Independent Report

Airoom – ECO Demonstration Action

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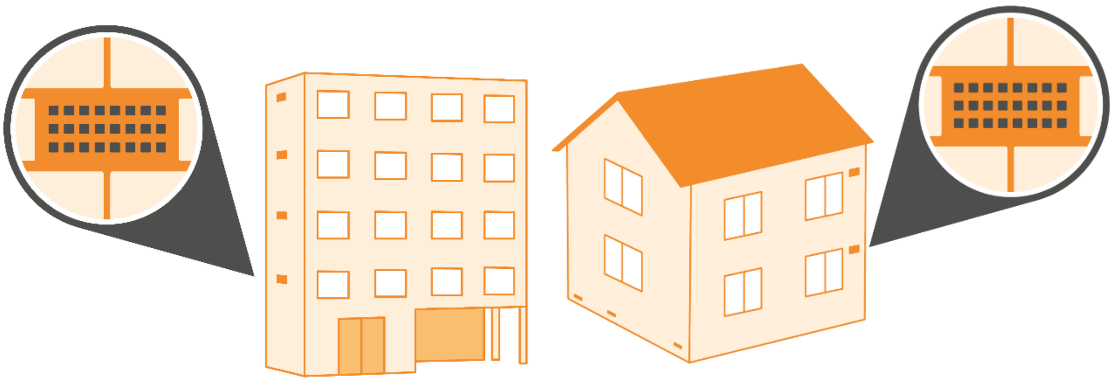

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Acknowledgments

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Executive Summary

Airoom is a smart IoT-enabled smart ventilation control system that replaces air bricks that provide ventilation to habitable areas of a home. It monitors relevant environmental parameters like temperature, humidity and CO_2 and subsequently opens or closes air-vents to optimise ventilation. Using cloud-based IoT algorithms, Airoom minimises cold airflow whilst ensuring sufficient air exchange to prevent moisture build-up or poor indoor air quality.

This independent report includes analysis of the data gathered though a large scale field trial completed as part of a ECO3 Demonstration Action. The objective of the trial being to determine the level of impact installation of the Airoom system has on the cost of heating a home. Airoom systems were installed in 257 properties over the winter of 2021/22 with the Heat Transfer Coefficient (HTC) of the homes measured for a period of at least three weeks whilst the Airoom system was active and three weeks whilst the air bricks were open at all times (modelling a pre-installation scenario).

Strict statistical analysis of the data gathered during the trial produced “Dataset 1” which shows that the Airoom system led to a reduction in the HTC (an reduction in the amount of heat a home loses) of 1% (+1%/-3%). Data from further analysis incorporating building physics principles to account for uncontrolled variables produced a “Dataset 3” of reduced size due to additional data cleansing, this suggests that the average energy saving per household was 3.9% (+2.1%/-2.9%).

Dataset 1 determines that the Airoom system can lead to a lifetime bill saving of £104 (-£217 to £217) for gas heated homes (SAP10 tariff, £0.0364/kWh), or £473 (-£983 to £983) in electrically heated households, (SAP10 tariff of £0.1649/kWh). If the Ofgem price cap energy prices were to be used, the savings reflected would be £201 (£-417 to £417) at a unit cost of £0.07/kWh for gas heated homes, or £803 (£-1670 to £1,670) for electrically heated homes at unit price of £0.28/kWh.

Dataset 3 suggests that lifetime bill saving resulting from Airoom installation would be £425 (£104 to £626) in gas heated households (SAP10 tariff, 0.0364/kWh), or £1927 (£473 to £2,836) in electrically heated households, (SAP10 tariff of £0.1649/kWh). When applying the Ofgem price cap tariff values, these savings would be £818 (£201 to £1204), for gas heated homes, or £3,273 (£803 to £4,815) for electrically heated homes.

In achieving this improvement there is no significant increase in the relative humidity of homes as a result of managing airflow.

Further study is recommended to more fully understand the impact of the Airoom system and the mechanisms that drive this. This should include more detailed air tightness testing as well as looking at the impact in properties with a more representative number of air bricks (those in the trial had an average of 2.2, whereas the UK average is thought to be around 4).

Introduction

Project overview

This report details the outcome of the Airoom ECO3 Demonstration Action trial. This trial involved the installation of the Airoom system in 257 homes in three areas of the UK (Greater Manchester, London, and Portsmouth) with the performance of the system monitored between November 2021 and March 2022. The data gathered has been independently validated by a team of researchers, building physics experts and statisticians.

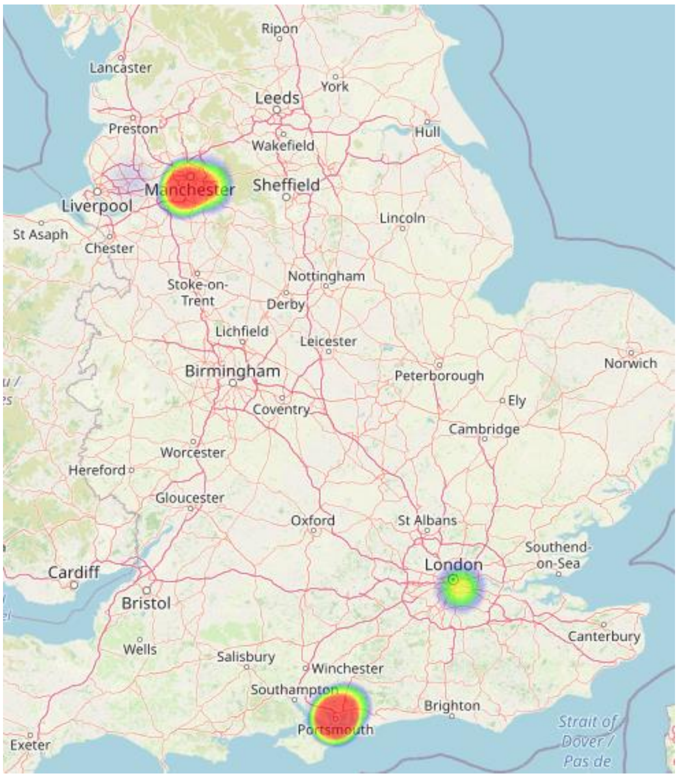

Figure 1: Heat map of Airoom installations

Product overview

Airoom is a smart passive ventilation system that has been designed as a retrofit replacement for existing air bricks that ventilate the habitable area of a home. The system includes:

- One or more Airoom smart air bricks with variable apertures to control the level of airflow passing through
- An Airoom home hub that serves two purposes; it measures temperature, humidity and CO_2 within the home and also acts as a bridge between the smart air bricks and the Airoom cloud-based control system
- The Airoom cloud-based control system which receives the data measured within the homes, combines this with external weather data and uses algorithms designed by AirEx to determine the optimum state for the smart air bricks

The control logic has been developed such that air flow is controlled to decrease the heat loss within a home, only allowing uncoinstrained ventilation when the measured conditions within the home present a risk of poor air quality or condensation.

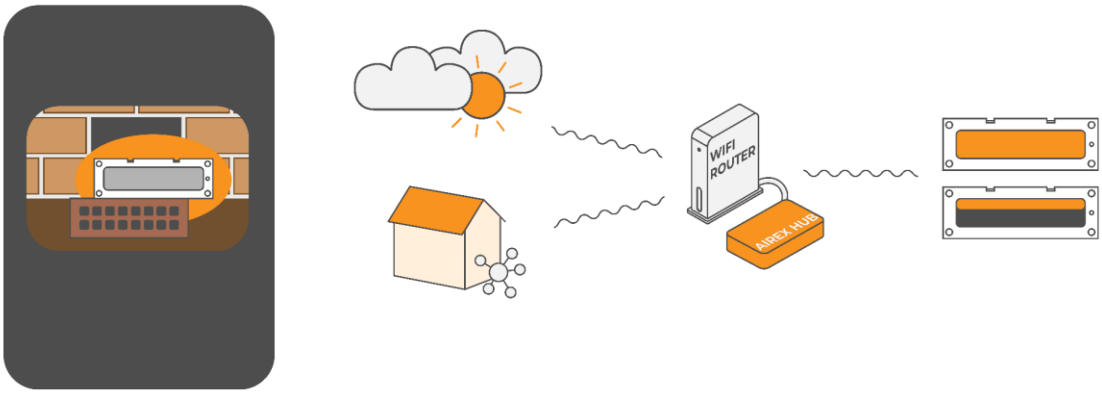

Figure 2: Airoom system overview

Methodology

The objective of the trial was to test the effect of the Airoom system on the thermal performance in trial homes at scale. The *a priori* hypothesis being that the installation of the system would result in an improvement in thermal performance measured by the Heat Transfer Coefficient (HTC).

A paired design was used to reduce the variability in conditions, particularly due to the behaviour of occupants. It is worth noting that this still leaves a number of potentially significant external variables e.g., house size, number of occupants, number of external walls, etc that vary within the sample dataset. As such, a range of categorical variables on the dwellings were also collected to discriminate the effects of these parameters where possible.

Airoom installations were completed in a total of 257 properties between October 2021 and January 2022. These installations were completed predominantly in purpose-built blocks of flats (two properties were purpose-built maisonettes). The properties had a range of different heating systems, were predominantly of cavity wall construction, had between 1 and 3 bedrooms (average 1.6), and had between 1 and 7 occupants (average 1.7).

It is not possible to accurately determine to what extent the installation of Airoom had an impact on the total ventilation area of a home i.e. how much the effective area of the Airoom in its open state differed from the pre-existing air brick. Whilst the effective area of Airoom is known there is no practical way to measure that of the pre-existing air brick. Based on figures quoted by air brick manufacturers it is estimated that the change in effective area is ±10%.

Figure 3: Example of typical trial dwellings

Ahead of the installation of the Airoom systems, air tightness testing was carried out in a random sample of 40 homes. This involved both blower door tests and Build Test Solutions' (BTS) Pulse test. Following the installation of the Airoom system the same tests were carried out in these properties, firstly with the Airoom air brick fully open and secondly with the Airoom air brick fully closed. The project team were unable to access all 40 properties for the second round of testing, reducing the sample size to 25. Air tightness was measured using the Pulse system with the Airoom air bricks in the open and closed state for a further group of 65 properties.

Additional temperature and humidity sensors were deployed in 206 homes to allow for the calculation of the HTC using BTS's SmartHTC technique. An average of three sensors were placed in each home, located in the main bedroom, kitchen and living room. Sensors were in all cases out of direct sunlight and at least 2m away from any major heat source at mid height relative to the room. Each property was monitored for a minimum three-week period with the Airoom system in both active mode (in which the smart air bricks control airflow) and open mode (in which the vents are always open). On average the monitoring period for systems in the active state lasted 32 days and for the open state 37 days. Approximately 50% of the properties began the trial in active mode before changing to open mode with this inverted for the other 50%. Fundamental issues which prevented the calculation of HTC were identified in a minority of cases reducing the effective sample size to 174 properties.

Throughout the trial the Airoom system measured temperature, humidity, and CO_2 levels with the vent state (open or closed) also logged. Additional third-party weather data as used by the Airoom cloud-based control system was also recorded.

