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Estimation of the Heat Loss Coefficient of Two Occupied Residential Buildings through an Average Method

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Abstract: The existing performance gap between the design and the real energy consumption of a building could have three main origins: the occupants' behaviour, the performance of the energy systems and the performance of the building envelope. Through the estimation of the in-use Heat Loss Coefficient (HLC), it is possible to characterise the building's envelope energy performance under occupied conditions. In this research, the estimation of the HLC of two individual residential buildings located in Gainsborough and Loughborough (UK) was carried out using an average method. This average method was developed and successfully tested in previous research for an occupied four-story office building with very different characteristics to individual residential buildings. Furthermore, one of the analysed residential buildings is a new, well-insulated building, while the other represents the old, poorly insulated semidetached residential building typology. Thus, the monitored data provided were filtered in order to apply the abovementioned average method. Even without fulfilling all the average method requirements for these two residential buildings, the method provides reliable HLC values for both residential buildings. For the house in Gainsborough, the best estimated HLC value was 60.2 W/K, while the best approach for Loughborough was 366.6 W/K. Thus, despite the uncertainty sources found during the analysis, the method seems promising for its application to residential buildings.

Keywords: heat loss coefficient; average method; building envelope's in-use energy performance

1. Introduction

The majority of buildings constructed in the European Union in the past were built without considering any thermal regulations, since energy efficiency was not considered a major issue until the 1970s [1]. It is well known that buildings in the EU are responsible for a considerable percentage of the energy consumption and CO_2 emissions in accordance with H2020 Energy Efficient Buildings. Therefore, the building sector is currently in a decarbonisation process to reduce the problem [2].

However, achieving an energy efficient building is not a simple task. Several buildings designed to obtain a considerable reduction in energy consumption have failed during this process. This is because there is still an important difference between the real performance and the theoretical performance given by the designers [3]. A considerable number of studies have shown that the real energy consumption can be up to two to five times higher than the predicted energy consumption [4,5].

The energy performance difference, commonly known as the performance gap, has numerous different causes. Some are due to such factors as the construction or operation [6]; others derive from such data uncertainties as the climate conditions affecting the building, or the behaviour of the occupants. Several analyses have been carried out to study how a specific climate and the behaviour of the occupants can affect the energy behaviour of the building [7,8]. Moreover, the shape of the building is also linked to its energy efficiency [9]. Hemsath and Bandhosseini [10] and Montazeri et al. [11] have done research into how the relation between the height and the width of a building can affect the heat transfer. However, one of the main reasons for this performance gap is the energy performance of the building's envelope [12]. Several works of research have focused on the monitorisation of the indoor energy of a building in order to test different retrofit solutions under different climatic conditions [13]. Last but not least, the high cost of monitoring buildings forces researchers to develop methods that can obtain robust results with a limited number of variables [14].

Achieving an accurate estimate of the real energy consumption is a complex task. This is due to the numerous problems found when estimating each of the different causes that create uncertainties in the energy consumption calculation. These problems can directly affect the modelling and simulations in the estimation process of an accurate energy consumption value. In order to solve the current problems in the building sector, the International Energy Agency IEA-EBC Programme [15] has been developed. This programme involves energy research and innovation with collaboration from several countries.

Therefore, the informal group formed by different organizations, named DYNASTEE [16], is taking part in the IEA-EBC Annex 71 [17] project called "Building Energy Performance Assessment Based on In-situ Measurements". This Annex is the step that follows the previously developed IEA-EBC Annex 58 titled "Reliable building energy performance characterization based on full scale dynamic measurements", where the characterization of buildings' energy performance based on dynamic measurements was investigated. Therefore, the aim of the IEA-EBC Annex 71 is to improve even further the characterization methods for the real energy performance of building envelopes and to provide in-situ quality assurance methods. The aim is to develop steady-state and dynamic data analysis techniques, along with good quality in-situ measurements. Therefore, the aim of the Programme is to monitor in-use buildings to obtain reliable, quality data and thus be able to provide accurate and reliable Key Performance Indicators (KPIs) of the building's envelope energy performance using different methods [17].

One of the most important analyses carried out within the previous Annex 58 was the Round Robin Box test [18], in which the participants tested the thermal behaviour of the box by shipping it to different countries. Then, the obtained data was analysed using four main methods. On the one hand, averaging methods and simple or multiple linear regression [19–21] were used to estimate the stationary thermal properties of the box envelope. In this case, the HLC (Heat Loss Coefficient) is the main KPI that was estimated. This parameter considers the building's heat transmission through the envelope and the ventilation and/or infiltration losses per temperature degree difference between indoors and outdoors in [W/K]. On the other hand, the ARX (Auto-Regression models) (ARMAX) [22] and State Space models [23] were used to estimate the stationary and dynamic thermal properties of the box envelope [24].

The ongoing Annex 71 is now focused on the in-situ estimation of the thermal behaviour of in-use building envelopes. Therefore, the aim of this paper is to demonstrate the validity of the average method developed in [25,26] for an occupied office building into two residential buildings, as never done before. The behaviour of the heating system, the internal heat gains and the solar gains is very different in office buildings compared to residential buildings. However, due to the difference found in the weight of the heat gain sources within an office building, it is possible that some of the average method requirements that limit the valuable monitoring periods for accurate HLC estimation cannot be fulfilled for residential buildings. Thus, the limits the method found when working in a residential building are also analysed.

The method is applied to two case study individual residential buildings with different sizes, occupation, internal gains, use, monitoring period and envelope insulation characteristics. The data from the analysed residential buildings is provided by the Annex 71. The first building is in Gainsborough (UK) (see Figure 1a) and is a well-insulated, occupied building. It is one of the four social houses monitored in [27] and the HLC 'theoretical value' given by the Annex 71 is 49.9 W/K. The latter value is estimated based on the building design characteristics. The Gainsborough case represents a not very detailed monitoring system of a real in-use house, but with a very long monitoring period of three years. However, the second house, in Loughborough (UK) (see Figure 1b), is inhabited by synthetic occupants. Moreover, it is a traditional uninsulated semidetached residential building. This house has already been tested through the co-heating method in [28] and the HLC 'theoretical value' is 382 W/K. The dataset used for the house analysed in Loughborough can be found in [28], where the house 1 (HT1) files were studied. The Loughborough case represents a very detailed monitoring system of a synthetic occupants' in-use house, but with a short monitoring period of one month.

(**a**) (**b**)

Figure 1. (**a**) North side of Gainsborough house; (**b**) front side of Loughborough house [28].

