A RETROFIT OF A VICTORIAN TERRACE HOUSE IN NEW BOLSOVER: A WHOLE HOUSE THERMAL PERFORMANCE ASSESSMENT

Historic England

RESEARCH REPORT

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A RETROFIT OF A VICTORIAN TERRACE HOUSE IN NEW BOLSOVER:

A WHOLE HOUSE THERMAL PERFORMANCE ASSESSMENT

EXECUTIVE SUMMARY

Soki Rhee-Duverne and Dr. Paul Baker

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Glasgow Caledonian University

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USEFUL DEFINITIONS

Air permeability

Air permeability refers to the uncontrolled loss of air from the inside to the outside of a building and the air infiltration travelling from outside to inside. This loss or gain of air through cracks, holes or gaps in the fabric is often described as draughts. Achieving a good level of air tightness is important for the energy efficiency of the building as the benefits of improved insulation and more energy efficient heating systems are lost if warm air can leak out of the building and cold air can leak in.

Air pressurisation test

An air pressurisation test measures the air permeability of a building envelope. It is quantified by measuring the rate of airflow through a blower door/fan to create a pressure difference between the inside and outside the building. The test is usually carried out over a range of pressure differences (e.g. 10 to 70 Pa) and the airflow at 50Pa calculated. The blower door/fan is mounted to a temporary airtight screen fitted to the entrance door with all vents sealed or closed. It is then operated to blow air in or out of the dwelling to create a pressure difference of 50 Pa.

Co-heating test

The co-heating test is method to determine a dwelling's heat loss coefficient (HLC) in Watts/Kelvin. The HLC is calculated by measuring the daily heat input in Watts obtained by recording the electrical energy required to maintain a steady temperature of approximate 25°C. The daily heat input is then plotted against the daily difference in temperature between the inside and the outside of the building to determine the heat loss coefficient. In order to obtain a sufficient temperature difference, the coheating test is usually carried out during the winter months. Once the data has been collected, it is then adjusted to compensate for solar gains.

Heat loss

Heat loss (often described as fabric heat loss) from a house results from a combination of conduction, convection and radiation through the dwelling's walls, floors and roofs (fabric heat loss) and via air leakage through the gaps and joints (otherwise known as background ventilation heat loss).

Hygrothermal modelling

Hygrothermal modelling determines the movement of heat and moisture through buildings. It is often used to predict the hygrothermal performance of buildings to prevent the degradation of the building fabric particularly after the application of insulation systems.

Low-emissivity glazing

Low-e glazing has a specially designed coating applied to the surface of the glass to improve its thermal efficiency. The coatings reflect radiant infrared energy, helping to retain radiant heat on the side of the glass where it originated, while letting visible light pass. This results in more efficient windows because radiant heat originating from indoors in winter is reflected back inside.

Standard Assessment Procedure

The Standard Assessment Procedure (SAP) is the Government's method of evaluating the energy efficiency of homes. It has been used since 1993. SAP rates homes based on the annual energy costs for space heating, water heating, ventilation and lighting under standardised conditions. It uses a scale of 1-100, the higher the rating, the better the energy efficiency and lower the annual energy costs. SAP also provides an energy consumption per unit floor area metric and produces an estimate of annual carbon emissions.

1. CONTEXT

1.1 BACKGROUND

Energy consumption in the UK domestic building stock of 26.5 million properties uses around 30% of total UK energy consumption. This is a rise of 23% over the last 35 years and is responsible for generating around 40 million tonnes of carbon emissions per year.[i] The Department of Environment and Climate Change (DECC) estimates that of the 7.8 million solid walled houses in the UK, 98% have minimum or possibly no insulation.[ii] Of these, it is estimated that there is potential to install solid wall insulation in around 6.9 million houses.[iii] The Sustainable Development Commission (SDC 2006) estimates that 70% of the current UK domestic building stock will still be in use come 2050,[iv] by which date the UK Government has committed to reducing greenhouse gas emissions by 80%, based on a 1990 benchmark. This goal is colloquially known as the 'C80' target.[v]

1.2 PRESSURES ON TRADITIONAL BUILDINGS

The drive to improve the energy performance of existing dwellings is a key action in meeting the Government's commitments to reduce carbon emissions, maintain fuel security, lower domestic fuel bills and tackle fuel poverty. It also represents one of the greatest demands for change in the historic built environment today. Furthermore, these pressures have led to opinion that the traditional housing stock should perhaps be demolished and replaced with new low-carbon dwellings,[vi] reinforcing existing assumptions that older buildings with solid walls are inherently energy inefficient and that they will require substantial adaptation to meet acceptable standards of energy performance. Combined with significant tightening in Building Regulations and Government initiatives, such as the Green Deal, greater demands are being placed on traditional buildings. There are pressures to both adapt and to provide evidence to identify and validate the actual benefits – in terms of financial and carbon savings – of sympathetic retrofit improvements for traditional buildings.

1.3 BEHAVIOUR OF TRADITIONAL BUILDINGS

In many respects traditional buildings are models of sustainable development. Traditional buildings have solid masonry walls and are constructed from hygroscopic materials. They respond differently to modern buildings to environmental changes, particularly to heat and moisture. The materials are often locally sourced and are durable in comparison to the energy used to produce them. If modern retrofit technologies are misapplied without fully understanding the behaviour of traditional constructions, these interventions could potentially be detrimental to the health of the building and its occupants.

1.4 PERFORMANCE OF TRADITIONAL BUILDINGS

Available data suggest that actual energy use in traditional buildings is often less than predicted, and that there can be wide discrepancies between the measured energy performance and assessments made using simulation models. There are likely to be many reasons for this; for example, some traditional buildings have better levels of insulation and are more airtight than assumed, while their thermal mass may also help to improve thermal stability. In addition, levels of energy use associated with occupant behaviour may be lower than assumed in these models, such as in SAP (Standard Assessment Procedure) and RdSAP (Reduced data Standard Assessment Procedure), used as the basis for Energy Performance Certificates by the UK Government. In consequence, energy efficiency measures may not provide the savings predicted, and the UK Government's targets for greenhouse gas reduction may not be met.

1.5 MEASURING AND MONITORING PERFORMANCE

Obtaining measured energy and thermal performance data for traditional dwellings is important as it allows assumptions to be tested, predictions based on calculation to be validated, and more appropriately, effective and cost efficient energy-saving improvements to be devised. Comparatively little measured data exist on the thermal performance of the building envelope of traditional dwellings before and after the installation of energy efficient measures. Recent initiatives have focussed on a target-led approach to achieve a specified level of carbon reduction which is generally inappropriate for traditional buildings and may lead to damage to the original fabric.[vii] Studies have also investigated the performance of specific elements, such as traditional windows and solid walls.[viii] If our understanding of the behaviour of traditional buildings is to improve, it is critical that testing of fabric improvements is undertaken, and the analysis of the results are fed back in order to carry out improvements in a sympathetic manner. Measurement and long term monitoring of performance will also crucially allow a considered assessment of risk from moisture accumulation as a consequence of fabric improvements.

2. INTRODUCTION TO NEW BOLSOVER MODEL VILLAGE

New Bolsover Model Village was built by Bolsover Colliery Company in 1891 on the outskirts of Bolsover, Derbyshire, to accommodate their workforce at the nearby Bolsover Colliery. The design of the Model Village was influenced by the emerging garden city movement and represents an early application of its vision. It was the first of a series of model mining villages developed by the Company. At New Bolsover, double terraces of brick houses were built on three sides of a large, square 'village green' which served as a playground for children, as well as providing ample areas for shrubberies and flowerbeds. The school, which also served as a village hall, was on the fourth side of the square. As well as the 194 colliery workers' houses and the school (unfortunately now demolished), there were 12 villa properties for the colliery officials and administrative staff, a co-operative store, a Miners' Welfare, a Methodist Church (also now demolished), an orphanage, along with allotments and space for cricket, bowls, tennis and football.

Today around a two-thirds of the houses are owned by Bolsover District Council which are leased as social housing; the remainder are owner occupied. The terraces, which are made up of two and three storey houses, with slate roofs and solid brick walls, still largely retain their intended architectural uniformity. However, their significance has been diminished by the replacement of most original windows and doors. New Bolsover is within the Bolsover Conservation Area and is Grade II listed.

In 2011 the opportunity arose for Historic England to lease for a year a vacant end of terrace house in New Bolsover from the District Council. The house is typical of many traditional English dwellings in both form and construction. It therefore provided an ideal subject for investigation. The Council also agreed to the implementation of a package of measures to improve the thermal performance of the building envelope. Taking into account the building's listed status, an additional requirement for these energy-saving improvements was to preserve and, where possible, enhance the heritage significance of the house. This led to the decision to restore single glazed windows and panelled external doors, to match the original designs, with compensatory energy-saving measures.

3. PROJECT SUMMARY

Historic England undertook the refurbishment of an unoccupied Victorian end-of-terrace house to measure the actual improvement in thermal performance and air tightness of the building envelope before and after retrofit. The principal goals of the project were to facilitate informed decisions on improving the thermal and energy efficiency of traditionally constructed buildings; to better understand the energy use in traditionally constructed buildings and also the potential benefits and impacts of different kinds of adaptation to reduce that energy use, including technical risks due to moisture.

