samples with an average thickness of 28.3 ± 0.2 mm were tested at an average temperature of 20.0°C. While the technical documentation of the aerogel plaster declared a thermal conductivity $\lambda_D$ of 0.028 Wm$^{-1}$K$^{-1}$ at a reference temperature of 10°C, the test results showed that the in situ sample had a thermal conductivity of 0.0297 ± 0.0004 Wm$^{-1}$K$^{-1}$. Besides the higher reference temperature, the cause presumably can be found in the on-site mixing of the aerogel plaster. This is confirmed by the measured dry volumetric mass density of 250.6 ± 1.6 kgm$^{-3}$, which is 14% higher than the declared density of 220 kgm$^{-3}$.
Hereafter, the test was performed on two other non-oven dried samples ($\mu = \text{ca.} 0.04 \text{kgkg}^{-1}$) that were closer to the expected moisture content in the material. This sample was found to have a thermal conductivity of $0.0335 \pm 0.0004 \text{Wm}^{-1}\text{K}^{-1}$. Indeed, this value is very close to the calculated thermal conductivity based on the temperature and moisture conversion coefficients of related materials from EN ISO 10456:2007 for conversion from one set of conditions to another. Since this value is more representative for the actual situation, it will be included in the further analysis of this paper.

3.2. Exterior wall

In situ heat flux measurements were performed during winter by mounting a heat flow meter (HFM) on the internal surface and a set of thermocouples on both sides of the wall. Before renovation this was done during 14 days in March 2018 ($\theta_{e,avg} = 6.8 \pm 8.4\, ^\circ \text{C}$) on a northwestern façade of an occupied dwelling ($\theta_{i,avg} = 20.5 \pm 2.3\, ^\circ \text{C}$); the measurement after renovation took place from 20 to 24 December 2018 ($\theta_{e,avg} = 11.0 \pm 2.1\, ^\circ \text{C}$) on a northeastern façade of the dwelling where the co-heating test was performed ($\theta_{i,avg} = 27.3 \pm 0.6\, ^\circ \text{C}$).

To identify the thermal resistance of the wall, the measurement data was analyzed using the average method ('avg.'). Because of the high heat capacity of the brick façade, equation (1) is used over a period which is an integer multiple of 24 h. The conditions to define which estimates of $R_{\text{tot}}$ are reliable, as described in ISO 9869-1:2014, were fulfilled both before and after renovation. Thanks to the rather constant indoor and outdoor temperature during the latter test, also this limited data set of only 4 days was sufficient to meet the convergence criteria.

$$R_{\text{tot}} = \frac{1}{h_i} + \frac{\sum_{k=1}^{n} (\theta_{e,k} - \theta_{i,k})}{\sum_{k=1}^{n} q_k} - R_{\text{HFM}} + \frac{1}{h_e}$$ \hspace{1cm} (1)

where $h$ is the surface coefficient of heat transfer [Wm$^{-2}$K$^{-1}$]; $\theta_{e,i}$ is the temperature difference across the wall [$^\circ \text{C}$]; $q$ is the density of the heat flow rate [Wm$^{-2}$]; and $R_{\text{HFM}}$ is the heat resistance of the heat flow meter [m$^2$KW$^{-1}$].

This semi-stationary, passive characterization method of on-site measurements assumes a steady state heat flow where thermal mass is neglected [7]. The standard suggests a method to correct the heat flux measurements for these storage effects ('corr.'). Therefore thermal mass factors $F_i$ and $F_e$, based on estimations of the thermal properties of the wall, are proposed. The equations for these storage correction factors and the corrected heat flux can be found in the aforementioned standard. Since the measurements didn’t allow to estimate the change in heat stored in the wall (which is one of the criteria to be fulfilled to use the uncorrected 'avg.' without additional simulations, the analysis method was used both without ('avg.') and with ('corr.') correction for storage effects.

**Table 1.** Theoretically design and expected material properties of the outer wall.

| Layer | BEFORE RENOVATION | AFTER RENOVATION |
|-------|-------------------|------------------|
| Si    | $h_i$ (Wm$^{-2}$K$^{-1}$) | 7.7 $\rightarrow$ 7.2 $\pm$ 0.5$^a$ | 7.7 $\rightarrow$ 7.6 $\pm$ 0.4$^a$ |
| 1     | Gypsum plaster    | Aerogel plaster  |
|       | $d$ (m)           | 0.010 $\pm$ 0.005$^b$ | 0.015 $\pm$ 0.005$^b$ |
|       | $\lambda$ (Wm$^{-1}$K$^{-1}$) | 0.52 $\rightarrow$ 0.454 $\pm$ 0.054$^c$ | 0.028 $\rightarrow$ 0.0335 $\pm$ 0.0004$^d$ |
| 2     | Brick & Mortar    |
|       | $d$ (m)           | 0.27 $\pm$ 0.01$^d$ |
|       | $\lambda$ (Wm$^{-1}$K$^{-1}$) | 1.28 $\rightarrow$ 0.684 $\pm$ 0.058$^c$ & 1.5 $\rightarrow$ 0.454 $\pm$ 0.054$^c$ |
|       | $f_{\text{joint}}$ (-) | 0.28 $\rightarrow$ 0.256 $\pm$ 0.039$^d$ |
| se    | $h_b$ (Wm$^{-2}$K$^{-1}$) | 25 $\rightarrow$ 15.7 $\pm$ 3.5$^a$ | 25 $\rightarrow$ 15.8 $\pm$ 3.2$^a$ |

