Department for Energy Security & Net Zero

LEEDS BECKETT UNIVERSITY
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DEEP Report 2.12

Case Study 19BA

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Prepared for DESNZ by

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Executive summary

19BA is a mid-terraced pre 1900 solid walled home where airtightness improvements and room-in-roof retrofits have been installed. Building performance testing has been undertaken to collect data on the performance and risks of these improvements, and to evaluate the accuracy of modelled predictions on the retrofit performance and risk.

The airtightness improvements in 19BA consisted of sealing around fenestrations and penetrations and boxing in of services, undertaken in order to investigate the impact of a non-invasive airtightness retrofit. The room-in-roof retrofit involved installing wood fibre boards to the sloping ceilings, knee walls and dormer walls. Cumulatively the retrofits reduced the heat transfer coefficient (HTC) of the home by (18 ± 13) W/K, or (7 ± 5) %, according to coheating tests. Individually the retrofits did not make statistically significant reductions to the HTC, but the room-in-roof was responsible for approximately two thirds of the measured reduction.

Fabric heat losses in the home, represented over 60 % of the total heat loss, and the uninsulated solid walls represented around half of this. Substantial fabric heat loss remained post-retrofit. Because of this, the energy performance certificate (EPC) rating for the post-retrofit dwelling was insufficiently improved to achieve a band C. The exception to this was observed in the reduced data Standard Assessment Procedure (RdSAP) default model, which has an embedded simplification in its assumptions concerning room-in-roof geometry. This simplification results in extremely high heat losses being predicted, which, in turn, when the room-in-roof is insulated, means that a 30 % reduction in HTC is predicted. Measurements suggest these savings are unrealistic, the room-in-roof retrofit achieving a smaller 5 % reduction to HTC. This has implications for decisions about insulating rooms-in-roof, and the accuracy of EPC.

Initially, the airtightness and room-in-roof retrofits reduced infiltration in the home from 24 to 19 $m^3/(h \cdot m^2)$ @ 50Pa and from 21 to 17 $m^3/(h \cdot m^2)$ @ 50Pa, respectively. However, the coheating test caused accelerated drying causing the silicon and plaster air barriers to shrink and crack, meaning the post coheating airtightness of the home increased up to 20 $m^3/(h \cdot m^2)$ @ 50Pa. This suggests airtightness improvements may be temporary. The air leakage pathways were also complex and interconnected, meaning that without stripping back fabric to install a continuous air barrier, the improvements made redirected rather than eliminated most of the air leakage paths.

Incorporating the measured infiltration rates increased the modelled predictions of heat loss, since these were higher than defaults in RdSAP, however, this was offset by incorporating the measured U-values, which were lower than the defaults. The dynamic model predicted much lower energy demand, since it incorporated useful gains. Thus, the steady-state models predict higher fuel bill and retrofit savings than the dynamic models. RdSAP does not allow infiltration rates to be altered, and so predicts no benefit from airtightness improvements, however, the Building Research Establishment Domestic Energy Model (BREDEM) and dynamic models suggest there may be savings of between 6 and 9 $kWh/m^2/yr$.

Overheating in the home was assessed as relatively low, since 19BA is a mid-terrace house shaded by neighbours. The overheating risk present in the room-in-roof bedrooms was mitigated by insulation. This is a significant consideration when making decisions around retrofitting homes with a room-in-roof. The combined retrofits cost £19,419, (85 % on the room-in-roof), however, 40 % of this was unforeseen additional spend on rebuilding a wall behind the knee wall and relocating plumbing. Enabling costs have implications for retrofit budgeting and the allocation of risk. Despite the room-in-roof achieving larger savings, the airtightness retrofit was more cost effective.

1 Introduction to 19BA

Case study 19BA is a four bed 1900 mid-terrace in which airtightness and room-in-roof retrofits were undertaken. The airtightness retrofit consisted of general sealing of air leakage paths, without significant deconstruction of the building fabric. The room-in-roof retrofit consisted of new insulation to the ceilings of the loft and eaves voids, new insulation to the sloped ceilings and insulation to the knee walls and dormer external wall. The performance of each retrofit was assessed for airtightness and thermal performance.

1.1 DEEP field trial objectives

19BA is one of fourteen DEEP case studies, which, collectively, investigate the research objectives listed in Table 1-1, though not all the objectives are addressed by each case study.

Table 1-1 DEEP research objectives

Objective	Rationale
Model input accuracy	Policy relies on models with known limitations, exploring inputs and model robustness will improve policy advice.
Unintended consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality and comfort risks.
Cumulative impact	Piecemeal retrofits are common, clarity is needed on the impact of various options including achieving EPC band C.
Fabric vs. ventilation	Insulation influences fabric and ventilation heat loss, yet models currently only attribute savings to U-value changes.
Floor retrofit	80 % of homes have uninsulated floors, clarity on the benefits may increase installation from 0.5 % of Energy Company Obligation (ECO) measures.
Airtightness retrofit	Infiltration undermines retrofits, balancing airtightness and indoor air quality is an unexploited ECO opportunity.
Neighbour risk	We investigate whether whole house or staged retrofits affect condensation risk for neighbours.

1.2 Case study research questions

Over the course of the three-year project and following advice from the Department for Energy Security and Net Zero (DESNZ), the wider DEEP steering group and expert QA panel, questions have been proposed and objectives refined to develop the seven discreet research questions listed below, which are used to discuss the findings:

1. *What combinations of retrofits are needed to bring solid walled homes up to EPC band C? Do these represent value for money and what challenges do they face?*
2. *To what extent do unintended consequences reduce energy efficiency savings and increase moisture risks, when insulating solid walled homes?*
3. *Are methods to reduce the potential risk of unintended consequences when retrofitting solid walled homes effective and appropriate?*
4. *How significant is airtightness in domestic energy efficiency and is improving airtightness a practical, low risk retrofit measure for inclusion in domestic energy efficiency policy?*
5. *How accurate can energy modelling of retrofits be and how can EPCs be improved for use in retrofit performance prediction?*
6. *How can thermal modelling support risk management and retrofit energy modelling predictions?*
7. *How effective are low pressure Pulse tests and quick U-building (QUB) tests as alternatives to the blower door test and coheating test?*

Data collected from case study 19BA contributes to the formation of a body of evidence from the DEEP project which addresses these questions.

1.3 Case study house information

Shown in Figure 1-1, 19BA is a four-bedroom terraced house in West Yorkshire. It was built between 1900 and 1910, and the solid external walls are made from 9-inch bricks. There are two external walls (front and rear) and two party walls shared with neighbours (17BA and 21BA). The house is sandwiched between two roads. While the north west elevation faces the busier road, this is the rear elevation. The front elevation faces south east and the quieter road. The house has a centrally located chimney stack, although this is blocked.

Accommodation-wise, to the front there is a hallway with stairs leading up to a split level first floor landing. The living room has a rectangular single-storey bay window set into the front façade. The kitchen also has a single-storey rectangular bay window, which is set into the rear façade. The rear hallway provides access to the busy main road and stairs down to the basement. The entire ground floor is suspended timber. The basement runs the full length and breadth of the house. There is a small WC off the first floor landing.

Stairs lead up to two bedrooms on first floor. Bedroom 1 faces south east, with windows set in the front façade. Bedroom 2 faces the busy main road to the rear of the house. Bedrooms 3 and 4 are located on the second floor as rooms-in-roof. There is another split-level landing on the second floor, where there is a small bathroom. In Bedroom 3, a gable dormer window sits in the middle of the sloping ceiling and faces south east. Bedroom 4 has a sloping ceiling with a single rooflight. There was a large cupboard that used to house the gravity fed cold water tank before the current gas combi boiler was installed, but this was removed during the room-in-roof retrofit. A small loft space is accessible through a hatch in Bedroom 4.

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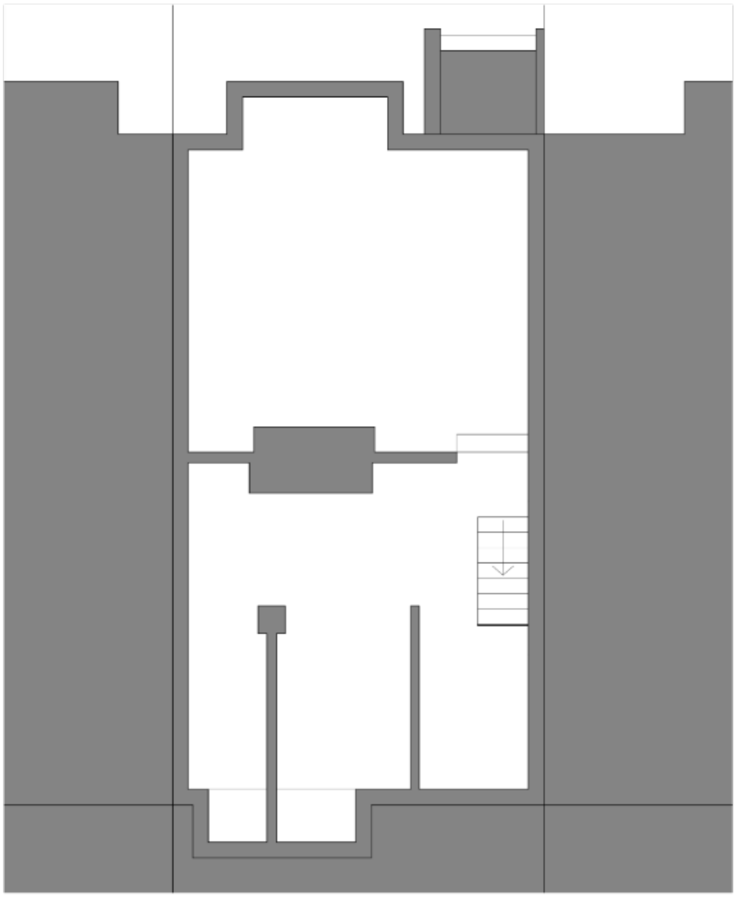
This is a typical construction for the area, though less so nationally. Nearly 1.5 million homes in England and Wales were built between 1900 and 1918, representing almost 5 % of England and Wales' housing stock [1]. Four-bed terraced houses account for around 2 % of all homes [2], thus there may be around 28,000 homes similar to 19BA, although many may not have basements. While it is unlikely that the results from 19BA are directly transferrable across all terraced properties in general, the features of the case study do enable a deeper understanding of airtightness, heat loss across party walls and the impact of partial room-in-roof retrofits.

Figure 1-1 Case study house – front elevation (LHS), rear elevation (RHS)

Figure 1-2 Case study house site location plan

Floor plans, elevations and sections are presented in Figure 1-3, Figure 1-4 and Figure 1-5, respectively.



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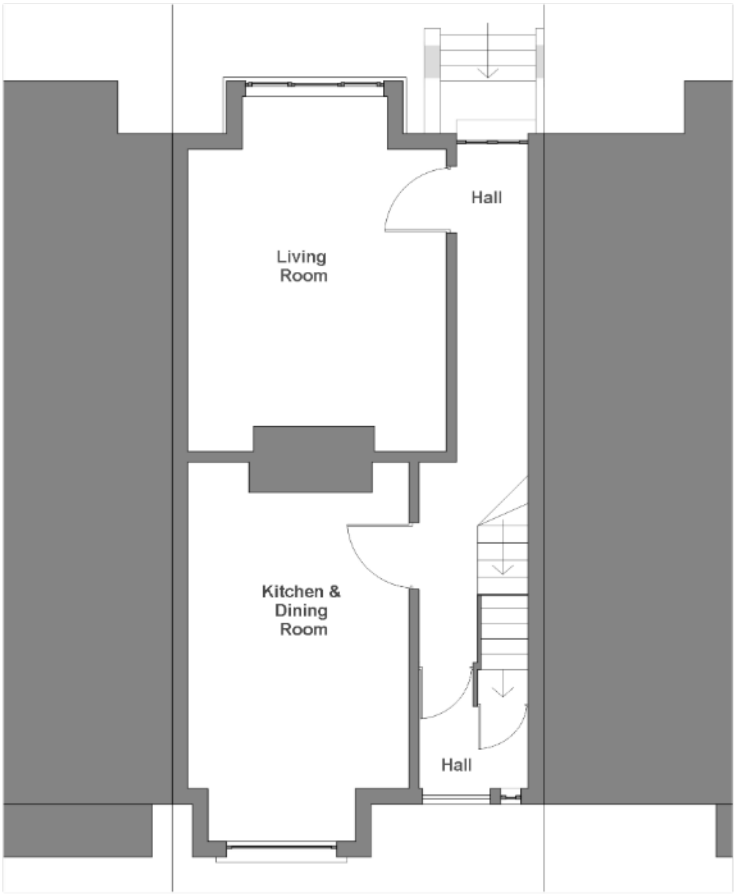
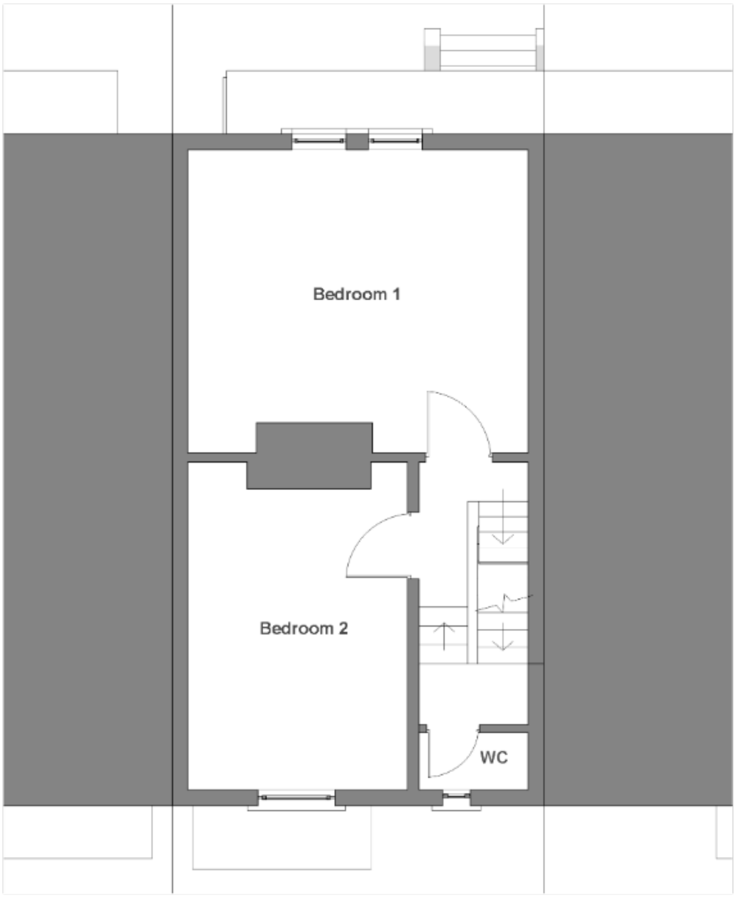


Ground Floor



First Floor

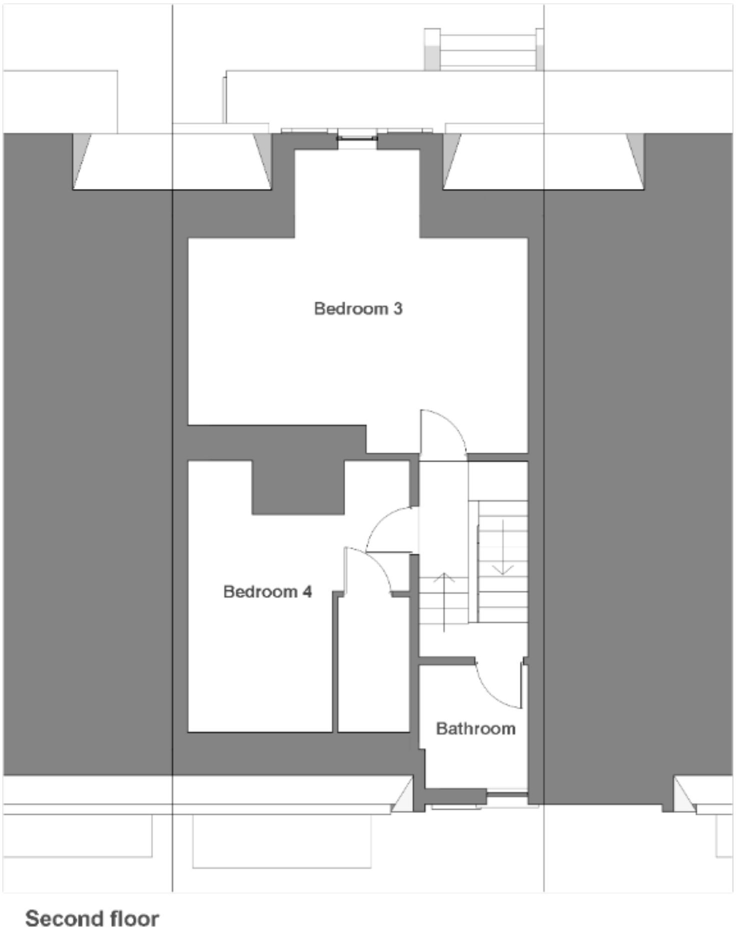


Figure 1-3 House floor plans

Figure 1-4 Elevations

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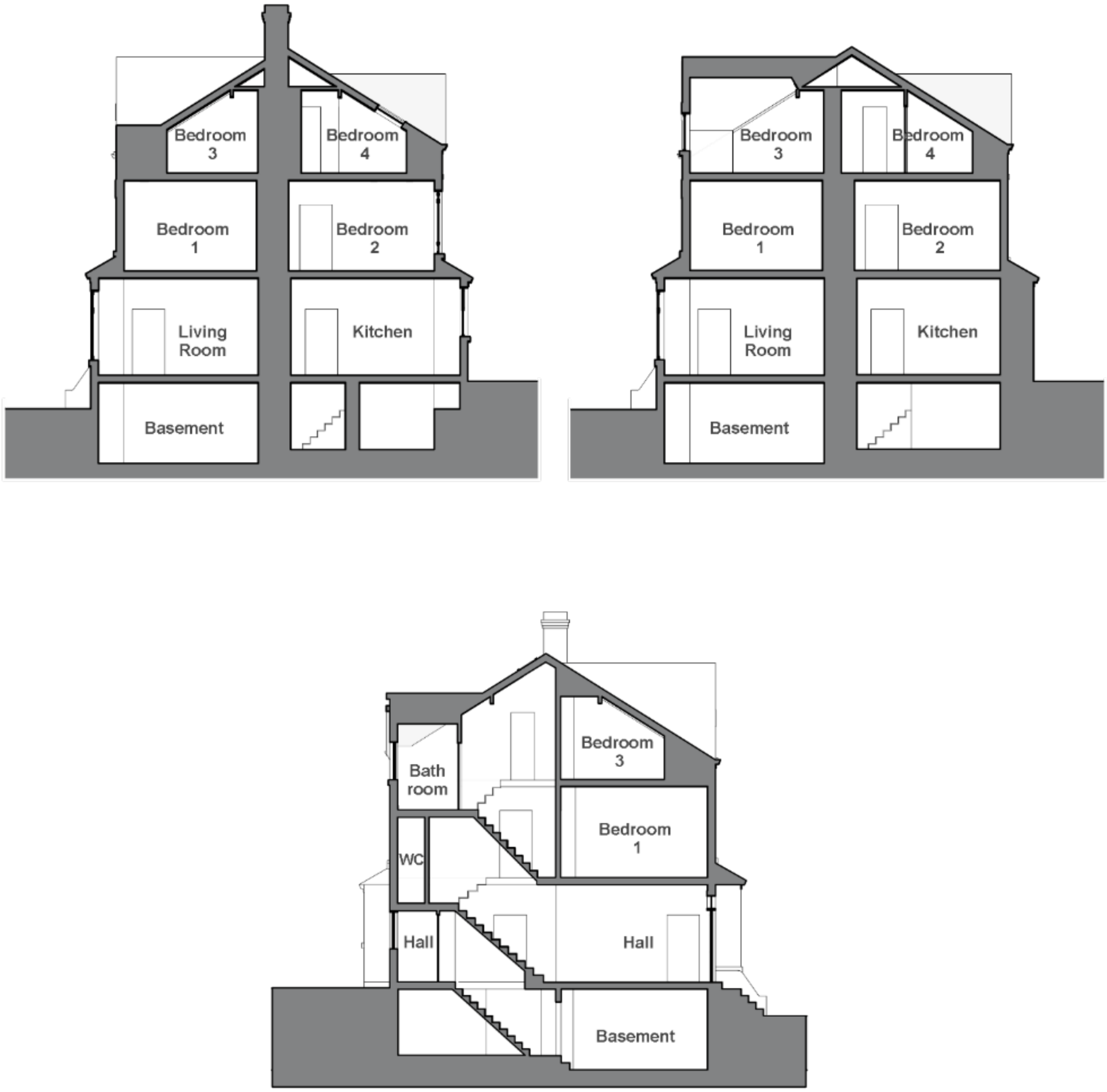

Figure 1-5 House sections

The dimensions of each element in the home are listed in Table 1-2 and used to allocate heat losses and generate thermal models in RdSAP, BREDEM and Dynamic Simulation Modelling (DSM).

Table 1-2 House dimensions

Detail	Measurement
Volume	368 m^3
Total floor area	132 m^2
Total heat loss area	195 m^2
Ground floor	49 m^2
External wall	55 m^2
Windows	16 m^2
Door	4 m^2
Sloping roof	22 m^2
Roof above front and rear bays	2 m^2
Ceiling to loft void	15 m^2
Dormer roof	10 m^2
Dormer cheek	1 m^2
Dormer wall	4 m^2
Knee wall	12 m^2
Ceiling to eaves void	7 m^2
Party wall	144 m^2

The construction details are summarised in Table 1-3. The features to note are the presence of undetectable insulation in the room-in-roof. In Bedroom 3, insulation was detected within the stud walls, eaves space, flat ceiling and sloping ceiling using a thermal camera.

Once the retrofit work started, a large hole was found in the party wall between 19BA and 17BA. In Bedroom 4, the sloping and flat ceilings were already insulated, but the stud wall was not. There were also a large number of disregarded items in the loft that made it hard to determine whether the eaves were insulated pre-retrofit.

1.4 Retrofit approach

The retrofit details and U-value targets for each element are listed in Table 1-3.

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Airtightness	23.1 m^3/(h·m²) @ 50 Pa	General sealing of air leakage paths
Room-in-roof	a) Bedrooms 3 and 4 ceiling to loft voids, cold roof, insulated with 75 mm mineral wool	a) Mineral wool between and above joists 400 mm @ 0.040 W/(m·K) Target U-value 0.10 W/(m²·K)
	b) Bedrooms 1 and 2 ceiling to eaves voids, poorly insulated with approximately 175 mm mineral wool	b) Mineral wool between and above joists 400 mm @ 0.040 W/(m·K) Target U-value 0.10 W/(m²·K)
	c) Bedrooms 3 sloping ceiling, insulated with 10 mm polystyrene	c) Wood fibre to sloping ceiling 50 mm x 0.038 W/(m·K) between rafters 40 mm x 0.041 W/(m·K) on top of rafters Target U-value 0.38 W/(m²·K)
	d) Bedrooms 4 sloping ceiling, insulated with 25 mm polyisocyanurate boards	d) Wood fibre to sloping ceiling 50 mm x 0.038 W/(m·K) between rafters 40 mm x 0.041 W/(m·K) on top of rafters Target U-value 0.38 W/(m²·K)
	e) Dormer pitched roof, insulated with 10 mm polystyrene	e) Wood fibre to sloping ceiling 50 mm x 0.038 W/(m·K) between rafters 40 mm x 0.041 W/(m·K) on top of rafters Target U-value 0.38 W/(m²·K)
	f) Bedroom 3 knee wall, lath and plaster with 75 mm mineral wool	f) Wood fibre to knee wall 75 mm x 0.038 W/(m·K) between studs 40 mm x 0.041 W/(m·K) on top of studs Target U-value 0.27 W/(m²·K)
	g) Bedroom 4 knee wall, lath and plaster, uninsulated	g) Woodfibre to knee wall 75 mm x 0.038 W/(m·K) between studs 40 mm x 0.041 W/(m·K) on top of studs Target U-value 0.27 W/(m²·K)
	h) Bedroom 3 external dorma wall, solid brick uninsulated	h) Wood fibre to external wall 52 mm x 0.041 W/(m·K) Target U-value 0.57 W/(m²·K)

[1] Target U-values are based on assumed construction details and may vary from Approved Document Part L limiting values according to manufacturer recommendations or space limitations.