The measures installed were internal wall insulation, additional loft insulation, under floor insulation and minor improvements to the services with the addition of thermostatic radiator valves and re-fitting of the insulation jacket on the hot water cylinder. In addition, due to the heritage status of the building, the plastic coated aluminium windows were replaced with single glazed timber windows following the original design for Bolsover Village. Secondary glazing was installed to the windows to improve their thermal performance. Analysis of the energy performance of the house was carried out using the measured data as input into a SAP model allowing a comparison of the building's energy performance before and after refurbishment.

In conjunction with the fabric improvements, monitoring was installed to assess the impact of the internal wall insulation and the risks associated with moisture accumulation in the walls. The assumption being that insulation may affect the interstitial temperature and vapour permeability of the building envelope leading to a build-up of moisture and damage to the building fabric. Permeable and impermeable internal wall insulation systems were installed to enable a comparative assessment of their technical risk. Sensors were installed at the interface of the cold face of the insulation and the masonry as hygrothermal modelling indicated that the greatest risk of condensation could occur at this location.

The research report presents the findings of this fieldwork carried out by Historic England, in collaboration with Dr. Paul Baker from Glasgow Caledonian University. The report comprises of the whole-house thermal performance tests and energy analysis before and after fabric improvements. Interim results of the data collected from the post-intervention monitoring of the two internal wall insulation systems will be published at the end of 2015 and the final report from the monitoring will be released in 2018.

3.1 PROJECT OUTPUTS

The principal outputs of the project were to:

- To determine the improvement in thermal performance of the building envelope before and after installation of energy efficiency measures through a co-heating test;
- To determine the contribution made by the each building element to the total fabric heat loss by *in-situ* U-value measurements;
- To quantify the effectiveness of the measures in terms of energy and carbon, both individually and in combination by use of the SAP model;
- To assess the cost efficiency of the improvements by calculating energy savings and the payback periods;
- To assess the long term moisture risks associated with internal wall insulation by comparing a permeable and an impermeable system;
- To compare measured performance with predictions based on standard assessment models.

4. CONDITION SURVEY OF THE HOUSE

The dwelling is a two-storey, three bedroom end-of-terrace house originally constructed in the 1891 which had been upgraded during the 20th century with the addition of a modern bathroom at the rear of the house. The house sits on high ground on an east-west axis. The front of the house (the east elevation) is semi-shaded and the south gable wall is the most shaded from the sun and exposed to the south-westerly driving rain. The rear west wall has the greatest exposure and receives substantial solar gain during the afternoons. Typical of some houses of this type, the rear is facing the street and the back door is used as its main entrance.

Figure 1: Front elevation, before refurbishment

Figure 2: Rear elevation, before refurbishment

Initial fabric and damp surveys of the house were conducted at the commencement of the lease and floor plans of the dwelling were measured up. A summary of the details recorded are given below.

4.1 EXTERNAL

The property was constructed of solid masonry walls in a Flemish bond with a red dense, clay brick. The brickwork was largely undamaged and in good condition, however the pointing generally required renewal. The original mortar was a lime ash, which lay beneath a poorly executed cement mortar repointing. The latter was failing in some areas, see Fig. 3.

Figure 3: Deteriorated mortar joints

Most of the perpends were open along the lowest course of brickwork. In particular, the top half of the gable wall had been extremely poorly re-pointed in cement in recent years. Dense mortar pointing is likely to have a detrimental effect on the brickwork in the future, and this was recommended for removal if damage to the brick could be avoided.

A narrow small cavity in the wall was noticeable on removable of one of the bricks however it was not possible to determine whether this was as a result of natural deterioration, poor workmanship or part of the original design, see Fig. 4.

Figure 4: Small cavity in the wall

Figure 5: Removal of the door frame revealing a cavity in the wall

A further investigation during the renovation indicated that the cavity could be more widespread, see Fig. 5.

The house has a slate tiled roof with terracotta ridge tiles with some failure of the mortar bedding. The plastic rainwater goods have cracked in places and require replacement.

Vegetation at the base of the walls suggests that rainwater, which has accumulated in these areas, has saturated the brickwork. The east wall has been laid with a plastic membrane and gravel allowing water ingress at the base of the wall but preventing trapped moisture escaping. A short period of damp monitoring of the subfloor space undertaken prior to the refurbishment works suggests that there has been water penetration in recent years due to the high ground levels, the laid polythene sheet and open joints, see Figs. 6 & 7.

Figure 6: Illustration of sub-floor space

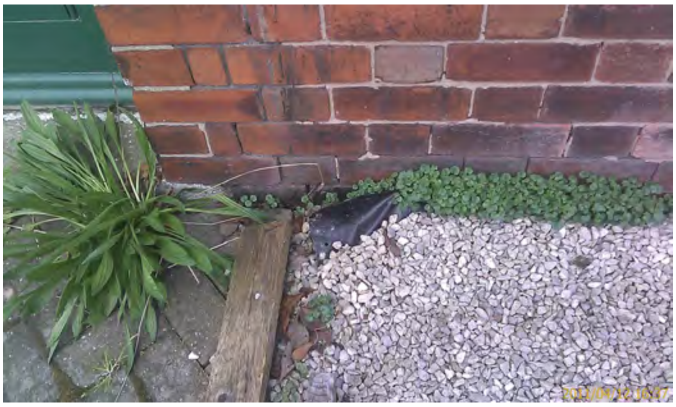


Figure 7: Vegetation at the base of the front elevation

Ground levels at the rear west wall of the building were nearly at internal floor level and a damp proof course had been injected into headers at the wall base. Paving slabs were irregularly laid and channelled water towards open joints in the wall, see Fig. 8. A sample taken from the lower west wall during the damp survey indicated high moisture content due to the high ground level and the drainage problems. However, this was the only damp sample suggesting the house did not at the time exhibit general problems with moisture.

Figure 8: Irregularly laid paving slabs at the rear of the house channelling water to base of the rear elevation

4.2 INTERNAL

The ground floor of the dwelling has a timber suspended floor in the front and a solid concrete floor in the rear of the house. The suspended timber floor has a void of approximately 380mm beneath. Boards ran in an east-west direction and the joists ran in a north-south axis, spaced at approximately 440 cm^3. The floor rests on a brick honeycomb wall. There was evidence from a change in colour that the boards on the east side of the room have been damp in the past. However the brief period of monitoring of the sub-floor void, prior to the refurbishment works, confirmed that moisture levels were now acceptable.

The main loft had insulation laid between the ceiling joists but it had been poorly and unevenly installed. A subsequent survey with an infrared camera during the co-heating test illustrated the patchiness of the insulation, see Fig. 9. There were no apparent signs of damp or decay in the roof space.

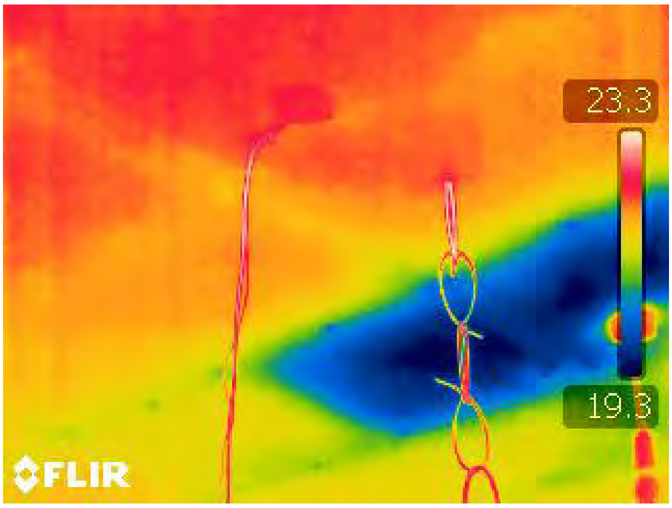


Figure 9: Infrared photo of the ceiling in the main bedroom

The original timber single glazed windows had been removed during the 1980s and had been replaced with plastic coated aluminium windows: double-glazed casement windows on the front elevation and single-glazed sash windows to the rear, see Figs. 10-13.

Figure 10: Original timber casement window on a neighbouring house

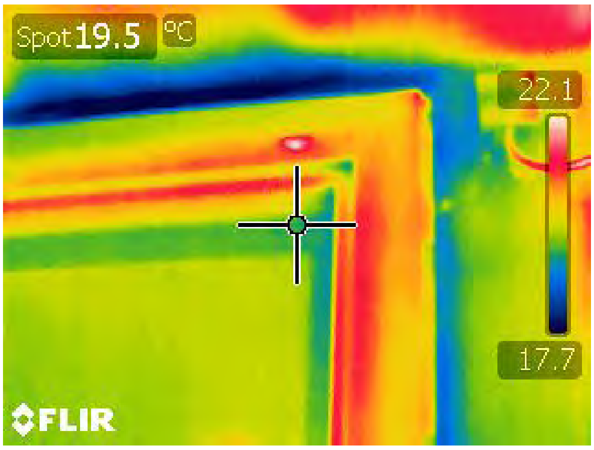
Figure 11: Original timber sash window

Figure 12: Plastic coated double glazed aluminium window on the front elevation

Figure 13: Plastic coated single glazed aluminium window on the rear elevation

The windows were in poor condition and were not wind and water-tight. The mastic sealant used to seal window frames had deteriorated and it had become brittle and had cracked over time. Infrared images indicated significant thermal bridges through the window frames, see Figs. 14 & 15.