Both houses show two extreme building situations: The first showing occupied, well-insulated, residential building conditions with a not very detailed monitoring system, but monitored for a long period; while the second is a synthetic occupant controlled, uninsulated residential building with a very detailed monitoring system, but monitored for a short period. Thus, these two cases are considered suitable for this research work, since they represent the extreme opposite situations for testing the average method in the residential building level.

2. Materials and Methods

2.1. Average Method

The average method can be used for the HLC estimation of in-use whole buildings. The formulas developed in [25,26], and used to estimate the HLC, are:

$$HLC_{simple} = \frac{\sum_{k=1}^{N}(Q_k + K_k)}{\sum_{k=1}^{N}(T_{in,k} - T_{out,k})} = \frac{\frac{\sum_{k=1}^{N}(Q_k+K_k)}{N}}{\frac{\sum_{k=1}^{N}(T_{in,k}-T_{out,k})}{N}} = \frac{\overline{Q} + \overline{K}}{\overline{T_{in}} - \overline{T_{out}}}\ [W/K] \quad (1)$$

$$HLC = \frac{\sum_{k=1}^{N}(Q_k + K_k + S_a V_{sol,k})}{\sum_{k=1}^{N}(T_{in,k} - T_{out,k})} = \frac{\frac{\sum_{k=1}^{N}(Q_k+K_k+S_a V_{sol,k})}{N}}{\frac{\sum_{k=1}^{N}(T_{in,k}-T_{out,k})}{N}} = \frac{\overline{Q} + \overline{K} + \overline{S_a V_{sol}}}{\overline{T_{in}} - \overline{T_{out}}}\ [W/K] \quad (2)$$

where Q_k is the heating system heat input in [W], K_k is the total electricity consumption of the building in [W], S_a is a fixed equivalent solar aperture to obtain the solar gains of the building in [m^2] regarding $V_{sol,k}$ (that is, the south global vertical solar irradiance [W/m^2]). Moreover, $T_{in,k}$ [°C] and $T_{out,k}$ [°C] are the indoor and outdoor air temperatures. There are N measurement points in the analysed period and k is the measurement correlative index.

The average method should only be used for periods with very low solar radiation and high space heating demand. For such periods, it is possible to ensure that the solar heat gains compared to the rest of the heat gains within the building (space heating plus all other internal gains excluding solar radiation) are less than 10%. By estimating HLC_{simple} and HLC, the weight of the solar gains in the HLC estimate can be analysed. By comparing the HLC to the HLC_{simple} of an analysed period, it is possible to check whether the solar gains represent a considerable part of the total heat gains within the building. Since the not directly measurable solar gains, together with the metabolic heat generation, are the main uncertainty sources of the method, while it is interesting to estimate the HLC_{simple}, it has no physical meaning.

The average temperature difference between the indoor and outdoor air during the testing period must be high (values close to or higher than 15 °C are recommended). Thus, measuring errors in temperature difference calculations will be minimized and high heating demands will also permit the heating supply to be accurately measured.

According to [25,26], in order to check the reliability of the HLC estimates for the whole building using the average method, it is interesting to test if the HLC accumulated average value is stabilised during the last 24 h of the selected periods through plotting the accumulated average of the HLC. If the estimate is stabilised within a ±10% band over the last 24 testing hours (see accumulated HLC average plots in Appendix A), it can be assumed that the obtained HLC with the average method is valid.

Finally, due to the complexity of accurately estimating the accumulated heat of the building, it is mandatory to have the same average building temperature at the beginning and end of the selected periods for estimating the HLC. This temperature will be the average temperature between the indoor and outdoor temperatures. If this is fulfilled, it can be assumed that there will be no accumulated heat in the building in the analysed periods, since the start and end points of the analysis will have the same thermal level. Then, similar conditions to stationary conditions could be assumed. This issue is fully demonstrated in Section 2.1 of [26].

2.2. Input Data

The monitoring systems of each given building measured different parameters. A combination of smart meters and dedicated sensors were used in both buildings to monitor each of the parameters in Table 1 with at least a 5 min frequency. The monitoring system of Gainsborough is described in detail in [27], while the monitoring system of Loughborough is described in detail in [28]. However, the input data provided were filtered in order to obtain common input parameters for both houses, as shown in Table 1. The filtering procedures were not the same due to the different characteristics of the monitoring systems.

For the Gainsborough house, only the total gas consumed by the boiler was provided. However, the mains water consumption of the house was also provided. The boiler was providing heat for both the space heating and the DHW (Domestic Hot Water). The Gainsborough boiler is a Potterton Promax combination boiler with an efficiency of 91% regarding the SAP procedure, according to the manufacturer [29]. Like most conventional boilers, it does not produce DHW in parallel with space heating. Thus, when DHW is required, the boiler stops the space heating supply and all the heat produced by the boiler is used for DHW production. In order to estimate the gas consumed by the space heating from the total gas consumption, the following assumption was considered: If there was gas consumption at the same time as there was mains water consumption, all this consumed gas was considered as gas consumption solely for DHW. In other words, only the gas consumption while no mains water was consumed was considered as space heating. This filter was applied on a five minute basis.

Moreover, for the Gainsborough building, only the electricity consumption was considered when estimating the internal gains (K). The occupancy heat created by the occupants' metabolic generation was neglected (part of K), as not enough information was provided to make an estimation. Different occupants lived in this building over the three winters of the data provided. Due to this, achieving occupancy patterns of the inhabitants to estimate the metabolic heat gain they produced was very complicated.

However, the Loughborough house is a traditional uninsulated building occupied by monitored synthetic occupants. This means that the house behaves as if real people were living inside. Thus, the metabolic heat gain produced by these synthetic users was also considered as a heat gain. All the internal heat gains, including the metabolic generation of the synthetic occupants, were measured by means of several watt meters that measured all the electrical consumptions occurring within the building. Moreover, for the Loughborough house, the heat output of the boiler to the space heating system was directly measured. In other words, it was not necessary to use the boiler efficiency or split the space heating and the DHW consumptions. Moreover, accurately measured synthetic profiles were added to simulate the occupants' behaviour. Therefore, all heat gains (Q + K), as well as the thermostat settings, were accurately known.