$^a$ EN ISO 6946:2017  
$^b$ estimation  
$^c$ IEA EBC Annex 55 [8]  
$^d$ measurement
The results for $R_{\text{tot}}$ in figure 3 show how the actual thermal resistance of the outer wall only improved with $0.34 \pm 0.07 \text{ m}^2\text{K}^{-1}\text{W}^{-1}$, which is significantly lower than the initially estimated increase of $0.52 \text{ m}^2\text{K}^{-1}\text{W}^{-1}$. These initial design calculations were based on static conservative values and hence underestimated the actual insulating quality of the existing masonry wall. Given their age, the bricks were probably fired in an uncontrolled oven on site, resulting in widely varying material properties of these bricks. By considering empirical material properties as mentioned in table 1, taking also into account a statistical spread, the gap between what is theoretically expected and the actual situation can be narrowed. To make the theoretical value consistent with the measured value, the theoretical properties before and after renovation were fitted to the empirical results in the further analysis of this study.

3.3. Building envelope

The objective of a co-heating test is to determine the heat loss coefficient (HLC) of the building, as a measure of the heat losses due to transmission ($\Phi_t$) and infiltration ($\Phi_{inf}$). Since these losses are both dependent of the indoor-outdoor air temperature difference $\Delta\theta_{i,e}$ [°C], they can be combined in one term, introducing the $\text{HLC} \ [\text{WK}^{-1}]$ in equation (2) [9].

$$\Phi_{h,\text{corr}} = \Phi_t + \Phi_{inf} - \Phi_s = \text{HLC} \cdot \Delta\theta_{i,e} - gA \cdot I_s$$

The heat generated by the convectors and dissipated by the fans ($\Phi_s$) was logged using electricity meters. This term was corrected ($\Phi_{h,\text{corr}}$) by adding the internal gains, coming from the standby losses of the boiler (28 W), and subtracting the heat exchange with both adjacent heated spaces through the party walls (on average 142 W). The former was estimated via a technical data sheet, the latter by means of flux sensors. The outside temperature was measured with a sensor on site and was in this analysis considered, for simplicity, as one constant parameter around the entire building envelope. During the test period it varied between 0.5°C and 13.2°C, with an average of 6.8°C. The entire interior space of the tested house is considered as one zone at a uniform temperature, which was determined as the volume-weighted average of the measured temperatures in every room. The solar gains ($\Phi_s$) are dependent of the global solar radiation $I_s$ [Wm$^{-2}$] and the overall solar aperture coefficient $gA$ [m$^2$]. On average, the solar radiation was 20.6 Wm$^{-2}$, based on data from a climate station nearby.

Equation (2) shows that there is a causal relationship with $\Delta\theta_{i,e}$ and $I_s$ as independent variables on the one hand and $\Phi_{h,\text{corr}}$ as dependent variable on the other. The unknown parameters HLC and $gA$ can be estimated using a linear regression analysis with the ordinary least squares as estimation method. To take into account the effect of (dis)charging the thermal mass of the building, daily average values are determined from dawn-to-dawn, starting from 08:00.

Finally, the share of transmission can be determined by estimating the heat loss coefficient for infiltration $H_{inf}$ from the blower door test. An air change rate $n_{50}$ of 6.8 h$^{-1}$ ± 8% was reported. This was only slightly better than the measured $n_{50}$ before renovation (8.9 h$^{-1}$ ± 12%) and was far from meeting the target value of 1 h$^{-1}$. Assuming a shielding coefficient $e$ of 0.05 ± 0.01, $H_{inf}$ only improved from 23 ± 6 Wk$^{-1}$ to 18 ± 4 Wk$^{-1}$. 

![Figure 3. Theoretical and empirical values for $R_{\text{tot}}$, before and after renovation.](image-url)
3.3.1. Simple linear regression. When the term for the solar gains in equation (2) is neglected, a simple linear regression analysis can be used to estimate \( HLC \). An intercept \( c \), containing all uncontrolled influences such as the sun, can be added to the equation. A two-sided hypothesis test showed that the regression coefficient is different from 0, confirming that \( \Delta \theta_{i-e} \) has a significant effect on \( \Phi_{h,\text{corr}} \). Figure 4 presents the results for \( HLC \) for a decreasing number of data points, considering the last days of the test. For 18 data points \( HLC \) is \( 114 \pm 24 \text{ WK}^{-1} \). On the contrary, the p-value for \( c \) was higher than the assumed significance level of 5%: the null hypothesis stating that \( c \) is equal to zero cannot be rejected, so it is possible that the regression line of the population goes through the origin. This is in line with expectations: when the indoor and outdoor temperatures are equal, the convectors shouldn’t supply any heat.