Figure 1-6 identifies where insulation was found in the home before any retrofit was carried out. The sequence of the staged retrofit approach is shown and illustrated in Figure 1-7 and Figure 1-8. Building performance evaluation (BPE) tests and whole house energy modelling were conducted at each retrofit stage to quantify changes in energy performance and the potential for condensation risk. The specific methodologies for these are described in the DEEP Methods 2.01 Report. The codes in Table 1-4 are shorthand to identify each retrofit stage to aid the discussion and presentation of results. As the retrofits are cumulative, the codes are combined to explain which stage is being discussed, e.g., the final code for stage 3 is 19BA.A.R.

Table 1-4 Phased retrofit stages

	Retrofit stage	Code	Retrofit date
1	Baseline	19BA.B	October 2020
2	Airtightness improvements	19BA.A	November 2020
3	Room-in-roof retrofit to Bedrooms 3 and 4	19BA.A.R	December 2020

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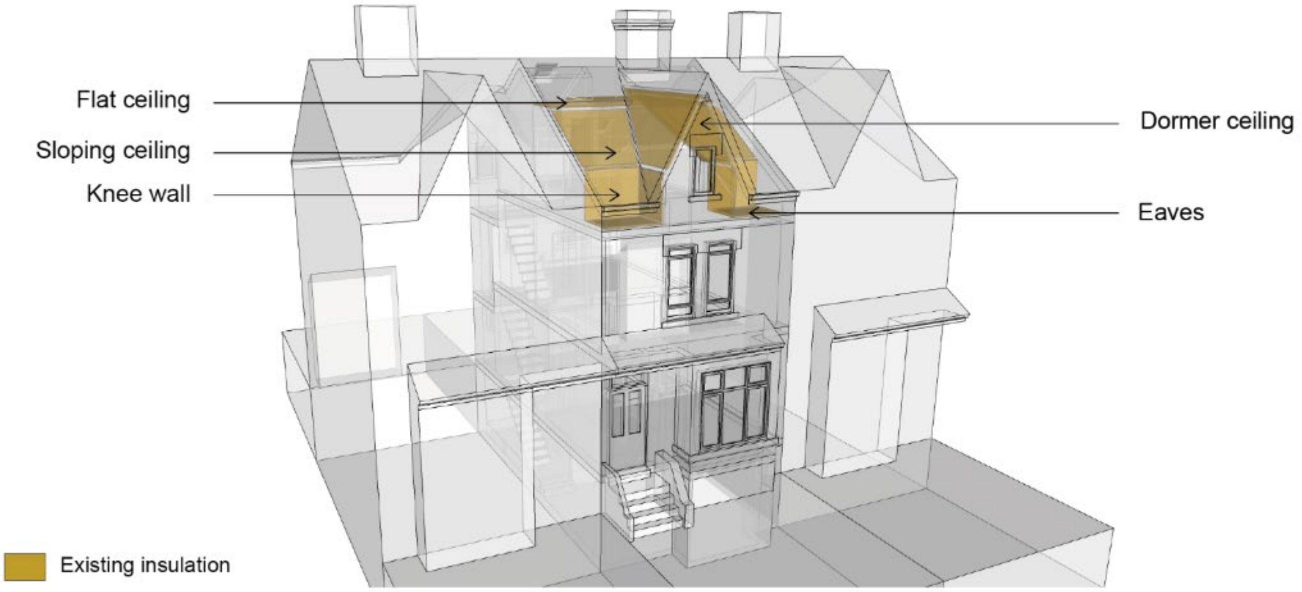

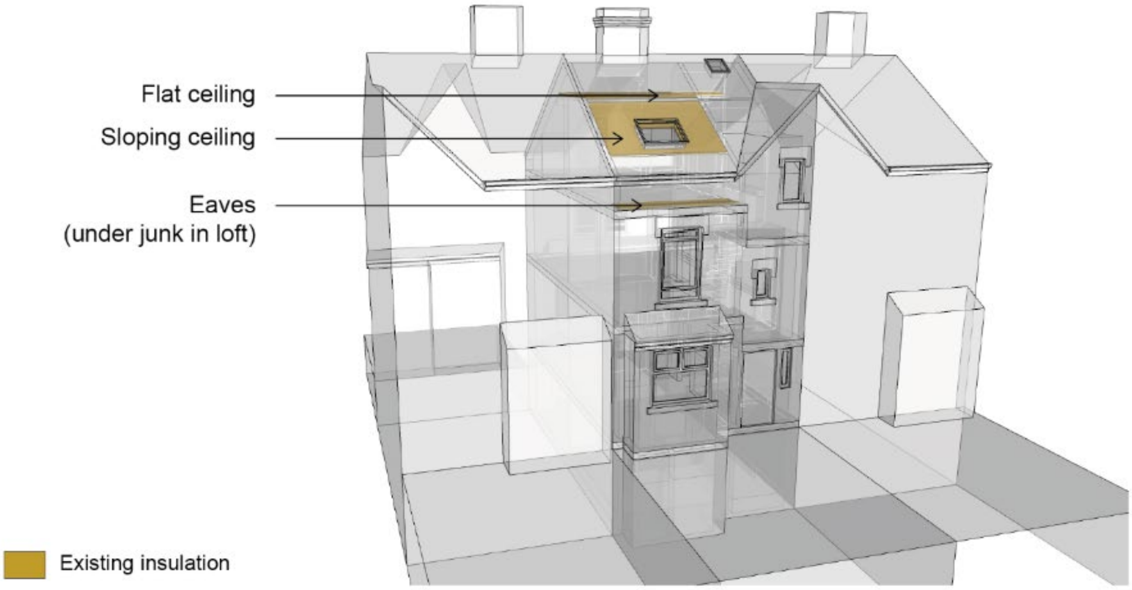

Figure 1-6 Stage 1: Insulation already in the property prior to the retrofit (19BA.B)

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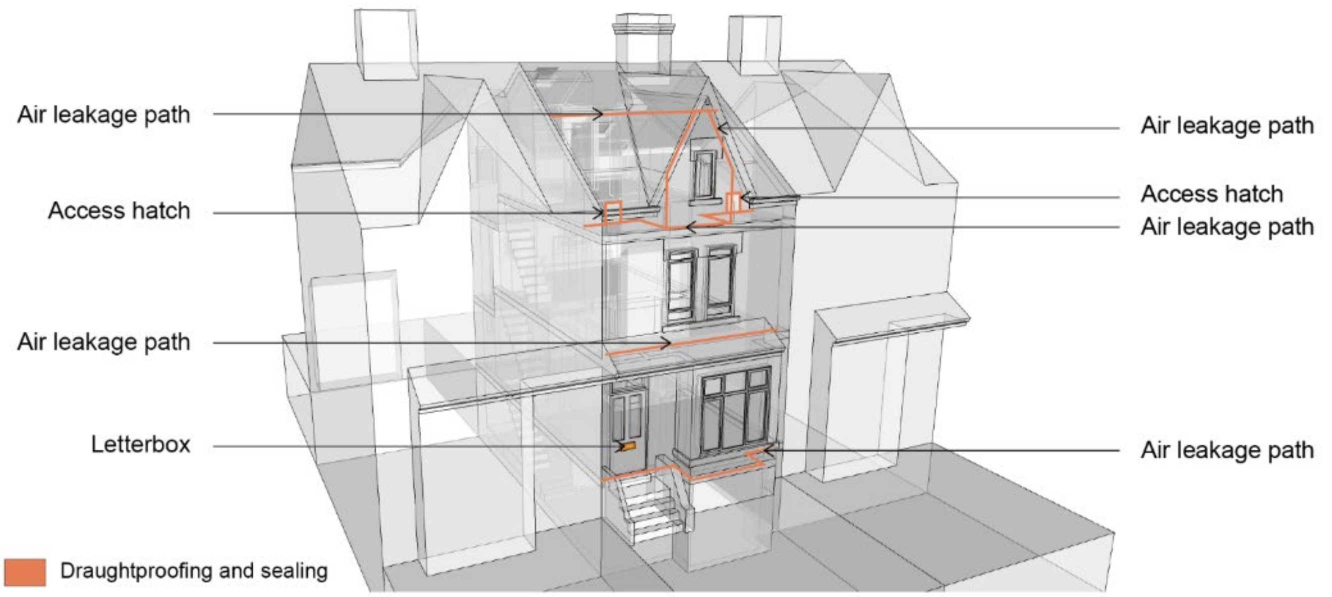

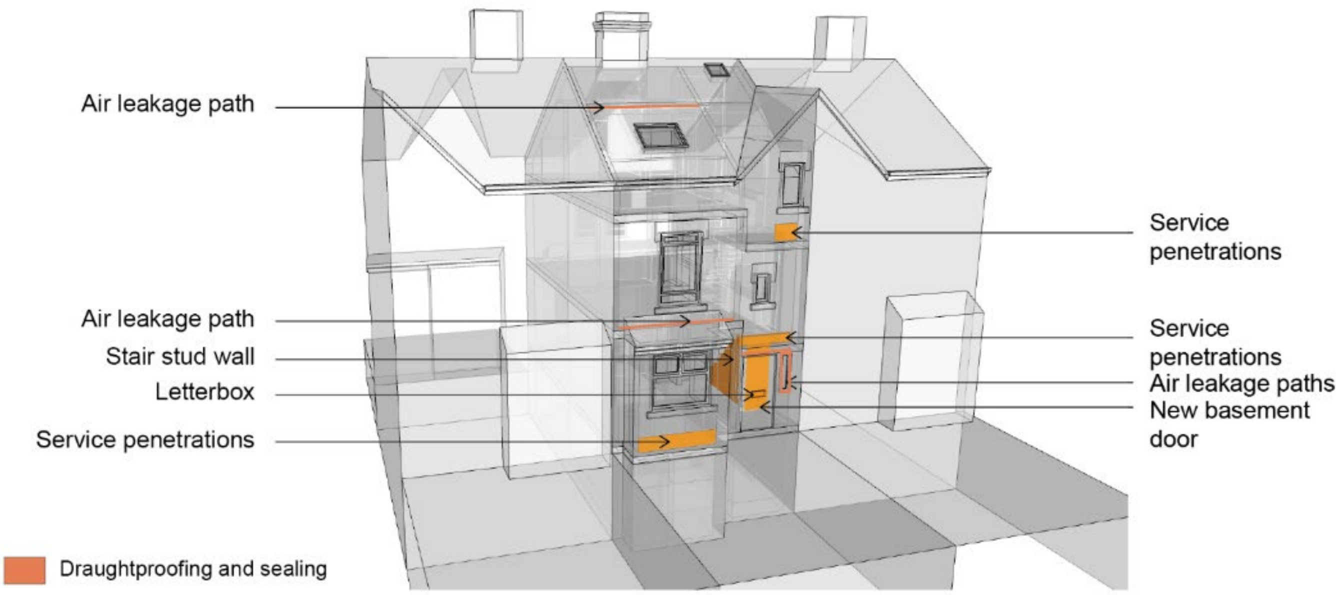

Figure 1-7 Stage 2: (19BA.A)

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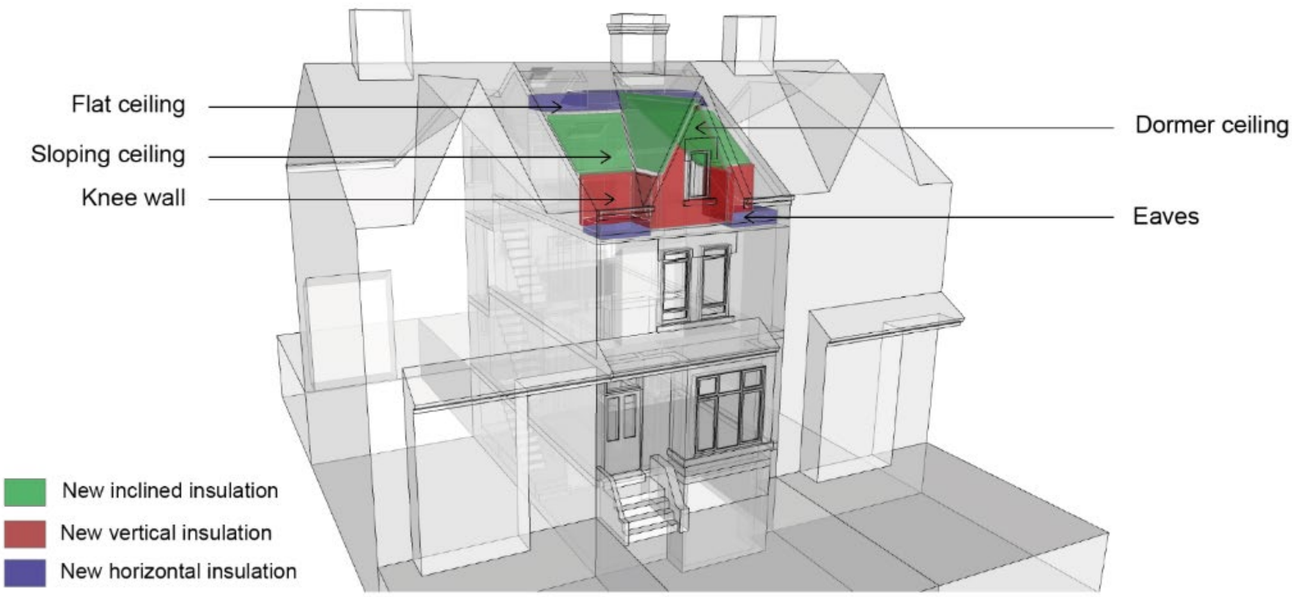

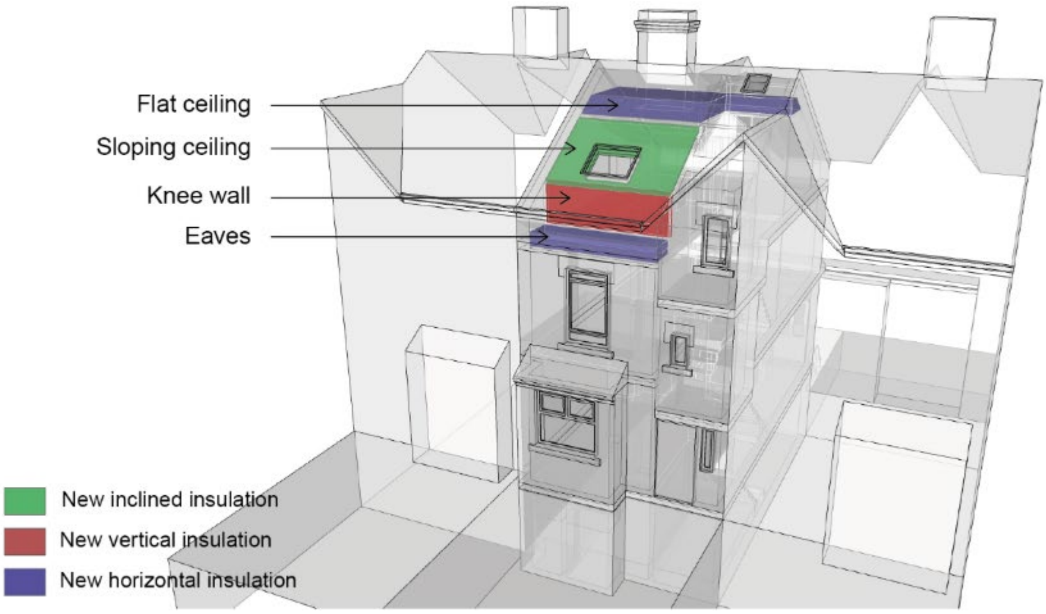

Figure 1-8 Stage 3: (19BA.A.R)

Case study and retrofit summary

19BA provides an opportunity to investigate the impact of piecemeal retrofit measures in a mid-terraced solid walled house, constructed in the 1910s.

Energy performance and airtightness data were collected for less common retrofit measures, including airtightness retrofit through general sealing and room-in-roof insulation.

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken on 19BA at each retrofit stage in accordance with the methodologies listed in the DEEP Methods 2.01 Report. This section outlines the specific implementation of these methods at 19BA, including variations.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the DEEP Methods 2.01 Report. The internal environmental data collected at 19BA includes air temperature, relative humidity (RH) and CO_2 levels. External environmental data were collected via a weather station located at the Leeds Beckett University Rose Bowl building, located approximately 1 mile from 19BA, and include vertical solar irradiance, air temperature and wind speed. This is supplemented by a heat flux plate (HFP) placed on the living room window to act as a proxy for vertical solar irradiation on site.

2.2 Measured survey

A detailed survey of the building was undertaken. From this, a digital version of the house was developed using SketchUp, which was used to calculate the dimensions of each element and draw up the plans shown in Figure 1-3. Plans, sections and elevations were exported directly to generate the geometry used in DSM. The construction makeup of the existing building was assessed, where access could be gained, to observe the material construction. Finally, core samples of the walls were taken for lab analysis of the material properties and to identify the construction layers, the method for which is described in DEEP Report 4.

2.3 Airtightness and thermography

Blower door tests were undertaken successfully at the baseline and retrofit stages. The results were used to identify airtightness changes related to the retrofit. They were also used to approximate the average annual heat loss attributable to background ventilation (HTC_v). Qualitative thermography of specific details was undertaken under depressurisation, along with thermography under normal conditions. This was done to capture and identify any changes between the baseline and retrofit stages. Pulse air tests were conducted during the testing programme to compare to the blower door test results.

Ventilation in the home was provided via trickle vents in all rooms and extract fans located in the kitchen and bathroom. These were not altered during the retrofits. It was beyond the scope of the DEEP project to undertake in-use monitoring of internal air quality under occupied conditions, which would have required longitudinal monitoring pre- and post-retrofit.

2.4 Heat flux density measurement and U-values

36 HFPs were installed in various places in 19BA to measure the baseline in-situ U-values and improvements achieved by the fabric upgrades, quantify the party wall heat exchange, calibrate energy and thermal model inputs, estimate the plane element fabric heat loss (HTC_f), and compare with the HTC disaggregation.

The HFP locations are listed in Table 2-1 and, for context, visualised in Figure 2-1, Figure 2-2 and Figure 2-3. Thermography was undertaken to identify the most representative location for each fabric element and, where possible, multiple locations in each element were measured.

Table 2-1 HFP locations

HFP	Element	Room
F1	Party wall	Living room
F2	Front external wall	Living room
F3	Window	Living room
F4	Ground floor	Living room
F5	Party wall	Hall
K1	Rear external wall	Kitchen
K2	Party wall	Kitchen
K3	Ground floor	Kitchen
K4	Ground floor	Hall
K5	Party wall	Hall
A1	Party wall	Bedroom 1
A2	Front external wall	Bedroom 1
A3	Party wall	Bedroom 1
A4	First floor ceiling	Bedroom 1
A5	First floor ceiling	Bedroom 1
B1	Rear external wall	Bedroom 2
B2	First floor ceiling	Bedroom 2
B3	First floor ceiling	Bedroom 2
B4	Party wall	Bedroom 2
B5	Party wall	First floor landing

AB1	Party wall	Bedroom 3
AB2	Knee wall	Bedroom 3
AB3	Dormer knee wall	Bedroom 3
AB4	Dormer knee wall	Bedroom 3
AB5	Knee wall	Bedroom 3
AB6	Party wall	Bedroom 3
AB7	Sloping ceiling	Bedroom 3
AB8	Dormer sloping ceiling	Bedroom 3
AB9	Front external wall	Bedroom 3
AB10	Dormer sloping ceiling	Bedroom 3
AB11	Sloping ceiling	Bedroom 3
AB12	Second floor ceiling	Bedroom 3
AB13	Knee wall	Bedroom 4
AB14	Sloping ceiling	Bedroom 4
AB15	Party wall	Bedroom 4
AB16	Second floor ceiling	Bedroom 4

The heat flux density from the individual HFPs, along with the internal and external air temperature data, were used to calculate in-situ U-values for each element. Where more than one HFP was located in a single element, a simple average was used. Where a repeat thermal bridge was measured (such as a ground floor joist for example) or an area of non-representative heat flux density was observed, a weighted average was calculated to provide an estimate of the whole element in-situ U-value.

It is important to note that the in-situ U-values are based on a limited set of heat flux density measurements, so may not be representative of the performance of the whole element in practice. Similarly, where areas of thermal bridging may be expected, such as near corners, heat flux density measurements may provide context for the whole fabric heat loss and inform weighted average calculations.

While the BRE calculator has the capacity to calculate the U-value of windows, it requires manufacturer's details of the window component parts included the glazing U-Value, the frame U-value and details of the internal construction to estimate the linear Ψ-value. These details were not available, and so the U-values for the windows had to be assumed. Consequently, this represents an area of uncertainty in the comparisons and energy models.