Summary of results

SmartHTC

Background

SmartHTC is a non-invasive method to measure the thermal performance of buildings, defined by the HTC. The HTC is a measure of the rate of heat loss per degree temperature difference between inside and out, all models of thermal performance or energy consumption in buildings are based upon this measure of thermal performance. The lower the HTC (measured in W/K), the better a building is at retaining heat.

HTC can be normalised by floor area to produce the Heat Loss Parameter (HLP) which is measured in W/m^2K. This metric allows for better comparison between properties of differing sizes as larger buildings will tend to have a larger HTC but may actually have better fabric performance than a smaller building.

The inputs to the SmartHTC are:

- Property characteristics obtained during a property survey e.g., floor area, location, built form, heating system, occupancy data, etc
- Energy consumption gathered from either a smart meter or by taking meter readings at the start and end of a monitoring period
- Internal temperature and humidity collected half-hourly

The SmartHTC method has been validated through field trials and comparison with the more invasive co-heating test. This showed that the results of the SmartHTC measurements agreed with those of the co-heating test within the combined uncertainty margins.[1]

Methodology

The collection of the data required in order to calculate the HTCs of the properties took place in three stages:

1. The initial home visit during which a home survey was undertaken, temperature and humidity sensors deployed, and initial energy meter readings taken. The vent mode (open or active) was also verified during this visit.
2. The midpoint home visit during which midpoint energy meter readings were taken and the vent mode was switched over i.e., from open to active or active to open as appropriate.
3. The final home visit during which final meter readings were taken and the temperature and humidity sensors were collected.

Approximately 50% of the properties in the sample began the trial in open mode with the other 50% starting in active mode. Each property was monitored for a minimum of 21 days in each mode, on average for 32 days in the active mode and 37 days for the open mode.

[1] Build Test Solutions. (2021). SmartHTC Validation Report

Temperature and humidity data was gathered at a minimum of two points within each home (average 3 points) with measurements logged every 30 minutes.

Of the 257 homes in which the Airoom system was installed the process outlined above was followed for 206. It was not possible to complete the process for the remaining households for a variety of reasons including residents moving home, COVID-19 concerns, illness, and death. Of the 206 homes in which data collection was possible the full HTC measurement was possible for 174 properties (with two distinct periods). The reasons the HTC could not be derived varied but included technical issues with faulty sensors (15), meter readings (16) and warm weather (1) invalidating some measurements.

Results and analysis

The results discussed in this section related to a subset of the trial data consisting of 144 properties (dataset 1). This subset was reached after cleansing the data to remove data points that appear clearly erroneous and to control for significant shifts in resident behaviour which would otherwise disproportionality impact the results. The full methodology for this process is outlined in the Data cleansing methodology section.

The SmartHTC measurements are shown in Figure 4, with the error bars showing the confidence interval at the 95% confidence level. The active mode measurements are plotted on the y-axis and the open mode measurements are plotted on the x-axis. The red line shows a x=y relationship i.e., no change in performance between the active and open mode periods and the blue line shows the regression through the origin. Figure 4 shows graphically the performance improvement during the period the systems were in active mode.

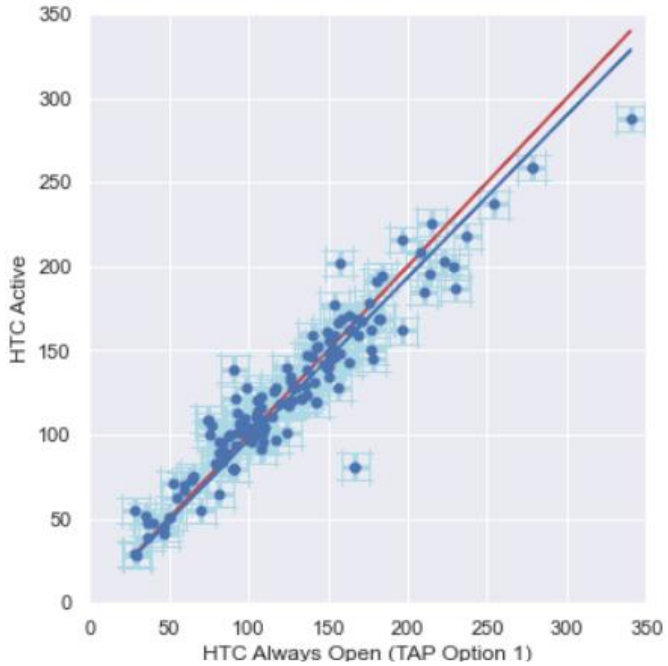

Figure 4: Scatter plot of HTC results in active and open modes with x=y line for comparison

The same impact is shown in Figure 5 which shows that the mean average improvement in HTC with Airoom in active mode was 1.0% (+1.0%, -3.0% at a 95% confidence interval) compared to the HTC when in open mode.

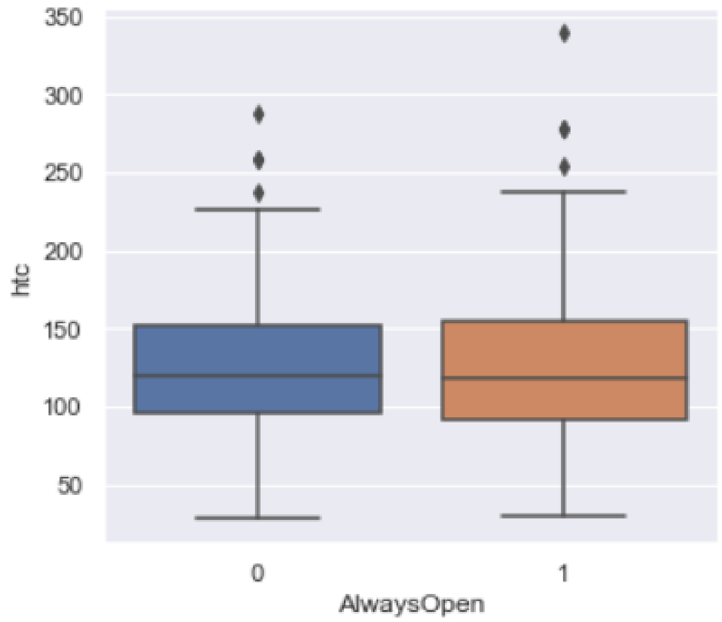

Figure 5: Box and whiskers plot of HTC results in active and open modes

In order to verify the significance of the results the Wilcoxon matched-pairs (or signed-rank) test (Wilcoxon test) has been used. This is the nonparametric equivalent of the parametric paired t-test and so is not sensitive to any non-normal distribution of HTC data. This test determined that for the sample of 144 pairs the difference in HTC between open and active had a p value of 0.85[2].

All confidence intervals included int his report were calculated using the Wilcoxon. As the distribution observed in this trial is non-normal the confidence interval is not typically symmetric. This can result from there being a skew in the data in one direction, for example a concentration of data points a distance form the median value.

Figure 6 and Figure 7 show the change in HTC between open and active modes across the sample. It can be seen that in the majority of cases the HTC improved when the Airoom system was in active mode.

[2] A p-value of 0.05 or less is typically considered to indicate a result is statistically significant, the result presented here falls outside of this range

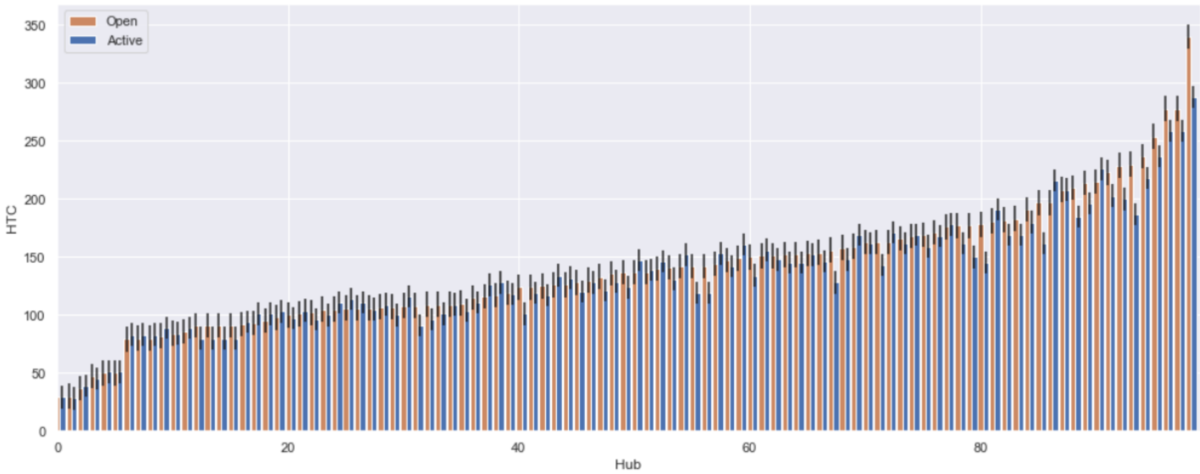

Figure 6: Bar chart of SmartHTC results in active and open modes

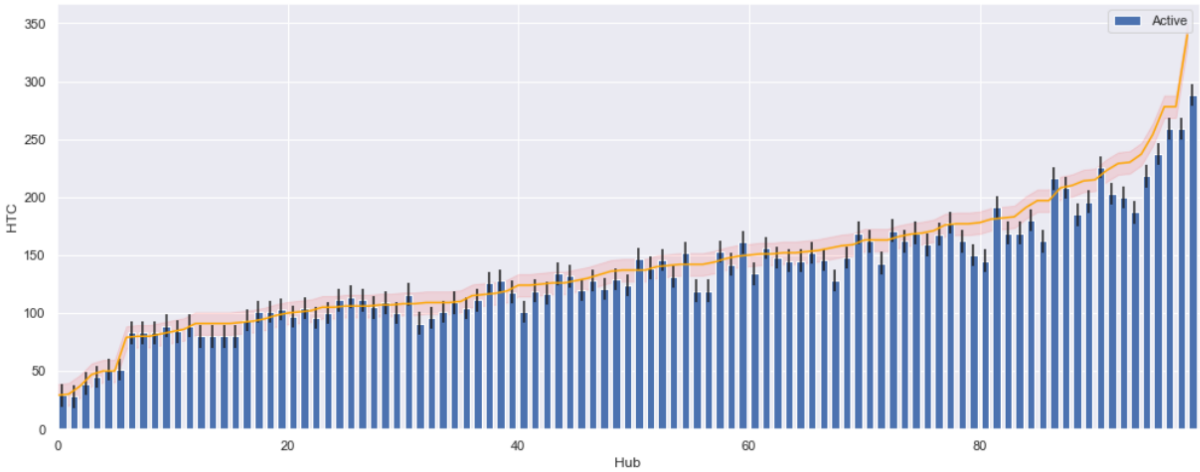

Figure 7: Graph showing SmartHTC results in active (blue bars) and open modes (orange line)

On average the Airoom smart air bricks were in their closed state for 50% of the time whilst set to active mode. There was significant variation in the percentage of time the air bricks were in their open state, ranging from 7% to 99% with a standard deviation of 23%. This indicates that the trial property included both under, and over-ventilated properties.