In order to estimate the solar gains, since only cloudy periods should be used for applying the average method, the radiation could be considered purely diffuse and thus similar on all façades. Therefore, a g-value of 0.5 could be applied to the total window area, as in [30]. Once this roughly estimated solar gain was obtained, it could then be compared to the averaged (Q + K) value of the selected periods to see whether the averaged period solar gains were below 10% as compared to the averaged period (Q + K). Then, the HLC estimate would mainly be dependent on the measured Q and K that can be accurately measured when compared to solar gains. Moreover, the propagation of the uncertainty of the sensors was also considered when estimating the HLC error bands. The provided sensor accuracy for the monitoring systems of the two houses can be seen in Table 2. Note that, as in the average method [25,26], other uncertainty sources related to the assumptions made by the method are not propagated to the HLC estimations carried out in this work. In the case of the solar gains uncertainty, apart from the accuracy of the pyranometer (considered 5% for this analysis), the solar aperture uncertainty was also considered. As done in [25,26], despite the solar aperture (S_a) being unknown, a 10% error was considered for the latter. Thus, the total uncertainty considered for the solar gains of both buildings was 15%.

Table 1. List of input parameters for applying the average method.

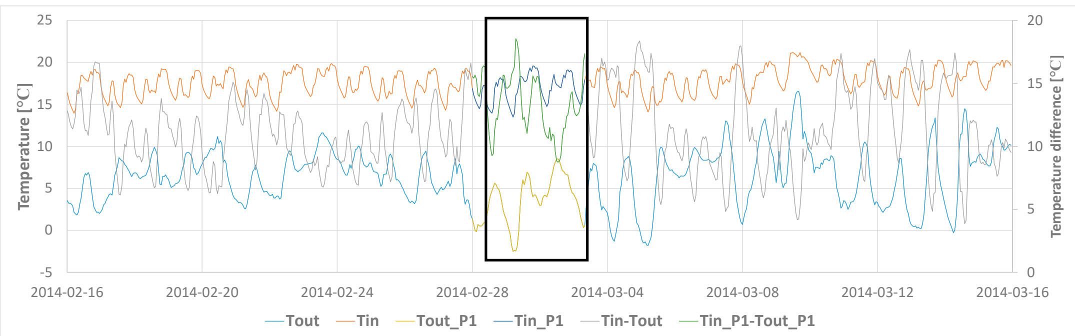
Sensors	Measured Parameter	Description
Thermocouple/Thermistors	Outdoor temperature (°C) $T_{out,k}$	On-site outdoor air temperature
	Indoor temperature (°C) $T_{in,k}$	Measured in different rooms of the house. In order to achieve a unique temperature for the building, a non-weighted average temperature was estimated using the following formula: $T_{in,k} = \frac{T_{in,1}+T_{in,2}+\ldots+T_{in,n}}{n}$
Energy consumption devices	Boiler heat output (kWh) Q_k	When required, the gas consumption was converted by boiler efficiencies to space heating system kWh supply. Hot water energy supply is not considered in this term.
	Total electricity consumption (kWh) K_k	Measured for the whole building or in each of the rooms of the house.
Pyranometer	Solar radiation (global horizontal solar irradiance [W/m^2]) H_{sol}	Obtained from the Waddington weather station. In order to apply the average method, it was converted into south global vertical solar radiation (V_{sol}) [31].

Table 2. List of measurements and provided accuracy for applying the average method.

Measurement	Gainsborough Accuracy	Loughborough Accuracy
Indoor temperature	±0.25 °C	±0.2 °C
Gas meter	±2%	±2%
Electricity consumption	±2%	Not provided (±2% assumed)
Outdoor temperature	±0.5 °C	±0.2 °C

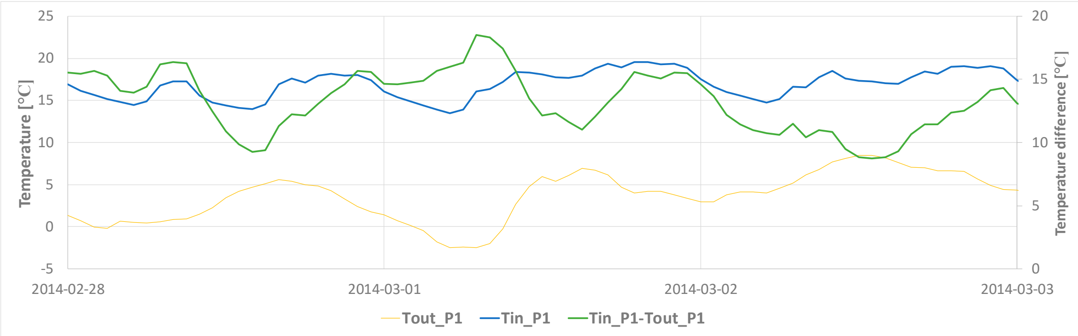
In Table 1, due to the high homogeneity of indoor temperatures during the analysed periods, the indoor temperature is considered as the non-weighted average of all the measured indoor temperatures. A full development of the properties of the HLC, regarding its estimation in buildings comprising different thermal zones with different indoor temperature set points, is mathematically developed and demonstrated in Section 2.2 from the reference [26]. There, the requirements to be able to estimate the whole building HLC by means of the sum of the zone HLCs are described. Such needs are basically to know individually each zone heat gain ($Q + K + S_aV_{sol}$) and each zone T_{in}. In both of the one family residential buildings analysed in this work, it was only possible to consider one thermal zone, as the internal heat gains ($Q + K + S_aV_{sol}$) could not be accurately split between the different rooms that make up the dwelling. Most of the internal gains were measured only on the whole building level. Furthermore, for each individual temperature measurement, the period averaged value has been compared to the period average of the non-weighted average indoor temperature. For all the analysed periods, the indoor temperature homogeneity of the buildings has been so high that the difference between the period averaged values of individual indoor temperatures and the non-weighted indoor temperatures have been within the sensor error band.

In order to see the behaviour of each of the monitored parameters, Figure 2a shows the evolution over one month of the indoor and outdoor air temperatures for the Loughborough building. There, the temperature difference between the interior and the exterior is also plotted. From Figure 2a, it can be concluded that the temperature difference between the exterior and interior is considerably high during the selected period. A zoom-in of Period 1, used later to apply the average method, is also presented in Figure 2b. Figure 3a shows the evolution of the solar gains (S_aV_{sol}), the space heating systems' heat input (Q) and the total electricity consumption, including the synthetic occupants' generation (K) for the Loughborough building, again including a zoom-in on period 1 in Figure 3b. If Figure 3a is analysed, it can be seen that it is not possible to find a three-day period where the solar gains remain below 10% when compared to the rest of the measurable heat gains (Q + K). Finally, as an example, Figure 4 shows the accumulated average plot of the HLC for period 1 in Loughborough. It can be seen how the HLC value stabilises along the duration of the period and remains within the 10% bands over the previous 24 h.