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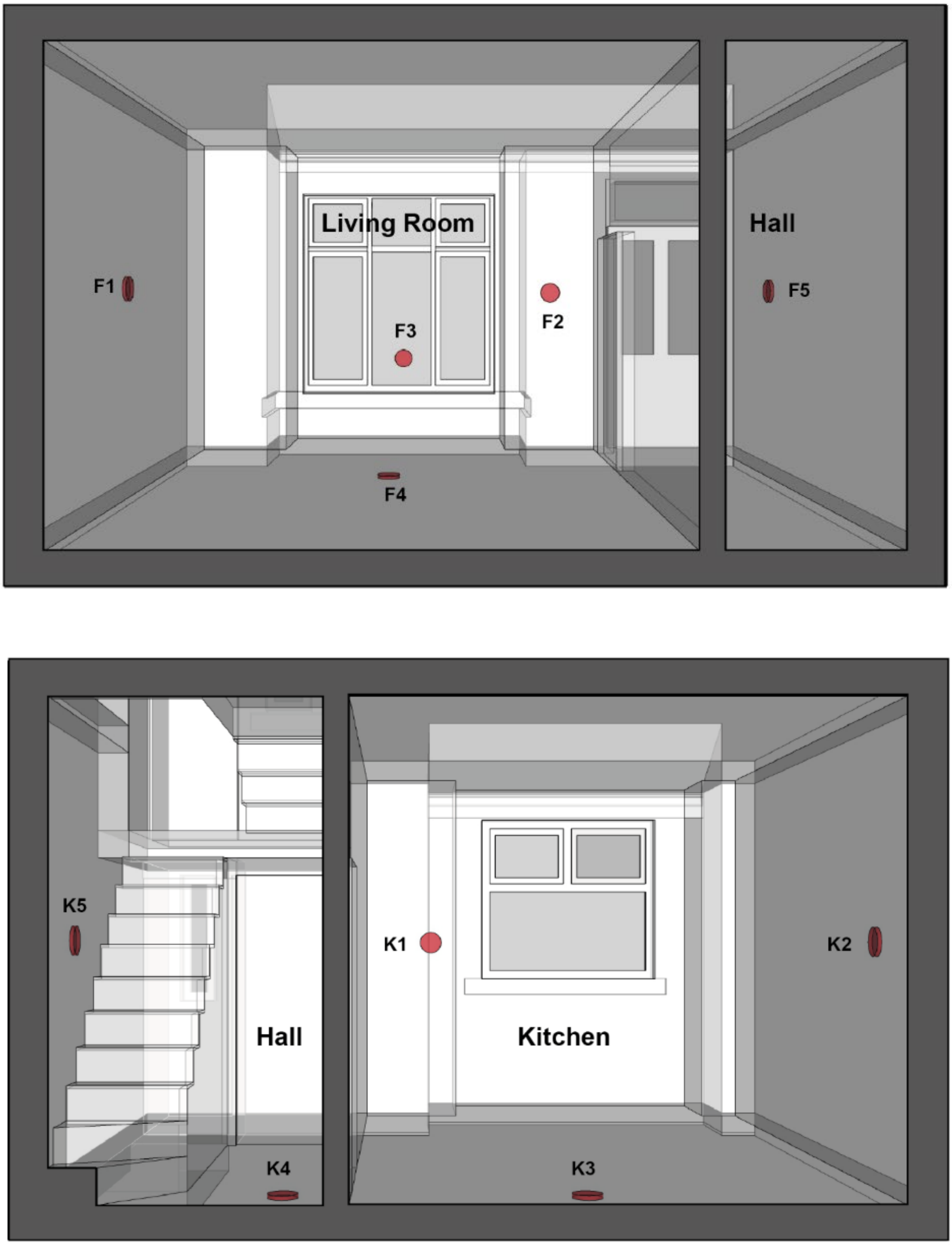

Figure 2-1 Ground floor HFP locations

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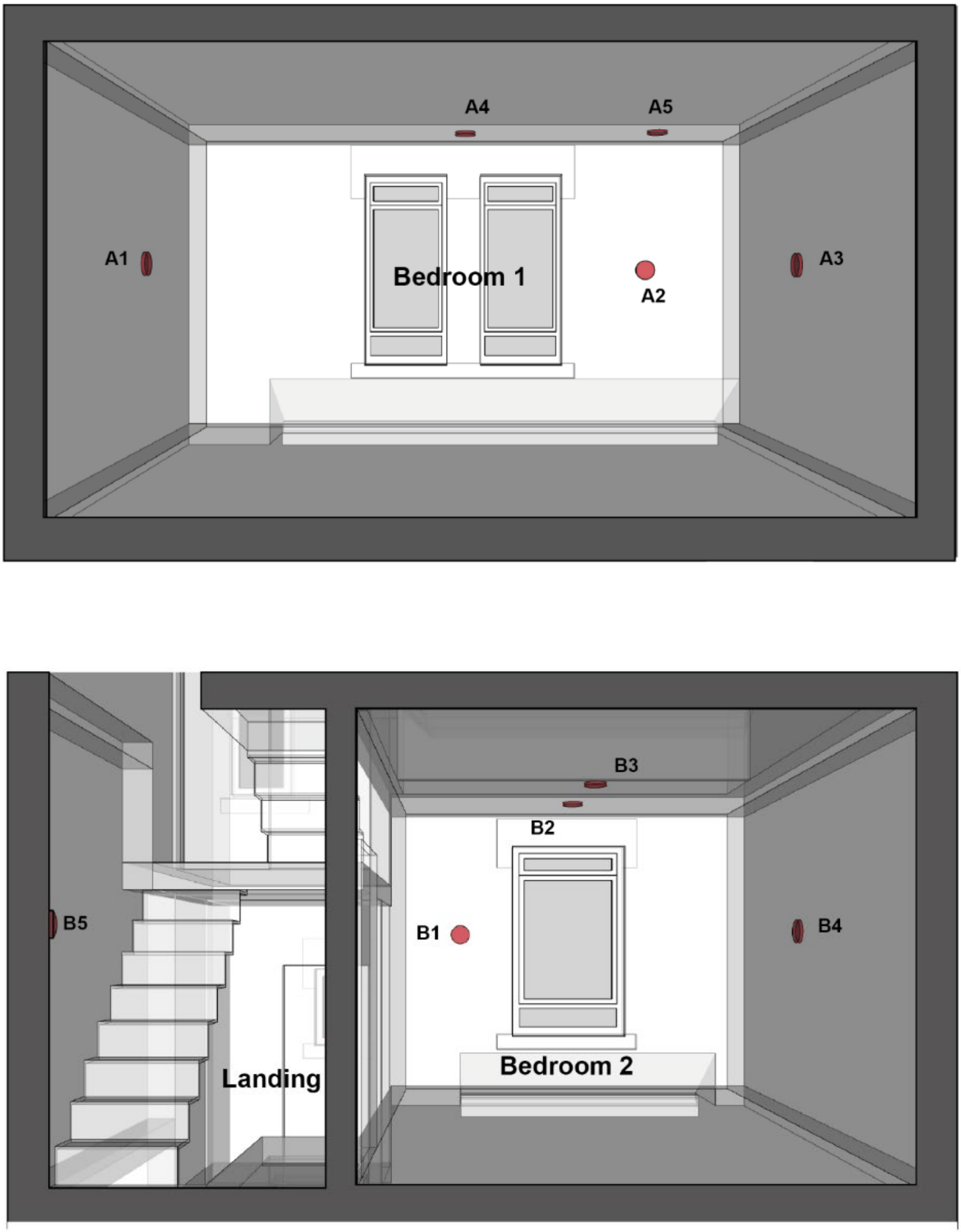

Figure 2-2 First floor HFP locations

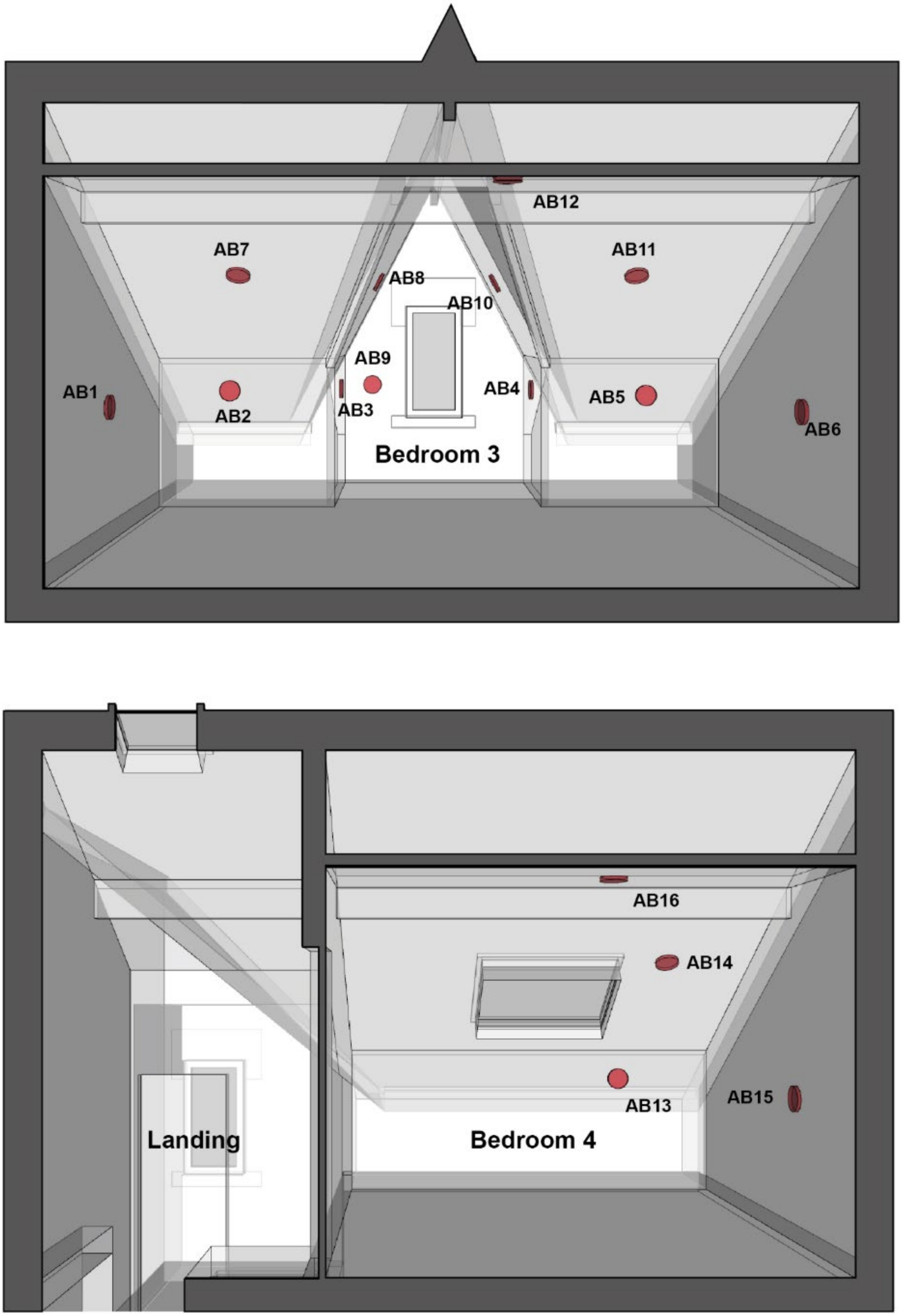

Figure 2-3 Room-in-roof HFP locations

2.5 Whole house heat transfer coefficient (HTC)

Coheating tests were successfully performed at each stage of the retrofit, as described in the DEEP Methods 2.01 Report, to provide a measured HTC. In addition to the coheating tests, QUB tests were undertaken, and the results are presented for comparison where available.

2.6 Whole building energy modelling

The modelling methodologies undertaken for this project are explained in detail in the DEEP Methods 2.01 Report. In summary, RdSAP, BREDEM and DSM (using DesignBuilder software version 7.0.0.088 [3]) energy models were used to calculate the HTC of the case study building at each retrofit stage. This produces a predicted HTC, which can be compared against the measured HTC from the coheating test. To understand how their predictions improve as specific data are used to replace default input data, the calibration procedure outlined in Table 2-2 was undertaken.

Table 2-2 Modelling calibration stages

Calibration step	Infiltration	U-values	Bridging
1	Default[2]	Default[2]	Default[3]
2	Measured[4]	Default[2]	Default[3]
3	Measured[4]	Calculated[5]	Default[3]
4	Measured[4]	Measured[6]	Default[3]

The models predict annual energy demand, annual fuel bills, carbon dioxide emissions, Standard Assessment Procedure (SAP) score and EPC band. Therefore, the success of the retrofit at achieving the policy aims can be evaluated. Based on the retrofit install costs, simple payback periods for each retrofit can also be calculated.

Case study method summary

A deep dive into the 19BA retrofit case study was undertaken involving coheating tests, blower door tests, and 36 heat flux density measurements of fabric elements, taken before and after the retrofit.

RdSAP, BREDEM and DSM energy models were undertaken to compare against these in-situ measurements. To investigate the appropriateness of using default data in energy models, a 4-step calibrated process was adopted.

These methods collectively investigated the energy performance associated with various approaches to retrofit, as well as the usefulness of predictive models.

[2] Provided by Appendix S RdSAP 2012 version 9.94
[3] Provided by Appendix K RdSAP 2012 version 9.94
[4] Derived from blower door test
[5] Derived from BRE calculator
[6] Derived from HFP measurements

3 Results

This chapter firstly presents the results of the in-situ field trials; airtightness tests, U-values and the whole house heat loss as measured by the coheating test. It then describes how the modelled predictions compare with the measured data and how successful the five calibration steps were at improving the predicted heat loss, including assessing thermal bridging. The model outputs are discussed in terms of their implications for EPCs, space heating, CO_2 emissions, fuel bills and paybacks. Finally, the potential surface condensation risks posed in the house at each retrofit stage are discussed.

The results of the in-situ measurements and modelling are presented here. The findings from each specific retrofit stage are presented followed by a discussion of the retrofit costs and risks.

3.1 Airtightness improvements

19BA is a large dwelling with many complex, interconnected air leakage pathways. This means the home had very high levels of infiltration, 23.8 $m^3/(h{\cdot}m^2)$ @ 50Pa, as shown in Figure 3-1, which is around three times the limiting value allowed for new build homes in England and Wales. The non-destructive airtightness improvements were only partially successful, and reduced infiltration to 20.6 $m^3/(h{\cdot}m^2)$ @ 50Pa, however this still represents a large amount of air leakage. The room-in-roof retrofit did not achieve any meaningful improvements with the final infiltration of the home assessed as 20.1 $m^3/(h{\cdot}m^2)$ @ 50Pa.

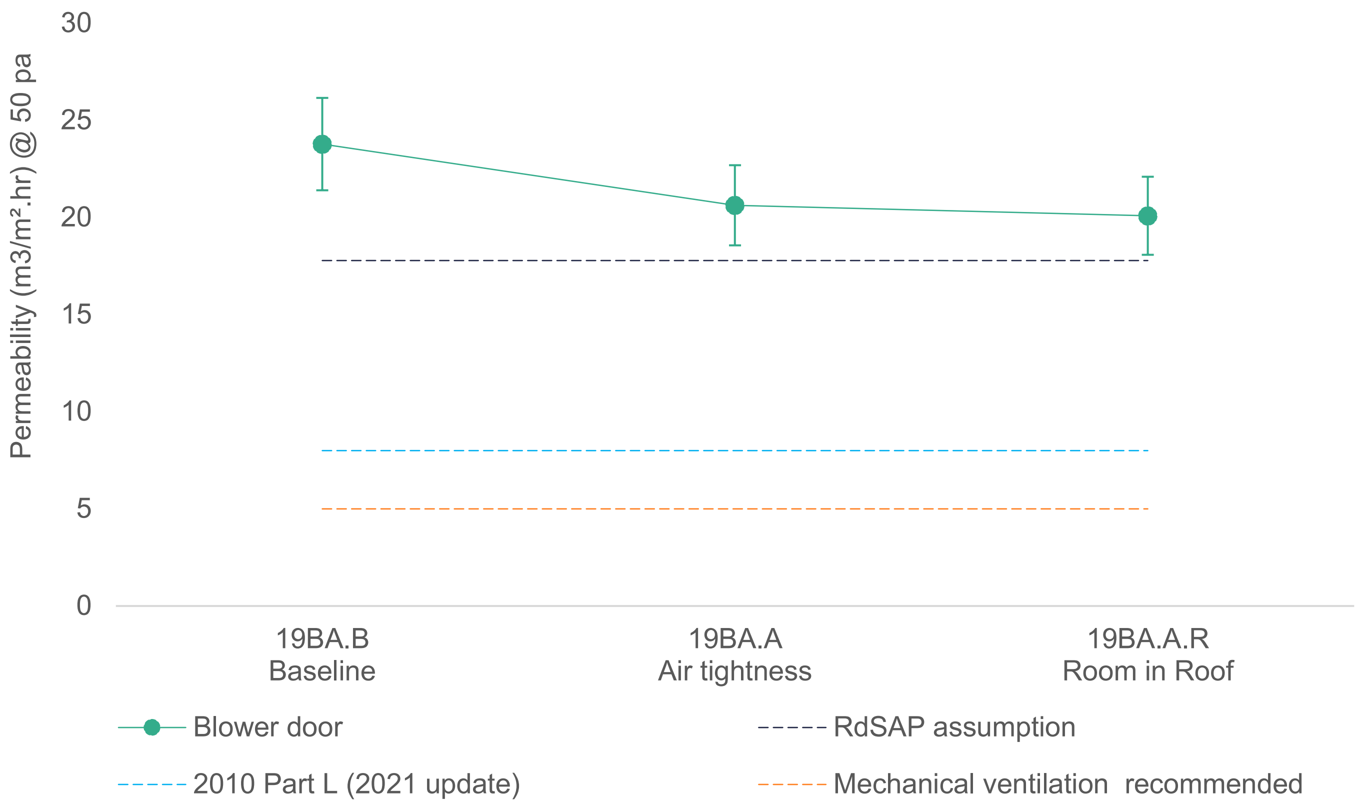

Figure 3-1 Airtightness improvements made at each retrofit stage

3.1.1 Air leakage pathways

Blower door tests were undertaken in 19BA before and immediately after each coheating test, with thermographic air leakage detection performed under dwelling depressurisation during the blower door tests completed after each coheating test.

At the baseline stage, the most severe leakage paths detected were at the cellar door, around service penetrations and openings through external walls, into the floor voids and other inter-connected wall/stair voids and around the external doors. Other significant areas of air leakage included the suspended timber ground floor and the intermediate floor perimeters.

Air leakage was detected in every room on the ground floor, with colder air being drawn in directly from outside through leakage around windows, doors, penetrations and junctions, and slightly less cold air being drawn up from the cellar through the ground floor, cellar door and around the stairs. These air leakage routes were found in most of the other DEEP case studies, though they were not so extensive as at 19BA.

Figure 3-2 shows infiltration in the living room at the bay and at floor junctions with the party and internal wall.

Figure 3-2 Air leakage in the living room around the bay window and ground floor perimeter

Figure 3-3 shows severe infiltration in the kitchen, as well as direct infiltration at the window and external wall junctions. Indirect air exchange at the two boxed-in voids either side of the bay and the bay roof can also be observed. In the halls both direct air leakage through external wall openings and infiltration drawn up from the cellar were observed, as shown in Figure 3-4.

Figure 3-3 Service penetrations in the kitchen bay

Figure 3-4 Air entering the front and rear halls from the cellar and directly from outside

A similar mix of direct and indirect air leakage was observed on the first floor, with direct air leakage through penetrations for the first floor WC and around the windows. Figure 3-5, Figure

3-6 and Figure 3-7 show direct air leakage at penetrations, openings and junctions, with cooler air being drawn into the habitable space directly from outside.

Figure 3-5 Infiltration at the first floor WC

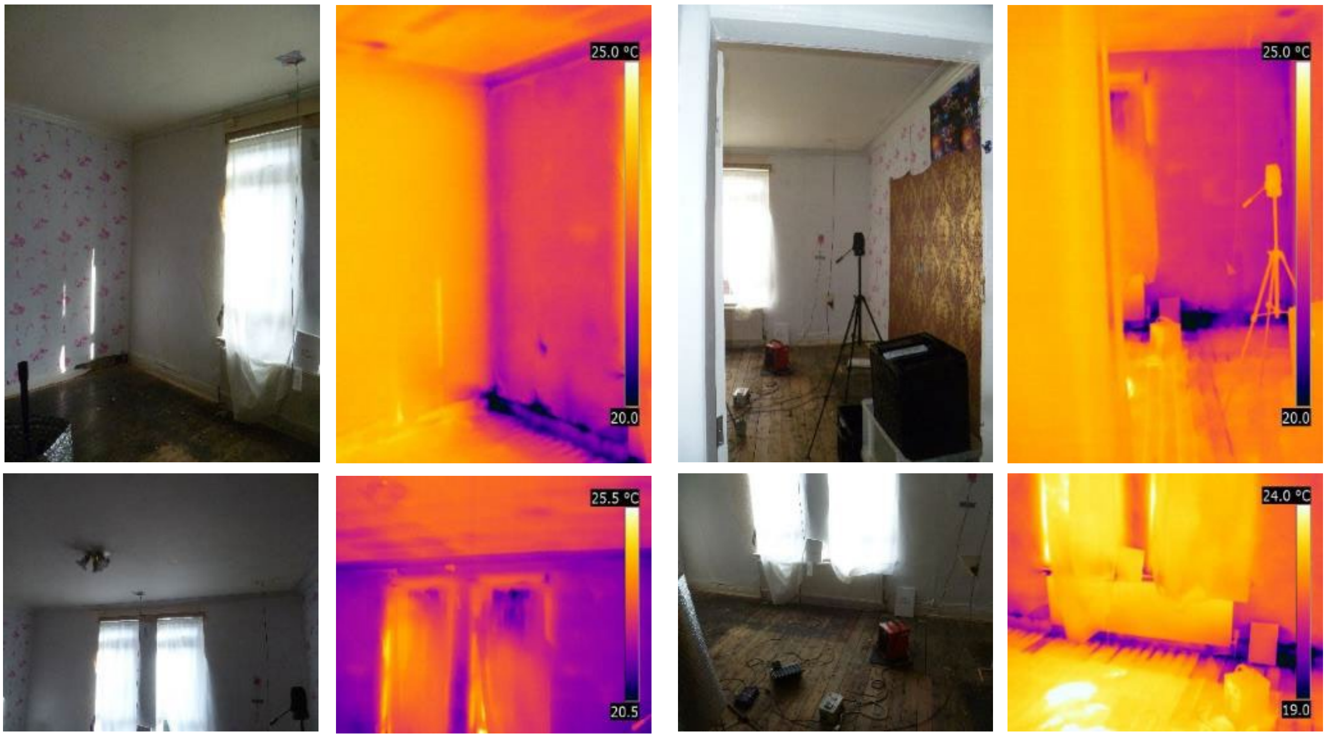

Figure 3-6 Direct air leakage in the front bedroom at the floor junction with the external wall and at the windows

Figure 3-7 Direct air leakage in the front bedroom at the floor junction with the external wall and at the window

Figure 3-8 shows that some more complex indirect air leakage pathways were present with air movement detected passing through connected voids within the structure, showing up as cooler surfaces or emerging some distance removed from where the air entered the building.

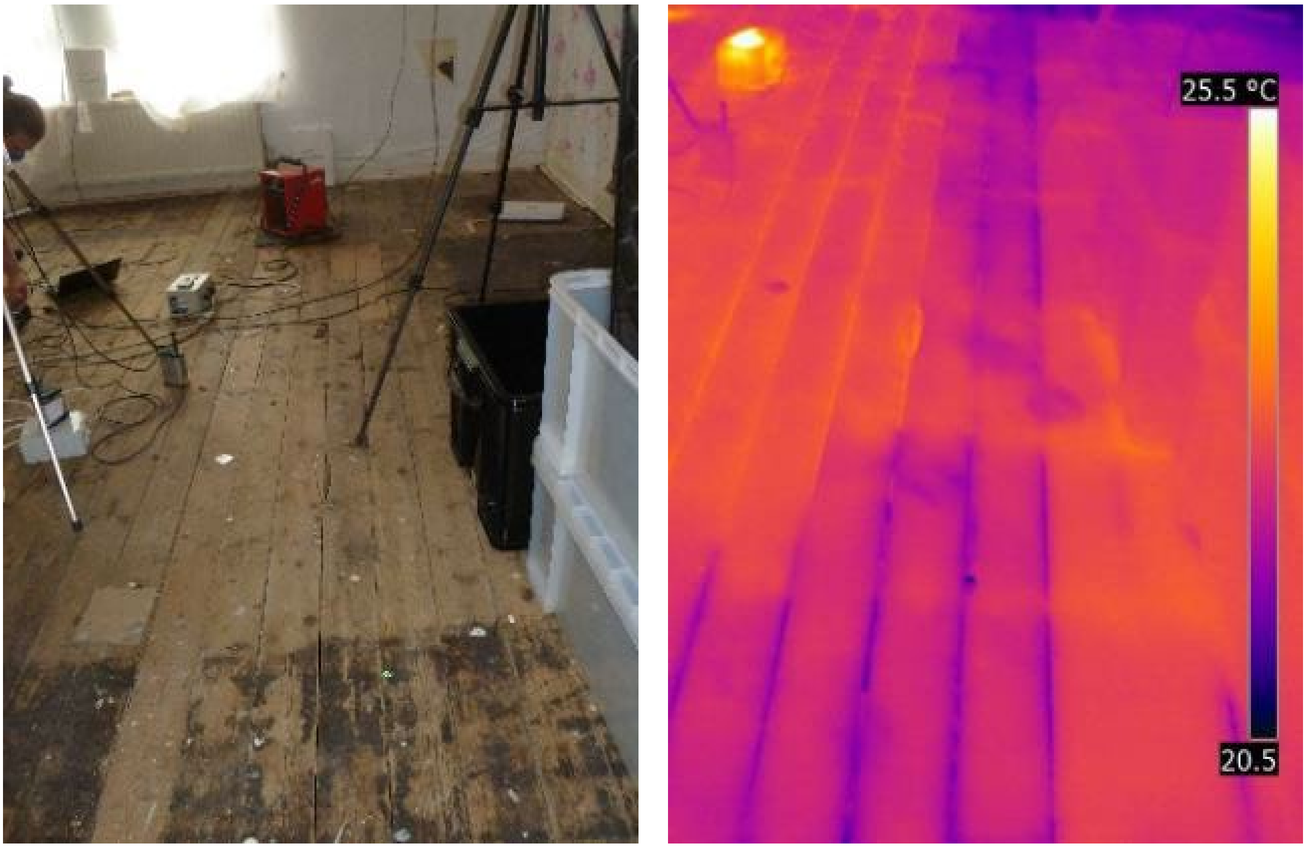

Figure 3-8 Indirect air leakage in the first floor bedrooms at the floor

Figure 3-9 shows air movement within the partition wall voids on the landing. As these voids appeared to be linked to the intermediate floor, the roof void, the loft space and the eaves void, it is not possible to know exactly where this air entered the house or the links between the internal spaces.