Air tightness

Background

Air tightness testing is used to measure the amount of air that escapes through gaps or the building fabric of buildings. Two different approaches to measuring air tightness were utilised in this trial, blower door tests and BTS's Pulse method (both tests being performed by BTS).

Blower door tests

A blower door test is used to measure the amount of air leakage in a property. The test involves the installation of a calibrated fan within a door which is sealed, whilst other openings to the building fabric are closed. The fan creates a pressure differential between the interior and the exterior of the building of 50Pa. The airflow into, or out from the home is then measured with a manometer to provide a measure of air permeability in $m^3/h/m^2$. Blower door tests are well established and are the industry standard with the process of completing a test governed by ISO 9972.

Pulse tests

The Pulse method has been developed by BTS as a method of measuring air permeability at lower pressures and causing less disruption. Instead of operating at 50Pa pressure the Pulse testing requires only a 4Pa pressure differential. This approach was favoured in this trial as the blower door testing protocol was found to be distressing for a significant proportion of the often-vulnerable residents participating in the trial.

Methodology

Two different air permeability testing regimens were used in this trial. One cohort had both blower door and pulse testing at three points:

1. During an initial home visit, prior to the installation of Airoom
2. During a second home visit, following the Airoom installation with the air brick set to the open state
3. During the second home visit with the air brick set to the closed state.

The second cohort had pulse testing only with two tests:

1. Following the Airoom installation with the air brick set to the open state
2. During the same home visit with the air brick set to the closed state.

Results were obtained for 25 homes in cohort one and 65 in cohort two. Unfortunately following the trial, it was discovered that in the majority of cases the experimental plan failed to produce the desired results. Namely, the Airoom systems did not change state between the tests of the system during which it was intended to be in open and close states. As such measurements were, in most cases, repeated with the vent state unchanged. It is worth highlighting that this error was the result of a flaw in the experimental process and not the Airoom system, the process did not account for the time taken for the Airoom system to receive and then act on a new command. Further details are provided in the Technical Details - Air Tightness section of the report.

Results and analysis

The limited data set available shows that the Airoom system can have a significant impact on the air tightness of a home. Figure 8 shows the air tightness measurements, with the error bars showing the confidence interval at the 95% confidence level. The active mode measurements are plotted on the y-axis and the open mode measurements are plotted on the x-axis.

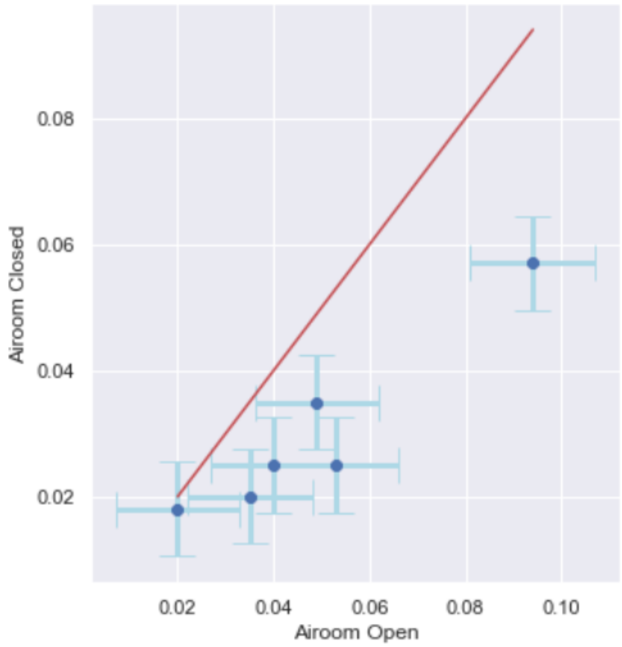

Figure 8: Scatter plot of air tightness results in closed and open states with x=y line for comparison

The same impact is shown in Figure 9 which shows that the mean average improvement in airtightness with Airoom in the closed state was 35.5% (±11.71%, n=6).

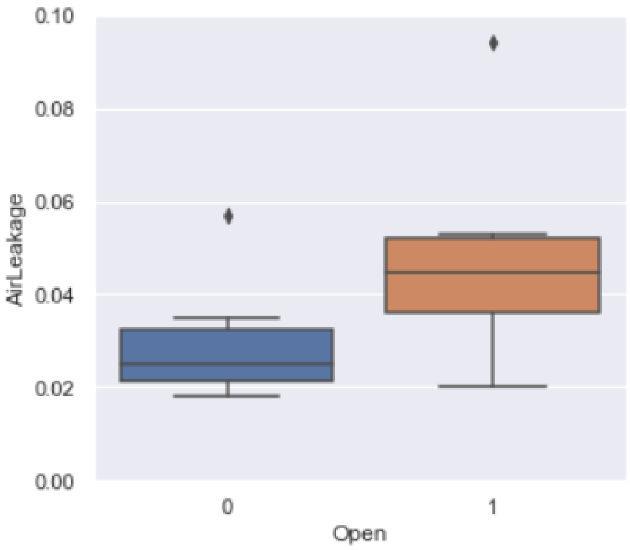

Figure 9: Box and whiskers plot of air tightness results in closed and open states

In order to verify the significance of the results the Wilcoxon test has again been used because of the paired, non-normal data distribution. This test verified that the difference in air tightness between open and active was significant (n=6, p=0.031). The Wilcoxon test is computed using medians as opposed to means, the test gives a median improvement of 0.015 (-0.007 / + 0.017) against median of 0.044, i.e., a median improvement of 33.7% at a 95% confidence interval.

Figure 10 shows the change in air tightness between open and closed states across the sample. It can be seen that in all cases the HTC improved when the Airoom smart air vents were closed.

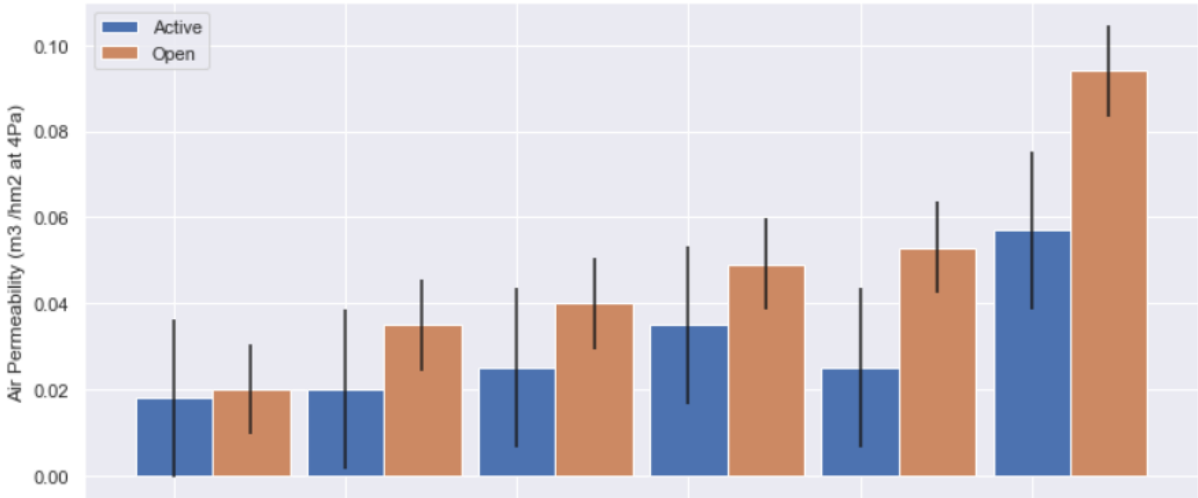

Figure 10: Bar chart of air tightness results in active and open modes

Humidity analysis

Background

The Airoom system has been designed to reduce heat loss from a home by managing unwanted ventilation. It is crucial however that ventilation is not reduced to a level which could negatively impact a home by creating an environment likely to result in condensation, damp, and mould.

Methodology

Airoom measures and logs temperature and humidity at ten-minute intervals. This data was gathered throughout the periods of both open and active modes of operation to enable comparison.

Results and analysis

The difference between average humidity levels whilst the Airoom systems were in open and active modes is shown in Figure 11. The active mode measurements are plotted on the y-axis and the open mode measurements are plotted on the x-axis. The red line shows a 1:1 relationship i.e., no change between the active and open mode periods. Figure 11 shows that there is no significant change in average humidity during the period the systems were in active mode.

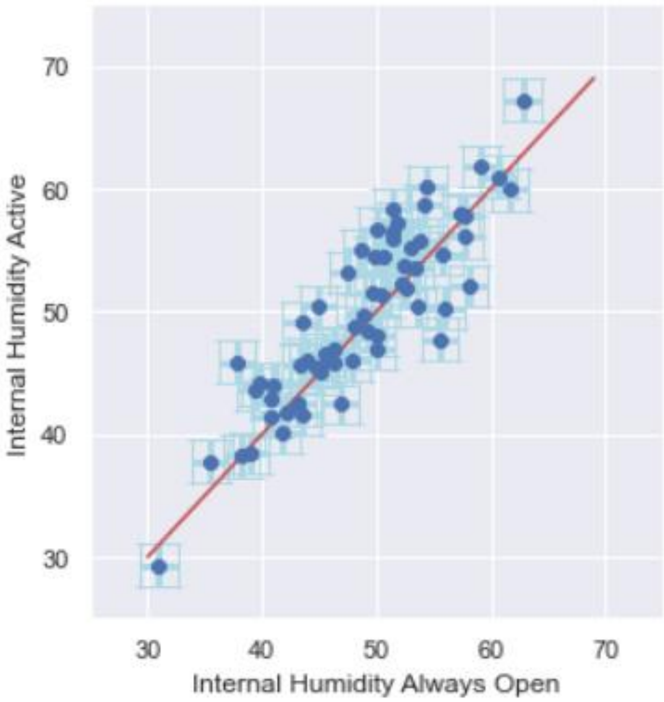

Figure 11: Scatter plot of humidity results in active and open modes with x=y line for comparison

The mean relative humidity increased by 2.2% (a 2.2 percentage point increase, as opposed to an increase of 2.2% relative humidity) when the air bricks were set to active mode as compared to open mode, which is considered to be a minor change. In addition, the median was +0.1% which shows that there was very close to an even split of dwellings with higher or lower humidity. On balance therefore, the internal humidity is not materially impacted by the operation of the Airoom system.

Healthy levels of indoor humidity

Typically, a relative humidity range of between 40-60% is considered a healthy indoor environment in an average home with an average occupancy level.[3] As such the proportion of time the internal humidity was within this healthy range whilst the Airoom system was in open and active modes was considered.

Figure 12 shows the mean internal humidity levels within the 40% - 60% range. It is clear that there is only a very small increase in average humidity when the Airoom system is in active mode as compared to open mode with no material difference between the two modes.