To make sure the results for these coefficients are the best linear unbiased estimators (BLUE), it is important to check whether the model satisfies the Gauss-Markov theorem (linearity, homoscedasticity and uncorrelated errors) and other assumptions (normality, exogeneity and influential elements). This can be done using formal test statistics or via charts as in figure 5 and 6. This revealed that the 2\(^{nd}\) of the 18 data points was a highly influential element, with a Cook’s distance higher than the critical value (figure 6 (a)). This outlier has high DFBETAs for both regression parameters, meaning that the inclusion of this individual observation leads to a high increase of \( c \) (figure 6 (c)) and decrease of \( HLC \) (figure 6 (d)). Despite a low \( \Delta \theta_{i-e} \), this data point has a relatively high \( \Phi_{h,\text{corr}} \), due to a remarkably high wind speed that day. Therefore, the result for \( HLC \) based on 16 data points \( (129 \pm 23 \text{ WK}^{-1}) \) is considered more representative. Indeed, this leads to a higher coefficient of determination \( R^2\text{adj} \) and a smaller CI, despite the lower number of degrees of freedom.

3.3.2. Multiple linear regression. Because the sun is generally considered as an important influencing factor explaining the variability in the heat input, \( I_s \) was included in the regression model as a second independent variable in a multiple linear regression model. Based on the condition indices, there is no multicollinearity between \( \Delta \theta_{i-e} \) and \( I_s \). However, the results for this third regression parameter \( gA \) don’t differ significantly from zero. The variable \( I_s \) has no significant influence on \( \Phi_{h,\text{corr}} \). Therefore, these results for \( HLC \) were shaded in figure 4. Moreover, this model doesn’t reduce the CI for \( HLC \), nor does it solve the problem of the highly influencing element. Apparently, the impact of the sun could be eliminated by carrying out the experiment during the shortest days of the year with the lowest solar altitude.

Alternatively the regression line can be forced through the origin, assuming that all involved heat flows in the building are well controlled. This leads to a strong reduction of the CI, as this fixed point is far outside the measured range for \( \Delta \theta_{i-e} \). But besides, this approach hardly influences the results in this case. Including more variables, such as the wind speed, didn’t improve the estimation.

![Figure 4](image-url). Theoretical values for \( HLC \) before and after renovation and empirical values based on a simple (SLR) and multiple (MLR) linear regression with (incl. \( c \)) and without (excl. \( c \)) intercept.
Figure 5. SLR analysis with intercept based on 18 data points with (a). Scatter plot with $\Phi_{h,\text{corr}} [W]$ as function of $\Delta \theta_{i-e} [^\circ\text{C}]$ with regression line; (b). Residual plot with Loess curve; (c). Histogram of standardized residuals with Gauss curve; (d). Normal Q-Q-plot with standardized residuals.

Figure 6. Detection of influencing elements in SLR with intercept based on 18 data points with (a). Indexplot of Cook’s Distance $D_i$; (b). Indexplot of Leverages $h_i$; (c). Indexplot of standardized $DFBETAS_{0(i)}$ for the intercept; (d). Indexplot of standardized $DFBETAS_{1(i)}$ for $\Delta \theta_{i-e}$. 
The initial design calculations showed an improvement of HLC from 382 to 163 WK\(^{-1}\) (-57%). Based on the measurement results of the preceding tests, these results were adjusted to an expected value of 258 ± 43 and 162 ± 38 WK\(^{-1}\) respectively, leading to an adjusted improvement of HLC with only 37%. The large decrease in HLC for the situation before renovation is mainly due to the better thermal resistance of the existing masonry. However, after renovation, this effect is largely neutralized by the inadequate airtightness and the higher thermal conductivity of the aerogel plaster. This rebound effect [10] results in a shortfall in energy savings by the renovation. This is solely based on the improvement of the building envelope and doesn’t take into account possible other rebound effects as a result of an increased comfort (e.g. a higher set point temperature) nor heat losses due to active ventilation.

The empirical results from the co-heating test confirm the theoretically expected HLC, since their CI overlap. Both approaches most likely give a good estimate of the actual HLC, where in this case the result of the co-heating test has a smaller CI and thus offers a more accurate estimate. After all, this test on the entire building provides a more overall estimate of the thermal performance of the building envelope, without having to make uncertain assumptions about the numerous influencing factors.

4. Conclusions
In order to verify whether a predetermined target of a renovation is actually being achieved, it is important to have information about the in situ performance of the building both before and after renovation. This case study showed that the performance of the existing building envelope was better than estimated by the assumed conservative default values, while the newly installed insulation material performed somewhat less than declared. A co-heating test is an accurate method to close this gap between the calculated and actual energy performance. However, this test is rather cumbersome, since it necessitates a lot of equipment, a sufficiently long test period during which the building cannot be entered and a large energy use. This study illustrates how a reliable estimate for HLC as a measure of the heat losses of a building due to transmission and infiltration can be made via a more manageable approach by means of a selection of well-chosen field measurements, such as in this study a GHP test, flux measurements and blower door tests, to better assess certain crucial but hard-to-predict characteristics.

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