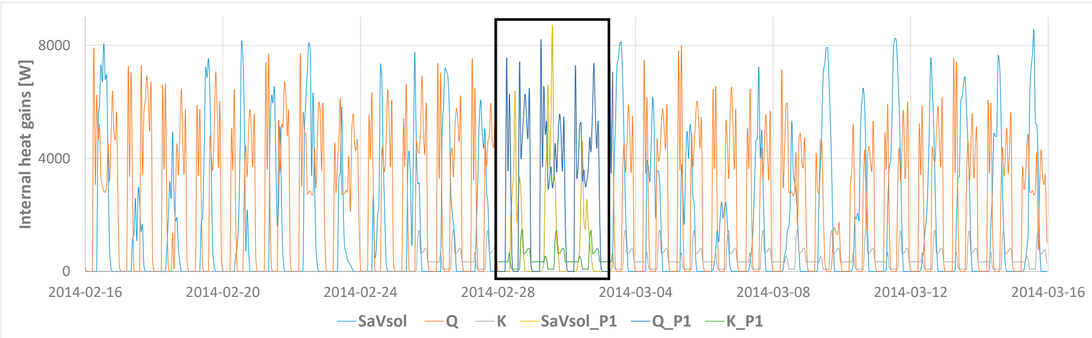
(**a**)

Figure 2. *Cont.*

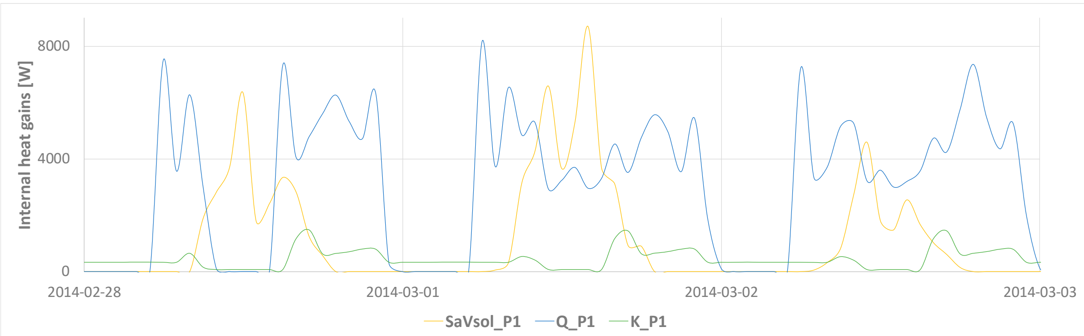


(**b**)

Figure 2. Indoor temperature, outdoor temperature and temperature difference: (**a**) for the whole dataset in Loughborough, (**b**) for period 1 in Loughborough.



(**a**)



(**b**)

Figure 3. Solar gains (S_aV_{sol}), space-heating systems' heat input (Q) and total electricity consumption, including synthetic occupants' generation (K): (**a**) for the whole dataset in Loughborough, (**b**) for period 1 in Loughborough.

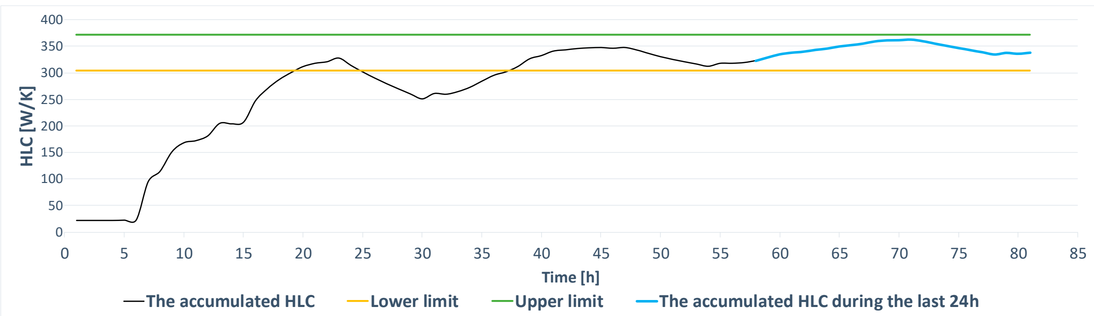


Figure 4. Evolution of the accumulated average of the heat loss coefficient for period 1 in Loughborough.

3. Results

The two houses presented have not been monitored for the same data periods. The house in Loughborough [28] was only monitored from 16 February to 15 March 2014. Unfortunately, the electrical consumption data started to be collected on 25 February, which limits the opportunity to find a suitable period within the provided data. The house in Gainsborough was monitored from 1 November 2012 until 30 April 2015. Thus, since a longer monitoring period was provided, it was easier to find suitable periods to estimate the HLC that fulfil the average method requirements.

As explained in Section 2, the average method is able to estimate the HLC of a building using short time periods (at least 72 h periods). However, due to all the requirements demanded by the average method from the periods for analysis, finding suitable periods when short data series are provided is not straightforward. In this case, it was necessary to ease some of the method requirements, taking more flexible limitations for the solar gains 10% weight requirement, and this relaxation effect on the HLC estimation was analysed.

In the next two subsections, both building data series are analysed separately. In order to demonstrate the reliability of the method, several useful independent periods should be found during the study of each building's data sets. Thus, the individual results obtained for each period will be independent from each other and can then be compared for the same building. Thus, an average HLC estimation value was calculated for each of the houses. Considering the characteristics of each house, the reliability of the results are now discussed.

3.1. Gainsborough HLC Estimation

Since a large dataset was provided for the house in Gainsborough, three consecutive winters are available to find suitable cold and cloudy periods to apply the average method. Thus, six useful periods that fulfil most of the average method requirements were found, see Tables 3 and 4.

Table 3. Necessary period averaged variable values to estimate the HLC_{simple} (simple Heat Loss Coefficient) and HLC (Heat Loss Coefficient) for Gainsborough. The variables included are the outdoor temperature (T_{out}), the indoor temperature (T_{in}), the temperature difference ($T_{in} - T_{out}$), the space heating heat input (Q), the electrical heat gains (K), the internal heat gains (Q+K) and the solar gains (S_aV_{sol}).