The doors were also poorly sealed and air cracks were visible as illustrated from the infrared images of thermal bridging, see Fig. 16.



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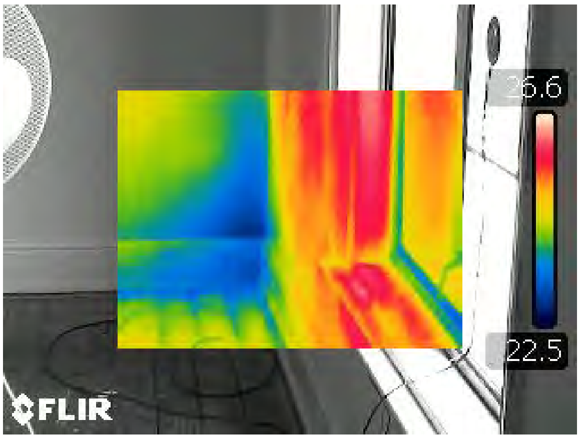

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Figures. 14, 15 & 16: Areas of thermal bridging on windows and doors

Figure 17: Thermal bridging on south-west corner of the gable bedroom

The original lime plaster had been retained as the wall finish on some areas of the internal walls. Where this has been lost, a modern gypsum plaster finish had been applied. The south gable wall on both floors had been dry-lined. This was apparent on the downstairs wall from a small damaged area on the plasterboard but was unclear on the upstairs wall. Subsequent infrared images taken of the upstairs gable wall suggested blown plaster (see Fig. 17), however upon removal during the renovation work, dry-lining was found. There was no insulation behind the plasterboards. The dry-lining and the re-pointing carried out externally on the south facing wall indicated that the wall had suffered from damp in the past.

Ventilation for the house was provided by mechanical extract fans in the kitchen and bathroom. There were air flues in the living room and in the main bedroom but they appeared to be blocked. There were air bricks on all the external walls however, the air brick on the east wall was situated below ground level and was covered by the laid polythene sheet and gravel. It was recommended to unblock and clear the debris from the air flues and air bricks to maximise ventilation.

The services were in working order. There were radiators in each room but without thermostatic radiator values. The programmer and thermostat was located in the kitchen. An old back boiler from the 1980s was installed behind an electric heater in the kitchen. The hot water cylinder with an estimated 100 litres capacity was in installed the second bedroom and was poorly insulated with a loosely fitted foam jacket. The bathroom was fitted with an electric shower. A new energy efficient boiler and the fitting of thermostatic radiator valves were recommended.

Figure 18: Front elevation, after improvements

Figure 19: Rear elevation, after improvements

5. FABRIC IMPROVEMENTS

The fabric improvements were undertaken in collaboration with Bolsover District Council. The house represented a type of popular traditional domestic building in the mid-late 19thC. It was regarded as significant for both belonging to the Bolsover New Model Village (which has Grade II status) and representing a significant proportion of the traditional English domestic building stock which is assumed to be the worst performing, in terms of its energy efficiency. Consequently, the aims of the fabric improvements were two-fold: to significantly improve the thermal and energy performance of the house whilst restoring the original character of the house by reinstating timber windows conforming to the original design for the village. The project was, however, constrained by the Council's limited budget, and recommendations by Historic England to carry out re-pointing and upgrade the services were not realised.

The emphasis of the refurbishment works were on improving the insulation quality of the house by the addition of internal wall insulation, replacement of the existing loft insulation with a greater thickness and the addition of sub-floor insulation. Airtightness measures were carried out by draught-proofing the windows and doors and taping the ground floor insulation joints, at the ceiling abutment and at the window and door reveals. The services were also improved by installing thermostatic radiator valves to improve the heating controls and the insulation jacket was re-fitted to the hot water cylinder. Minor fabric repairs were undertaken to the roof and the gutters, and air bricks were cleared of debris and unblocked. Replacement timber single glazed windows following the original design for the village were installed with low-e secondary glazing. The exception was the window in the gable bedroom which had a slim profile vacuum glazing fitted as secondary glazing. The improvements are summarised below.

5.1 INTERNAL WALL INSULATION

Internal wall insulation was installed on the external walls of the house to minimise the impact on the character of the house whilst at the same time improving its energy efficiency. Prior to choosing the insulation systems, a brief survey of available materials was carried out. There is a wide variety of insulation systems on the market from mineral wool which is the oldest type of insulation product in use to glass wool and expanded polystyrene (EPS) to products based on natural materials, predominantly wood fibre. In addition, over the past 20 years, polyurethane (PUR), polyisocyanurate (PIR) and phenolic foam boards have become very popular due to their relative affordability, ease of use and lower thermal conductivities (approximately 0.025 W/mK). The latest insulation innovation is aerogel which originated in applications within space technologies and the oil and gas industry. Its main advantage is its low thermal conductivity (approx. 0.013 W/mK), therefore it can be applied in about half the thickness of, for example, PIR to achieve the same thermal performance, however it is very costly.

The insulation materials roughly fall into three categories of moisture absorption which is an important consideration in choosing the appropriate system: hygroscopic, non-hygroscopic and permeable but non-hygroscopic. Of these, hygroscopic or ‘breathable’ insulation made from natural materials are thought to be more sympathetic to traditional buildings as this allows the natural transfer of moisture vapour. They have moisture buffering capabilities that may be beneficial in maintaining a healthy building and room comfort levels. Based on this survey, two types of insulation materials were installed at New Bolsover to allow a comparison of the performance of a hygroscopic and a non-hygroscopic system, see fig. 27:

1. On the ground floor an impermeable polyisocyanurate (PIR) insulation with aluminium foil facings on both sides and plasterboard in two variants were installed. The first (Type A) comprised of an integrated system with 65mm thickness of insulation with plasterboard, and an alternate system (Type B) with 55mm thickness of insulation with battens to provide a 25mm gap for a service zone to avoid puncturing the integrated vapour control layer. The PIR boards were fixed to the walls using timber battens, leaving a small air gap. Both systems were finished with a separate piece of plasterboard.

2. On the first floor, a vapour permeable system based on a wood fibre insulation was used (Type C). The system comprised of a lime plaster levelling coat for bonding specified with a 9mm thickness however in practice the thickness, applied to the walls varied between 9-25mm due to the uneven surface of the inner brickwork, see Fig. 20.

Figure 20: Varying thickness of the bonding coat of lime plaster

Figure 21: Lime plaster sandwich of the 100mm wood fibre insulation

100mm thick insulation boards were attached to the levelling coat and then finished with a thin layer of lime plaster, see Fig. 21. The insulation sandwich also includes a fine mineral layer composed of sodium silica that appears to provide a light vapour diffusion resistance.

The rationale for the choice of insulation materials were based on the following criteria:

- practical issues of ease of use, availability and cost;
- impact on heritage significance;
- an assessment of the moisture behaviour of walls at the interface of the fabric and the insulation systems;
- their thermal performance: PIR has a very low thermal conductivity value of typically λ = 0.022 W/mK. The thermal conductivity of the wood fibre-based insulation is higher, typically λ = 0.038-0.042 W/mK, and therefore required a greater thickness to achieve the required thermal resistance. The thickness of insulation used in each system was intended to give an approximate U-value 0.30 W/m^{2}K for the walls to meet current Building Regulations. This was based on the preliminary *in-situ* U-value measurements and data provided by the manufacturers;
- and a comparison of the benefits of a vapour permeable versus a vapour impermeable, closed system. The PIR impermeable system is more conventional, similar to insulation systems used in new build and is recommended by the Energy Saving Trust to reduce condensation risk.[ix] The wood fibre permeable system is designed to be more sympathetic for traditional building materials which are porous allowing vapour transfer. It has often been marketed for being more appropriate for retrofitting to the inside of solid masonry walls. The theory being that the wood fibre-based system has a greater potential for buffering moisture than the PIR system.

5.2 FLOOR AND LOFT INSULATION

The suspended timber floor was insulated with 100mm of wood fibre insulation between the floor joists supported on proprietary clips with an air tightness membrane over the joists. 100mm of PIR insulation was installed around the front perimeter of the wall. The first floor joists were insulated with 300mm of wood fibre insulation.

The existing insulation in the loft was replaced with 300mm of mineral wool insulation to the depth of the joists and 100mm of wood fibre on the loft hatch. The thickness of the attic insulation is intended to give the ceiling to the first floor rooms a U-value around 0.16 W/m^{2}K.

5.3 WINDOW IMPROVEMENTS

The plastic coated aluminium windows were replaced with single glazed accoya wood windows conforming to the original design. Two types of high specification secondary glazing were installed: a low emissivity secondary glazing on all the windows with the exception of one window in the gable bedroom where an experimental secondary glazing system using a slim profile vacuum glazing was installed, see Figs. 22-25.