Figure 3-9 The second floor landing with cooler air being drawn through partition wall voids

On the second floor, direct air leakage was observed around the openings, service penetrations and external wall junctions. However, with some complex junctions and detailing around the bathroom and cylinder cupboard, there was much more significant indirect air leakage through the connected voids.

Figure 3-10 displays the many and varied air leakage paths in the second floor bathroom, with direct air leakage around plumbing penetrations, the central light fixing, the extract vent and external wall junctions, and other complex air movement within the connected wall and ceiling voids.

Figure 3-10 The second floor bathroom showing both direct and indirect air leakage

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Figure 3-11 shows the cylinder cupboard which backs onto the bathroom providing some links to other voids. Figure 3-12, Figure 3-13 and Figure 3-14 show leakage paths in the front and rear bedrooms. Although the eaves voids in each room have different geometries, they suffer from similar issues, with access hatches and junctions not being airtight and allowing the voids to connect to create complex air movement pathways. The implication of multiple air leakage pathways is that significant destructive work would be required to achieve a single continuous air barrier.

Figure 3-11 Air movement within the partition walls at the cylinder cupboard

Figure 3-12 Air leakage at the eaves void access hatches in the front and rear bedrooms

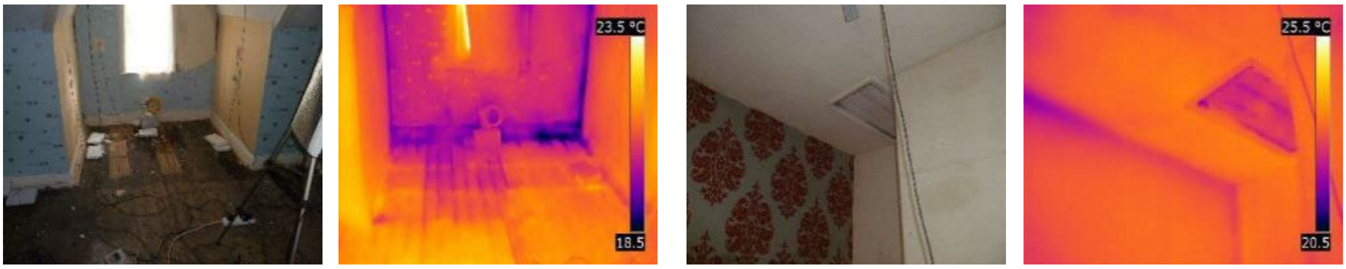

Figure 3-13 Direct air leakage in the front bedroom at the external wall junction with the floor and around the loft hatch

Figure 3-14 Air leakage at the windows in the front and rear bedrooms, and around the vent above the front bedroom window

3.1.2 Airtightness retrofit

Airtightness measures were undertaken in 19BA to understand what improvements could be achieved without destructive work. The points of air leakage identified in the pre-retrofit blower door tests were addressed using standard products and techniques available to the general public. Thus, only easily accessible leakage paths were addressed. Mastic sealants and foam fillers were applied to gaps in the internal envelope identified by thermographic leakage detection under dwelling depressurisation. Draught-stripping was installed at the external and cellar doors, and mastic was applied at the floor perimeters. This approach initially reduced mean air permeability from 23.8 to 18.8 $m^3/(h \cdot m^2)$ @ 50Pa. Figure 3-15, Figure 3-16 and Figure 3-17 show some of the interventions undertaken.

Figure 3-15 Mastic and foam fillers addressing the gaps identified in the airtightness tests

Figure 3-16 Sealed access hatches to the eaves voids

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Figure 3-17 Mastic sealant applied around window frames

Without addressing some of the more complex indirect air leakage pathways, the airtightness of the house following this airtightness retrofit was still relatively poor.

Figure 3-18 Thermographic detection of leakage at the kitchen bay

On the ground floor, air leakage up from the cellar appeared to be the main problem, with many of the direct air leakage paths from outside through the external walls at least partially addressed. Figure 3-18 shows an improvement in airtightness around the kitchen window and service penetrations, but now the air movement from underneath the kitchen units (not previously identified as a severe leakage path) appeared to have increased, at least proportionally.

As most exposed floor-wall junctions on the ground floor were sealed, areas that had not been treated became more obvious leakage paths, as illustrated in Figure 3-19, such as the base of the staircase and internal room junctions.

Figure 3-19 Air movement up from the cellar near the centre of the house

The external doors and cellar door had been improved, but there was still infiltration detected around them (Figure 3-20). The rear and cellar doors still allowed air leakage.

Figure 3-20 The rear (top) and cellar (bottom) doors showing air leakage

Figure 3-21 shows air movement through the intermediate floors detected around the centre of the dwelling. The emerging air was significantly cooler than the internal ambient temperature even though it was some distance from where it must have entered the building.

Figure 3-21 Air movement through intermediate floors in the centre of the dwelling

The artificially accelerated drying caused by the coheating test conditions appears to have reduced the improvement achieved by some of the mastic seals. The blower door tests undertaken directly after the airtightness retrofit identified that the home's air permeability had reduced to 18.8 $m^3/(h \cdot m^2)$ @ 50Pa. After the coheating test, when the mastic may have dried out causing it to shrink and crack thereby reducing its effectiveness, the final airtightness of the home was measured as 20.6 $m^3/(h \cdot m^2)$ @ 50Pa.

Some unaddressed air leakage paths still remained, and some of the less significant pathways identified previously appeared to have become more severe as other leakage routes were removed. Mastic applied to fresh plywood boxing in the WC had already begun to fail (Figure 3-22), although subsequent decoration and caulking may well re-seal these.

Figure 3-22 Un-adhered mastic sealant on the new boxing in the WC

The mastic applied to the intermediate floor perimeters on the external wall reduced leakage at this junction, but the infiltration only relocated to around the top of the skirting boards and through gaps between the floorboards, as shown in Figure 3-23.

Figure 3-23 Air leakage from the floor void in Bedroom 1 after sealing the floor wall junction

3.1.3 Room-in-roof retrofit impact on airtightness

The room-in-roof retrofit made an initial improvement in the airtightness, with the mean air permeability decreasing from 20.6 to 16.8 $m^3/(h \cdot m^2)$ @ 50Pa. However as with the airtightness retrofit, post-retrofit the infiltration rate increased, in this instance back up to 20.1 $m^3/(h \cdot m^2)$ @ 50Pa post coheating. This is again likely related to problems associated with accelerated drying and shrinkage of mastic, but also in this case shrinkage of the plaster drying on the walls of the new room-in-roof.

Figure 3-24 shows Bedroom 3, where the newly constructed or lined walls were freshly plastered and appeared to be airtight. However, where the new plaster joined the existing fabric, drying/shrinkage cracks had developed during the coheating test, allowing infiltration to be detected under depressurisation. This was noticeable around the window, which had just been plastered up to the frame but not yet decorated or caulked.

Figure 3-24 Failing mastic sealant at the unfinished plaster around the window in Bedroom 2

Figure 3-25 shows the same phenomenon in Bedroom 3, with air leakage through shrinkage cracks at junctions, which again might be reduced with subsequent decoration and caulking.

Figure 3-25 Air leakage through cracks in plaster and failed mastic seals at interfaces between elements in Bedroom 3 under depressurisation immediately following coheating

The same was observed at all the interfaces in all the rooms in the roof which, cumulatively, significantly undermined the airtightness improvement that would have otherwise been assumed to have been made. There were also some air leakage pathways that were not completely removed despite the creation of new internal wall surfaces and plastering of all the room-in-roof walls and ceilings. For instance, Figure 3-26 shows indirect air leakage emerging through holes in the internal partition wall between Bedroom 4 and the landing, which was part of the old airing cupboard where fixings had been removed, but which had not yet been decorated.

Figure 3-26 Air leakage under the floor from a boxed-in airing cupboard

Figure 3-27 shows air from the loft being drawn down the chimney breast creating a potential air leakage pathway.

Figure 3-27 Indirect air leakage through the floor in Bedroom 1 being drawn down the chimney breast

None of the bedrooms or landings in 19BA had floor coverings fitted, as the house was not occupied, and the retrofits did not extend to full decoration or final finishing. Many of the air leakage pathways detected might be expected to diminish when the house was occupied (as observed in the 52NP and 54NP case study homes), so this represents a worst-case scenario. Fitting carpets does not completely eliminate air leakage through floors but increases turbulence and reduces the rate of leakage. Final decoration with calking and re-sealing junctions also has a positive effect on dwelling airtightness, though the longevity of seals is dependent upon the sealants, substrates and surface preparation prior to sealing.

3.1.4 Alternative infiltration measurements: Low pressure Pulse tests and CO_2 decay tests

Two additional methods were used to derive the air leakage in the dwelling, carried out at each retrofit stage. Due to the size and high leakage rate of the house, neither proved successful.

No CO_2 decay curves proved suitable for analysis in 19BA. The CO_2 delivery mechanism employed was unable to increase the CO_2 concentration to a sufficiently elevated level for long enough periods for analysis.

Similarly, with a very high air leakage rate and a building volume >300 m^3, Pulse tests in the baseline condition and following the airtightness retrofit proved unsuccessful using the Model 1 Pulse kit available at the time, even using an expansion tank. With the Model 2 Pulse kit available following the room-in-roof retrofit, a Pulse test was undertaken and an air permeability result of 6.5 $m^3/(h{\cdot}m^2)$ @ 4Pa was obtained, although this came with the message: “Warning – achieved pressure range too low”. Using the conversion factor listed in CIBSE TM23 (2022) this Pulse result translates to a value of 29.8 $m^3/(h{\cdot}m^2)$ @ 50Pa, 48.5 % greater than the result obtained using a blower door on the same day.

Airtightness improvement summary

19BA had many complex air leakage pathways, meaning it had an exceptionally high infiltration rate of 23.8 $m^3/(h{\cdot}m^2)$ @ 50Pa. Infiltration was observed in areas commonly found to be weak points in fabric airtightness, including around penetrations and fenestrations, floor perimeters and behind sloping roofs. Additionally, in this home, the staircase, which was linked to the basement, was also observed to be leaky.

Sealing penetrations and around windows and doors initially reduced infiltration by 5 $m^3/(h{\cdot}m^2)$ @ 50Pa, and similarly the room-in-roof retrofit initially reduced infiltration by around 4 $m^3/(h{\cdot}m^2)$ @ 50Pa. However, in both instances, accelerated drying caused by the coheating test resulted in the seals provided by the sealant and plaster to shrink and crack so that the cumulative benefit of both retrofits was only to reduce the infiltration rate by around 3 $m^3/(h{\cdot}m^2)$ @ 50Pa. Had the sealants been allowed to dry naturally, this effect could perhaps have been avoided. Equally, as sealing in this manner is relatively imprecise, there is currently no robust means of checking whether it has been applied in an effective way.

Air leakage pathways were often redirected rather than eliminated, since there was no continuous airtight barrier and the retrofit did not attempt to create a new continuous airtightness perimeter. The creation of such a barrier would have been very disruptive, requiring destructive activity such as striping back wall finishes, floors and ceilings to apply a new parge coat or airtightness membrane. Such work would require removing any boxing in of services and surface mounted obstacles such as wall mounted kitchen and bathroom units.

3.2 U-value improvements

Three methods were adopted for deriving U-values:

1. **RdSAP default U-values:** Using age-related band default assumptions provided in SAP Appendix S, the most common approach used in EPCs for existing homes.
2. **Calculated U-values:** Used where construction details are known and a calculation is undertaken in separate approved software (e.g., the BRE U-value calculator).
3. **Measured U-values:** Used where in-situ heat flux density measurements are undertaken using an approved methodology. This approach is the most specialist and costly to undertake and so is least likely to be undertaken in retrofit projects.

All three methods are used in DEEP for comparison, and this section reports on the differences between them. The report considers the implications of the method selected for accuracy of energy and heat loss predictions, the contribution of fabric elements to HTC, and the predicted benefit achieved by the retrofit.

A summary of the pre- and post-retrofit U-values for each fabric element not altered in the retrofit is presented in Figure 3-28, while Figure 3-29 shows the U-values for the fabric elements that were improved during the room-in-roof retrofit. Where no heat flux measurement took place, only the calculated and default U-values are shown.

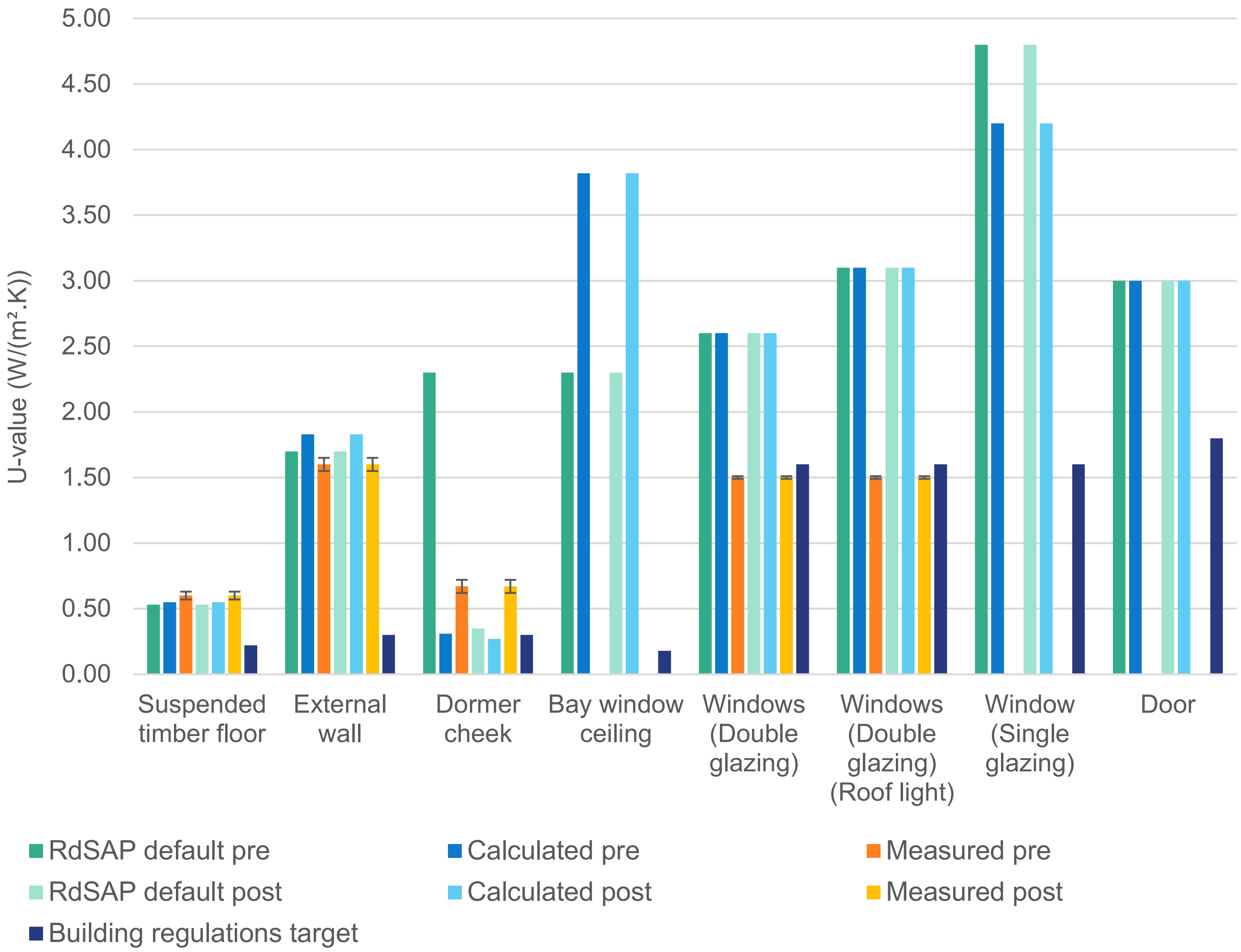

Figure 3-28 Pre- and post-retrofit U-values for uninsulated elements (W/(m²·K))

As can be seen, there were no changes in the measured U-values of the elements that were not insulated. Interestingly, the values measured for the suspended floor and external walls were similar to those calculated and the model defaults. Conversely, the window U-values derived from the heat flux measurements were much lower than the calculated and default values. However, the measurements were only representative of the centre pane U-values and thus did not account for heat loss from the frame, which takes place at a different rate than via the glass. This is, therefore, not a fair comparison with the calculated and default full-unit values.

Post-retrofit, the room-in-roof plane fabric element U-values were much improved where they were insulated. No change was observed in the dormer cheek value, as this element was already insulated and therefore did not have any additional insulation installed. All other surfaces did receive additional insulation as part of the retrofit, which saw improvements of between 35 % and 50 % in the U-values.

It is interesting to observe that a simplification in the RdSAP software resulted in all elements of the room-in-roof having a U-value of 2.30 W/(m²·K). This and other DEEP case studies show a substantial underestimate of the energy efficiency of existing rooms-in-roof. The consequence of this overestimate of heat loss is that RdSAP predicts much greater heat loss reductions when rooms-in-roof are insulated than may actually be the case.

The measured U-values were, however, more in line with the calculated U-values based on the site observations of the in-situ fabric, with the notable exception of the knee wall and loft which showed a substantial performance gap. The cause of this is not known, though it may be due to thermal bypass or inconsistency in the insulation at the point of measurement.

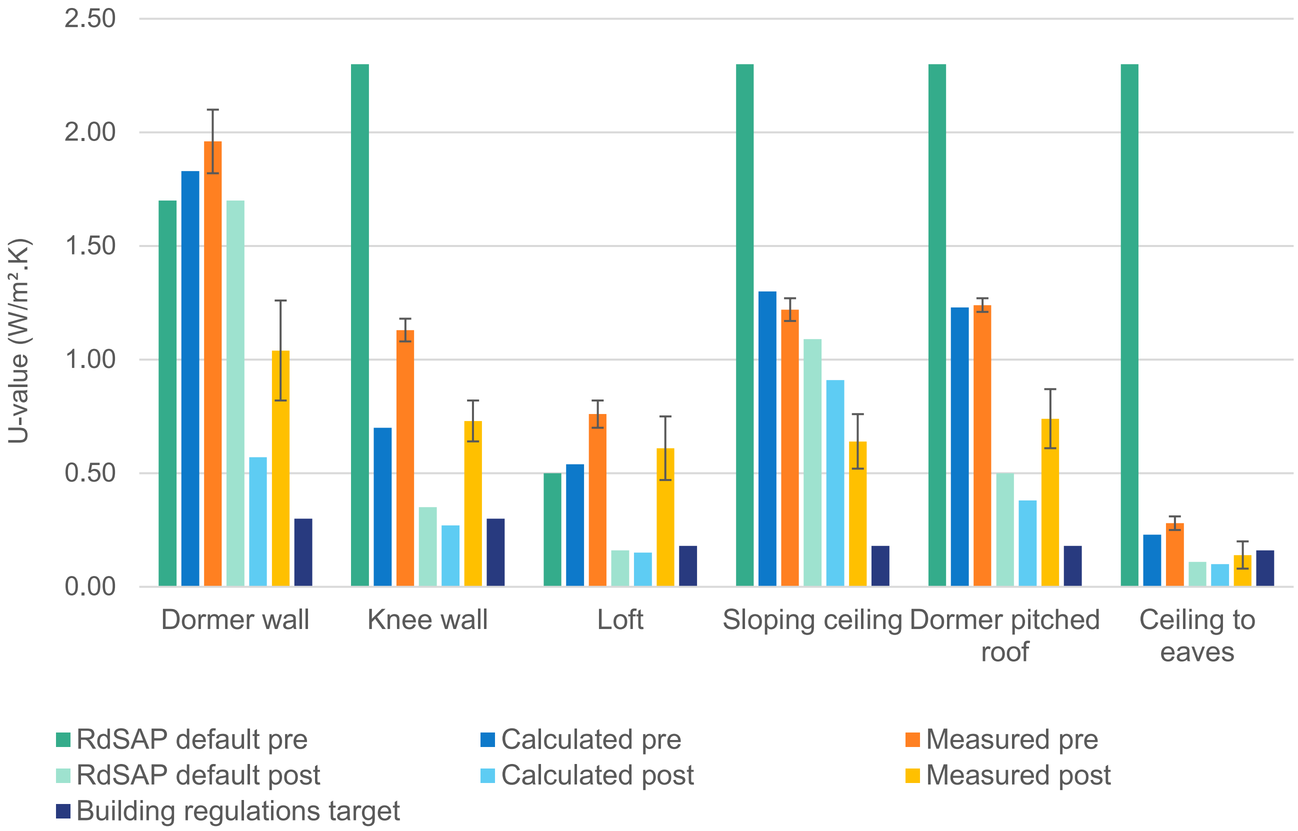

Figure 3-29 Pre- and post-retrofit fabric U-values for room-in-roof (W/(m²·K))

The pre- and post-retrofit U-values of the elements which were insulated are listed in Table 3-1, confirming that substantial reductions were achieved of between (20 ± 15) % and (50 ± 7) %.

Table 3-1 RdSAP default, calculated and measured U-values (W/(m²·K))

	Pre-retrofit			Post-retrofit U-value and % improvement		
	RdSAP Default	Calculated	Measured	RdSAP Default	Calculated	Measured
Dormer wall	2.30	1.83	1.96 ± 0.14	0.35 (85 %)	0.57 (69 %)	1.04 ± 0.22 (47 ± 26) %
Knee wall	2.30	0.70	1.13 ± 0.05	0.35 (85 %)	0.27 (61 %)	0.73 ± 0.09 (35 ± 10) %
Loft	0.50	0.54	0.76 ± 0.06	0.16 (68 %)	0.15 (72 %)	0.61 ± 0.14 (20 ± 15) %
Sloping ceiling	2.30	1.30	1.22 ± 0.05	1.09 (53 %)	0.91 (30 %)	0.64 ± 0.12 (48 ± 13) %
Dormer pitched roof	2.30	1.23	1.24 ± 0.03	0.50 (78 %)	0.38 (69 %)	0.74 ± 0.13 (40 ± 13) %
Ceiling to eaves	2.30	0.23	0.28 ± 0.03	0.11 (95 %)	0.10 (57 %)	0.14 ± 0.06 (50 ± 7) %

Despite the U-values being reduced, Table 3-2 shows there was a difference in the measured reduction achieved and that predicted by the RdSAP default input assumptions, and also by the BRE calculator based on site observations. In most instances, RdSAP predicted a larger reduction than was measured. This is because, when EPC assessors evaluate rooms-in-roof, they use a simplified set of assumptions about the roof geometry and thermal performance, not realistic in this case, leading to very large overpredictions of starting U-values and consequently larger predicted savings once insulation is installed.

Table 3-2 Summary of measured U-value reductions and gaps in performance (red = significant gap)

Element	RdSAP default predicted reduction	Calculated predicted reduction	Measured reduction	RdSAP defaults prediction gap	"as-built" performance gap
Dormer wall	1.95	1.26	0.92 ± 0.26	1.55 ± 0.10	0.34 ± 0.26
Knee wall	1.95	0.43	0.40 ± 0.10	1.55 ± 0.10	0.03 ± 0.10
Loft	0.34	0.39	0.15 ± 0.15	0.19 ± 0.15	0.24 ± 0.15
Sloping ceiling	1.21	0.39	0.58 ± 0.13	0.63 ± 0.13	-0.19 ± 0.13
Dormer pitched roof	1.80	0.85	0.50 ± 0.13	1.30 ± 0.13	0.35 ± 0.13
Ceiling to eaves	2.19	0.13	0.14 ± 0.07	2.05 ± 0.07	-0.01 ± 0.07

The calculated U-value reductions were significantly bigger than the measured reductions for the dormer wall and pitched roof. It is not known why this was, but it may be due to installation inconsistencies at the point of heat flux measurement or air movement around the elements (perhaps most likely given the extremely leaky nature of the dwelling).

Conversely, the room-in-roof sloping ceiling performed better than expected. The sloping ceiling did have some insulation which was installed by the landlord prior to the room-in-roof retrofit. This may indicate a performance gap with the pre-existing insulation. RdSAP predicted a much larger reduction in U-value than predicted by the design calculation, due to the limited inputs in RdSAP which assumed a greater quantity of insulation than was fitted.