Winter	Period				Input Data						
					$\overline{T}_{out}$ [°C]	$\overline{T}_{in}$ [°C]	$\overline{T}_{in}$-$\overline{T}_{out}$ [°C]	$\overline{Q}$ [W]	$\overline{K}$ [W]	$\overline{Q+K}$ [W]	$\overline{S_aV_{sol}}$ [W]
2012–2013	Period 1	2012-12-03 18:02	→	2012-12-07 19:02	2.6	21.2	18.6	1066.5	11.9	1078.4	491.7
	Period 2	2012-12-11 16:02	→	2012-12-14 11:02	−0.4	16.9	17.3	767.9	22.6	790.5	380.9
	Period 3	2012-12-18 23:02	→	2012-12-22 8:02	5.9	16.9	11.0	544.7	9.3	554.0	110.7
2013–2014	Period 4	2013-11-27 2:02	→	2013-11-30 8:02	7.0	21.7	14.7	326.8	459.2	786	336.9
	Period 5	2013-12-13 21:02	→	2013-12-17 3:02	9.5	21.7	12.2	393.8	453.7	847.5	282.0
2014–2015	Period 6	2014-11-26 3:02	→	2014-11-30 8:02	8.7	21.9	13.2	322.7	353.8	676.5	139.4

Table 4. The HLC_{simple} (simple Heat Loss Coefficient) and HLC (Heat Loss Coefficient) estimated values for Gainsborough.

Winter	Period	Output Data	
		HLC_{simple} [W/K]	HLC [W/K]
2012–2013	Period 1	57.9 ± 3.5	84.4 ± 8.5
	Period 2	45.9 ± 2.9	68.0 ± 7.2
	Period 3	50.2 ± 4.4	60.2 ± 6.6
2013–2014	Period 4	53.6 ± 3.8	76.6 ± 8.4
	Period 5	69.6 ± 5.7	92.7± 10.6
2014–2015	Period 6	51.4 ± 3.9	61.9 ± 6.1

The average value of the six HLC_{simple} estimations presented in Table 4 is 54.8 ± 4.1 W/K, and 74 ± 8.1 W/K for the HLC. As a comparison reference, the Annex 71 has provided a "theoretical HLC value" of 49.9 W/K. Note that the Gainsborough theoretical value only considers the envelope design transmittance values and design infiltration/ventilation characteristics, so it is not the "true" HLC value. However, as proven by [12], when design HLC values are compared to co-heating experimental HLC values, the co-heating HLC values are usually considerably higher than the design HLC values. These differences have been proven to be up to 100% higher in the co-heating HLC when compared to the design HLC values. Thus, the obtained results follow this proven trend of having higher experimental HLC values when compared to the design HLC values.

In order to analyse the spread and reliability of the estimated in-use HLC results for Gainsborough, it is indispensable to carry out a more detailed study of the data. As explained in Section 2.2, Gainsborough's gas consumption is not only providing space heating, but also DHW. Then, although a filter is developed to estimate the gas consumption for space heating and DHW production (see Table 5), this issue introduces an important uncertainty. The order of magnitude of the estimated energy dedicated to DHW is of the order of the estimated space heating requirements. However, periods 2 and 3 had no main water consumption and give very interesting information.

Table 5. Space heating (Q), Domestic Hot Water consumption (Q_{DHW}), total ($Q_{Tot} = Q + Q_{DHW}$) and corresponding DHW percentage of the total ($\%Q_{DHW}$) for the analysed periods in Gainsborough.

Winter	Period	Input Data			
		$\overline{Q}$ [W]	$\overline{Q}_{DHW}$ [W]	$\overline{Q}_{Tot}$ [W]	$\%\overline{Q}_{DHW}$ [W]
2012–2013	Period 1	1066.5	406.0	1472.5	27.6
	Period 2	767.9	0.0	767.9	0.0
	Period 3	544.7	0.0	544.7	0.0
2013–2014	Period 4	326.8	404.7	731.6	55.3
	Period 5	393.8	431.6	825.5	52.3
2014–2015	Period 6	322.7	46.6	369.2	12.6

If Table 5 is analysed, it can be seen how the second and third periods show null DHW consumption (actually they have null mains water consumption), while the space heating continues to work. Table 6 shows the individual indoor temperature measurements of the bedroom and lounge of the Gainsborough house.

Table 6. Indoor temperature (bedroom, lounge and both average temperatures), outdoor temperature and temperature difference for the analysed periods in Gainsborough.

Winter	Period	Input Data				
		$\overline{T}_{out}$ [°C]	$\overline{T}_{in\text{-}bed}$ [°C]	$\overline{T}_{in\text{-}lounge}$ [°C]	$\overline{T}_{in\text{-}average}$ [°C]	$\overline{T}_{in}-\overline{T}_{out}$ [°C]
2012–2013	Period 1	2.6	21.2	21.3	21.2	18.6
	Period 2	−0.4	18.3	15.4	16.9	17.3
	Period 3	5.9	18.5	15.4	16.9	11.0
2013–2014	Period 4	7.0	21.3	22.1	21.7	14.7
	Period 5	9.5	21.5	21.9	21.7	12.2
2014–2015	Period 6	8.7	21.3	22.6	21.9	13.2

From Table 6, for the second and third periods, the obtained indoor temperature is quite low in comparison to the rest of the indoor temperatures. Therefore, it can be concluded that the occupants are not at home during these two periods; this might provide accurate results of the HLC. Since there is no occupancy in the house during these two periods, it can be stated that there is no metabolic heat generation and no uncertainty in the space heating supply energy estimation due to DHW splitting, since 100% is used for space heating purposes. During these two periods, the boiler is working for security reasons to avoid excessive cooling of the house while vacant.

Another issue to take into account is the low heating consumption (Q) in the well-insulated Gainsborough building. This leads to several difficulties when searching for valid periods to apply the average method. On the one hand, the internal heat gains (Q + K) of the house are probably underestimated since, when splitting the space heating and the DHW consumption, some space heating heat is probably not considered. Furthermore, as shown in Table 3, for the last three periods, the heat generated by the electricity consumption is higher than the heat provided by the space heating. Note that period 1 has a very low electrical consumption for an occupied building. This phenomenon is not common in older, worse insulated buildings, since the space heating is usually the dominant internal heat gain in cold and cloudy periods. On the other hand, although cold and cloudy periods with low solar radiation have been selected, due to the low space heating requirements, the percentage of solar radiation as compared to the rest of the heat gains (Q + K) increased to an average of 35.1% for all the periods ($35.1\% \times (\overline{Q+K}) = (\overline{S_a V_{sol}})$). It must be highlighted that none of the periods can provide values that fulfil the requirement of having just 10% weight of solar gains as compared to the other internal heat gains (Q + K). However, periods 3 and 6 are the two closest to fulfilling the 10% weight requirement, since both are around 20% of weight.