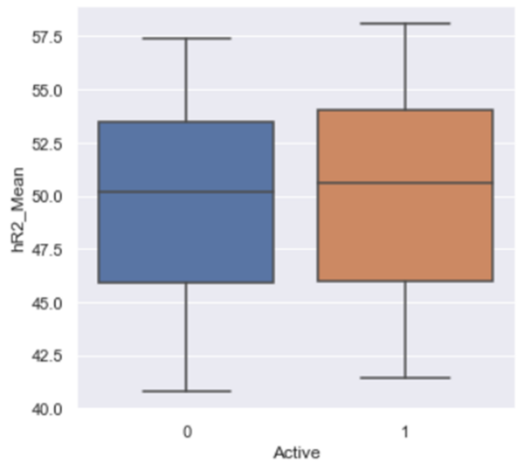

Figure 12: Box and whiskers plot of average humidity results in active and open modes

Figure 13 shows the percentage of time humidity was within the 40% - 60% humidity range. There is a small increase in the percentage of time spent in the healthy humidity range when in active mode as compared to open mode. The mean percent of times in the healthy ranges rises 2.0% from 73.2% to 75.2% whilst the median percent of time in the healthy ranges rises 4.4% from 81.7% to 86.1%.

The increase in the proportion of time when homes have a healthy internal humidity level when Airoom is in active mode appears to result mainly from a reduction in the amount of time the internal humidity is below 40%. It is speculated that this is due to the Airoom air bricks being closed during periods of very low external humidity.

[3] Arundel AV, Sterling EM, Biggin JH, Sterling TD. (1986) Indirect health effects of relative humidity in indoor environments. *Environ Health Perspect*.

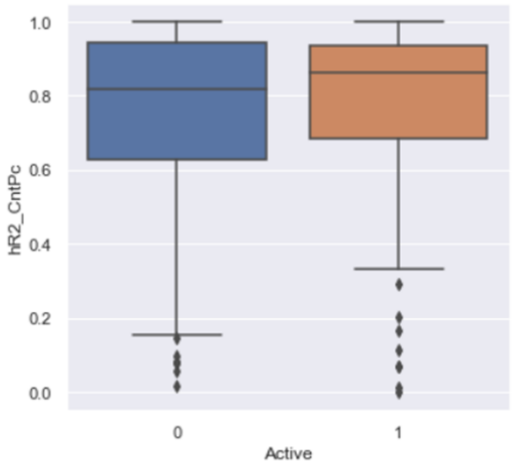

Figure 13: Box and whiskers plot of the percentage of time a home is in the "healthy humidity" in active and open modes

Technical details

Potential impact of Airoom

Airoom reduces the heat loss in a building, measured by the HTC, by reducing the heat loss through ventilation, it is useful to consider that:

$$H = H_T + H_V$$

where H is the total HTC, H_T is the HTC owing to transmission through the fabric of the building and H_V is the HTC caused by ventilation.[4] And that H_V can be expressed as:

$$Hv = c_p \, \rho \, q_v \, (t_i - t_o)$$

Where c_p is the specific heat capacity of air, ρ is the density of air, q_v is the air volume flow t_i is the internal temperature and t_o is the outside temperature.[5]

By reducing the air volume flow, Airoom reduces the H_V with this mechanism described by:

$$q_v = q_T + q_W$$

Where q_T is equal to the thermally induced air volume flows and q_w is equal to wind induced volume air flows. These two factors can in turn be described by:

$$q_T = C_D A_{eff} \sqrt{\frac{2gh\Delta t}{t_o}}$$

$$q_W = C_D A_{eff} \sqrt{\Delta C_P v}$$

Where C_D is the flow coefficient, A_{eff} is the effective area of an opening, g is acceleration due to gravity, h is the height of an opening, Δt is the temperature difference between the internal temperature and the outside temperature and v is the mean local wind velocity.[6]

As the parameters in both equations are known it is possible to model the minimum and maximum impact of Airoom moving from open to active modes in terms of air volume flow and HTC. This is achieved by considering the difference in these values when the air bricks are in the open and closed states.

The minimum potential impact of the system can be found by considering a situation where the vents remain open throughout the trial and there is therefore no change between the open and active modes. In this instance there would be no change in q_v and therefore no change in HTC.

[4] Li M, Allinson D, Lomas K. (2019) Estimation of building heat transfer coefficients from in-use data. *International Journal of Building Pathology and Adaptation*
[5] Carol, JS, Corvacho H, Silva P, Catro-Gomes, JP. (2010) Real climate experimental study of two double window systems with preheating of ventilation air. *Energy and Buildings*
[6] BSI (2014) S EN 12831-1 Heating systems and water-based cooling systems in buildings - Method for calculation of the design heat load

The maximum potential impact of the system can be determined by inputting a combination of physical constants and measurements taken during the trial (property characteristics, internal and external temperatures etc) into the above equations. For a typical property within the trial with 2 Airoom air bricks the HTC improvement could reach 20%. This is deemed to be conservative as up to 5 Airoom air bricks were installed in some homes.

HTC

Data cleansing methodology

The raw data gathered from the trial was analysed, and data cleansing used, to exclude from further consideration datapoints which appear erroneous. This has resulted in a dataset of 144 properties derived using a strict statistical methodology (dataset 1). Two additional datasets are presented here which further filter the data using building physics knowledge to exclude unlikely results.

The additional criteria utilised is outlined in Table 1 with the rational for examining these subsets provided in subsequent sections.

Name	Description	Size (properties)
Dataset 0	All data, only filtered to exclude properties with corrupted or duplicated data.	169
Dataset 1	As dataset 0 and additionally filtered to exclude properties where there was a change in total energy consumption between the two monitored periods greater than 2x the Inter Quartile Range[7]	144
Dataset 2	As dataset 1 and additionally filtered to exclude properties where the HTC of the home varied by more than 20% between the two monitored periods.	127
Dataset 3	As dataset 2 and additionally filtered to exclude properties where the HTC of the increased by more than 10% between the two monitored periods.	107

Table 1: Dataset overview

A summary of the impact of Airoom when these different datasets are examined is provided in Table 2.

Dataset	HTC improvement	Confidence interval	Wilcoxon p-value
0	0.6%	+1%/-3%	0.68
1	1.0%	+1%/-3%	0.85
2	2.0%	+3.0%/-2.0%	0.14
3	3.9%	+2.1%/-2.9%	<0.005

Table 2: Summary of HTC and HTC improvement for the three datasets of interest

Dataset 0

The results discussed in this section relate to the full dataset of the trial data, filtered only to remove corrupted or duplicated datapoints and consists of 169 properties. The SmartHTC measurements are shown in Figure 14 and Figure 15: Box and whiskers plot of HTC results in active and open modes, with the error bars showing the confidence interval at the 95% confidence level. The active mode measurements are plotted on the y-axis and the open mode measurements are plotted on the x-axis. The redline shows a x=y relationship i.e., no change in performance between the active and open mode periods and the blue line shows

[7] The interquartile range being defined as the difference between the 75th and 25th percentiles of the data.

the regression through the origin. Figure 14 shows graphically the performance improvement during the period the systems were in active mode.

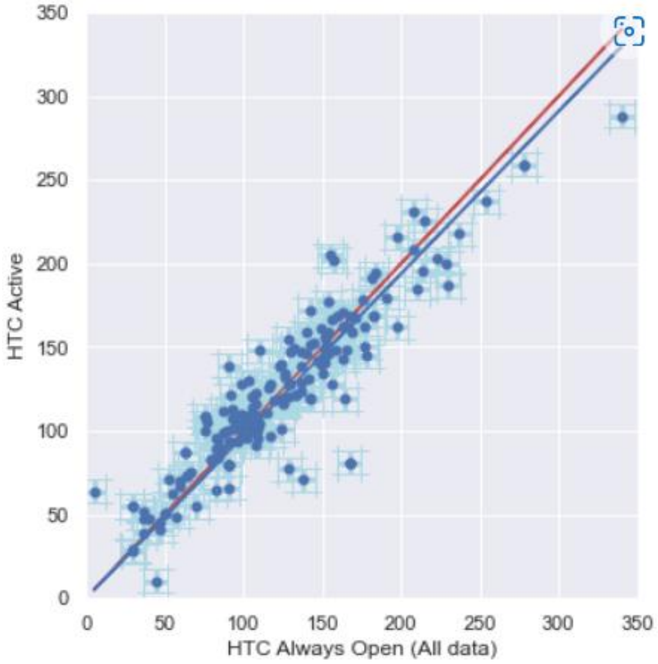

Figure 14: Scatter plot of HTC results in active and open modes with x=y line for comparison

The same impact is shown in Figure 15 which shows that the mean average improvement in HTC with Airoom in active mode was 0.6% (+1.0%, -3.0% at a 95% confidence interval) compared to the HTC when in open mode.

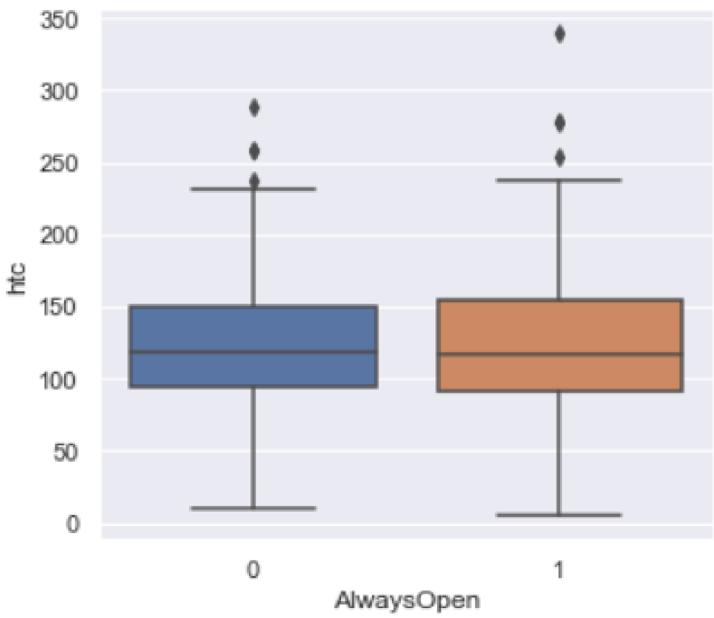

Figure 15: Box and whiskers plot of HTC results in active and open modes

In order to verify the significance of the results the Wilcoxon test has been used. This test determined that for a the sample of 169 pairs the difference in HTC between open and active had a p value of 0.68.

Dataset 1

Analysis of dataset 0 revealed 25 properties which showed a change in total energy consumption between the two distinct monitoring periods exceeding two times the interquartile range for the sample which indicates a significant change in resident behaviour (further explored in the Impact of occupants' behaviour section. This additional step results in a dataset of 144 properties with valid data for both monitored periods. The results calculated from this dataset are shown in full in the Summary of results. The average improvement in HTC with Airoom in active mode was 1.0% (+1.0%, -3.0% at a 95% confidence interval) compared to the HTC when in open mode.

Dataset 2

The mechanism and potential impact of the Airoom system is outlined in the section Potential impact of Airoom. It is clear that reducing airflow through air bricks during periods when the internal temperature of a home exceeds the external temperature will reduce heat loss. As such it is reasonable to deduce that, in homes where the HTC increases with the Airoom system in active mode, there are other mechanisms that are producing this effect.