The loft insulation also had a performance gap. Access to the loft space was limited and a new access hole had to be created, plus headroom in the loft was minimal, restricting the ability to install mineral wool. It is possible therefore that the mineral wool may not have had 100 % coverage of the loft area and some discontinuities persisted. This may be shown in Figure 3-30, although the image was taken under depressurisation and may reflect air movement as opposed to a discontinuity in the loft insulation. Either of these factors may have contributed to the loft insulation performance gap.

Figure 3-30 Possible discontinuities in loft insulation

3.2.1 Contribution of fabric heat loss (HTC_f) to HTC

Table 3-3 shows the plane element fabric heat losses derived from the heat flux density measurements pre- and post-retrofit. As can be seen, the walls were responsible for around half of all heat loss pre- and post-room-in-roof retrofit, while the roof heat loss itself appears to have reduced by (21 ± 5) W/K, meaning it was the second largest heat loss area in the home, but post-retrofit the windows and doors became responsible for more heat loss than the roof.

This may be considered a relative success, but on a whole house basis the saving was not significant, achieving a measured reduction equivalent to (13 ± 14) % of the total plane element fabric heat loss.

Table 3-3 Impact of retrofit on fabric plane element heat loss (excluding thermal bridging)

Element	Pre-retrofit (W/K)	*Proportion of heat loss*	Post-retrofit (W/K)	*Proportion of heat loss*
Roof	52 ± 2	(22 ± 1) %	31 ± 6	(15 ± 3) %
Floor	29 ± 1	(13 ± 1) %	29 ± 1	(15 ± 1) %
Doors and windows[7]	40	18%	40	20%
Walls	109 ± 4	(47 ± 2) %	101 ± 5	(50 ± 2) %
Total	**230 ± 7**	**-**	**201 ± 12**	

This is visualised in Figure 3-31, which illustrates how the RdSAP fabric heat losses and savings that result from the room-in-roof retrofit are significantly higher than those estimated by the BRE calculator or derived from heat flux measurements.

These latter two U-values are much more closely aligned, and the variation in the RdSAP defaults is largely due to simplified assumptions of the room-in-roof heat losses. The RdSAP assumptions about heat loss via walls, floors and windows give much more similar heat loss estimates to the calculations and measurements, although still slightly higher.

[7] No HFP recordings were obtained for doors or single glazed windows.

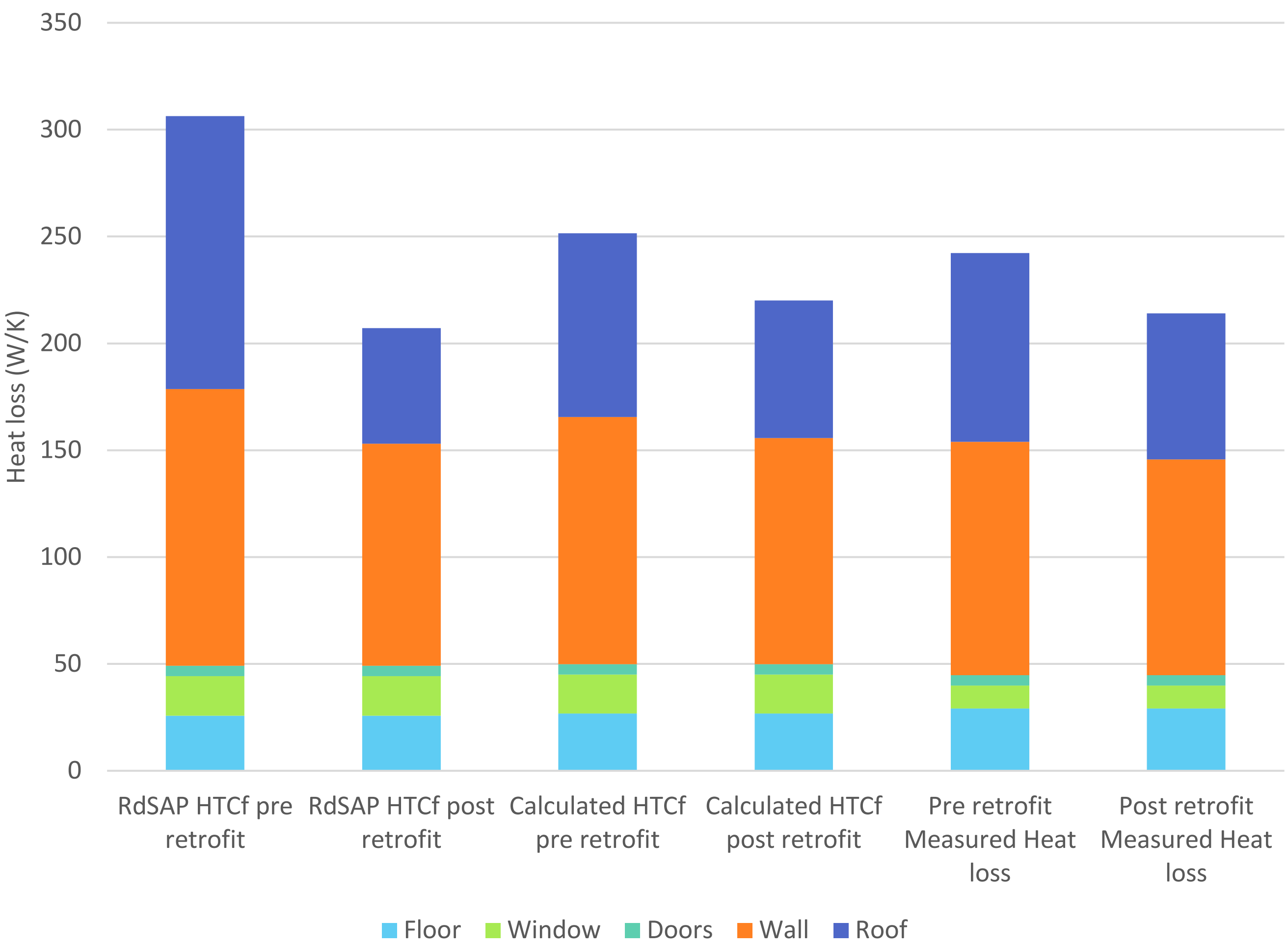

Figure 3-31 Heat loss of fabric elements pre- and post-retrofit, as recorded by heat flux density measurements

U-value improvement summary

The room-in-roof retrofit substantially reduced heat loss via the roof, in some instances by around a half. However, its impact on the whole house fabric heat loss was relatively small, since heat loss in this home was predominantly via the solid walls, which were not insulated

The RdSAP inputs for room-in-roof heat losses were simplified and, in this case study, the heat loss and predicted savings achieved by the retrofit were significantly higher than measured through heat flux or calculated via the BRE calculator.

The measurements also suggest that the fabric performance was slightly lower than predicted following site observations, meaning a performance gap was observed for three of the dormer walls, the dormer pitched roof and the loft insulation.

3.3 Whole house heat loss (HTC) improvement

The total measured heat loss for the dwelling at each stage is shown in Table 3-4. The heat loss in the home was only marginally reduced as a result of the cumulative retrofits, and it was not possible to measure a statistically significant reduction for the individual retrofits. Since such a large amount of infiltration heat loss and heat loss via the walls was taking place in the home, the ventilation and fabric improvements were not substantial enough to be measurable, despite the coheating tests themselves being highly accurate with uncertainties below 5 %. This is an important finding considering the potential for the use of real data to validate the success of retrofits.

Table 3-4 Test house HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC Uncertainty	HTC Reduction (W/K)	Percentage reduction
19BA.B Base case	269	5 (2 %)	-	-
19BA.A Airtightness	263	6 (2 %)	6 ± 8	(2 ± 3) %
19BA.A.R Room-in-roof	251	12 (5 %)	12 ± 13	(5 ± 5) %
Cumulative reduction			***18 ± 13***	***(7 ± 5) %***

The results are visualised in Figure 3-32, again showing the small change achieved by the retrofits relative to the whole house heat loss. This has implications for the significance of leaving solid walls uninsulated in the context of domestic energy efficiency policy.

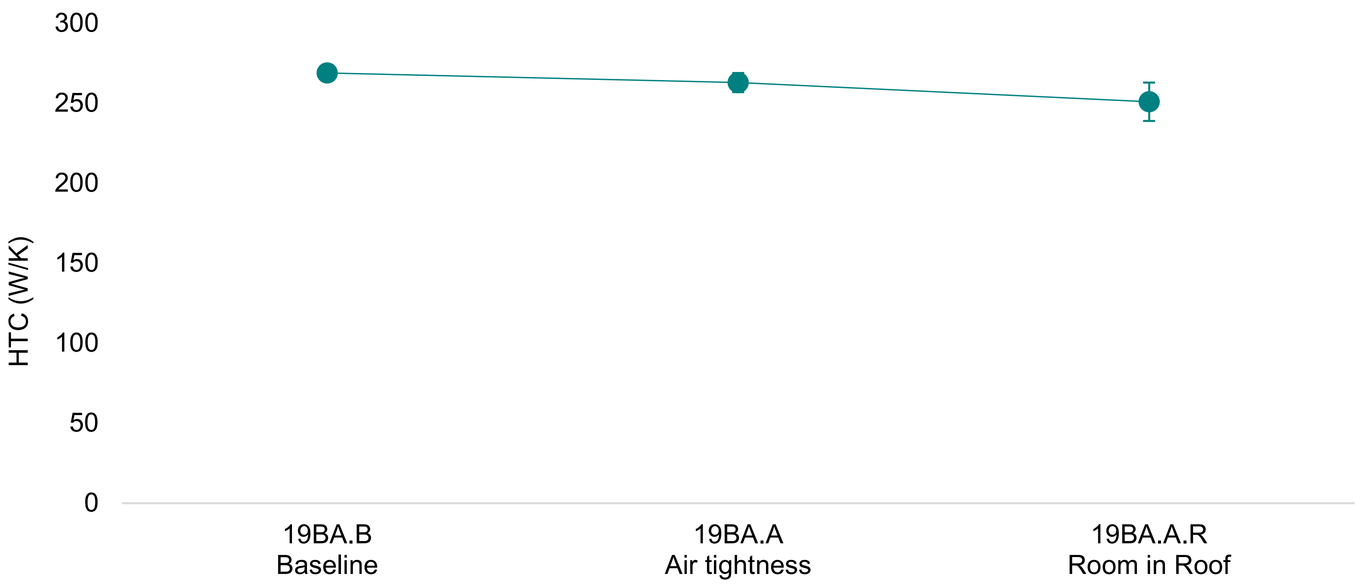

Figure 3-32 Coheating HTC at each retrofit stage

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Pre-retrofit there was a significant amount of air leakage in the home, with the infiltration rate measured at almost three times the maximum limiting value for new build homes. Despite this, the airtightness retrofit revealed that identifying and eliminating air leakage pathways was challenging and, in many instances, ineffective. Section 3.1.3 outlines the improvements that were achieved by the remedial sealing and boxing in of air leakage pathways, but the pathways were complex and were not eliminated but redirected. Additionally, seals failed after exposure to the accelerated drying conditions of the coheating test. Undertaking partial airtightness retrofits is therefore not likely to result in significant reductions in background ventilation heat losses because, while certain air leakage pathways were removed, air leakage became more extreme at the remaining pathways.

Furthermore, the case study shows how a room-in-roof retrofit can reduce plane element heat losses. However, it also highlights practical issues that arose as part of the installation process. As shown in Figure 3-33, there were substantial amounts of debris and repairs were needed which added significant time delays and costs to the project, as well as the disruption that removing the existing fabric surfaces caused. All these issues have real world implications for room-in-roof retrofits being installed at scale.

Figure 3-33 Debris behind knee walls (left), missing party wall brickwork between dwellings in eaves (middle) and substantial waste generated by the removal of existing surfaces (right)

The process of installing the new insulation required additional roof timbers to be installed to accommodate the thicker insulation. This added delay and cost to the project. However, replacing the existing room-in-roof fabric surfaces afforded the opportunity to ensure a ventilation gap existed between the insulation and the roof tiles. This is shown in Figure 3-34, along with the replacement of an aged waterproofing membrane under the roof slates with a new layer of breathable membrane to improve moisture management.

Thus, the retrofit provided confidence that the roof timbers were in good condition and the roof system was weathertight and not at risk of leaks. These benefits of the retrofit were not measurable via the building performance testing undertaken for this case study. However, they are important considerations for homeowners and landlords who may choose to undertake room-in-roof retrofits.

Figure 3-34 Installation of new breathable moisture membrane and additions to roof timbers (blue) to accommodate the extra thickness of the insulation

The coheating test suggests that the room-in-roof retrofit itself did not significantly lower the home’s HTC, achieving only a (12 ± 13) W/K or (5 ± 5) % reduction. One reason for this is that when the original room-in-roof ceiling was removed it was found that the sloping ceiling already had some phenolic foam insulation, as shown in Figure 3-35. This means the relative improvement for this element was lower than it would have been if the previous retrofit had not taken place.

Figure 3-35 Existing insulation found installed in the room-in-roof sloping ceiling

3.3.1 Aggregated and disaggregated HTC

The aggregate whole house HTC measured using the coheating test can be disaggregated into three individual components:

HTC_v (infiltration heat losses) can be estimated by applying the n/20 rule to the blower door test results.

HTC_f (plane element heat losses including repeated thermal bridging) can be approximated by measuring heat flow via HFPs on all elements and summing the area.

HTC_b (non-repeating thermal bridging heat losses) can be calculated by modelling each junction in thermal bridging software; though it is often erroneously assumed to be the remainder once the HTC_v and HTC_f are subtracted from the measured whole house HTC.

According to Equation 1, the equivalent HTC saving achieved from the airtightness improvements in 19BA is equivalent to approximately 12 W/K, which, combined with the new external glazing and doors, could account for the difference in the respective HTCs.

Equation 1 Estimation of ventilation heat loss (HTC_v) via the n/20 rule

$$HTC_v = \left(\frac{Permeability\ (m^3\ per\ m^2.hr\ @50\ pa) \times Volume\ (m^3)}{20 \times specific\ heat\ capacity\ of\ air\ (3\ MJ/m^3K)}\right) \times Shelter\ factor\ (0.85)$$

Notwithstanding the above result, more research is needed to investigate the n/20 rule of thumb, and any attempt to disaggregate the whole house HTC into fabric and background ventilation heat loss using the n/20 rule should be treated with caution. This is demonstrated in a recent publication, where this rule of thumb was shown to be inappropriate in a sample set of 21 buildings [4]. Investigation using a larger sample set would be required to identify an alternative rule of thumb for a range of UK archetypes.

The measured aggregate HTC from the coheating test and the disaggregated HTC calculated from summing HTC_v, HTC_f and HTC_b are presented in Figure 3-36.

Comparing these two approaches to deriving the whole house HTC is called *closing-the-loop* analysis. It is useful for both exploring where heat losses occur and as a reference point for the whole house HTC measured by the coheating test. HTC_f is derived by multiplying the area (m²) of each fabric element by its U-value (W/(m²·K)), HTC_v is described in Equation 1, and the calculation of HTC_b using thermal software is described in the previous chapter.

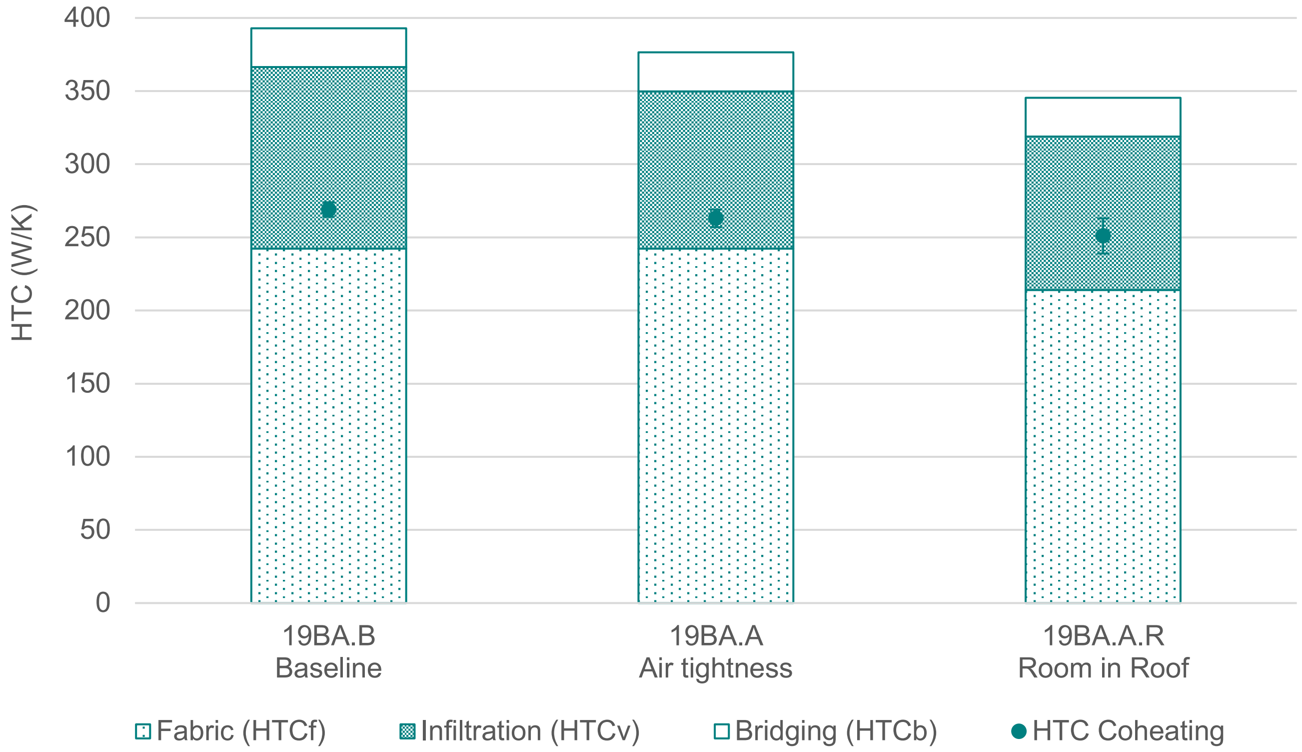


Figure 3-36 Aggregated vs. disaggregated measured HTC

The reasons for the discrepancies that tend to occur in these comparisons include:

- The n/20 rule is an average annual approximation which may not be appropriate for different building types or for different levels of wind exposure, geography or topography.
- HFP placements may not be representative or comprehensive of whole element heat loss, so HTC_f is most likely to be imperfectly estimated.
- Thermal bridging simulations contain simplifications in geometry and use default data on construction material properties, so may not be representative of actual HTC_b. The calculations also do not take point thermal bridges into consideration.
- Systematic uncertainty in the coheating test cannot be accounted for perfectly, due to, for example, party wall heat exchange, solar gains or wind. In addition, only quasi steady-state conditions are possible.
- The default U-values for the pre-retrofit external windows have to be assumed if specific performance details are not known.

Comparisons with other case studies in DEEP suggest that the background ventilation heat losses estimated by the n/20 rule in particular may be a significant cause of the lack of agreement in the closing-the-loop analysis of 19BA.

Background ventilation heat loss in DEEP case studies which have different built forms and construction to 19BA, generally makes up between 10 % and 18 % of the total heat loss in the closing-the-loop analysis. As can be seen in Figure 3-36, over 30 % of 19BA's heat loss may be via ventilation, which is consistent with other DEEP case study homes with similar building forms. Thus, it is likely that n/20 is an inadequate rule of thumb for large, mid-terraced homes with large areas of party wall and high levels of air leakage.

Table 3-5 Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b W/K
19BA.B baseline	242 (62 %)	124 (32 %)	27 (7 %)
19BA.A airtightness	242 (64 %)	108 (29 %)	27 (7 %)
19BA.A.R room-in-roof	214 (62 %)	105 (30 %)	27 (8 %)

Whole house heat loss improvement summary

Cumulatively, the airtightness improvements and the room-in-roof retrofits reduced the HTC of the home by (18 ± 13) W/K, representing (7 ± 5) % of the measured whole house heat loss. However, neither retrofit individually achieved a significant reduction in heat loss.

The retrofits achieved a relatively small reduction in HTC, because the heat loss in the home was dominated by fabric heat losses (over 60 %) and the majority of this was via external walls which were not improved in the retrofits.

Air leakage pathways in the home were complex and interconnected, and thus airtightness retrofits could not create a new continuous air barrier in the dwelling, which would have required disruptive and destructive activity. As a result, no meaningful HTC reductions were observed. However, although it may only be possible to redirect rather than eliminate air leakage, this may still be beneficial in removing unwanted draughts which can affect thermal comfort.

Moreover, the retrofits would have been more successful if the house had not already had some insulation applied to the room-in-roof sloping ceiling. Similarly, the savings may have been larger if the coheating test had not caused accelerated drying and cracking of the new sealant applied around penetrations, window and doors, and of the new plaster on the walls in the room-in-roof. Such failures of seals and cracks in sealant and plaster affect homes over time, and so, while they were accelerated in these tests this may be reflective of the longer-term performance of the retrofits.

The room-in-roof retrofit was disruptive, caused significant amounts of waste and revealed additional fabric repairs that were needed. Although this resulted in the retrofit being more costly and delayed, it afforded the opportunity to undertake general maintenance to increase the longevity of the fabric and manage ventilation and moisture risk in the room-in-roof, which are benefits that may influence whether these retrofits take place at scale across the housing stock.

It was not possible to reliably disaggregate heat losses from fabric ventilation and thermal bridging for several reasons, specifically because the n/20 rule of thumb may be inappropriate for homes like 19BA.

3.4 Measured vs. modelled retrofit performance

3.4.1 Measured vs. Modelled HTC calibration step 1: Default input data

The measured HTC values for each retrofit stage are plotted against the HTC values predicted by the models using default RdSAP input data in Figure 3-37. The results of these comparisons are as follows:

- DSM predicts HTC closer to the measured coheating HTC, while both steady-state models predict much higher HTCs. RdSAP predicts higher HTC than BREDEM since the software makes a simplified assumption about the room-in-roof geometry, assuming there are two external gable walls instead of party walls in the room-in-roof, and that the U-values are much higher than the age band defaults for these elements.
- At this stage, the airtightness retrofit shows no improvement in the models since RdSAP default data does not allow infiltration rates to be changed.
- RdSAP predicts a very large reduction in HTC following the room-in-roof retrofit, of around 30 %. This large reduction is because of the simplified assumptions it makes about the room-in-roof geometry and U-values.
- BREDEM and DSM predict only a modest reduction in HTC (13 % and 11 %, respectively) resulting from the room-in-roof retrofit, since they use age band U-values for the room-in-roof elements.