There is a final issue to remark concerning the possible user behaviour regarding the ventilation system control and/or window opening. The individual HLC values estimated for the Gainsborough house in the unoccupied periods 2 and 3 and the occupied period 6 are very close to each other. While occupied periods 1, 4 and 5 have higher HLC values as compared to the unoccupied periods 2 and 3. It might be that the users were opening windows or increasing the ventilation system set points during periods 1, 4 and 5, thus increasing the ventilation rates and, consequently, the in-use HLC values during those periods. During period 6 (the one with the lowest weight of solar gains together with period 3), the building was also occupied, but the HLC is similar to the unoccupied periods 2 and 3.

Remember that the HLC of a building is the sum of two different coefficients (HLC = UA + C_v); the transmission heat loss coefficient (named the UA-value), which considers the heat losses transmitted through the whole building envelope (including the thermal bridges), and the infiltration and ventilation heat loss coefficient (named C_v). The user behaviour can affect the part of the HLC term related to C_v by interfering in the ventilation system and/or by means of window opening. However, it cannot affect the UA-value part, since the UA-value can be considered constant throughout the life of the building, unless the building envelope is refurbished or the building envelope insulation layer is damaged by mould growth, humidity problems, etc. Therefore, a considerable part of the HLC value will remain constant and could not be modified due to the users' behaviour.

Considering that the main issues for the Gainsborough house are related to the uncertainties created by the solar gains and the occupants of the building, the closest HLC result to the fulfilment of the original method is provided by period 3.

3.2. Loughborough HLC Estimation

However, the Loughborough house provided shorter periods for the dataset. In this case, only one month's data was provided, so it was more difficult to find suitable periods that fulfil all the average method requirements. In this case, only two periods were found fulfilling almost every requirement (Tables 7 and 8).

Table 7. Necessary period averaged variable values to estimate the HLC_{simple} (simple Heat Loss Coefficient) and HLC (Heat Loss Coefficient) for Loughborough. The variables included are the outdoor temperature (T_{out}), the indoor temperature (T_{in}), the temperature difference (T_{in} - T_{out}), the space heating heat input (Q), total electricity consumption, including synthetic occupants' generation (K), the internal heat gains (Q+K) and the solar gains ($S_a V_{sol}$).

Winter	Period				Input Data						
					$\overline{T}_{out}$ [°C]	$\overline{T}_{in}$ [°C]	$\overline{T}_{in}-\overline{T}_{out}$ [°C]	$\overline{Q}$ [W]	$\overline{K}$ [W]	$\overline{Q+K}$ [W]	$\overline{S_a V_{sol}}$ [W]
2013–2014	Period 1	2014-02-27 23:59	→	2014-03-03 7:59	3.5	16.8	13.3	2999.5	445.2	3444.7	1059.2
	Period 2	2014-03-05 22:59	→	2014-03-09 0:59	7.9	17.7	9.8	2410.6	442.3	2852.9	1032.6

Table 8. The HLC_{simple} (simple Heat Loss Coefficient) and HLC (Heat Loss Coefficient) estimated values for Loughborough.

Winter	Period	Output Data	
		HLC_{simple} [W/K]	HLC [W/K]
2013–2014	Period 1	258.4 ± 14.4	337.9 ± 27.2
	Period 2	290.2 ± 21.4	395.2 ± 37.6

The obtained average value for the HLC_{simple} is 274.3 ± 18.2 W/K, and for the HLC, 366.6 ± 32.9 W/K. The latter value is close to the HLC "theoretical value" given by Annex 71 of 382 W/K. Note that this theoretical value was obtained through the co-heating method. Since the analysed data for the Loughborough case has synthetic occupancy, and it is known that the windows have not been opened and no mechanical ventilation system is present, the co-heating HLC values and the average method HLC estimations are performed with a very similar use of the building. Thus, the average method HLC and the co-heating method HLC should be comparable.

From Table 7, it can be concluded that none of the selected periods fulfil the requirement of having a lower solar gain weight than 10% as compared with the rest of the internal gains (Q + K). In Loughborough, the solar gains are 30.75% of (Q + K) for the first period and 36.19% of (Q + K) for the second. Therefore, the average percentage for both periods is 33.47%. If longer periods of data had been available, for example, a whole winter period, it is often possible, in northern areas such as Loughborough, to find two to four cloudy and cold periods per winter, where more suitable periods for analysis could have been found.

4. Discussion

In order to analyse the spread and reliability of the estimated in-use HLC results, a detailed discussion was developed for each of the residential buildings of Sections 3.1 and 3.2. Remember that the average method was developed for its application to an occupied office building and some of the original method requirements were eased to make it applicable to the two different tested residential buildings. Therefore, it was important to observe each house individually, since they are not affected by the same characteristics.

The analysis shows some variation between the individual HLC estimates of both buildings (see Tables 4 and 8). For the Gainsborough building case, this variability is probably caused by the uncertainties due to the space heating estimations based on total gas consumption measurements, unknown metabolic heat generation of the occupants, unknown window opening behaviour, and/or ventilation system operation by the occupants and on the uncertainties related to the solar gains. For the Loughborough house; however, due to the availability of only one month's monitoring data, it was not possible to have proper cold and cloudy periods for analysis, so the main uncertainty comes from the uncertainty associated to the solar gains estimation. Then, the common main issue responsible for the spread between the individual HLC for both houses is probably the uncertainty related to the solar gains estimation.

The weight of the solar gains in the HLC estimates can be analysed in detail by comparing the HLC_{simple} against the HLC. For Gainsborough, not considering the solar gains in the HLC estimation leads to an average HLC_{simple} value of 54.8 ± 4.1 W/K; while the consideration of the solar gains increases the average HLC estimation to 74 ± 5.6 W/K. Although, in absolute values, the effect of considering the solar gains is just 19.2 W/K, in well-insulated buildings such as the Gainsborough case, not considering them leads to an approximate deviation over the HLC estimate of 26%. In contrast, for Loughborough, not considering the solar gains in the HLC estimation leads to an average HLC_{simple} value of 274.3 ± 18.3 W/K; while the consideration of the solar gains increases the average HLC estimation to 366.6 ± 23.5. Although, in absolute values, the effect of considering the solar gains is much higher, 92.3 W/K; in poorly insulated buildings, such as the Loughborough case, it leads to a deviation of about 25% over the HLC estimate. Note that, for the Loughborough case, the availability of longer monitoring periods could have provided periods for analysis with much lower solar gains and the latter deviations for the HLC due to solar gains would have been considerably lower.