Efforts have been made, both with the experimental methodology and with the data cleansing methodology outlined previously, to control for other factors impacting heat loss in a building. It is clear from analysis of the data that, as might be expected, this has not been fully successful. As such it is reasonable to further filter data in an effort to exclude properties where an uncontrolled factor impacting heat loss is apparent.

This results in Dataset 2 of 127 properties in which all properties where the thermal performance of the home varied by more than 20% between the two monitored periods are excluded form analysis. This approach outlined is based on the established methodology implemented by the BRE when evaluating the AirEx subfloor air brick for inclusion in SAP Appendix Q.[8]

The SmartHTC measurements for this subset are shown in Figure 16, with the error bars showing the confidence interval at the 95% confidence level. The active mode measurements are plotted on the y-axis and the open mode measurements are plotted on the x-axis. The redline shows a x=y relationship i.e., no change in performance between the active and open mode periods and the blue line shows the regression through the origin. Figure 16 shows graphically the performance improvement during the period the systems were in active mode.

[8] BRE. (2022) BRE Technical Report - SAP Appendix Q– Evidence underpinning the saving attributed to the AirEx system

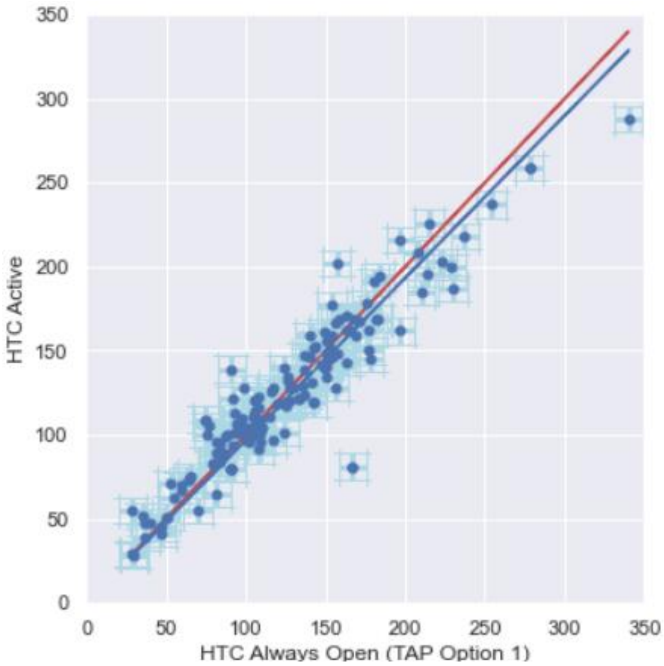

Figure 16: Scatter plot of HTC results in active and open modes with x=y line for comparison

The same impact is shown in Figure 17 which shows that the mean average improvement in HTC with Airoom in active mode was 2.0% (+3.0%, -2.0% at a 95% confidence interval) compared to the HTC when in open mode.

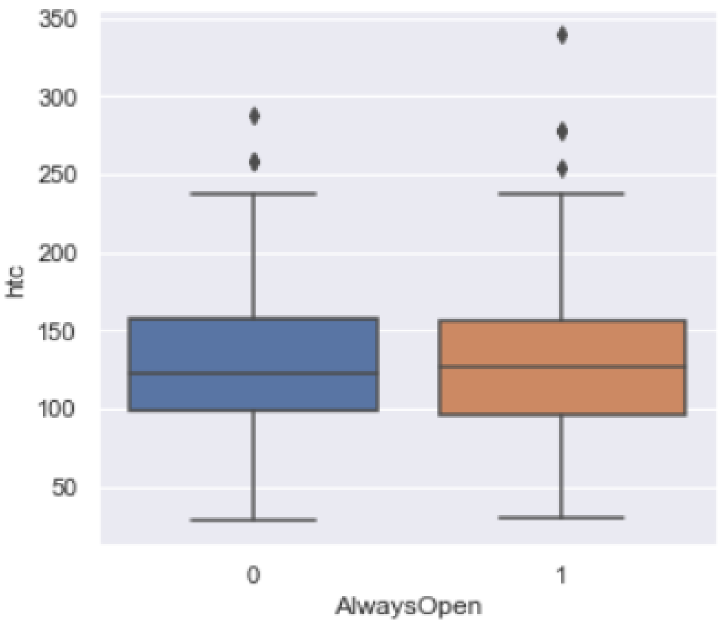

Figure 17: Box and whiskers plot of HTC results in active and open modes

In order to verify the significance of the results the Wilcoxon test has been used. This test determined that for the sample of 127 pairs the difference in HTC between open and active had a p value of 0.14.

Dataset 3

Dataset 3 builds upon the methodology used to derive dataset 2 and excludes from analysis all properties where the thermal performance of the home decreased by more than 10% with the Airoom system in active mode. The rationale for Dataset 3 being that the SmartHTC measurement has a quoted uncertainty of ~10% and so a property in which no change in thermal performance resulted could conceivably show an HTC increase of up to 10%.

The SmartHTC measurements for this subset are shown in Figure 18, with the error bars showing the confidence interval at the 95% confidence level. The active mode measurements are plotted on the y-axis and the open mode measurements are plotted on the x-axis. The redline shows a x=y relationship i.e., no change in performance between the active and open mode periods and the blue line shows the regression through the origin. Figure 18 shows graphically the performance improvement during the period the systems were in active mode.

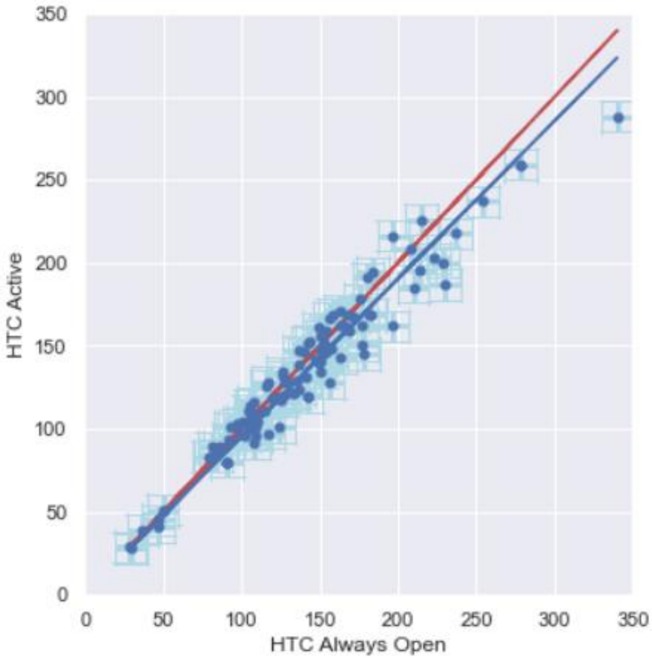

Figure 18: Scatter plot of HTC results in active and open modes with x=y line for comparison

The same impact is shown in Figure 19 which shows that the mean average improvement in HTC with Airoom in active mode was 3.9% (+2.1%, -2.90% at a 95% confidence interval) compared to the HTC when in open mode.

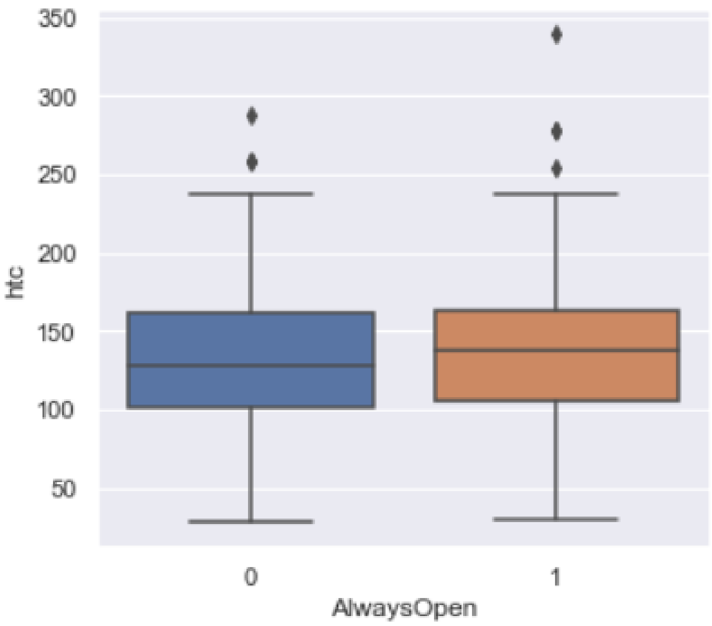

Figure 19: Box and whiskers plot of HTC results in active and open modes

In order to verify the significance of the results the Wilcoxon test has been used. This test determined that for a the sample of 107 pairs the difference in HTC between open and active had a p value of <0.005.

Whilst this dataset has the advantage of removing some datapoints that appear to be the result of uncontrolled variables it must be acknowledged that in doing so the sample size is reduced. Further study is necessary to attempt to control for these factors within experimental design as opposed to *post facto* data analysis.

Uncertainty estimates and confidence intervals

Each SmartHTC measurement is provided with an individual uncertainty estimate. This figure is an estimate of the accuracy of the individual HTC measurement, designed to account for effects such as the accuracy of monitoring equipment, accuracy of meter readings, occupancy, weather, solar gain, heating system efficiency etc.

In the use case of a paired trial such as this, where measurements taken in the same property across two different periods are compared, the “long term” sources of uncertainty are effectively controlled for, although daily variations (e.g., behavioural changes such as patterns of occupation or window opening in response to daily weather) are not. For the purposes of this report, we calculate the confidence intervals using standard statistical methods.

As such, SmartHTC results have been calculated with a median confidence interval at a 95% confidence level, consistent with the Wilcoxon test. The confidence intervals for the Wilcoxon test are estimated from the sample, bounded by the nth smallest and nth largest values in the sample population, where n is a function of the confidence level, 95% in this case. These are generally not symmetrical.

Factors impacting HTC

In an effort to understand the impact that the Airoom system has on a property a number of different factors that could have impacted the scale of HTC improvement, such as property type, detachment, occupancy, number of bedrooms, number of air bricks, heating system, heating controls, etc have been investigated. Correlations were observed with factors such as occupancy, number of external walls, and heating system. However, it is worth noting that the HTC results show a wide range across the sample and that there may be cross-correlation between different variables.

Number of bedrooms

As can be seen in Figure 20, there is no significant relationship between the number of bedrooms a property has and the HTC improvement.