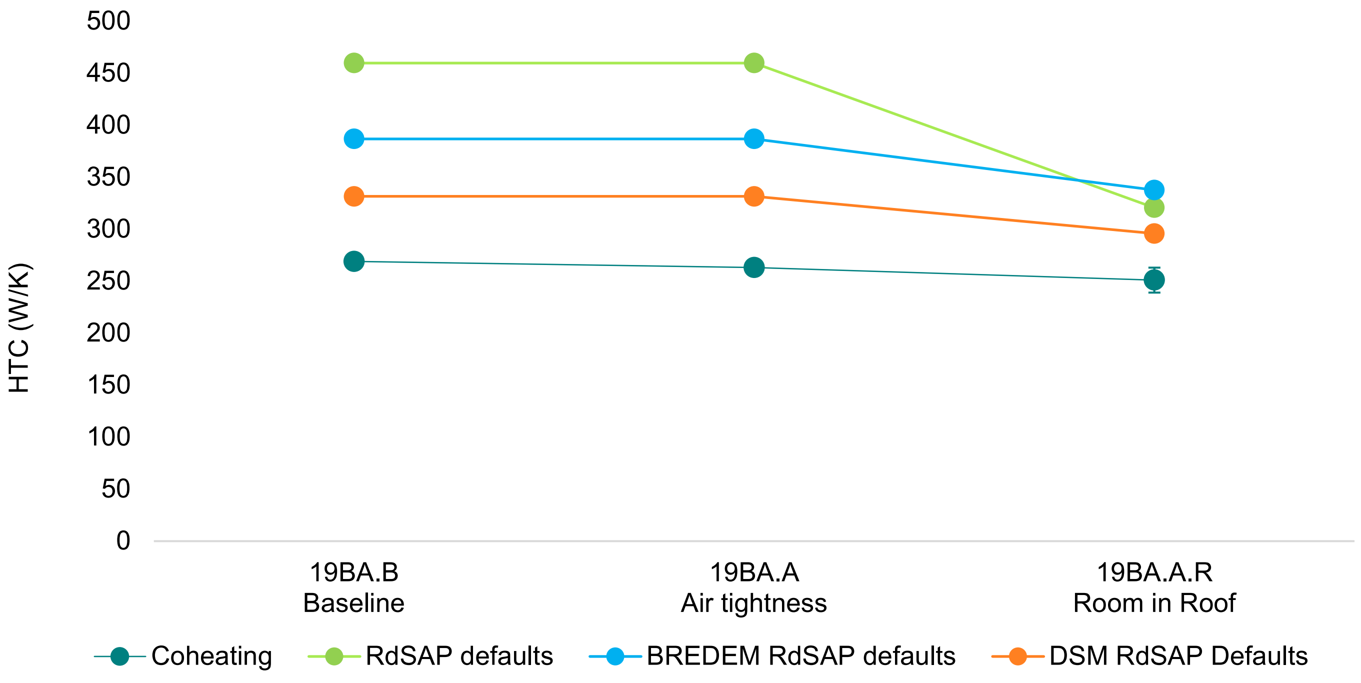


Figure 3-37 Measured vs. modelled HTC calibration step 1: Default input data

3.4.2 Measured vs. modelled HTC calibration step 2: Measured infiltration

In the first calibration step, the models use infiltration rates derived from the blower door test, as these data are the most likely and most cost-effective measurements to acquire in practice. The impact of this compared to the previous calibration stage can be seen in Figure 3-38:

- RdSAP is not included in this step as infiltration cannot be altered in the software.
- A relatively small increase in HTC is observed in the models overall, since the default infiltration rate of the house in RdSAP is slightly lower than that measured.
- In this stage the benefit of the airtightness retrofit is captured, seeing HTC drop by around 4 %.

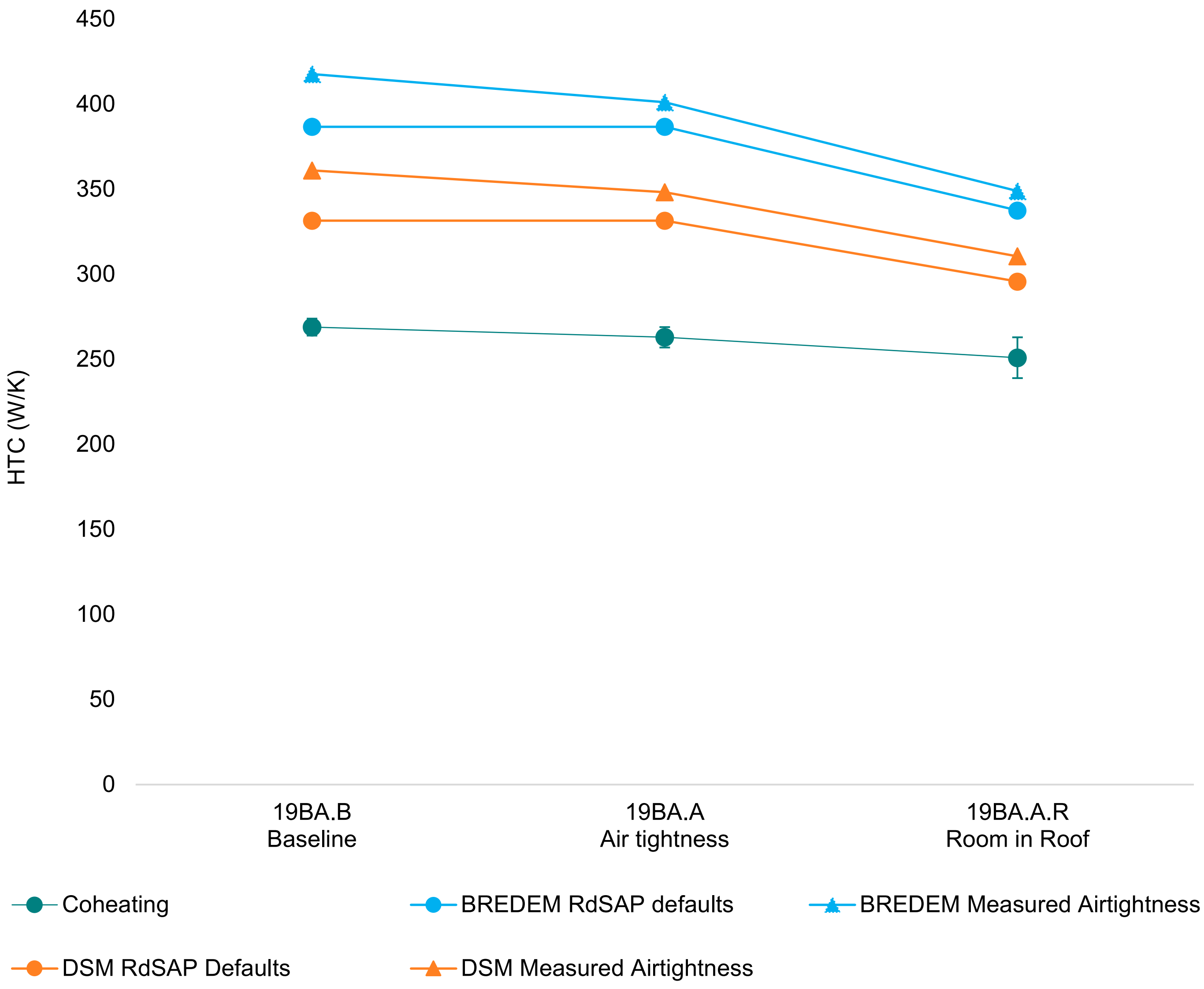


Figure 3-38 Measured vs. modelled HTC calibration step 2: Measured infiltration

3.4.3 Measured vs. modelled HTC calibration step 3: Calculated U-values

In this step, the models include the U-values defined using the BRE calculator, which requires a more detailed survey. It often relies on either assumptions about or destructive investigations to establish the nature and thickness of construction layers. The impact of this compared to the previous calibration stage can be seen in Figure 3-39:

- RdSAP is not shown since it is not possible to include calculated U-values in the software.
- Using calculated U-values results in both the steady-state and DSM models predicting lower HTC across all models, since the measured U-values for the walls are lower than the calculated values.
- The calculated U-values also suggest a slightly smaller improvement was made by the room-in-roof retrofit compared to default U-values, which overestimate the saving achieved.

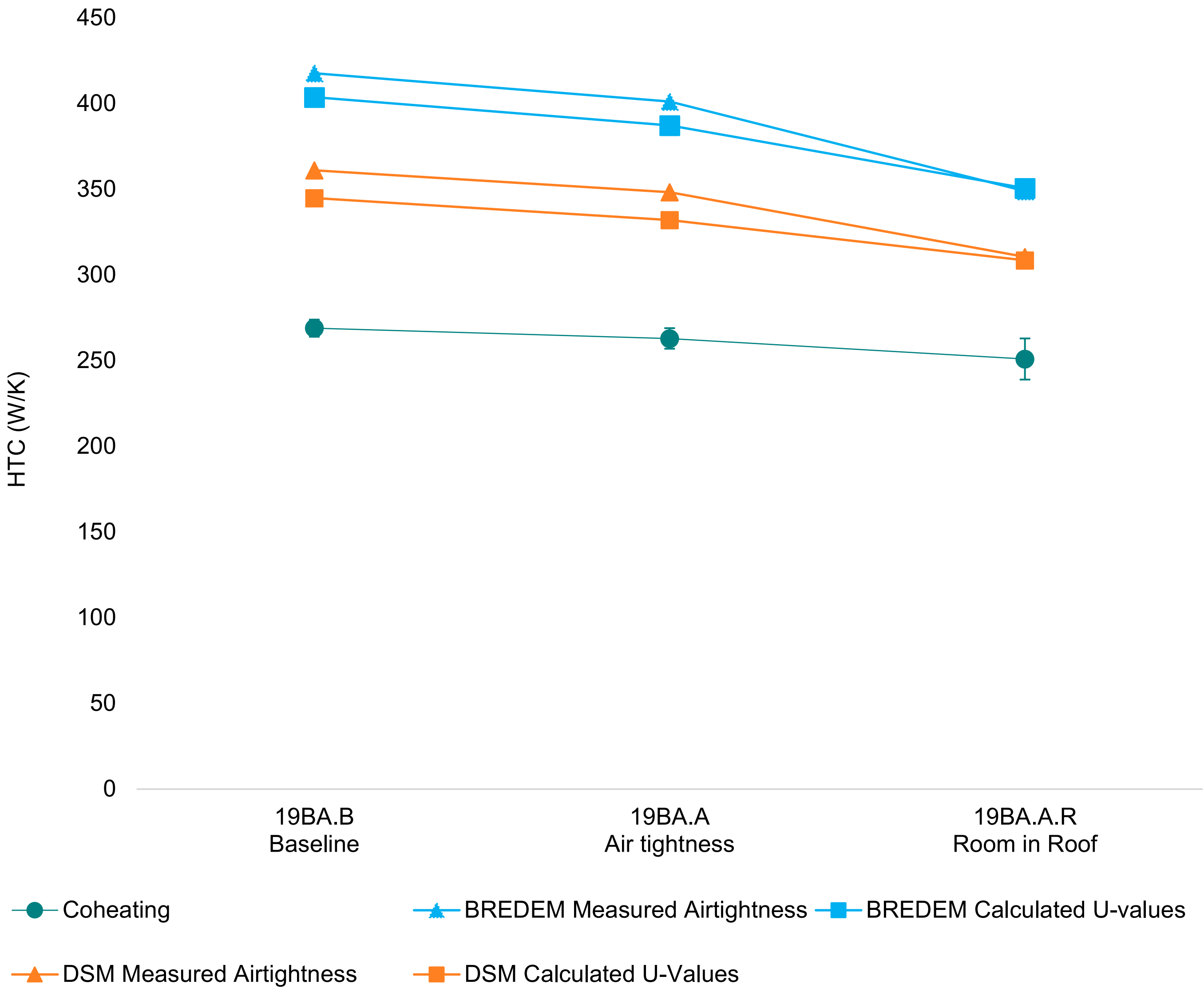


Figure 3-39 HTC Measured vs. modelled HTC Calibration step 3: Calculated U-values

3.4.4 Measured vs. modelled HTC calibration step 4: Measured U-values

In this step, the models use the measured U-values, requiring resource-intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-40:

- Including the measured U-values reduces the HTC predicted by all the models, since the external wall U-values were measured to be lower than the calculated and default predictions used in the models.
- Despite updating the models with the measured airtightness and U-values, the predicted HTCs for all models are still substantially higher than measured by the coheating test.
- The RdSAP predictions become significantly different when the actual U-values are included, reducing by almost 30 % pre-room-in-roof retrofit. This shows that using the room-in-roof simplification in the RdSAP model results in predicting significantly more heat loss than may actually be taking place in the home.
- When including the measured U-values, RdSAP predicts that the room-in-roof retrofit would only reduce HTC by 8 % rather than the 30 % reduction predicted when the RdSAP default assumptions about the room-in-roof are used. This has major implications for the perceived effectiveness of room-in-roof retrofits and the accuracy of EPCs for homes with room-in-roof retrofits generally.

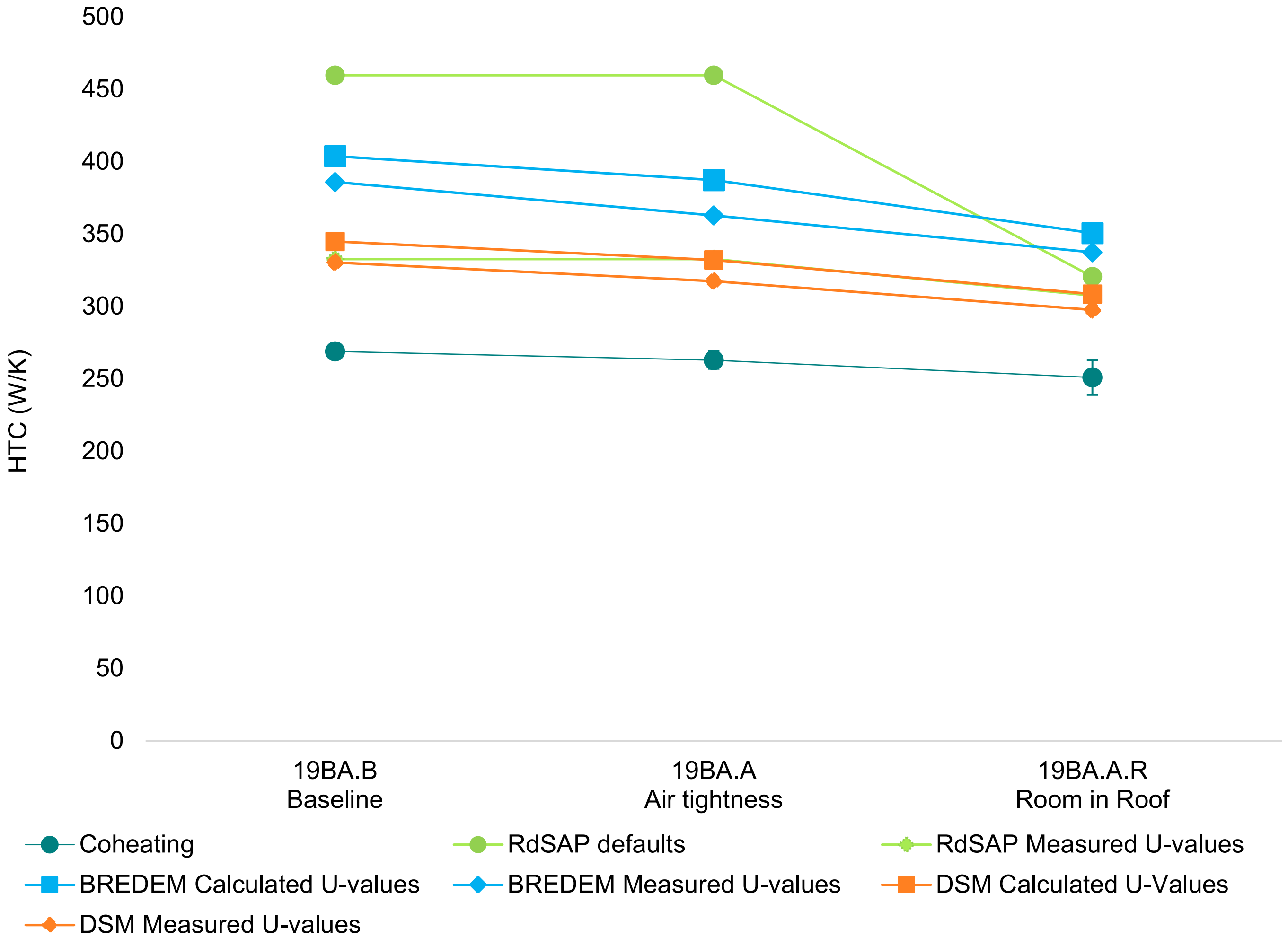


Figure 3-40 HTC Measured vs. modelled HTC calibration step 4: Measured U-values

Measured vs. modelled HTC summary

The RdSAP default assumptions about room-in-roof heat loss appear to cause significant overestimation of HTCs. This means they also overstate the effectiveness of insulating rooms-in-roof. This simplification has implications for the accuracy of EPCs for homes with this feature and for the perceived effectiveness of room-in-roof retrofits.

The HTCs for the models which rely on default values for infiltration and U-values roughly match the HTCs for the models which use measured values for infiltration and U-values. The reason for this seeming correlation is that the defaults underpredict ventilation heat losses and overpredict fabric heat losses. Thus, incorporating the measured air leakage increases HTC predictions, while including the measured U-values brings the predictions back down, offsetting the increase.

These compounding errors result in the default inputs predicting seemingly accurate HTCs but for the wrong reasons. This means that replacing either the default input data for ventilation heat loss or fabric heat loss with measured data, might not necessarily improve the model accuracy.

Despite differences in the absolute measured and modelled HTCs, the models and coheating test do agree on the relative reduction achieved at each stage, i.e., 4 % to 6 % reduction achieved by the airtightness improvements and 6 % to 13 % achieved by the room-in-roof retrofit. However, using RdSAP to generate EPCs would predict no change at all from the airtightness retrofit, as it does not allow assessors to alter the infiltration rate.

3.5 Predicting EPC band, annual space heating and carbon emissions

EPC bands, space heating requirements, carbon reductions and fuel bill savings are commonly used for retrofit policy evaluation. DEEP did not perform any longitudinal monitoring of energy consumption pre- and post-retrofit in the case study homes, however the energy models can predict the impact of the retrofits on these metrics.

All the models share matching occupancy profiles and internal heat gain inputs as defined in the RdSAP conventions and described in detail in the DEEP Methods 2.01 Report. Matching occupancy profiles were used to provide a useful comparison between the modelling approaches, based on changes to fabric inputs only. However, despite having matching assumptions for gains and occupancy, the resulting space heating demand from the RdSAP, BREDEM and DSM models differed substantially.

Dynamic and steady-state models are fundamentally different, in that DSM calculates heat balances and demand at an hourly timestep, whereas RdSAP and BREDEM calculate these for a typical day of each month and extrapolate the results for an annual prediction. Thus, the complex interactions between heat gains and heat demand that take place over a diurnal cycle are only represented at this resolution in DSM. It is beyond the scope of this project to confirm which approach is more accurate, but it is clear that the RdSAP and BREDEM models consistently predict higher space heating demand than when DSM is used to mimic coheating test conditions.

This is significant when considering the success of retrofits and calculating paybacks or impacts on EPC levels and fuel poverty for policy evaluation, i.e., RdSAP age-band default data are found to underestimate baseline EPC scores, and thus overestimate retrofit savings. This suggests that the current defaults contained in RdSAP are overly pessimistic.

3.5.1 Potential reasons for differences in annual model outputs

Fundamental differences between steady-state and DSM models cause inherent discrepancies in the predicted heat loss and energy calculations of the DEEP case studies. The differences between the models are discussed in the DEEP Methods 2.01 Report, and summarised here:

Internal heat gains from occupants, lighting and equipment
The total heat gain from each of these sources in DSM is adjusted to closely match that in BREDEM. However, as they are hourly heat balance calculations, there may be periods when useful gains offset fuel use as they align with periods of heating.

Heating set points and schedules
These have been adjusted to match those used in BREDEM. However, the hourly resolution of the weather data means that, in some instances, heating demand can occur in warmer daylight hours within DSM models. Equally, some heating may occur during periods of lower temperatures in the morning and evening.

Hourly vs. daily average external temperature
The external air temperature used in the hourly heat balance calculations naturally differs from the total daily average.

Solar gain through glazing
BREDEM limits glazing orientation to the cardinal and ordinal directions, whereas the dwelling is modelled in its true orientation in DSM. This can lead to differences in internal solar gain, particularly during daylight hours in heat demand periods.

Hourly vs. daily average solar irradiance (external surface temperatures)
External surface temperature is an important part of dynamic hourly heat loss calculations through all plane elements in DSM. Higher external surface temperatures lead to lower heat loss, which is more pronounced in dwellings with a greater area of south facing plane elements. The reverse can occur during darker winter months, although the thermal mass of the construction can retain some heat after sundown.

Geometry
DSM models exclude areas and volumes for chimney breasts, partition walls and intermediate floors in the total heated space. This inherently means a smaller volume of air is conditioned than in the RdSAP calculations.

Weather
Due to the temporal resolution and variability of weather, it is not possible to match the BREDEM inputs in the same way as the internal gains. The weather file used in the DSM is selected due to the close similarity to monthly average external temperature values (CIBSE Test Reference Year file for Leeds) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 19BA
For the 19BA baseline scenario, using measured infiltration rates and U-values, BREDEM predicts a space heating demand of 4,015 kWh/year higher than the DSM prediction. In the majority of the other DEEP case studies, the HTC value has the greatest influence on the annual space heating demand estimates. BREDEM (and therefore SAP/RdSAP) uses a bottom-up method to calculate the HTC used in the heat balance calculations, based on the thermal transmittance, area of construction and background infiltration rates. The DSM models mimic the coheating test conditions and therefore use a top-down method to calculate HTC. Using an

unrestricted version of the BREDEM software, it is possible to overwrite the HTC with that calculated by the DSM model.

Following this adjustment, the normalised annual space heating demand in BREDEM for 19BA is 15,276 kWh, compared to the DSM estimate of 14,301 kWh, meaning that BREDEM predicts a demand which is higher by 975 kWh. The BREDEM calculations can be further normalised using the DSM volume of conditioned space (18.05 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 227 kWh higher than the DSM estimate. There is a relatively small difference in internal solar heat gain, which is 634 kWh/year higher in the DSM, emphasising the large difference between HTCs as the primary difference in predicted heat demand.

3.5.2 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government have an ambition that all homes, where practically possible, will achieve EPC band C by 2035 [5]. The impacts of the retrofits on EPC in this case study as predicted by each model at each calibration stage are shown in Figure 3-41. The heat demand predicted by DSM is the only output that differs in the comparative EPC calculations.

- All the models predict the baseline house as EPC band D, except the post-retrofit RdSAP model which incorporates measured U-values. The reason for this may be that, when the measured U-values are input for the room-in-roof, it results in 22 m^2 less heat loss area than the other models, thereby reducing the plane element and linear thermal bridging heat loss assumptions. In addition, it incorporates lower assumed infiltration heat losses than were measured, while the other models use the actual, higher, infiltration rate.
- The cumulative airtightness and room-in-roof retrofits were not sufficient to bring the EPC to a band C in either of the other modelled scenarios. This is mainly because heat loss via the solid walls dominates the overall thermal performance of the home, and these were not insulated as part of the retrofits.
- Despite differences in the steady-state and dynamic models and the impact of incorporating measured data to replace default inputs, all the models predict a broadly similar EPC rating.

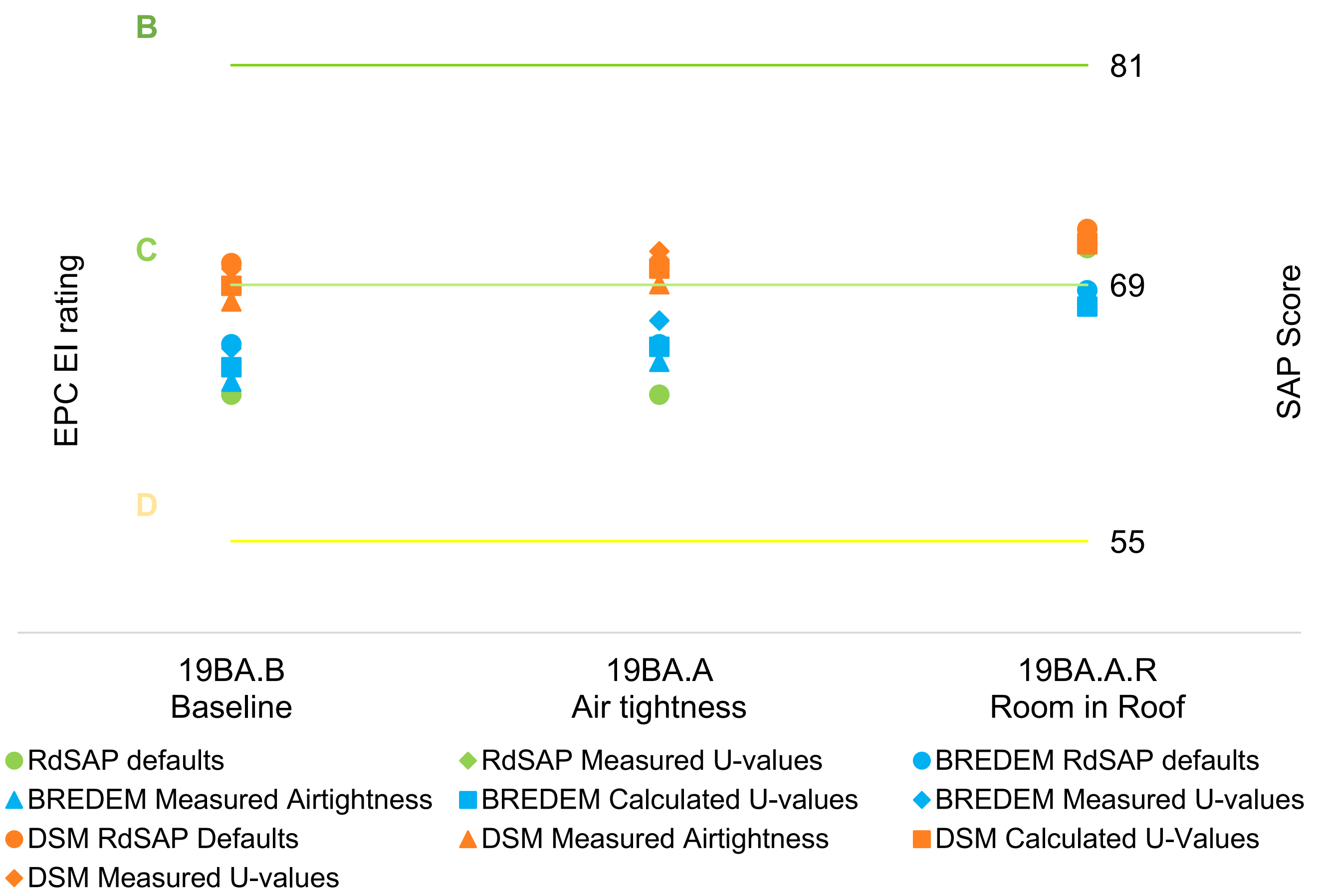


Figure 3-41 Impact of retrofit on EPC band

3.5.3 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting an annual space heating target of 90 kWh per m² for retrofits [6]. The predicted annual space heating demand for the case study retrofits is shown in Figure 3-42.