Moreover, as commented before, it was impossible to ensure that the roughly estimated solar gains (S_aV_{sol}) are less than 10% compared to the rest of the internal gains (Q + K) in the houses, even if the short periods with the lowest solar radiation were considered for analysis. Besides, considering that the weight of solar gains as compared to the rest of the heat gains (Q + K) were, on average, 35.1% for Gainsborough and 33.47% for Loughborough, it could be considered that the 10% solar gains weight requirement in the HLC estimation should be extended to about 40% for these two residential buildings. Since the accurate estimation of the solar gains is a hard task to perform, this extension on the solar gains weight requirement can increase the uncertainty and spread in the estimated HLC values.

However, despite the uncertainties created by several sources, interesting results were obtained. As commented in Section 3.1, period 3 provided the most reliable results for Gainsborough, since it is not affected by the occupants behaviour, thus several uncertainty sources are avoided. The estimated HLC value for this period is 60.2 W/K, which is close but higher than the "theoretical value" 49.9 W/K provided by the Annex 71. These two values differ 17%. However, as commented in the mentioned section, the "theoretical value" only considers the design values, so it tends to underestimate the HLC. However, it can be used for comparison. Thus, the obtained value with the third period seems logical and promising. In the case of Loughborough, despite the solar gains, there are not any other uncertainty sources. Moreover, the provided "theoretical value" is estimated using the co-heating methods, so both HLC values are comparable. In this case, while the average estimated HLC value for both periods is 366.6 ± 22.8 W/K, the co-heating HLC value is 382 W/K. These two values only differ by 4%, which means that, despite the non-fulfilment of the solar gains requirement, the difference between the two values remains low. Thus, these results can also be considered reliable.

5. Conclusions

From the analysis, it can be concluded that the average method developed for an office building can be also applied to residential buildings with different characteristics and provide interesting results. However, it was necessary to ease one of the requirements of the average method. Despite that, promising results could be obtained for both of the buildings.

In the case of Gainsborough, the house is a well-insulated building. Therefore, the reduced internal gains generated inside the building due to the proper insulation reduce the possibilities to find periods with lower solar radiation effect than the internal gains. Based on the discussion section analysis, despite the wide range of the results obtained in the Gainsborough building, the best HLC estimate value is considered to be 60.2 ± 5.4 W/K for period 3. This period was selected as the best period due to two main reasons. The first reason providing reliability to this result is that, during this period, the occupants were not at home. Thus, the uncertainties related to the DHW and space-heating split are avoided. The second reason to select this model is that the solar gains during this period were the lowest compared with the rest of the heat gains inside the building, if compared with the rest of the periods analysed. However, some of the results obtained for this house do not differ considerably from this value, such as period 2 and period 6, which are the other two periods less affected by the uncertainties. However, period 1, period 4 and period 6 differ more than 20% affected, mainly by the occupants behaviour and solar gains effect.

Nevertheless, something very different happens when the Loughborough house is analysed. In this case, the house is not a well-insulated building. Therefore, the estimated HLC results are considerably higher. The results obtained for Loughborough in the two periods where the HLC was estimated are very similar and the average HLC results for both of them is quite similar to the "theoretical value" estimated with the co-heating method. In other words, due to the bad insulation, the accurately measurable space heating needs are high in order to keep the house warm, which makes the average method more insensitive to the uncertainties associated to the method.

Moreover, the Loughborough building considers synthetic profiles to simulate the occupants' behaviour, meaning heat gains inside the building can be estimated accurately. Thus, it has been easier to provide good HLC estimation results for the two analysed periods identified for the method's application. However, due to the short period of monitoring data provided, it was not possible to find more suitable periods that fulfilled all the average method requirements. The latter would have permitted the uncertainty of the solar gains in the Loughborough HLC estimations to be reduced.

In [25,26], the average method has been successfully applied to a whole four-story office building before and after retrofitting. The average method found several suitable periods fulfilling all the requirements, including the requirement for the solar gain to be below 10% of the other measurable internal heat gains represented by (Q + K). This research has shown that the application to buildings with considerably lower (Q + K), such as these two residential buildings, makes it hard to find suitable periods. However, even using periods with a higher weight of solar gains provided some HLC estimates within a decidedly narrow range for different independent periods. Furthermore, it is obvious that the better insulated the residential building is, the harder it will be to obtain periods where the solar gains become negligible as compared to (Q + K), since the space heating (Q) will be very low, even in cold and cloudy periods. Thus, the need to accurately measure and/or estimate the other internal heat gains (K) and solar gains ($S_a V_{sol}$) will become crucial for accurate HLC estimation using the average method in well-insulated residential buildings. Once a method for accurate solar gains estimation has been developed, the 10% criteria for the solar gains could be made more flexible, to the extent the accuracy of the solar gains estimation techniques permit. Accurate metabolic heat generation estimation techniques, based on anthropogenic CO_2 decay analysis, or artificial vision techniques, will also help to improve the accuracy of the average method to a great extent.

Moreover, it must be stated that the need to measure the real space heating provided to the house is also a major issue regarding the method's accuracy. If only gas consumption is available, too many assumptions regarding the efficiency of the boiler and the percentage of heat used for space heating versus DHW have to be applied. Calorimeters in the head of the space heating circuit could be a good option to accurately measure the real space heating provided to the house, as was done in the Loughborough house of this research.

In this work, the average method was applied to two residential buildings at a latitude of 53° N. Even if the method only seems applicable to northern countries, such as the UK, it has been proven in [25,26] that the method is also applicable in northern areas of such countries as Spain, where, in general, the weather is warmer than in northern countries. Therefore, it must be concluded that the majority of countries in Europe would be able to fulfil the weather-related requirements of the presented method, excluding solely the southern areas of Mediterranean countries.

Finally, it can be concluded that the proposed method can be applied to different residential building types. In this case, the method was able to provide promising results for a well-insulated house and for a poorly insulated one. Nevertheless, the variation between individual HLC estimates should be reduced to make the average method robust enough to be able to energetically certify the in-use behaviour of building envelopes.