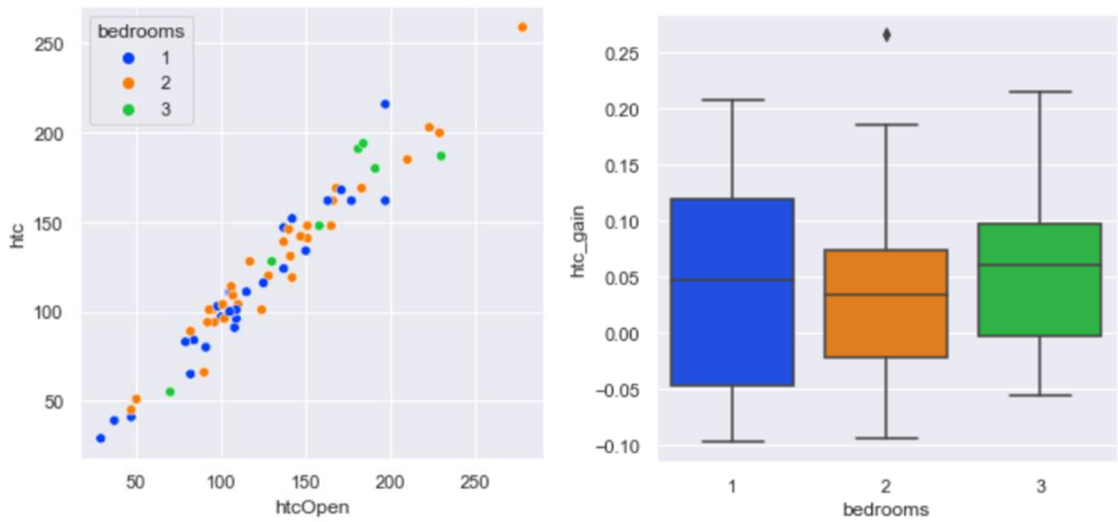

Figure 20: a) Scatter plot of SmartHTC results in active and open modes showing the number of bedrooms b) Box and whiskers plot of HTC improvement for properties with differing numbers of bedrooms

External walls

As can be seen in Figure 21, the HTC improvement is greater for properties with fewer external walls. This aligns with expectations and also with the findings on the AirEx (sub-floor level air bricks) study. It can be assumed that properties with a higher number of external walls are likely to have a higher overall heat loss (due to increased infiltration losses through cracks and gaps in walls, windows, etc), as such, the Airoom system's impact would be proportionately smaller. The data suggests that the impact of Airoom installation in properties with 3 external walls is minimal but the sample size for such properties is low and prevents the drawing of any firm conclusions.

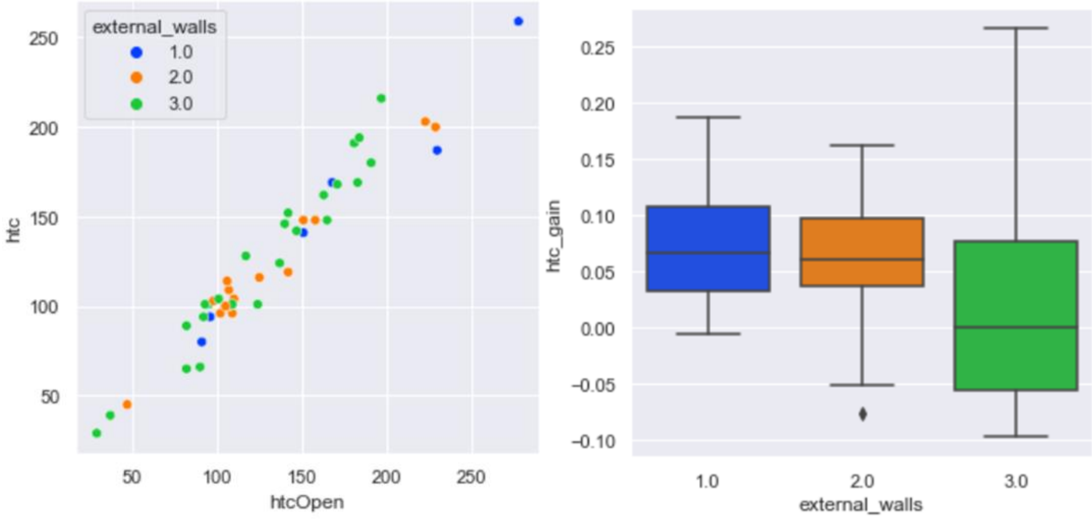

Figure 21: a) Scatter plot of SmartHTC results in active and open modes showing the number of external walls b) Box and whiskers plot of HTC improvement for properties with differing numbers of external walls

Occupancy

As can be seen in Figure 22, the HTC improvement is greater for properties with fewer occupants. This aligns with expectations and also with the findings on the AirEx (sub-floor level air bricks) study. It may be assumed that this can be attributed to fluctuations in occupancy in larger households i.e., differences in 'recorded' vs 'actual' occupancy levels, particularly in more crowded properties. As occupancy is a key input to SmartHTC this could have impacted results if, for example there was a change in the frequency or regularity of window opening, moisture generation (showers and cooking) or other appliance use. Further investigation would be required to confirm this assumption.

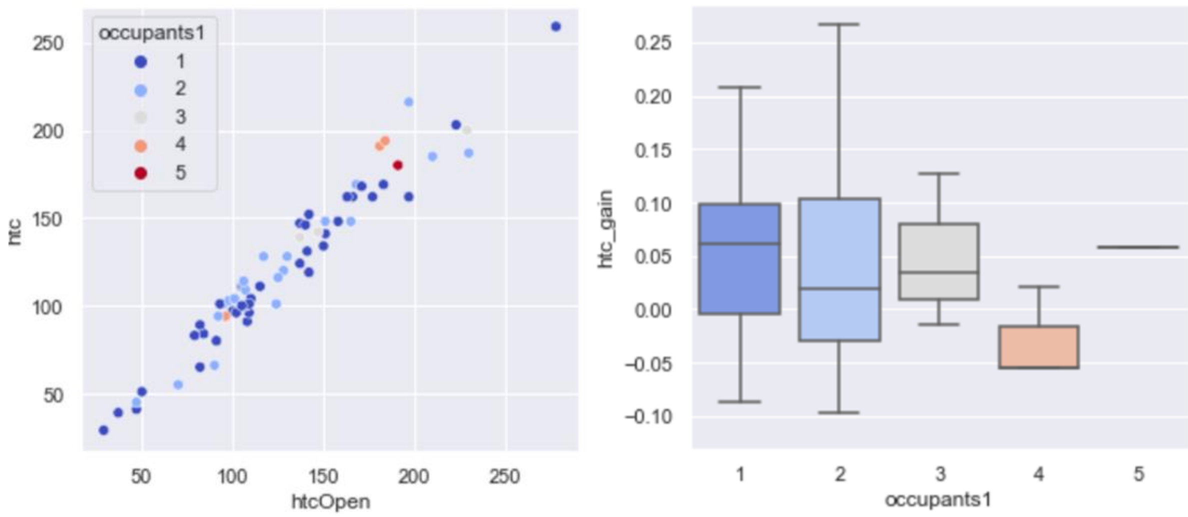

Figure 22: a) Scatter plot of SmartHTC results in active and open modes showing the number of occupants b) Box and whiskers plot of HTC improvement for properties with differing numbers of occupants

Number of air bricks

As can be seen in Figure 23, there is no relationship between the number of air bricks installed in a property and the HTC improvement.

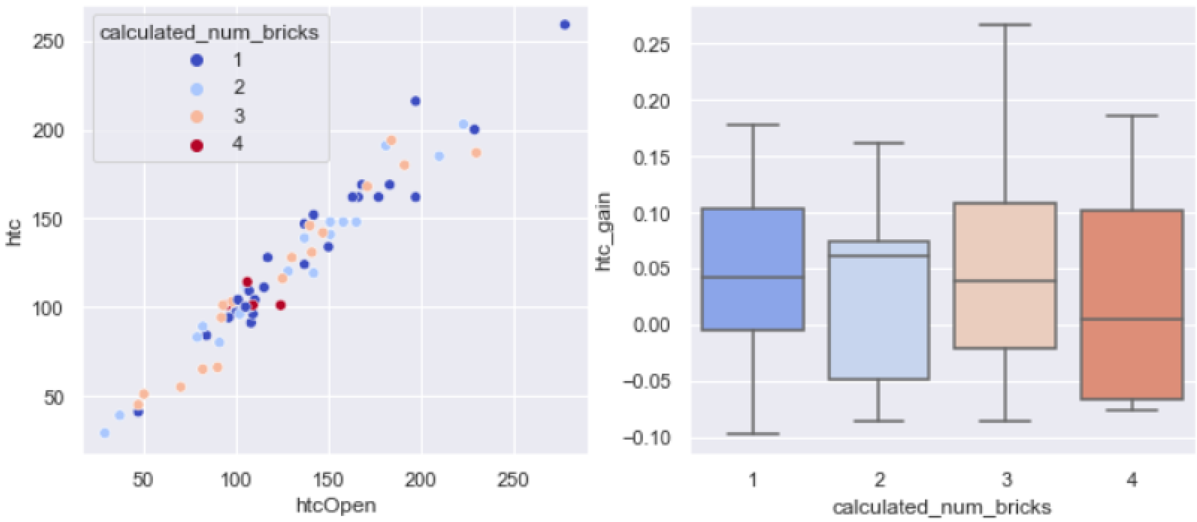

Figure 23: a) Scatter plot of SmartHTC results in active and open modes showing the number of Airoom air bricks installed b) Box and whiskers plot of HTC improvement for properties with differing numbers of installed Airoom air bricks

As it is likely that homes with more air bricks are larger an effort was made to control for this by examining the floor area per air brick as shown in Figure 24. Again, no significant relationship was found.

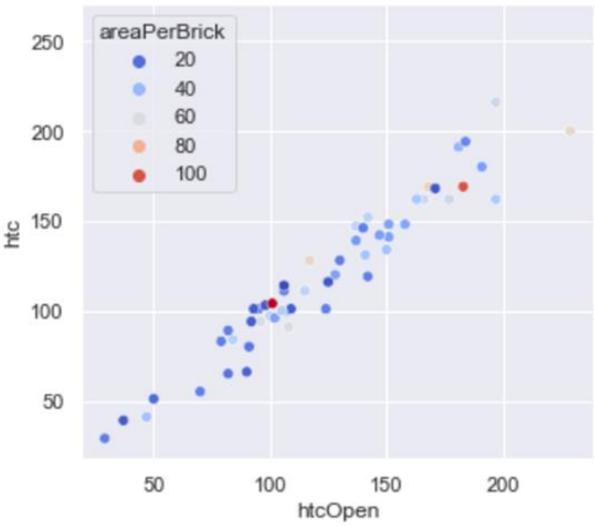

Figure 24: Scatter plot of SmartHTC results in active and open modes showing the floor area per Airoom air brick installed

Next the impact of “missing” air bricks (meaning the number of pre-existing air bricks that it was not possible to replace with an Airoom air brick) was examined. As can be seen in Figure 25, the HTC improvement is greater for properties with fewer missing air bricks. This aligns with expectations as the Airoom system is controlling a higher proportion of the total ventilation area of the home.