5.4 IMPROVEMENTS TO SERVICES AND DRAUGHT-PROOFING

Minor improvement to the services were undertaken with better controls provided to the radiators with the installation of thermostatic radiator valves and the refitting of the foam insulation jacket to the hot water cylinder.

Both the front and rear doors were draught-proofed and a draught lobby was re-instated in the kitchen providing additional insulation to the house.

Figure 22: Restored casement window on the front elevation

Figure 23: Secondary glazing on the casement window

Figure 24: Restored windows on the rear elevation

Figure 25: Detail of the slim profile vacuum glazing

6. MEASUREMENT OF THE THERMAL AND ENERGY PERFORMANCE OF THE HOUSE

The thermal performance of the building envelope before and after the refurbishment was determined by co-heating tests and air tightness measurements. The thermal performance of the individual building elements before and after improvements was obtained by *in-situ* U-value measurements using heat flux sensors.[x] Further details on the method is described in section 2 of the research report. Details of the house and data from the thermal performance tests were added to a SAP model to determine the improvement in energy performance of the house.

6.1 CO-HEATING TEST

The co-heating test is a procedure which establishes how much heat is being lost from a building without the vagaries of differing occupancy patterns and is regarded as the only reliable way to measure the whole house thermal performance. It involves electrically heating the interior of the building to 25°C over a period of 1-3 weeks, see Fig. 26. The test provides the heat loss coefficient (W/K) of the house which gives a measure of the thermal performance of the building envelope.[xi] The figure is then refined to compensate for solar gain following the approach given by Baker and van Dijk.[xii]

Analysis of the co-heating test data was initially undertaken using a steady state method which was refined using a dynamic model based on the LORD program[xiii] reducing the uncertainties found in co-heating test method and improving the reliability of the data. Further details on the dynamic analysis of the data are given in the Appendix A of the research report.

Figure 26: Co-heating test set-up

Air pressurisation tests were also undertaken before and after fabric improvements to determine the air permeability of the house. *In-situ* U-value measurements were carried out on all building elements pre and post works to assess their individual contribution to the total heat loss of the house.

6.2 DETERMINING ENERGY PERFORMANCE

Analysis of the energy performance of the house was determined before and after fabric improvements. Results from the thermal performance tests, the air permeability tests, construction details of the house and services were used as input data for a full SAP model with the Stroma software to determine the energy characteristics of the house. The full SAP model is more sophisticated than the reduced version (RdSAP) which is used to generate Energy Performance Certificates (EPCs). It provides a more detailed breakdown of the energy characteristics of the house. Additional analysis of the energy data was undertaken to calculate the energy consumption per unit floor area, the energy and carbon savings per annum against the cost of the measures and their payback periods.

7. THE MONITORING OF MOISTURE RISK FROM INTERNAL WALL INSULATION

Understanding the risks due to moisture accumulation from installing wall insulation is important for solid walled dwellings, since inappropriate application of insulation can undermine the durability of the building by increasing the risk of timber decay and mould growth.[xv] The two insulation systems selected represent both vapour permeable and more conventional vapour control approaches to manage moisture in buildings.

The data gathered will enable a better understanding of the hygrothermal behaviour of solid walls in response to internal and external environmental loads, and the effects of adding thermal insulation. Specifically, the project is investigating whether there is a risk of condensation and moisture problems due to the internal wall insulation at the interface between the internal wall insulation and the brick walls.

Thirty-two relative humidity, temperature and wood block resistance sensors have been installed at this juncture on each elevation on both floors. The wood block resistance sensors are being used as proxy moisture measurements, together with the relative humidity and temperature, to assess the moisture risk behind the internal wall insulation, see Figs. 27 & 29. Wood block resistance measurements provide an alternative check against relative humidity measurements and are complementary to humidity measurements as they are slower to respond and more sensitive to cumulative build-up of moisture particularly in very damp conditions, beyond the hygroscopic region. Relative humidity is more suitable to capture both short-term fluctuations and as well as long-term trends and is reliable in the hygroscopic region.

The sensors have been hard wired to data loggers from which the data is downloaded remotely and collected for analysis. Monitoring has been in progress since December 2011 and it will continue until 2017. A detail layout of the sensor installation is illustrated in Fig. 27. An interim report of the post-intervention monitoring will be published in late 2015.

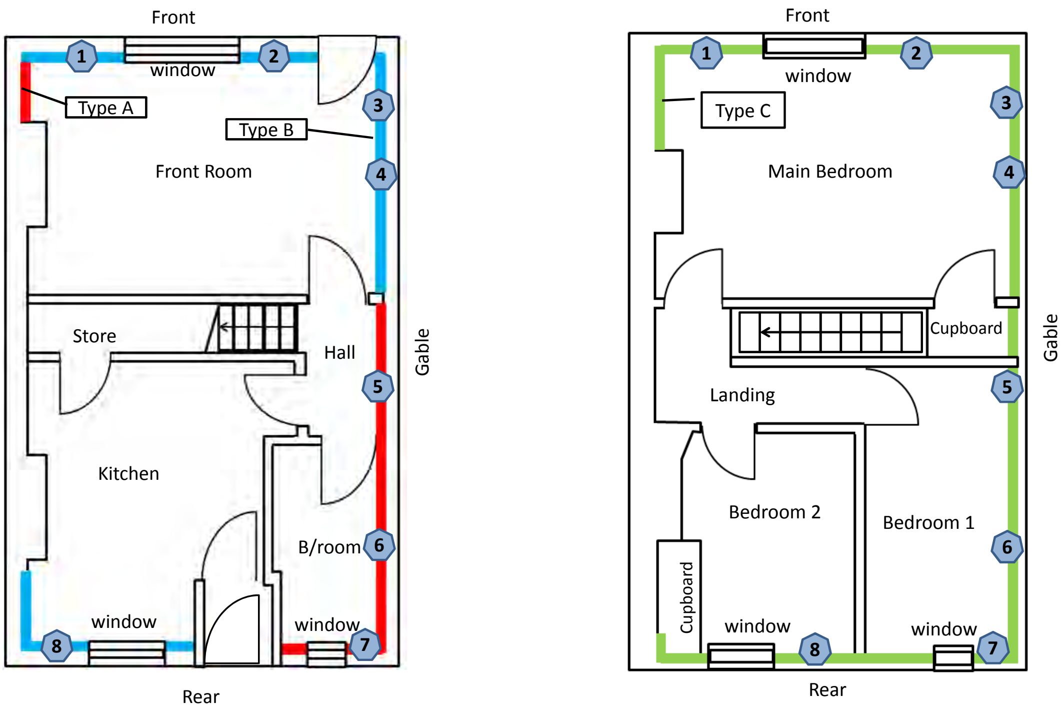

Figure 27: Plan of the monitoring locations with two sensors in each location positioned at low and high level

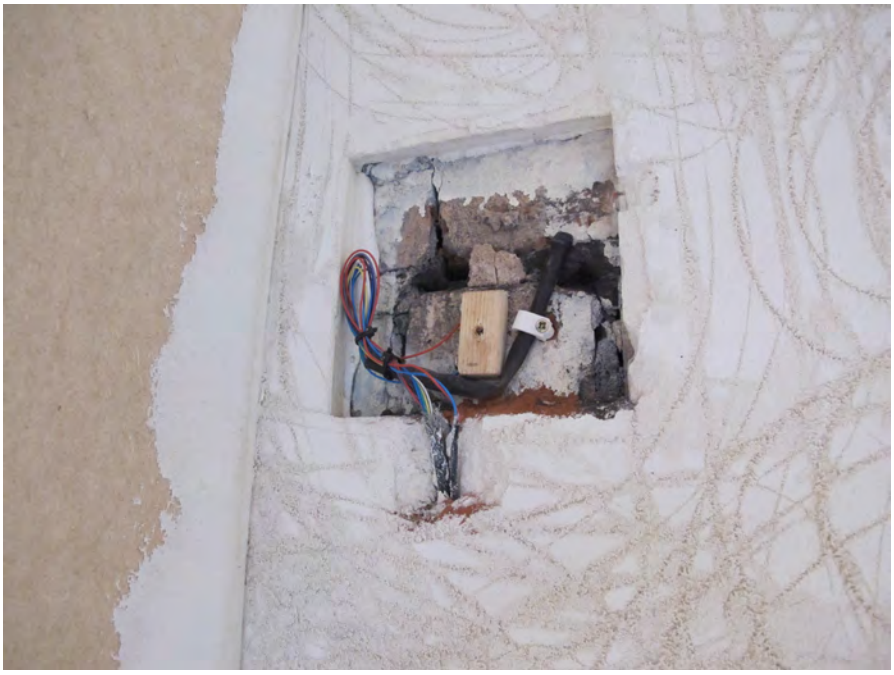

Figure 28: Relative humidity/temperature and resistance sensors fixed on the wall prior to the installation of internal wall insulation