Author Contributions: During the study, the collaboration of all the authors was essential to develop the current analysis. The cooperation of both universities supplied the article very interesting results and conclusions. The idea of the analysis came out during one of the IEA-EBC Annex 71 meetings, whereby all the authors developed the conceptualization of the paper. During the collaboration I.U., A.E. and K.M.-E. were responsible for applying the methodology. On the other hand, P.E. and E.G. edited the provided data in order to fix the same parameters and values for both universities and ensure the use of the same exact data. Once the methodology was already set, it was validated by the members of both universities. Since both of the research groups applied the method to the corresponding data, the results were compared in order to ensure their reliability. In order to reflect all the work, I.U. and A.E. were the members in charge in order to write and review the paper. Then, all the authors read and commented their agreement with the article. Finally, it must be commented that the funding for the article was acquired by A.E., P.E. and E.G. through the coordinated project mentioned below, where also K.M.-E. and I.U. participate. All authors have read and agreed to the published version of the manuscript.

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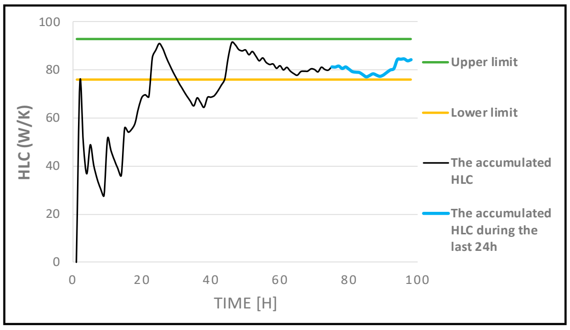
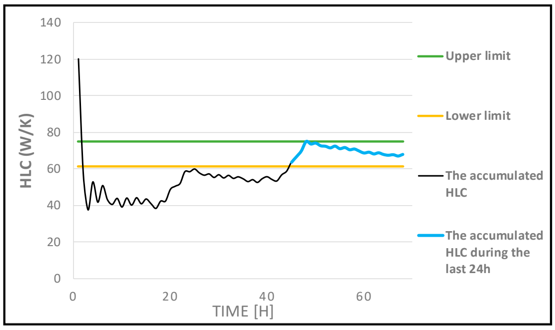
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

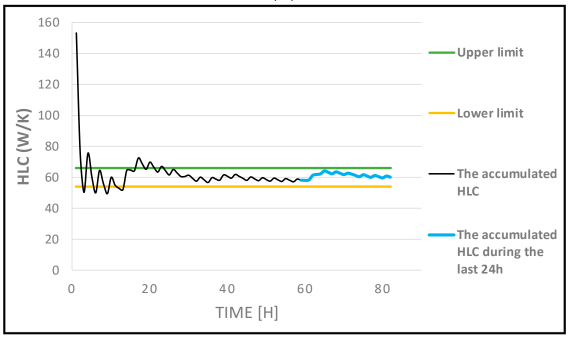
In order to justify the stabilization band requirement of the average method, where the estimated HLC value should be within a 10% error band in the accumulated average plots over the last 24 h of the selected periods, all the graphs are plotted in Figure A1 for Gainsborough and Figure A2 for Loughborough.



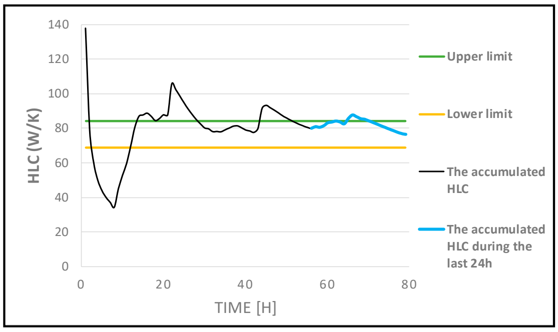
(**a**)



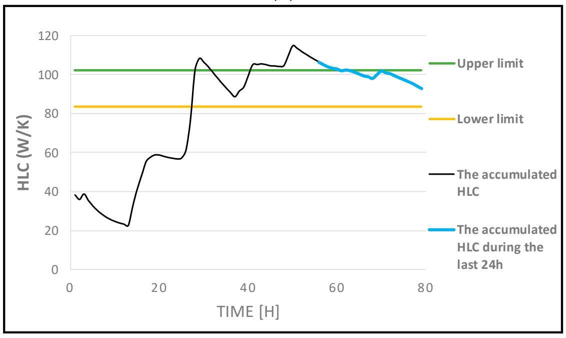
(**b**)



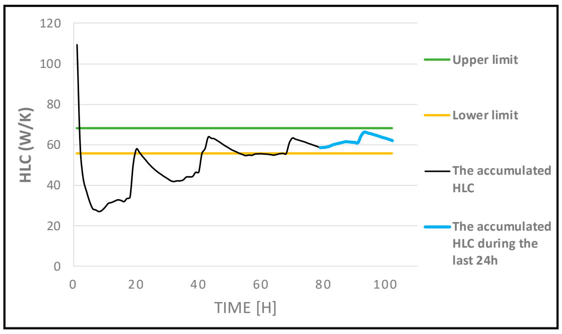
(**c**)



(**d**)

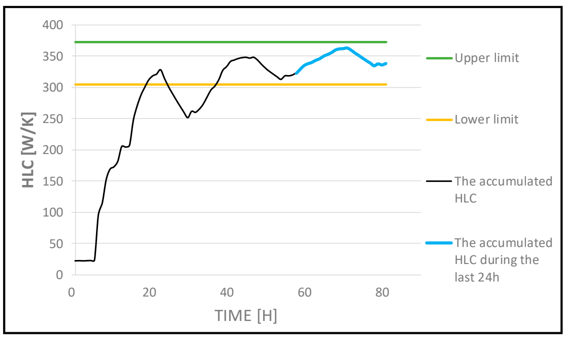


(**e**)

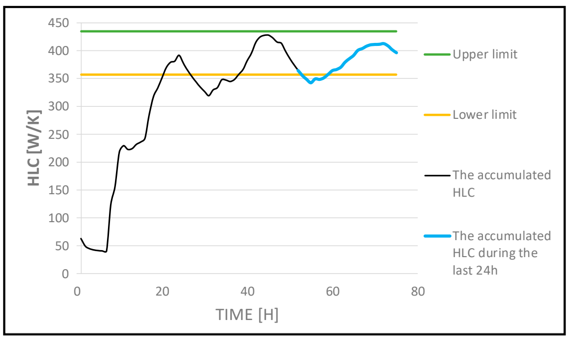


(**f**)

Figure A1. Evolution of the accumulated average of the Heat Loss Coefficient for (**a**) period 1, (**b**) period 2, (**c**) period 3, (**d**) period 4, (**e**) period 5 and (**f**) period 6 in Gainsborough.



(**a**)



(**b**)

Figure A2. Evolution of the accumulated average of the Heat Loss Coefficient for (**a**) period 1 and (**b**) period 2 in Loughborough.

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