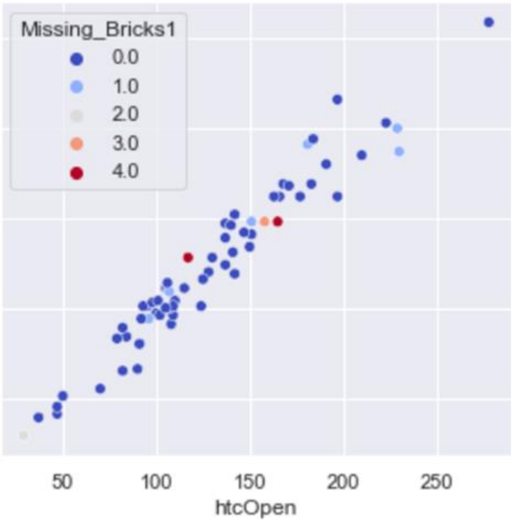

Figure 25: Scatter plot of SmartHTC results in active and open modes showing the number of "missing bricks"

Heating system and heating controls

As can be seen in Figure 26, the HTC improvement is greater for gas heated homes as opposed to those reliant on electric heating. It is not possible to draw too firm conclusions from this as there is strong correlation between the heating system used and the geographic location of the property. The majority of gas heated homes were in Portsmouth whilst the electrically heated homes were generally in Manchester. Given the impact that changes in weather can have on HTC calculations, this is important to consider.

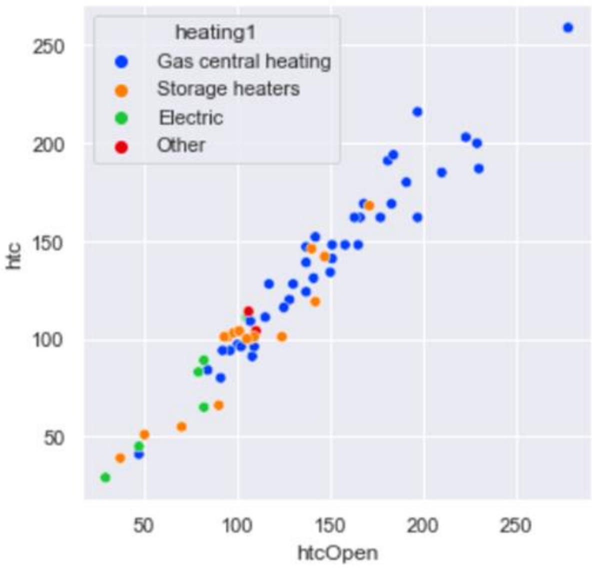

Figure 26: Scatter plot of SmartHTC results in active and open modes showing the properties main heating system

Different heating systems may also be related to differing heating behaviour. Occupants of electrically heated homes are more likely to be in fuel poverty as such. It may be assumed that, given the nature of electrical heating control systems, residents may turn off the room heaters in unoccupied rooms. Gas central heating is by definition more centrally controlled and as it is more affordable a degree of 'comfort-taking' may be expected meaning the heating system is used more which results in larger HTC improvements.

As can be seen in Figure 27, there is no significant relationship between the type of heating controls installed in a property and the HTC improvement.

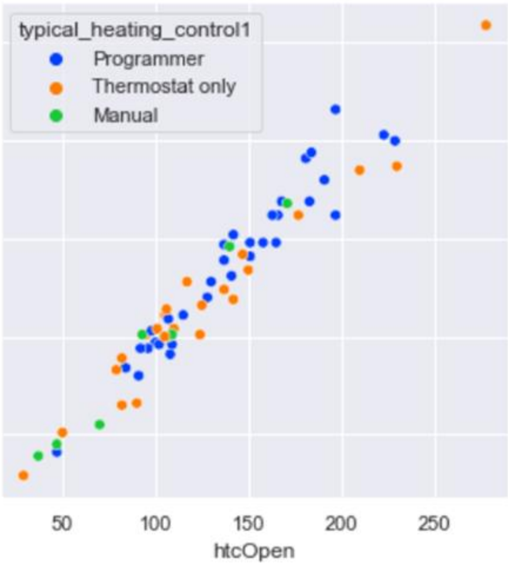

Figure 27: Scatter plot of SmartHTC results in active and open modes showing the heating controls used by the properties main heating system

Impact of occupants' behaviour

Homes are complex environments with many variables able to impact the results of a trial such as this. It is clear that there is a considerable amount of 'noise' in the data set and as efforts have been made to understand and quantify how occupants' behaviour may have impacted the HTC results.

The main source of CO_2 within a home is human respiration with ventilation and infiltration managing these levels. As such, regular high levels of CO_2 may indicate that a home is under ventilated relative to the number of occupants. This could be caused either by inadequate ventilation or by over-occupancy.

Figure 28 shows the average daily range in CO_2, by hour of the day (the x axis) for 102 properties with reliable CO_2 data (the y axis). The colour range shows high CO_2 concentrations (>2400ppm) in red and low CO_2 concentrations (400pppm) in green, yellow fields showing medium levels of CO_2 concentrations.

The properties shown towards the top of Figure 28, are those with a high daily range of CO_2 values. These typically show peak concentrations in the morning and evening (with a slightly higher proportion of peak concentration in the evenings) and lower CO_2 levels in the middle of the day. The dwellings towards the bottom of Figure 28 have consistently lower CO_2 levels. The variation between these groups could result from either daily variation in occupancy levels and/or varying levels of ventilation throughout the day.

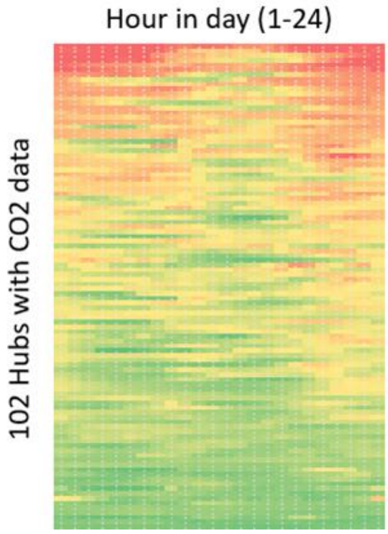

Figure 28: Heatmap of average CO2 for each property across a day

Similarly to CO_2 the main source of indoor humidity is human behaviour through respiration, bathing and cooking with the main mechanism managing this level being infiltration and ventilation.

Figure 29 shows the average daily range in indoor humidity, by hour of the day (the x axis) for the same 102 properties in the same order (the y axis). It is coloured to show the relative range of humidity in each dwelling with similar colour-coding as in Figure 23 (red meaning high and green meaning low humidity levels).

It can be seen that there is a more uniform pattern of humidity levels as opposed to CO_2 across the sample with most dwellings having a similar diurnal pattern. Given that humidity levels are driven by occupant behaviour it can therefore be inferred that the daily variation in occupancy level is broadly comparable across the dataset.

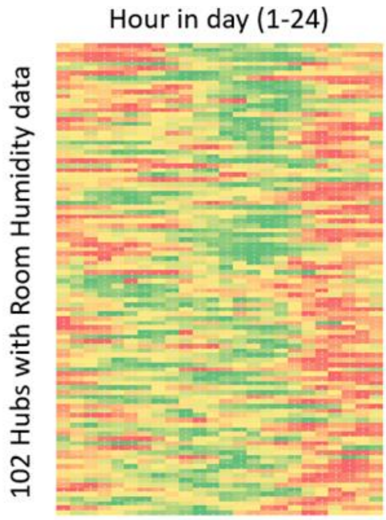

Figure 29: Heatmap of average humidity for each property across a day

Owing to the fact that daily occupancy patterns appear to be broadly consistent across the sample it is reasonable to discount this as the mechanism responsible for the variation in daily CO_2 levels. This leaves variation in ventilation levels throughout the day as the most probable cause of this pattern. The most likely mechanism for varying ventilation levels throughout the day are the opening and closing of windows.

To further investigate this assumption, Figure 30 plots the HTC improvement (the y axis) against the ratio of maximum to minimum daily CO_2 (the x axis). Observing the whole dataset (i.e., not following the outlined data cleansing methodology), it's clear that there are more outliers (properties in which the HTC got worse) where CO_2 levels are low. This again suggests that varying ventilation has a significant effect on the HTC results.

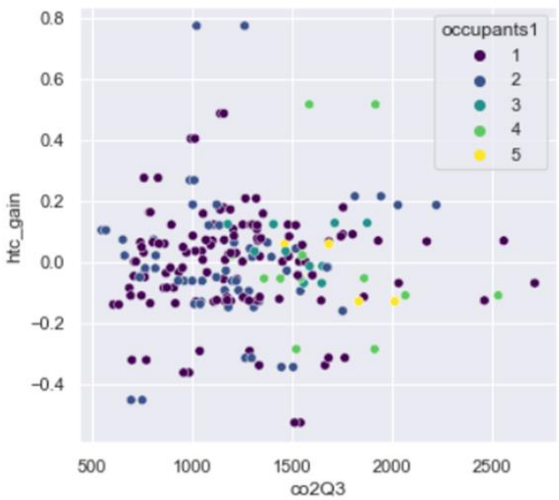

Figure 30: Scatter plot of HTC improvement against average CO2 level

Figure 31 plots HTC improvement against the ratio of the average maximum and minimum hourly CO_2 levels. Homes with high fluctuations of CO_2 levels throughout the day in general have smaller (or even negative) HTC improvements whereas the largest HTC improvements are in homes with more consistent CO_2 levels. It may be assumed that this is a key driver in obtaining 'negative' HTC improvements being observed in these properties. Here, occupants' window-opening behaviour potentially overrides the Airoom system's impact, further research is required to confirm this assumption.

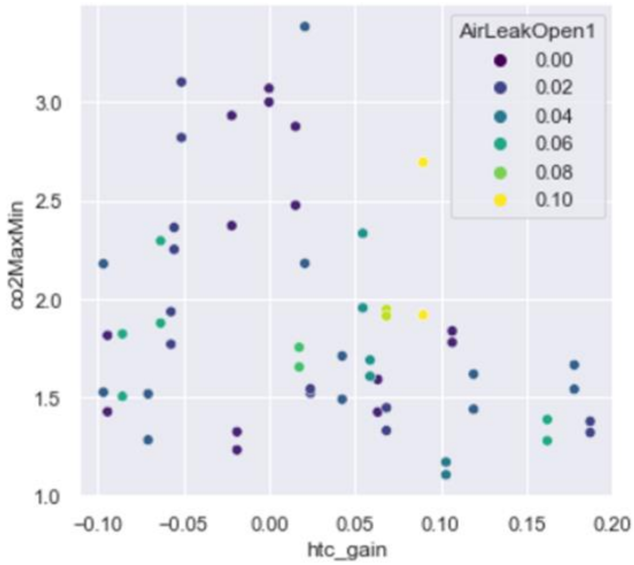

Figure 31: Scatter plot of the ratio of maximum and minimum hourly average CO2 level against HTC improvement

Air Tightness

Sample size

Of the 90 properties in which 2 or 3 air tightness tests were carried out the vast majority produced results that make direct assessment of the impact the Airoom system has on air tightness of a home impossible. This was caused by an oversight in the experimental design which was not identified until the conclusion of the trial.

The Airoom devices within a home communicate with the Airoom cloud-based control only periodically (on average every 30 minutes). At this point measured data is transmitted from the in-home devices to the cloud, the Airoom algorithms then determine whether vents should open and close and transmit this command to the in-home devices. It is also possible to manually override the vent behaviour to stay open at all times or stay closed at all times. This manual override was used to set the air brick state while the air tightness testing was performed. Unfortunately, as data is transmitted only half hourly at the most between the in-home divides and the cloud-based control system in the vast majority of cases the tests were completed before the state was able to change. As such measurements were taken of the same state twice.