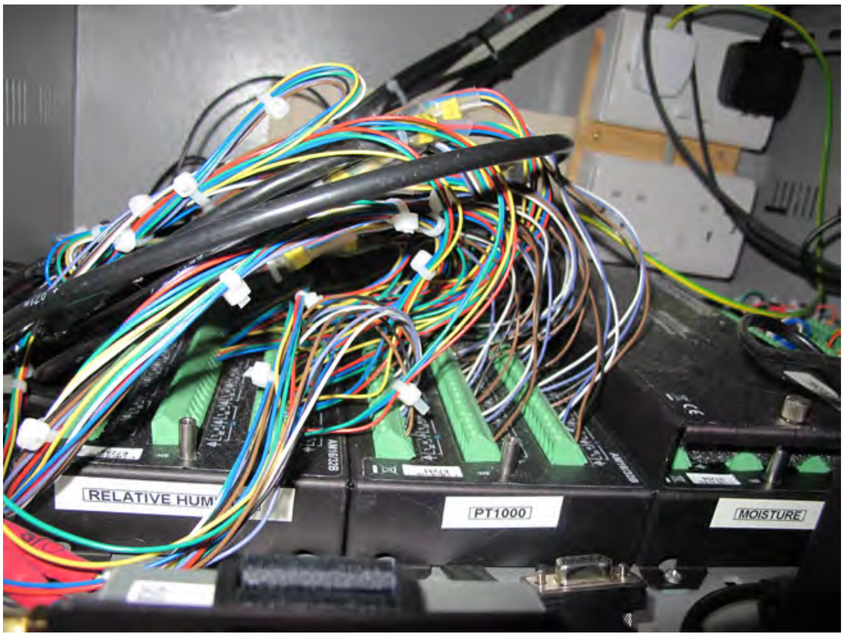

Figure 29: Data loggers hard wired to sensors installed in the house

In addition, laboratory studies and hygrothermal modelling using the WUFI 1D programme, frequently used for condensation risk analysis and the assessment of the risk of mould growth and fabric decay, are being undertaken to validate both the data from the fieldwork and the modelling. The results from the laboratory tests and the modelling will be published as separate reports in the future. This work is part of a wider programme of research where Historic England is investigating the impacts of insulation and risks from moisture accumulation in solid walls.

8. KEY FINDINGS OF THE THERMAL AND ENERGY PERFORMANCE OF THE HOUSE

A summary of the principal findings are given in Table 1:

New Bolsover performance	**Before refurbishment**	**After refurbishment**
SAP rating	E 46	D 65
EI rating	E 41	D 62
Energy consumption /yr /m^2	347 kWh/hr/m^2	210 kWh/hr/m^2
Energy cost	£1093/yr	£697/yr
Kg Carbon/yr/m^2	70 kgCO2/yr/m^2	43 kgCO2/yr/m^2
Whole house heat loss coefficient (dynamic analysis)	251 W/K	143 W/K
Heat loss parameter	2.9 W/m^2K	1.7 W/m^2K
Air permeability	13 $m^3/(h.m^2)$	10 $m^3/(h.m^2)$

Table 1: Results from thermal performance tests and energy analysis

8.1 FABRIC PERFORMANCE TESTING

The co-heating tests have indicated that the fabric improvements have significantly reduced the heat loss of the house. The more robust dynamic analysis has estimated savings of 43% with the heat loss co-efficient dropping from 251 W/K to 143 W/K and the heat loss per unit floor area (or otherwise referred to as the heat loss parameter) improving from 2.9 W/m^2K to 1.7 W/m^2K. These figures included the heat loss by conduction through the building envelope, including thermal bridges and ventilation heat loss during the test period. Further details can be found in section 3.4 of the research report.

The dynamic analysis was more reliable than the steady state method as the data suggested that a high degree of uncertainty can occur with a steady state method of analysis of the co-heating test. This was particularly apparent in the pre-intervention test where the external environment and its variability, and poor air tightness had a greater impact. The post-intervention test result was more reliable than the pre-intervention test due to the better insulation and air tightness with an error factor of +/-16 W/K. This was based on the dynamic analysis given by the LORD model.

There was a notable discrepancy between the measured heat loss using a dynamic method of analysis state and the modelled assessment using the default data contained within the SAP database. There was a 23% difference before fabric improvements between the measured value after dynamic analysis of 251 K/W and the modelling figure obtained from a full SAP analysis of 382 K/W. The discrepancy increased after refurbishment works with a 32% difference. Using the measured data the heat loss coefficient was 143 K/W, and modelling provided a heat loss coefficient of 209 K/W, see Fig. 29.

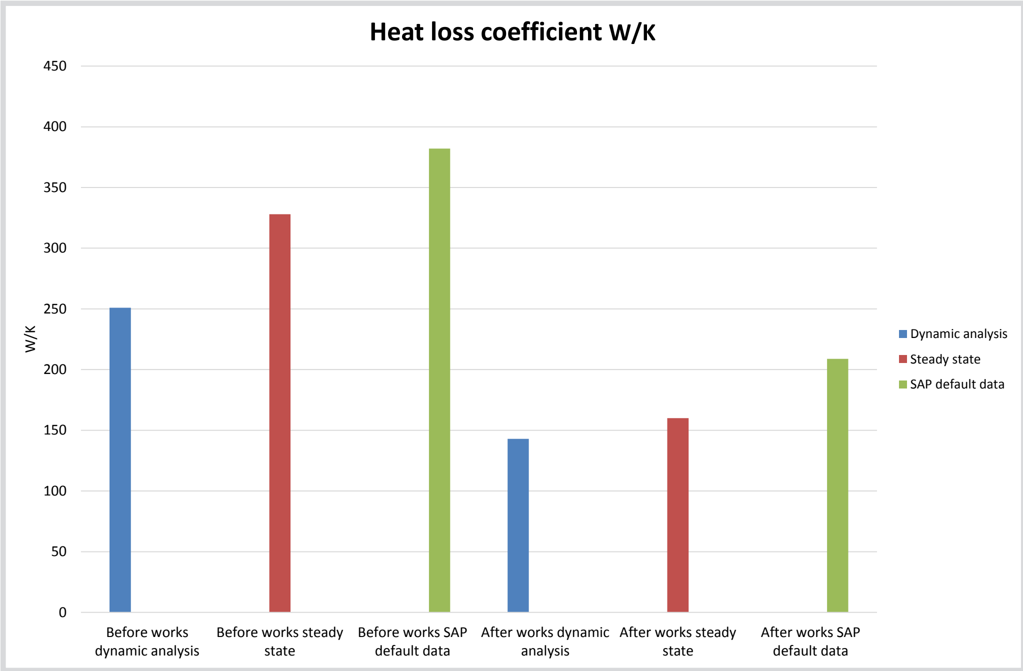

Figure 30: Range of heat loss coefficients depending on the method of analysis

Significant improvements in the thermal performance of all the building elements have been made due to the installed measures. A summary is given below and further detail is provided in section 3.3, Table 5 of the main report, Thermal performance assessment of end terrace house, New Bolsover.

- The greatest reduction in heat loss was achieved with the walls with an 82% reduction, from 139 W/K to 25 W/K. The average U-value of the walls improved from 1.66 W/m²K to 0.31 W/m²K, achieving the target U-value for retained elements after works as prescribed in Part L of the Building Regulation Standards;[xvi]
- Replacing the plastic coated aluminium windows with timber and high specification secondary glazing has reduced the heat loss of the windows and doors by 43% from 56 W/K to 32 W/K. On average the U-value of these windows improved from 4.4 W/m²K to 2.03 W/m²K;[xvii]
- The heat loss in the suspended timber floor (which comprises of 43% of the total ground floor area) has been reduced by 41% from 39 W/K to 23 W/K. The equivalent improvement in U-values being 0.34 W/m²K to 0.16 W/m²K, achieving the target U-value as described in Part L;
- Replacement of the loft insulation has reduced the heat loss by 56% from 13 W/K to 6 W/K. The target U-value of 0.2 W/m²K having been exceeded as the U-value improved from 0.34 W/m²K to 0.16 W/m²K;
- Default thermal bridge calculations indicated a small reduction in heat loss of 4% from 26 W/K to 25 W/K.

Air pressurisation tests have indicated that the ventilation heat loss was reduced by 19% with the air permeability falling from 13 m³/(h.m²) to 10 m³/(h.m²) meeting the maximum allowed at 50 Pa given in Part L of the Building Regulations.

When analysed by the proportion of each element to the total heat loss, post-intervention, ventilation and thermal bridges have become more significant, whereas the contribution from the walls have become considerably less. The contribution from ventilation before and after fabric improvements have risen from 16% to 27%, suggesting that improving areas of poor airtightness is an area for further work. For further detail, refer to Figure 12 in the research report.

8.2 ENERGY PERFORMANCE

To analyse the energy performance of the house before and after fabric improvements, the measurements from the *in-situ* U-value testing of building elements and details of the building's construction and services were used as input data into the SAP calculation software STROMA FSAP 2009 [xviii]. A summary of the main findings has been determined for the whole refurbishment and for each individual retrofit measure.