- The BREDEM model predicts higher space heating requirement than DSM. This follows a trend found in other DEEP homes and can be attributed to differences in the way the models deal with internal gains, as described in Section 3.5.1.
- RdSAP assumes that the entire top floor was retrofitted, when in fact, only the two bedrooms were, while the landing area was not. Thus, the EPC (which uses RdSAP defaults) predicts greater savings than BREDEM.
- As observed in the HTC analysis, adding measured airtightness to the models increases space heating demand generally, since the home had more air leakage than the default inputs predict. Conversely, adding in the measured U-values reduces space heating demand, since the default U-values were worse than measured, effectively cancelling out the change from adding the measured infiltration rate.
- The cumulative reductions in the BREDEM and DSM models are 15 % and 17 %, respectively, when the airtightness measurements are included, compared to 13 % and 11 % when the measured U-values and infiltration rates are used. The RdSAP default model predicts a 30 % reduction, which is between two and three times more. The SHDF 90 kWh target was not achieved in any scenario.

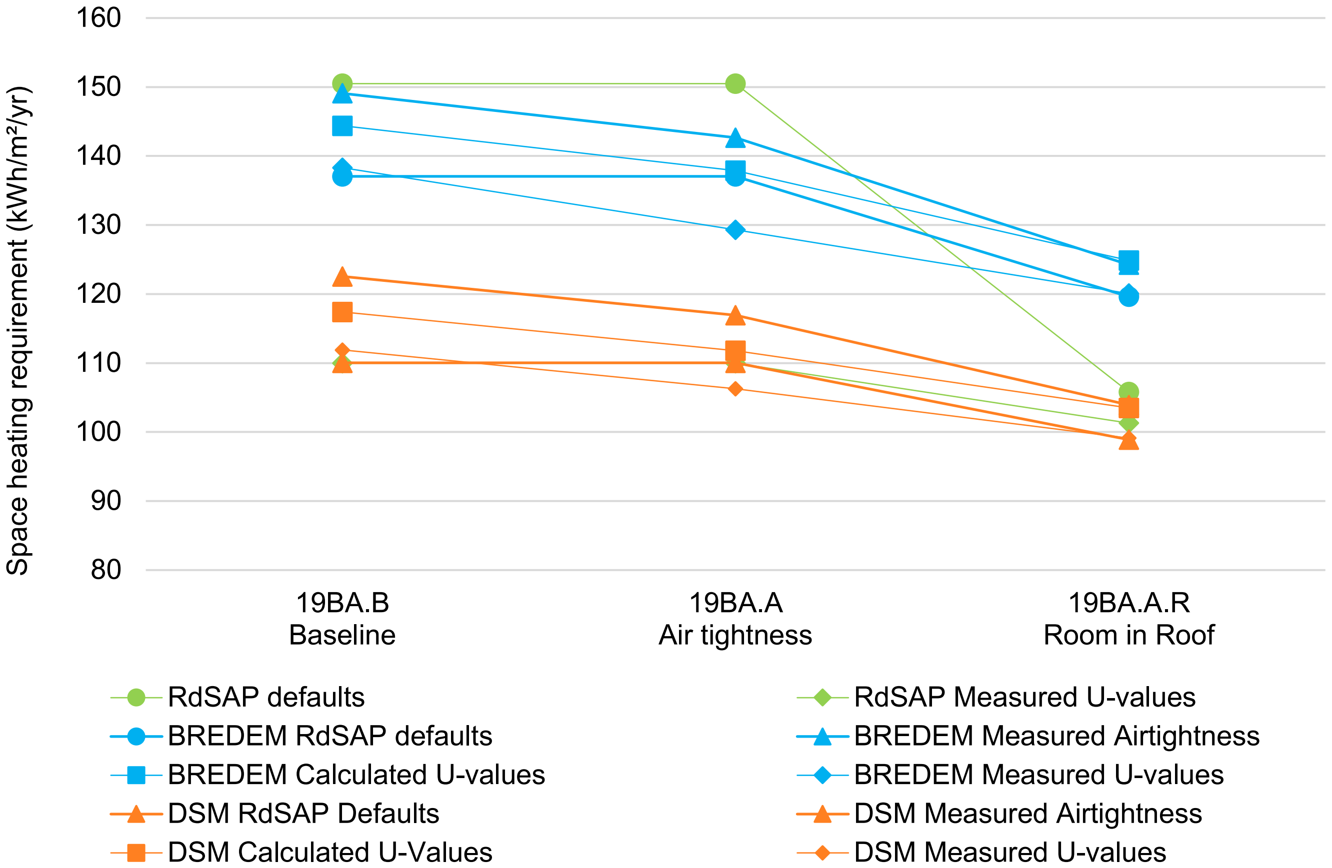


Figure 3-42 Predicted cumulative reduction in annual space heating demand

3.5.4 Impact of retrofits on CO_2 emissions

Heating homes is responsible for around 15 % of the UK's CO_2 emissions [7], The predicted CO_2 emissions for the case study home after each retrofit are shown in Figure 3-43.

- Airtightness retrofits marginally reduce the predicted CO_2 emissions in all models except the RdSAP model used for EPCs, since this does not capture savings achieved via improvements to infiltration rate.
- The cumulative reductions in CO_2 predicted in the RdSAP model vary from 24 % when default values and simplification to the room-in-roof geometry are made, down to just to 6 % when the actual room-in-roof geometry and measured fabric U-values are accounted for. This highlights the influence of defaults and simplifications on the predicted CO_2 emissions from the home.
- In BREDEM and DSM, the predicted reductions in CO_2 emissions are 12 % and 14 %, respectively, when airtightness measurements are used, and 11 % and 9 %, respectively, when measured U-values are used. This suggests that room-in-roof and airtightness retrofits alone may not achieve substantial CO_2 reductions in solid walled homes, which may have implications for UK net zero policy targets.

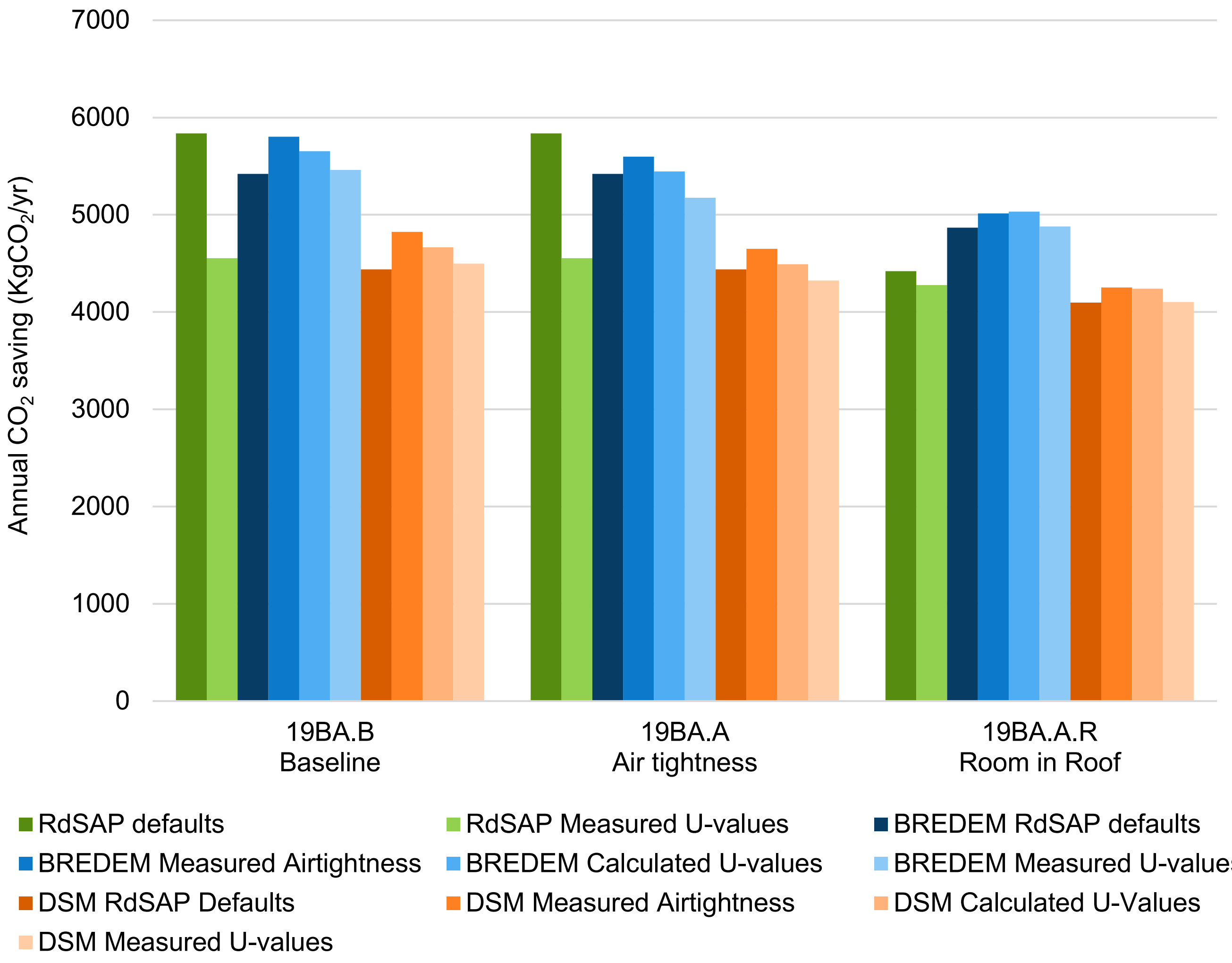


Figure 3-43 Annual CO_2 emissions following each individual retrofit

Predicting EPC band, space heating and carbon reduction summary

The choice of model and inputs significantly affects the predicted absolute energy efficiency of the case study home. Specifically, there are two phenomena affecting the RdSAP model predictions.

The first is the assumption that all the room-in-roof space is retrofitted, plus simplified room-in-roof geometry and fabric heat loss in the default RdSAP model, which is used for EPCs. This results in a substantial overestimation of heat losses, and therefore erroneously suggests the room-in-roof retrofit would significantly reduce heat losses, such that the home may achieve an EPC band C rating post-retrofit.

Secondly, when the simplifications are overruled by inputting the measured U-values, it results in an underestimation of the heat loss in RdSAP, thereby making the home appear to have lower plane element and linear thermal bridging heat losses, to the extent that it is predicted to have an EPC band C, even pre-retrofit.

According to the BREDEM and DSM models, which do not have these room-in-roof issues, the room-in-roof and airtightness retrofits improve the home’s EPC, though not enough to achieve an EPC band C in this case study. The predicted percentage savings are similar but absolute savings are not, which has implications for payback calculations.

Additionally, the retrofits reduce space heating requirements, but again the reductions are not sufficient to achieve the SHDF target.

Similarly, the home’s CO_2 emission predictions are reduced by the retrofits, but not on a scale which is meaningful for supporting net zero carbon ambitions.

Generally speaking, heat demand outputs from DSM models result in consistently lower EPC ratings and carbon emissions because of differences in the way they are calculated and how they account for gains compared to steady-state models.

3.6 Overheating risk of retrofitting

As part of the overall DEEP project, Loughborough University carried out parametric analysis of overheating scenarios, using a 10-year weather data file. The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited in the PAS2035 guidance [8].

Two metrics are used to assess whether a dwelling overheats. Criteria A of TM59 is taken from another CIBSE publication, TM52: The limits of thermal comfort: avoiding overheating in European buildings [9]. The two assessment criteria are defined as follows:

A. For living rooms, kitchens and bedrooms: the number of hours during which ΔT (difference between the operative and comfort threshold temperature) is greater than or equal to one degree (K) during the period May to September inclusive, shall not be more than 3 % of occupied hours.

B. For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1 % of annual hours (note: 1 % of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours).

Overheating assessment was carried out at each stage of the retrofit. Following the TM59 guidance, the initial assessment was completed using the CIBSE Design Summer Year 1 (DSY1) file for a 2020s high emission scenario at the 50th percentile, for Leeds in this instance. There are three DSY files available for the 14 UK regional locations, which use actual year weather data that simulate different heatwave intensities. DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 represents a longer, less intense warm spell [10]. Assessment was also carried out for future weather scenarios, using the DSY1 files for the 2050s and 2080s high emission scenarios at the 50th percentile.

In the context of the DEEP project as a whole, a large proportion of the windows in 19BA can be opened to provide natural ventilation, this is helped by a relatively large stairwell that provides a ventilation path up through the house to all floors. It is important to note that the airtightness of 19BA is very poor which adds to overall air change. The percentage of openable area for each window is shown in Figure 3-44.

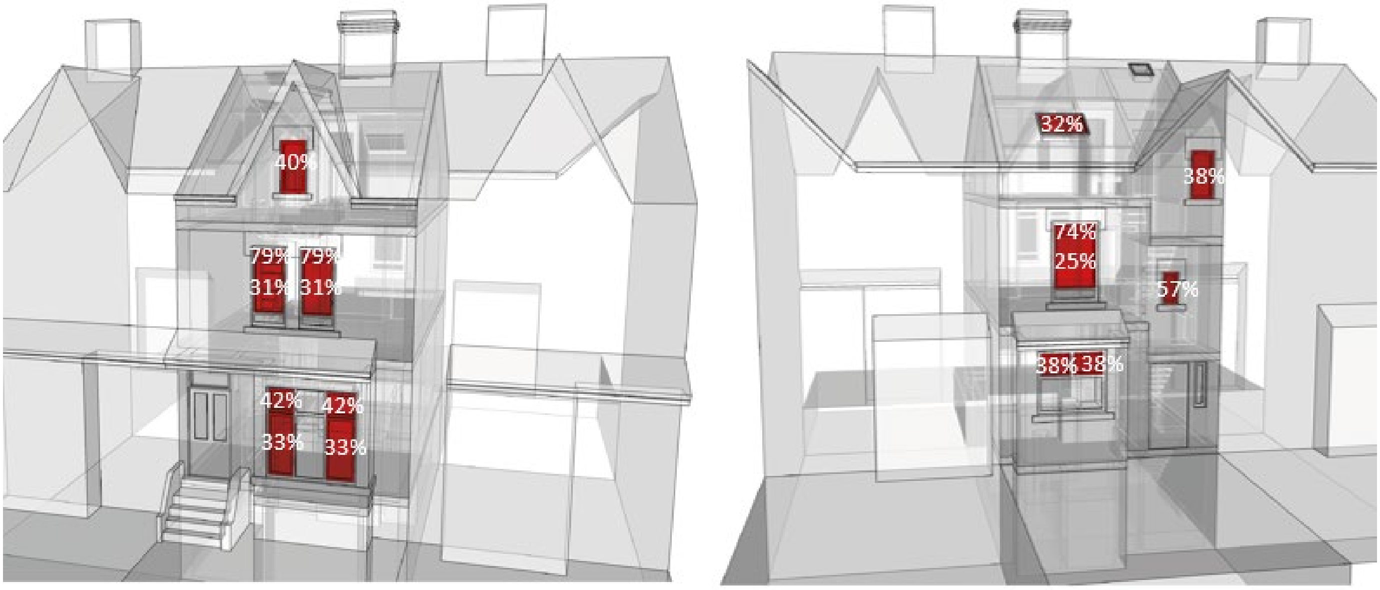


Figure 3-44 Percentage of opening area for openable windows

The large proportion of opening windows, internal ventilation paths and protection from solar exposure by neighbouring dwellings, all lead to relatively low estimated overheating when evaluated under the TM59 methodology. This is illustrated in Figure 3-45, with the results emphasising the impact of solar heat transfer through the poorly insulated roof structures that are connected to Bedrooms 3 and 4. The room-in-roof retrofit measures help reduce this overheating risk to below the Criteria A threshold, even in future climate scenarios.

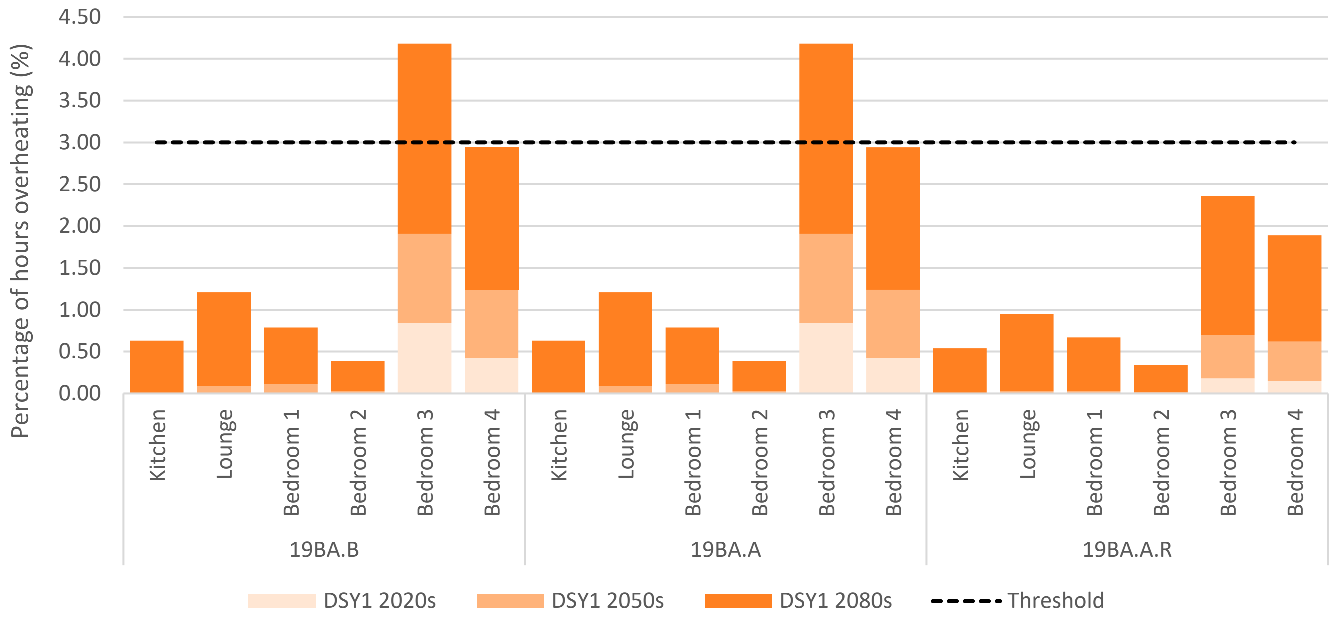


Figure 3-45 Modelled overheating under TM59 Criteria A

The overheating risk increases under Criteria B for all the bedrooms (Figure 3-46), although those on the first floor are at much lower risk. It is only under the 2080s climate scenario that they exceed the Criteria B threshold. The bedrooms in the roof on the second floor are most susceptible to overheating due to heat exchange through opaque elements. This does improve after the room-in-roof retrofit, but only under the current (2020s) climate scenario.