Impact on HTC results

As can be seen in Figure 32, no significant relationship between the air tightness of a property and the HTC improvement was found. As outlined in the Impact of occupants' behaviour section this could be due to window opening behaviour overriding the impact of the fabric air tightness.

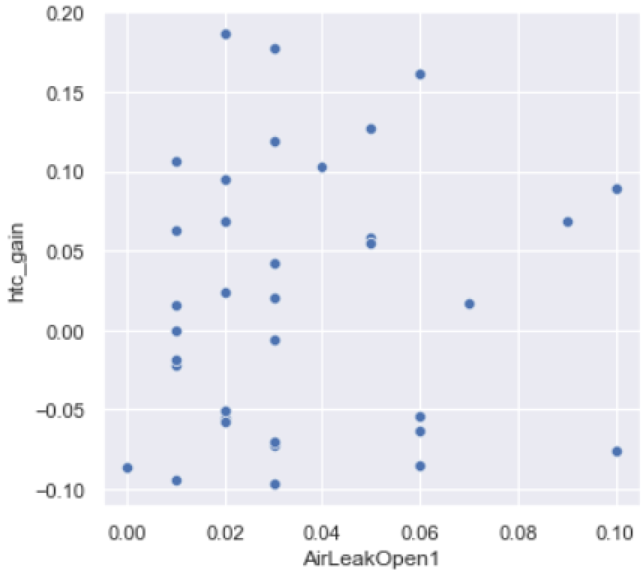

Figure 32: Scatter plot of HTC improvement and air tightness

Limitations

Whilst all due care and effort was taken with regards the design and delivery of this trial, there are some limitations which are examined here.

Sample representation

The trial was conducted predominantly in purpose-built blocks of flats (two properties were purpose-built maisonettes). The properties had a range of different heating systems, were predominantly of cavity wall construction, had between 1 and 3 bedrooms (average 1.6), and had between 1 and 7 occupants (average 1.7). This is not representative of the UK housing stock as a whole and neither is the low number of air bricks replaced (2.2).

Monitoring of the impact of Airoom in a range of property types would be preferable but the cost of such a trial would not offer sufficient value-for-money for energy bill payers. Furthermore, the requirement that installations only be carried out in homes with fuel poor occupants further restricts the possibility of a representative trial. By concentrating on one property type it allowed for the impact of built form, detachment, and property size to be controlled to an extent.

Limitations of SmartHTC

The SmartHTC method of measuring HTC is the most cost effective and practical way to measure the thermal performance of a building. The only other method of determining this would be a Co-heating test which is not appropriate for the purposes of evaluating the Airoom DA. Not only because of the cost (~£5,000 per test)[9], but also because homes need to be decamped for up to 21 days[10] inconveniencing residents and making it impossible to assess in-use performance. Using the SmartHTC method, there are however some variables that cannot be controlled for which are outlined below.

Impact of weather

Whilst the SmartHTC method does account for climatic variation by both taking measurements over a period of time (a minimum of 21 days in this trial) and by accounting for changing external temperatures it is impossible to fully control for the impact of local weather variation. Two specific factors which vary over time and are not controlled for are variations in wind spread and direction and solar irradiance leading to solar thermal gain.

A variation across the two monitored periods in either of these variables could have significant impacts on the measured HTC. It is important to note that wind speed and wind direction affect not only ventilation and infiltration but also the rate of convective and conductive heat loss from a building.

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9 Deb C, Gelder LV, Spiekman M, Pandraud G, Jack R, Fitton R (2021) Measuring the heat transfer coefficient (HTC) in buildings: A stakeholder's survey *Renewable and Sustainable Energy Reviews*

10 Farmer D, Johnston D, Miles-Shenton D (2016) Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating). *Energy and Buildings*

Occupants' behaviour

The impact of occupant behaviour is, so far as possible, controlled by designing the experiment as a repeated measures trial. However, individual resident behaviour can change over the length of the trial. Three mechanisms which may play a part in this are residents manually covering the vents whilst in open mode due to discomfort caused by the cold air infiltration, residents opening windows more during periods of warmer weather and changes in the pattern of use of electrical devices in response to rising energy prices.

The project team are aware anecdotally of instances of all three of these behaviours. Unfortunately, it is not possible to directly quantify the scale or magnitude of the impact these might have on specific trial results. It is however possible to understand the potential impact some of these behaviours might have.

The impact of window opening on HTC has been investigated in previous studies with the finding that HTC total heat loss can increase by more than 10% for homes where windows are regularly opened.[11] Given that the homes within this trial were in general, more airtight than the average UK home. It is not unreasonable to suspect that manual ventilation i.e., the opening of windows is frequently used by residents.

Competing control priorities

The Airoom system has been designed to ensure that, whilst it manages ventilation to improve the thermal efficiency of a home, it does not result in an unhealthy environment for residents or buildings. To ensure this, CO_2 and humidity levels are monitored by the system and ventilation allowed if these measurements mean this is required. The Airoom control logic is complex, but simplistically the vents will open should there be a potentially unhealthy level of CO2 in the internal atmosphere or if the combination of humidity and temperature risks condensation, damp, or mould.

Because of these factors, Airoom would be expected to be in its open state more often when there are factors, either physical or due to occupancy, within the home that led to potentially unhealthy conditions more often. These include but are not limited to homes: with low levels of ventilation, which are "over occupied", where excess moisture is generated e.g., though drying of clothes or cooking.

[11] Jack R, Loveday D, Allinson D, Lomas K. (2016) Quantifying the Effect of Window Opening on the Measured Heat Loss of a Test House. *Sustainable Ecological Engineering Design*

Cost savings

The purpose of this DA was to determine the cost savings impact of the Airoom system. The method used to determine the average cost savings was as follows:

- The average percentage HTC improvement per property was calculated along with the boundaries of the confidence interval
- The heat demand reduction for a typical UK home was then calculated by multiplying the average percentage HTC improvement and the bounds of the confidence interval by the average UK heating energy demand for a domestic dwelling
- The annual bills savings and lifetime bills savings were then calculated for both gas and electrically heated homes using average energy prices included in SAP10[12]
- As an additional exercise the impact of Airoom is examined using energy costs from the April to September 2022 energy price cap and the HTC improvement calculated from additional analysis using building physics (dataset 3)

Cost impact (dataset 1, SAP energy costs)

Gas heated homes

	1.0% improvement	2.0% improvement	-2.0% improvement
Heating demand reduction (kWh/year)	115	239	-239
Annual savings (£)	4	9	-9
Lifetime bill savings (£)	104	217	-217

Electrically heated homes

	1.0% improvement	2.0% improvement	-2.0% improvement
Heating demand reduction (kWh/year)	115	239	-239
Annual savings (£)	19	39	-39
Lifetime bill savings (£)	473	983	-983

[12] All bill savings are rounded to the nearest whole pound

Cost impact (dataset 3, SAP energy costs)

Gas heated homes

	3.9% improvement	6.0% improvement	1% improvement
Heating demand reduction (kWh/year)	468	688	115
Annual savings (£)	17	25	4
Lifetime bill savings (£)	425	626	104

Electrically heated homes

	3.9% improvement	6.0% improvement	1% improvement
Heating demand reduction (kWh/year)	468	688	115
Annual savings (£)	77	113	19
Lifetime bill savings (£)	1927	2836	473

Cost impact (dataset 1, April 2022 energy costs)

Gas heated homes

	1.0% improvement	2.0% improvement	-2.0% improvement
Heating demand reduction (kWh/year)	115	239	-239
Annual savings (£)	8	17	-17
Lifetime bill savings (£)	201	417	-417

Electrically heated homes

	1.0% improvement	2.0% improvement	-2.0% improvement
Heating demand reduction (kWh/year)	115	239	-239
Annual savings (£)	32	67	-67
Lifetime bill savings (£)	803	1670	-1670

Cost impact (dataset 3, April 2022 energy costs)

Gas heated homes

	3.9% improvement	6.0% improvement	1% improvement
Heating demand reduction (kWh/year)	468	688	115
Annual savings (£)	33	48	8
Lifetime bill savings (£)	818	1204	201

Electrically heated homes

	3.9% improvement	6.0% improvement	1% improvement
Heating demand reduction (kWh/year)	468	688	115
Annual savings (£)	131	193	32
Lifetime bill savings (£)	3273	4815	803

Environmental impact

	1.0% improvement	3.9% improvement
Heating demand reduction (kWh/year)	115	468
CO_2 saving for gas heated homes (kg/year)	21	86
CO_2 saving for electrically heated homes (kg/year)	46	186

The following constants were used in these calculations:

SAP unit gas price (£)[13]	0.0364
SAP unit electricity price (£)[13]	0.1649
2022 unit gas price (£)	0.07
2022 unit electricity price (£)	0.28
Average UK heating energy demand (kWh/year)[14]	12,000
Lifetime (years)	25
CO_2 conversion for natural gas (kWh/kg)	0.184
CO_2 conversion for electricity (kWh/kg)	0.398

[13] BRE. (2022), The Government's Standard Assessment Procedure for Energy Rating of Dwellings
[14] Ofgem. (2019), Review of Typical Domestic Consumption Values 2019

Conclusion

Strict statistical analysis of the data gathered during the trial produced “Dataset 1” which shows that the Airoom system led to a reduction in the HTC (a reduction in the amount of heat a home loses) of 1% (+1%/-3%). Data from further analysis incorporating building physics principles to account for uncontrolled variables produced a “Dataset 3” of reduced size due to additional data cleansing, this suggests that the average energy saving per household was 3.9% (+2.1%/-2.9%).

Dataset 1 determines that the Airoom system can lead to a lifetime bill saving of £104 (-£217 to £217) for gas heated homes (SAP10 tariff, £0.0364/kWh), or £473 (-£983 to £983) in electrically heated households, (SAP10 tariff of £0.1649/kWh). If the Ofgem price cap energy prices were to be used, the savings reflected would be £201 (£-417 to £417) at a unit cost of £0.07/kWh for gas heated homes, or £803 (£-1670 to £1670) for electrically heated homes at unit price of £0.28/kWh.

Dataset 3 suggests that lifetime bill saving resulting from Airoom installation would be £425 (£104 to £626) in gas heated households (SAP10 tariff, 0.0364/kWh), or £1927 (£473 to £2836) in electrically heated households, (SAP10 tariff of £0.1649/kWh). When applying the Ofgem price cap tariff values, these savings would be £818 (£201 to 1204), for gas heated homes, or £3273 (£803 to £4815) for electrically heated homes.

In achieving this improvement results this there is no significant increase in the relative humidity of homes as a result of managing airflow with healthy levels of indoor humidity being maintained.

Analysis of the data makes clear that the residential home is a complex environment with many factors governing heat loss and energy consumption. Best efforts have been made to control for these factors through both the experimental methodology and in the subsequent data analysis. However, further investigation is warranted to more fully understand the mechanisms though which Airoom results in a reduction in the HTC.