8.2.1 Improvement in energy performance from the fabric improvements

The SAP rating improved by 19 points from E 46 to D 65 and the Environmental Rating improved by 21 points from D 41 to E 62. With a hypothetical new A-rated boiler, the modelling indicated that the SAP and EI ratings would have achieved C 73 and C 72 respectively. In both instances, the final SAP rating exceeds the national average SAP rating for UK dwellings of D 55 given by the Department of Communities and Local Government,[xix] see Fig. 31.

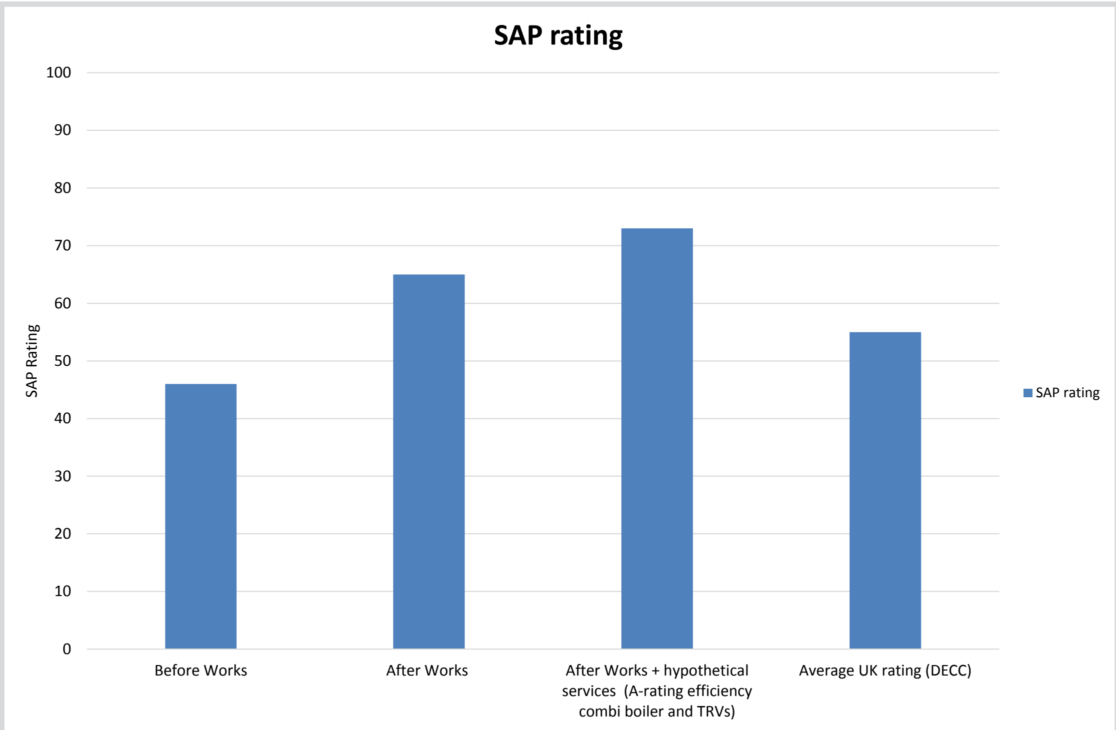

Figure 31: Comparison of SAP ratings

The total savings achieved in the cost of energy per annum was £396. With a hypothetical new A-rated boiler the savings could be as much as £550. Both amounts are more than the DECC estimate of savings that typical households can make from solid wall insulation which varied from £190 to £306 depending on the type of solid wall.[xx] Older estimates by the EST put typical household savings at between £445 and £475 per year.[xxi] The apparent reason given by DECC for their lower figures than the values provided by the Energy Saving Trust is that their figures take account of the real performance of the solid wall insulation once installed. However, it is unclear whether the differences could be a result of an assumed performance gap (where a factor is applied to the U-value which presumes that the performance is poorer than specification) or if their figures are from actual measurements.

The total annual energy consumption was reduced by approximately 40% to 17,707 KWh/yr from 30,446 KWh/yr. This is lower than the Ofgem figure for the typical medium energy consumption of 19,800 KWh for a UK domestic dwelling.[xxii] By per unit area per annum the total energy use fell by 137 KWh/yr/m^2 from 347 kWh/yr/m^2 to 210 kWh/yr/m^2. With the hypothetical inclusion of a new A-rated boiler, the total annual energy consumption was assumed to be 12,726 KWh/yr or 151 KWh/yr/m^2, see Fig. 31.

The total annual carbon emissions were reduced by 39% from 6192 Kg/yr to 3667 kg/yr. By per unit area per annum, the total annual carbon emissions fell from 70 Kg/yr/m2 to 43 Kg/yr/m^2. With the hypothetical inclusion of a new A-rated boiler, the total annual carbon emission fell to 2681 Kg/yr or 32 Kg/yr/m^2, see Fig. 32.

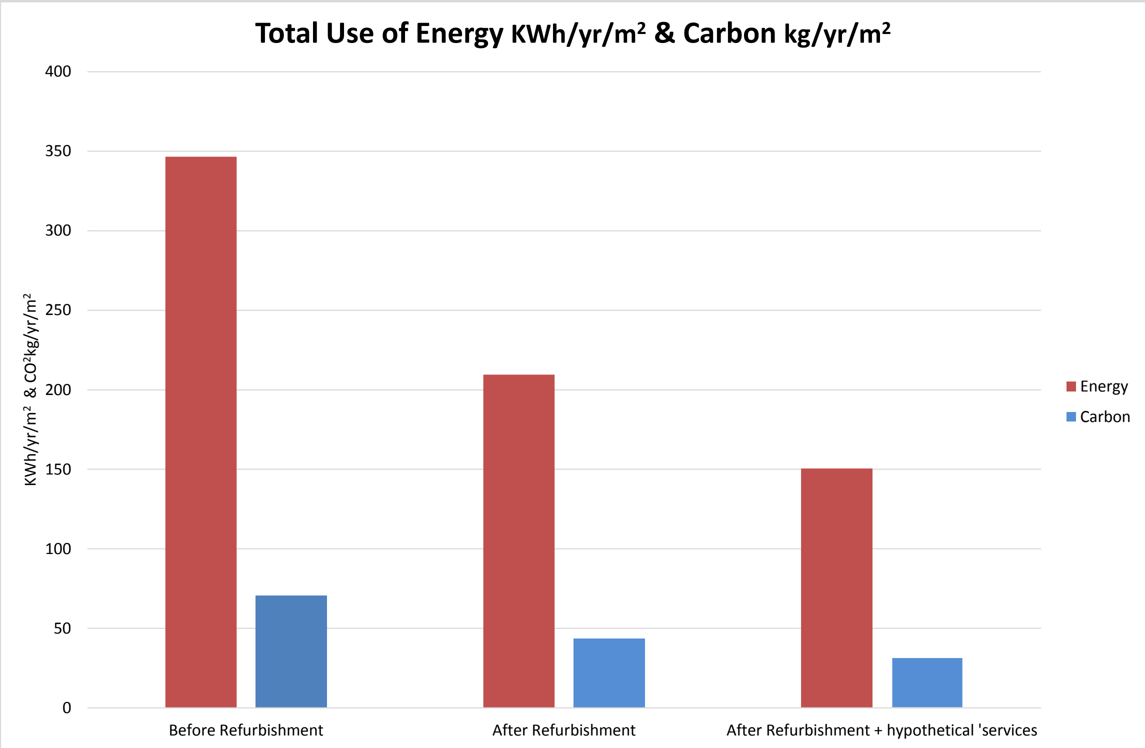

Figure 32: Total energy and carbon use before and after refurbishment, including installation of hypothetical services

8.2.2 Improvement in energy performance by individual measure

When analysed by the retrofit measures, the greatest improvement to the SAP rating was by the installation of the PIR internal wall insulation followed by installation of new services and the wood fibre internal wall insulation. Not surprisingly, the wood fibre insulation gave the highest EI rating, see Fig. 33.

However the wood fibre insulation was found to be the most expensive measure at £18,475 for the whole house. The cost of the PIR insulation for the whole house was almost half that amount at £9666. The least costly of all the measures was loft insulation at £494 which achieved the greatest relative benefit in terms of improvement in the SAP and EI ratings against cost, see Fig. 34.