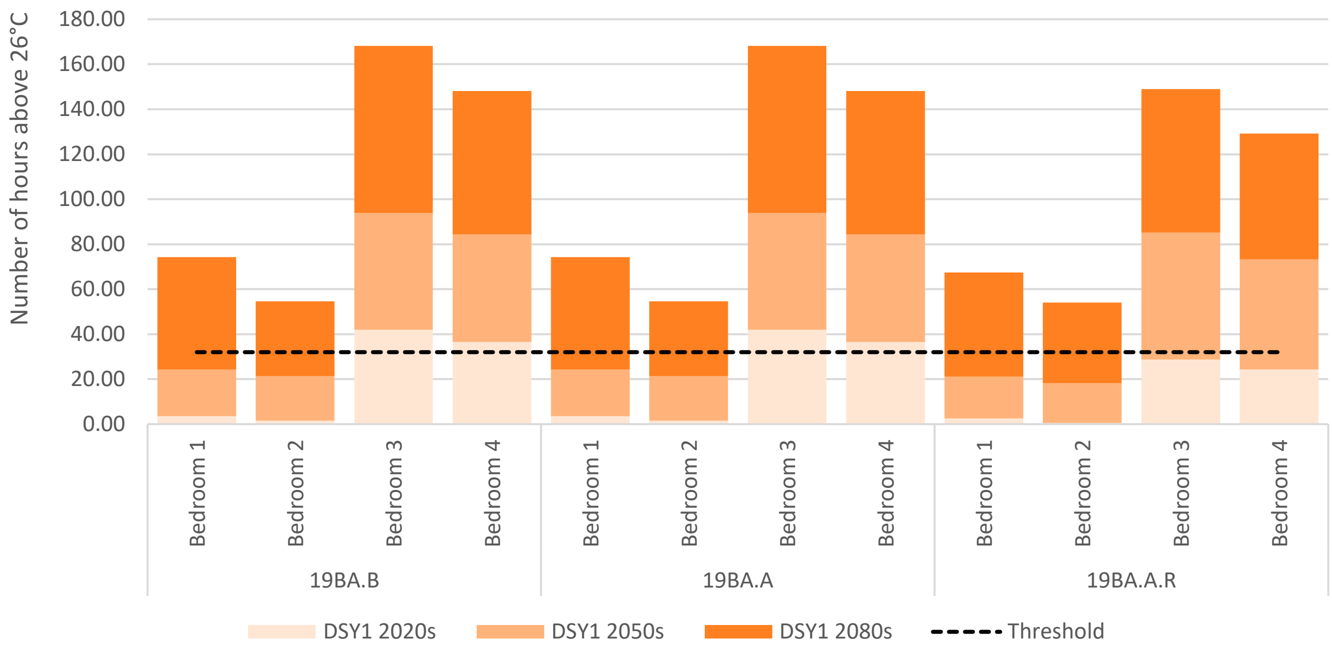
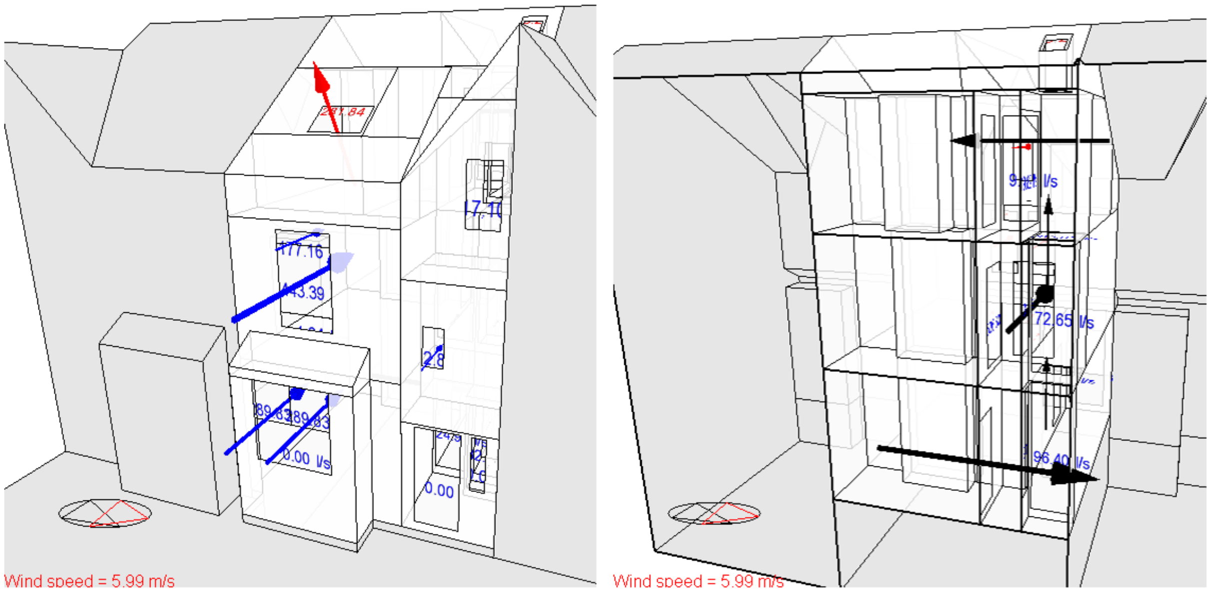
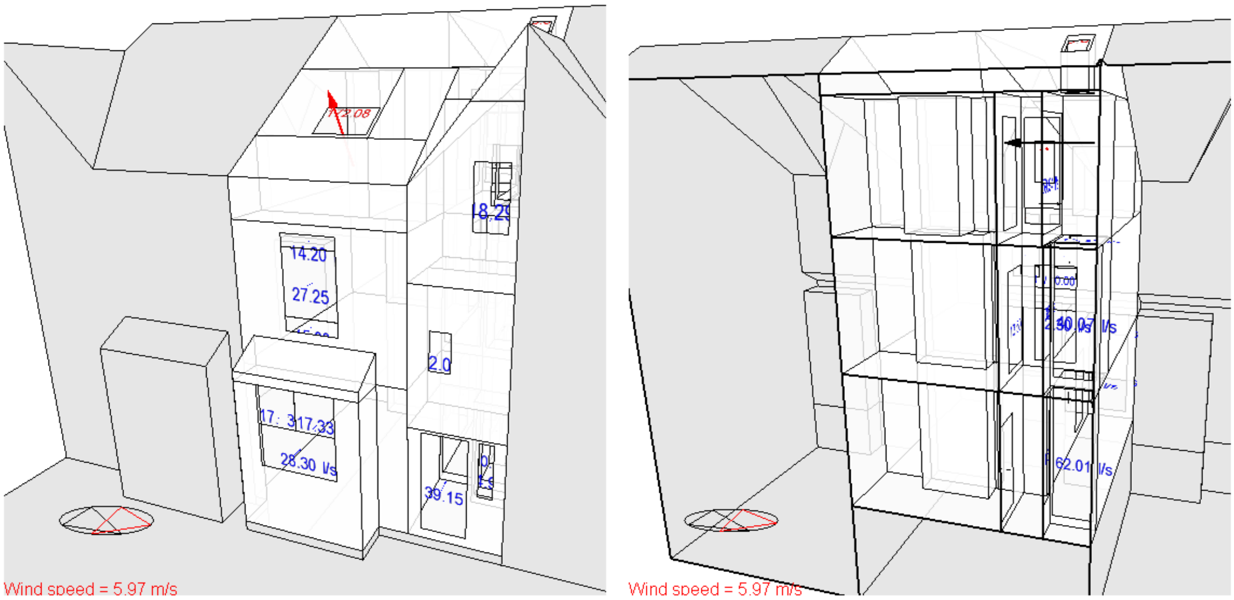


Figure 3-46 Modelled overheating under TM59 Criteria B

The main reason for increased overheating risk in the bedrooms is that the internal doors are specified as closed during the night which limits natural air flow routes during these times. The section cut images in Figure 3-47 illustrate this. Blue arrows represent air entering the building, red arrows represent air leaving and black arrows represent air moving from one internal space to another. In the first pair of images, for 20:00 on June 25th, air moves up and through the dwelling while the internal doors are open. The second pair of images shows greatly reduced airflow later that night, at 01:00 on June 26th, when all internal bedroom doors are set to be closed. The wind speed is almost identical in both instances.



(a) Airflow through dwelling at 20:00 on June 25th



(b) Airflow through dwelling at 01:00 on June 26th

Figure 3-47 Natural ventilation airflow paths with internal doors open and closed

Overheating risk of retrofit summary

In 19BA, the room-in-roof retrofit does help reduce the overheating risk in all spaces under Criteria A, but this is significantly more pronounced for the bedrooms that are in the room-in-roof on the second floor of the dwelling. This reduced risk is achieved by mitigating heat transfer through the opaque building elements in that area. It is important to reiterate that no window shading devices are included in these models, and the case studies represent a worst-case scenario. It is beyond the scope of this work to explore mitigation measures.

Overall, the overheating risk in 19BA is relatively low compared to the other houses in the DEEP project, due to shading from the two large party wall areas, a large proportion of openable windows and clear natural ventilation airflow paths from the front to the back of the building and up through the stairwell.

3.7 Retrofit costs and payback

This section looks at the costs of undertaking the retrofit described in this case study. However, as this is only a single case study it should not be used to generalise the costs of retrofits nationally. Undertaking work in existing homes can have tremendously variable costs, depending on the specification of the work as well as the condition of the house prior to the retrofit.

The cost data presented here may not be representative of the national retrofit market, since retrofits tend to be labour intensive and there are variations across the country based on regional differences in construction labour markets. The data discussed here originate from a single contractor in the North of England and relate to only one house type and a limited range of retrofit specifications. Decoration costs are excluded from the costs reported here, since landlords undertake their own decent homes repairs following the retrofits and take on some of the decoration work. Although costs associated with decorating are outside the scope of this project, they have been found to represent around 14 % of the cost of internal wall insulation.

The costs of the 19BA retrofits are outlined in Table 3-6 and Table 3-7. As discussed in Section 3.3, substantial additional work was needed, which appears to have increased installation costs by over 45 %. Most of these extra costs were incurred during the room-in-roof retrofit. Removing the existing fabric to make way for insulation caused substantial disruption, clearance costs and extra plumbing costs, and revealed the need for additional fabric repairs which were not identified at the beginning of the retrofit. This illustrates the risk to retrofit budgeting of requiring additional remedial work to repair faults, which may be a barrier to the uptake of retrofits at scale.

Table 3-6 Cost of retrofits

Retrofit	i) Retrofit activity	Retrofit costs	ii) Additional enabling work required	Enabling work costs
19BA.A Airtightness	Seal around ground and intermediate floor, trickle vents, extract vents and penetrations. Remove and replace boxed-in areas in bathrooms and WCs. Draught strip windows and doors.	£2,290	Add door furniture to cellar door. Patch damaged plaster. Repoint damaged brick work.	£529
19BA.A.R Room-in-roof	Install wood fibre boards to sloping ceilings and knee walls. Install mineral wool to flat ceilings. Replaster all surfaces. Install new skirting boards.	£11,000	Install new Velux. Rebuild brick work to party wall. Replace damaged floorboards. Replace central heating and hot water pipe work and radiators.	£5,600
Total		**£13,290**		**£6,129**

Other costs were incurred because the existing fabric needed adapting prior to the installation, i.e., the roof timbers were not deep enough to support the thick insulation. These additional costs may not always be present in homes having room-in-roof retrofits, but it is important to consider that it is not possible to predict the extent of these additional costs prior to the retrofit budget being decided. This risk must be accepted by the householder, the financing organisation or the installer themselves.

The cost of the airtightness retrofit is interesting, since, although the materials required were relatively low cost (silicon, draught strips and timber for boxing in pipework), the labour costs were substantial. Several workers took several days to install all the measures. There may be limited scope for reducing the cost effectiveness of airtightness retrofits, since they are labour intensive. Despite this, they were more cost effective than the room-in-roof retrofit at reducing heat losses (W/K), as shown in Table 3-7.

Table 3-7 Breakdown of the costs of the retrofits

Retrofit	Cost	Proportion of total cost	Treated area (m^2)	Cost per area (£/m^2)	Cost per W/K reduction
19BA.A Airtightness	£2,819	15 %	132	£21	£470
19BA.A.R Room-in-roof	£16,000	85 %	63	£248	£1,383
Total	**£19,419**				

3.7.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown in Figure 3-48, based on SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These values do not reflect current fuel prices and are shown only for illustration.

The default RdSAP model predicts the highest annual fuel bill, since it assumes much higher heat losses from the room-in-roof.

- When the RdSAP prediction includes the measured U-values, HTC drops significantly, as not only were the measured U-values lower than the defaults, but the heat loss area is also assumed to be 22 m² less than the other models.
- The airtightness retrofit is thought to reduce fuel bills by around 3 % to 4 %, while the room-in-roof retrofit is predicted to be more successful saving 4 % to 9 % by models other than the EPC, which predicts a 21 % saving. This highlights the risk that EPC may predict much greater savings for room-in-roof retrofits than are achieved in practice if they use the simplified approach.
- Models using the RdSAP default inputs do not consider any reductions relating to the airtightness retrofit, regardless of which model is used.

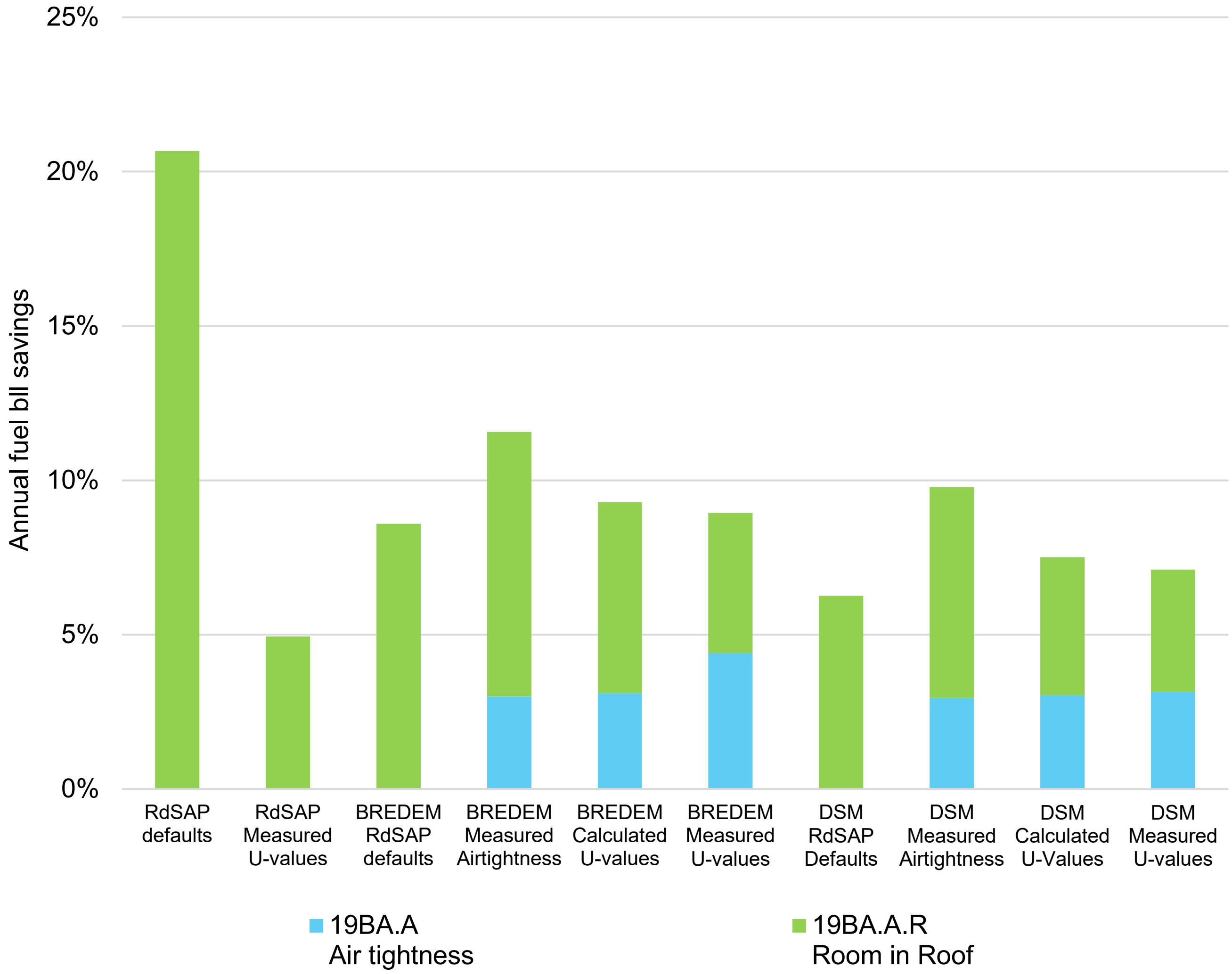


Figure 3-48 Predicted annual fuel bill savings achieved by the retrofits

3.7.2 Predicting simple payback of retrofits

The simple payback time (i.e., not considering fuel price inflation or discount rates) calculated from the retrofit costs and annual fuel bill saving estimates for this case study are shown in Figure 3-49. Recent fuel and retrofit price increases will significantly affect payback rates.

- Neither retrofit appears to be cost effective, with payback times ranging between 61 and 438 years depending on which model assumptions are selected.
- There are no predicted savings for the airtightness retrofit for models that use the RdSAP default inputs, since these do not predict any savings.
- Where models consider changes in infiltration rates, the airtightness retrofit is more cost effective as it is a fraction of the cost, and only slightly less effective than the room-in-roof retrofit. This suggests that airtightness retrofits, despite their complexity and only partial success, may still be cost competitive with other fabric retrofits.
- The additional remedial work involved in the retrofit was substantial, however the payback times without these additions would still be over 100 years.
- DSM predicts longer payback rates, since it assumes a lower space heating demand in the homes pre- and post-retrofit.

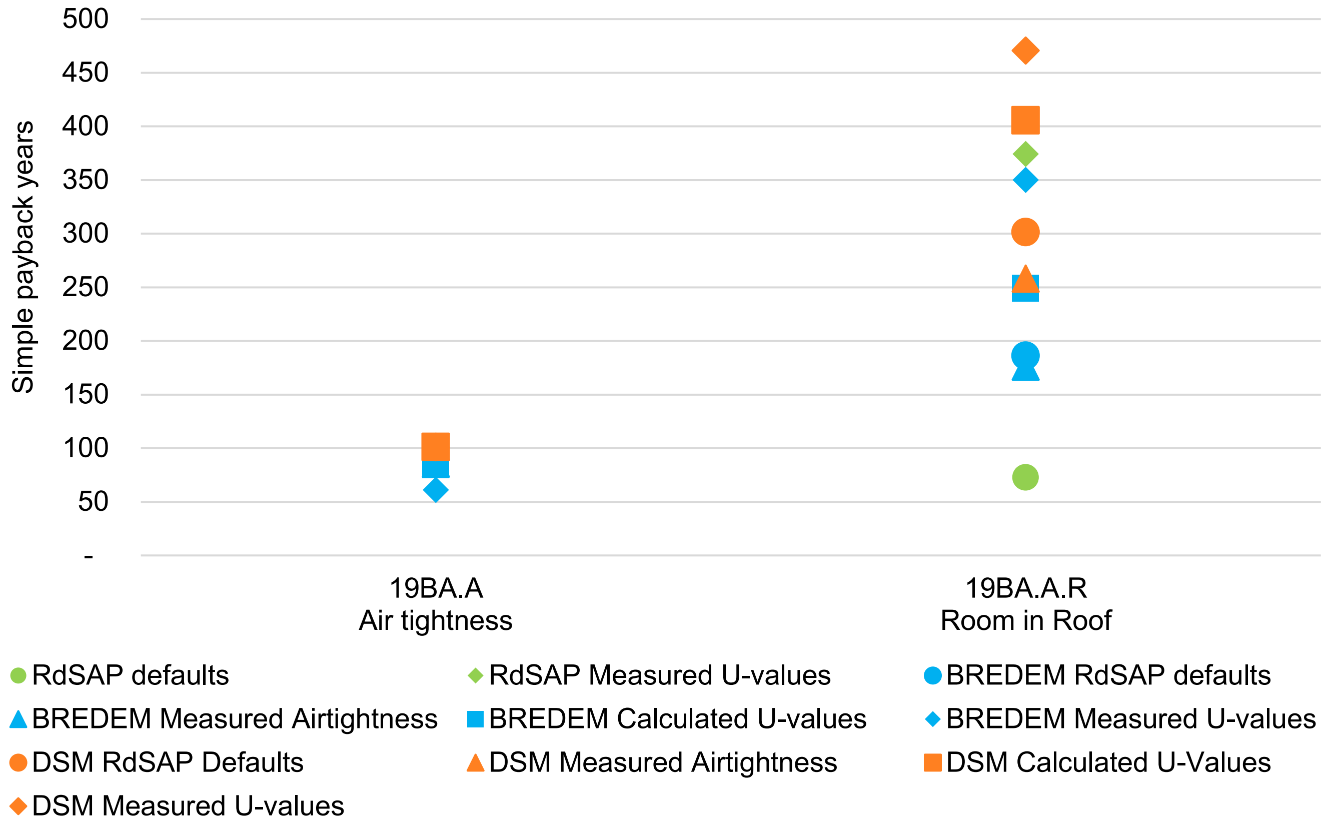


Figure 3-49 Simple retrofit paybacks

Retrofit costs summary

The installation costs shown are relatively unrepresentative of a standard retrofit and, as discussed, the fuel bill savings are only provided for illustration as they are based on the price assumptions in SAP 2012, which are out-of-date at the time of publication of this report. However, some useful interpretations remain.

The retrofit costs in this case study may be higher than other homes, since remedial and repair work was needed. The annual fuel bill reduction estimates suggest that neither retrofit achieved paybacks of less than than 60 years, and some were over 400 years, though the airtightness improvements were generally more cost effective than the room-in-roof retrofit.

The exception is the RdSAP default model, which substantially overpredicts heat losses from the uninsulated room-in-roof, and therefore predicts large savings when it is insulated. This gives the appearance that the retrofit is relatively cost effective and achieves high fuel bill savings (£228). However, this merely describes the consequence of the unrealistic input assumptions in the baseline model. This sort of inconsistency has significant implications for policy or finance mechanisms that rely on the accuracy of fuel bill savings predicted by EPCs.

4 Conclusions

This case study has identified important findings about the performance and risks associated with retrofitting solid walled homes, and investigated the models used to predict performance and risk. The main issues are discussed below.

Infiltration heat losses and EPCs
The case study home had exceptionally high air leakage. The initial infiltration rate of 23.8 $m^3/(h \cdot m^2)$ @ 50Pa is almost three times the maximum allowable rate for new build homes. This infiltration rate, if not addressed, would undermine the performance of other fabric retrofits to some degree. EPCs for existing homes currently do not support alterations to the assumed air leakage, and thus are not able to predict or capture the benefits achieved from airtightness retrofits, even though BREDEM and DSM predict they were responsible for around a third of the cumulative retrofit whole house heat loss reductions. This case study highlights that, for some homes, excessive rates of air leakage result in background ventilation heat loss. However, currently, no policy mechanism to directly incentivise airtightness improvements exists.

Inadequacy of the n/20 rule of thumb
The closing-the-loop evaluation undertaken suggests that the heat loss associated with air leakage in this home made up around 30 % of whole house heat losses, over 120 W/K. There was a particularly large volume of air leakage, substantially more than observed in other DEEP case study homes where infiltration was responsible for around 10 % to 20 % of HTC. It is probable, therefore, that the n/20 rule of thumb is not appropriate for homes similar to this case study with high levels of air leakage. This case study home also has a large area of party wall which may affect its suitability for this conversion factor.

Longevity of airtightness improvements
In the case study the airtightness retrofit initially reduced infiltration from 23.8 to 18.8 $m^3/(h \cdot m^2)$ @ 50Pa, and similarly the room-in-roof retrofit reduced airtightness from 20.6 to 16.8 $m^3/(h \cdot m^2)$ @ 50Pa. However, in both instances the accelerated drying that took place during the coheating test resulted in the airtightness increasing back to around 20 $m^3/(h \cdot m^2)$ @ 50Pa due to substantial shrinking and cracking of newly applied silicon seals and plaster. This shrinkage may naturally take place over many years and indicates that sealing up cracks and gaps in homes may be successful, but can perhaps only be considered a temporary improvement.

Room-in-roof retrofit modelling assumptions
The simplification applied to the room-in-roof geometry and fabric performance in RdSAP resulted in a very large overestimate of heat losses, making the HTC for the RdSAP baseline home 460 W/K, while the estimate in BREDEM, which does not apply this simplification, was 387 W/K. This phenomenon results in the room-in-roof retrofit appearing to be much more effective than it was measured to be, reducing HTC by a predicted 30 % compared to a measured (5 ± 5) %.

Unknown levels of insulation in homes
Removal of the room-in-roof fabric to allow the installation of the planned insulation revealed some pre-existing phenolic foam insulation installed on parts of the sloping roof. Thus, the potential improvement that could be made in this case study was less than had there been no insulation. The degree to which undocumented fabric improvements persist in the housing stock will impact the potential success of retrofits.

Uninsulated solid walls dominate heat loss even after other elements are retrofitted
Reducing the room-in-roof and infiltration heat losses in the home achieved only a marginal reduction in HTC of (7 ± 5) %, and was not successful in bringing the house up to EPC band C, nor did it achieve the SHDF target heat loss. The main reason for this was that almost two thirds of the home's heat losses were due to fabric heat loss and over half was via the uninsulated solid walls. This highlights the importance of insulating solid walled homes.

Fabric performance gaps
The insulation added to the room-in-roof was measured as reducing the U-values by between 35 % and 50 % on the sloping roofs and knee and dormer walls. However, these reductions were generally smaller than the BRE calculator suggested, and a performance gap was observed for the loft which only reduced U-values by 20 %. The reasons for the performance gaps are not known, but in the case of the loft may have been access restrictions limiting the ability to install the mineral wool effectively. The exception was the sloping ceiling, which performed better than predicted, indicating there may have been some underperformance from the incumbent insulation on this element. These findings highlight that stated performance cannot always be measured, even where there are no clear deviations from installation best practice. This could be due to inconsistencies in the installation or products, or uncertainty in the measurement techniques.

Adding measured data to models might not always improve accuracy
The modelling investigations in this report show that the infiltration rate in the home was underestimated by the model but the fabric heat losses were overestimated. These two confounding positions had the effect of cancelling out the changes which resulted from adding in the measured data, i.e., the initial default predictions were broadly similar to the calibrated predictions, but for the wrong reasons. Hence, it is uncertain that more accurate predictions can be achieved by including measured data in models.

Overheating is reduced by room-in-roof retrofits
Solar gain through both transparent and opaque elements is the main cause of overheating. Since 19BA is a terraced property it is relatively shaded. The base case therefore has lower overheating risk than homes with more exposed surfaces. Having said this, the room-in-roof bedrooms were anticipated to be at risk of overheating. Retrofitting the room-in-roof reduced the potential for solar penetration and the retrofit successfully removed the overheating risk in the bedrooms according to TM59 Criteria A, and reduced the risk according to Criteria B. The airtightness retrofits had very little effect on overheating since the air leakage was so large pre- and post-retrofit, and therefore the difference was marginal.

Additional costs incurred during retrofits
The total costs for the retrofit increased by over 45 % from £13,290 to £19,419, mainly due to the repairs which were needed to the fabric of the building, which were only uncovered once the destructive room-in-roof retrofit began, such as rebuilding the party wall behind the knee wall, increasing the depth of the roof timbers and relocating existing plumbing. This is a substantial financial risk for retrofits, though it is not clear how this risk is normally shared between the funder, consumer and installer.

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