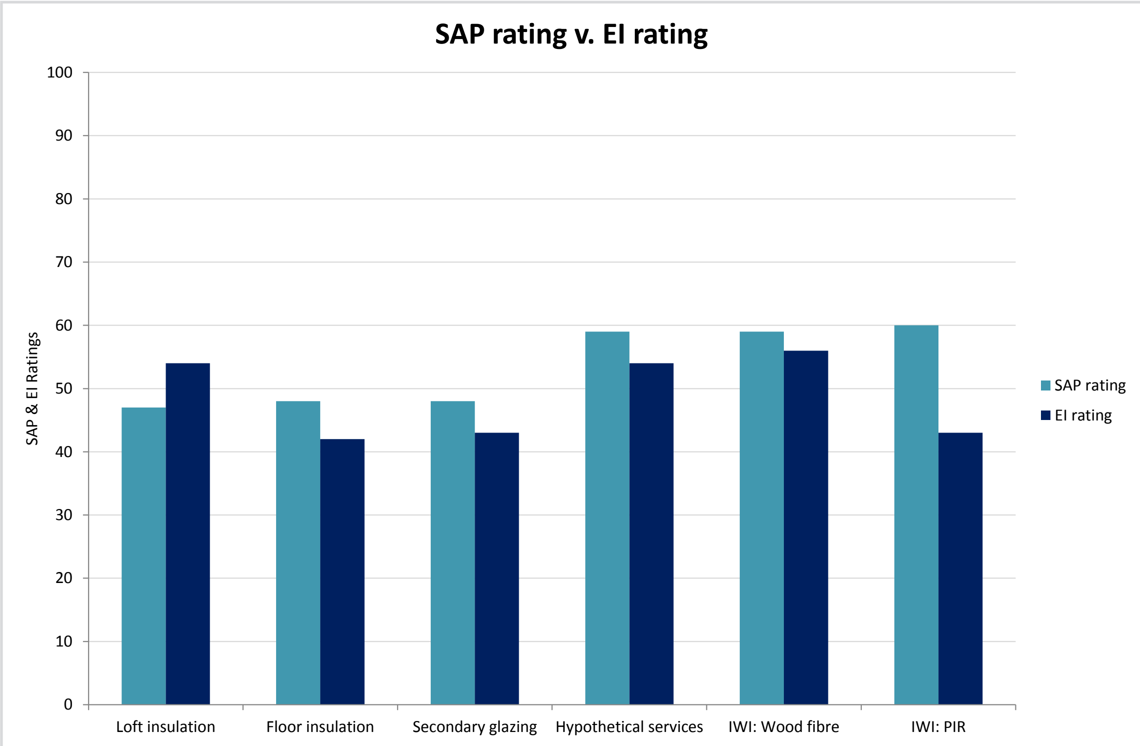

Figure 33: SAP and EI ratings of the individual measures

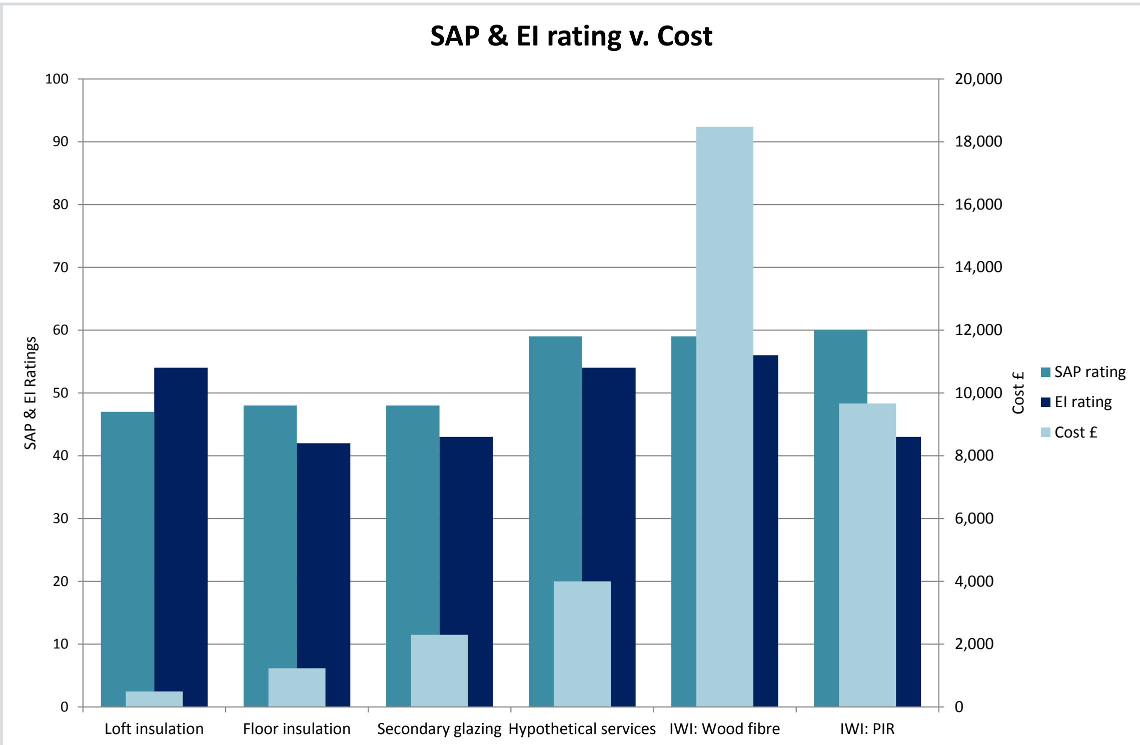

Figure 34: A comparison of SAP & EI ratings against cost of each measure

However, by measure, the SAP model indicated that the replacement loft insulation gave the lowest amount of energy and carbon savings. The greatest energy and carbon savings per annum is achieved by installing a new A-rated boiler, followed by installing internal wall insulation, see Fig. 35.

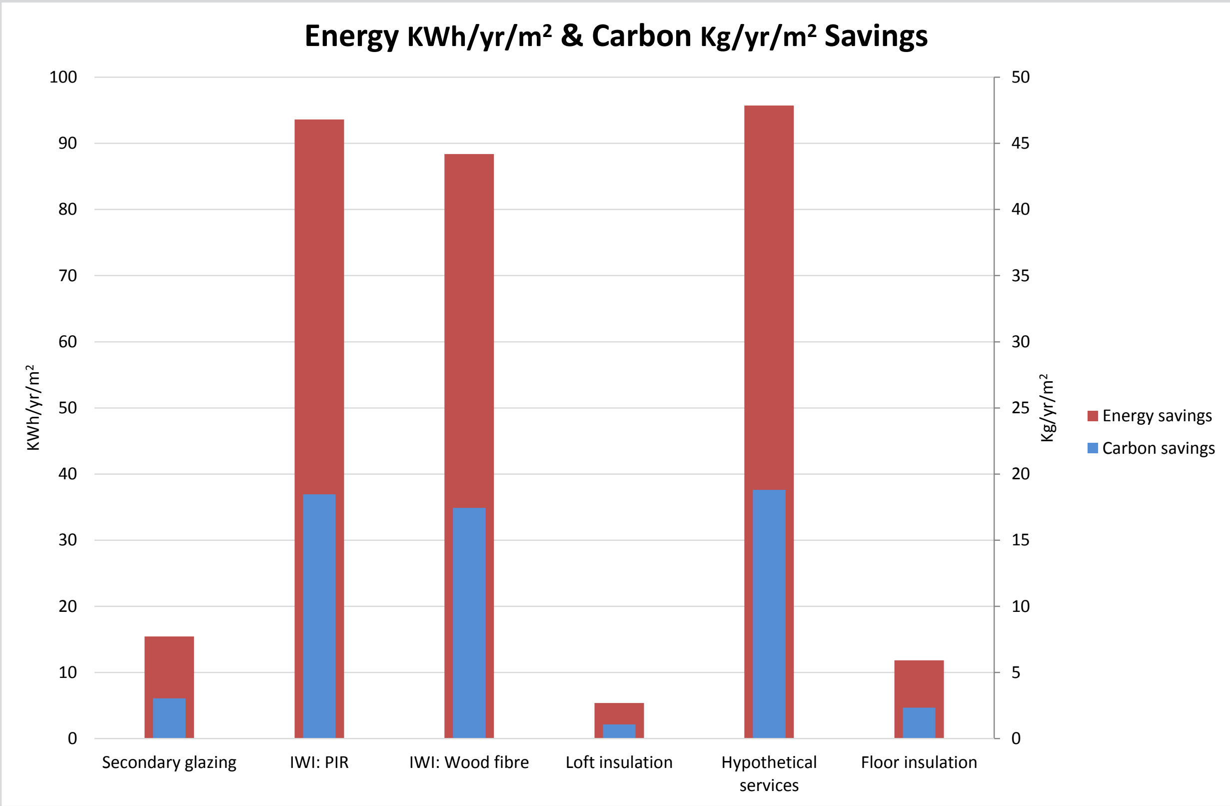

Figure 35: Energy and carbon savings for each measure

The greatest benefit in terms of energy reduction and payback in years was achieved by changing the services, see Fig. 36. There was a 28% reduction in energy use of 96 KWh/m^2 of energy saved each annum, taking 15 years to payback the estimated cost of £4000 of the new boiler. Both internal wall insulation systems achieve good energy savings, however the cost and the payback period were high, particularly for the wood fibre insulation system. Loft and floor insulation have an unexpectedly high payback period of 34 and 38 years respectively.

This is probably due to the small amount of financial savings obtained each annum from these measures as the existing loft insulation was replaced with a greater thickness of 300mm and the floor insulation only applied to the suspended timber floor in the living room, see Fig. 36. A study by DECC suggests that there are diminishing returns on savings from increasing the depth of loft insulation, stating that the first 25mm of loft insulation provides approximately half the anticipated saving.[xxiii]

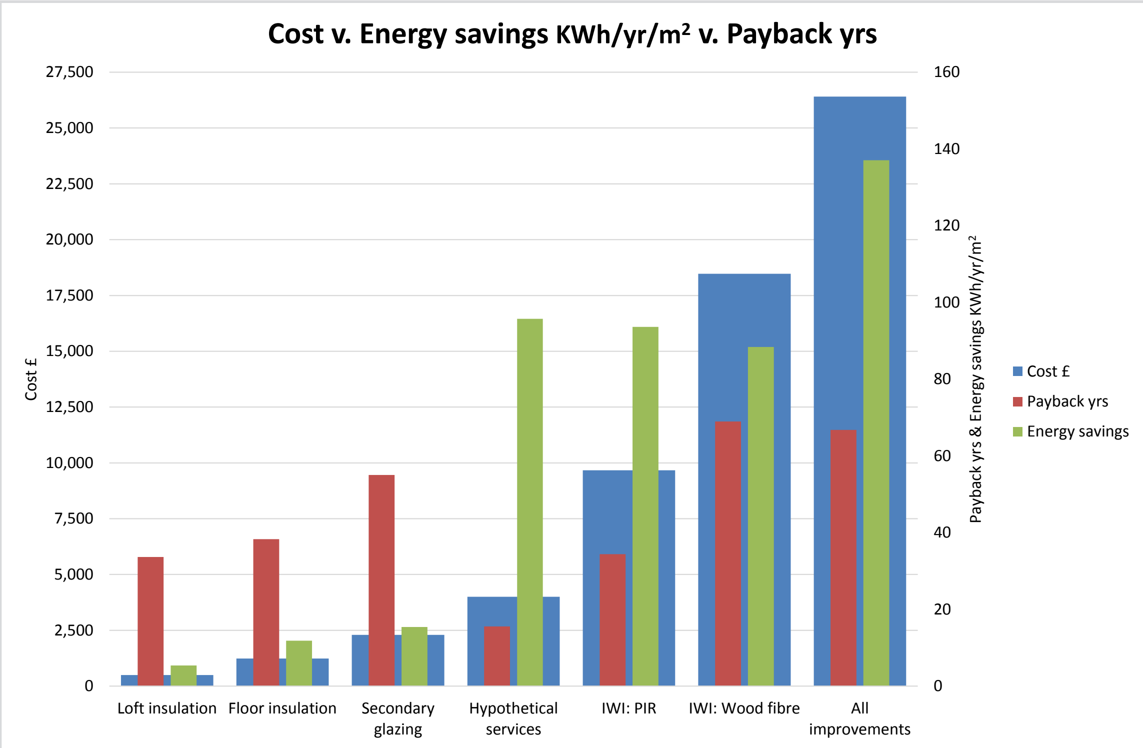

Figure 36: Comparison of cost, payback and energy savings of individual measures

9. DISCUSSION AND CONCLUSIONS

The project was successful in restoring the character of the house and in significantly improving its thermal and energy performance.

The results indicated a 43% reduction in heat loss after fabric improvements and that on average, the improvements to the walls and the floors and the replacement loft insulation met the required target U-values given in Part L of the Building Regulations. A comparison between the actual and predicted thermal performance of the house suggested that calculations underestimated the real thermal performance of the house by 23% pre-intervention works, and by 32% post intervention works.

The findings also showed that the energy use was reduced by 40% after fabric improvements and that improving the services provided the biggest return on investments. Post-intervention the SAP rating jumped 21 points to D 65 which was higher than the national average of D 55. With the replacement boiler the SAP rating would have reached C 73. Hypothetically, replacing the old back boiler with a new A-rated boiler reduced the energy use by 28% and required 15 years to payback the estimated cost of £4000. In addition, nearly £400 per annum was saved from the fuel bill of the house after refurbishment works.

The interim results from the post-intervention monitoring at the interface of the internal wall insulation systems and the walls have indicated that the walls have different hygrothermal performance. They are affected by the type of insulation, the orientation, the degree of shelter and the prevailing weather. An interim report will be published in late 2015.

However, the project has highlighted some practical and technical challenges. Practical issues arose as building contractors were unfamiliar with working with lime and the wood fibre insulation resulting in some wastage of the insulation material affecting project costs. The lime parging coat introduced undesirable moisture into the building resulting in high levels of humidity at the beginning of monitoring period. A longer period of drying than specified by the manufacturer would have been desirable, though this would have increased project costs. The cost of the fabric upgrades were quite high and there were long payback periods for some of the measures. Wood fibre insulation having the highest payback period of 69 years, the secondary glazing of 55 years and the PIR insulation of 34 years. These figures do throw into question the Golden Rule, a key principle behind the success of the Government's Green Deal.[xxiv]

Further, recommendations to Bolsover District Council to upgrade the boiler and repair the pointing of the house were unfortunately not realised. Modelling showed that solely replacing the old boiler caused the SAP rating to jump by 13 points to D 59. Though not desirable, the failure to address the pointing reflects a common occurrence on the ground where repair and maintenance is often neglected.

Technically, the analysis of the data from the co-heating tests highlighted the importance of carrying out a dynamic analysis in order to reduce the uncertainties caused by the variability of the external climate. It is also worth noting that co-heating tests only provide a picture in time of a building's thermal performance for a specific set of climate conditions over a short period of a few weeks.

10. GENERAL RECOMMENDATIONS

- To ensure that the house is in a good state of repair before carrying out any energy efficiency improvements

- The most effective and cost-efficient method of improving the energy performance of the house is to upgrade the boiler. This also has the added benefit of having a minimum or no impact on the significance of the house.

- Building contractors have to properly understand the use of materials specified and the purpose of all parts of the system. If necessary, to question the literature provided by the manufacturer on the application of the system and to ask for more guidance.

- To ensure that the specifications are appropriate for the type of building and that the works carried out are adequately supervised.

- The use of the wood fibre insulation internal wall insulation system could be more appropriate for heavy masonry construction with high thermal mass than for buildings constructed with a single skin brick wall.

- There is a need for more data from long-term monitoring of internal wall insulation to enable a better consideration of the risks from moisture accumulation in masonry walls and to define more clearly the boundaries of safe levels of moisture in masonry materials.

- Energy modelling in SAP requires further refinement to improve the discrepancies between the measured energy performance of real buildings and assessments using simulation.

NOTES

[i] BRE (2008), Domestic Energy Fact File. London. The Building Research Establishment.

[ii] This is based on a DECC estimate that 122,000 properties had installed SWI, which equates to approximately 2% of solid walled properties. DECC (2012), *Estimates of Home Insulation Levels in Great Britain.* London. Department of Energy and Climate Change.

[iii] DECC (2012), *Final Stage Impact Assessment for the Green Deal and ECO.* London. Department of Energy and Climate Change.

[iv] Sustainable Development Commission (2006), *Stock Take: Delivering improvements in existing housing,* London.

[v] HM Government, Climate Change Act (2008), *Carbon Target and Budgeting – The Target for 2050*. London.

[vi] Boardman, B., Darby, S. & Killip, G. et.al. (2005), *40% House,* Environmental Change Institute, Oxford University, Oxford.

[vii] *Low Energy Victorian Terrace House,* Camden Council. http://www.levh.org.uk

[viii] English Heritage (2008), *Research into the Thermal Performance of Traditional Timber Windows;* English Heritage (2013), *Research into the Thermal Performance of Traditional Brick Walls.*

[ix] EST (2002), *Good Practice Guide 138: Internal Wall Insulation in Existing Housing.* London. The Energy Saving Trust.

[x] English Heritage (2013), op.cit.

[xi] Wingfield, J., Johnston, D., Miles-Shenton, D. & M. Bell (2010), *Whole-house Heat Loss Method,* Leeds Metropolitan University.

[xii] Baker, P. & van Dijk, H. (2008) *PASLINK and dynamic outdoor testing of building components,* Building and Environment, 43 (2), p. 143-151.

[xiii] Gutschker, O. (2004), LORD – *Modelling and Identification Software for Thermal Systems, Brandenburg Technical University of Cottbus.* Germany.

[xiv] Standard Assessment Model (2009), http://www.stroma.com/certification/software/sap-software-fsap

[xv] Sustainable Buildings Traditional Alliance (2014), *Moisture Risk Assessment and Guidance, draft consultation document,* see, http://sdf.pht.surefirehosting.co.uk/downloads/Moisture-guidance-consultation-doc-2.pdf

[xvi] HM Government Approved Document LIA (2010), *Conservation of Fuel and Power in New Dwellings.* The Building Regulations.

[xvii] Post-intervention average U-value is based on low-e secondary glazing, the vacuum secondary glazing has not been included in the average value.

[xviii] The following should be noted: the values for air permeability entered into the Stroma SAP worksheets were based on the given calculated value as it was not possible to enter in the measured values from the air pressurisation tests; the calculations assumed default occupancy as given in SAP 2009; the services were hypothetically modelled as no work was carried out for the building services; that it was assumed that all the windows had low-e secondary glazing installed rather than including the one window with the vacuum secondary glazing unit; calculations of payback for the windows only included the cost of the secondary glazing units; the calculations for the two internal wall insulation systems assumed that each had been installed on both floors.

[xix] DCLG (2012), *Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007.* London. Department of Communities and Local Government.

[xx] DECC (2012), *Annex A, Final stage Impact Assessment of the Green Deal and ECO.* London.

[xxi] See, http://www.energysavingtrust.org.uk/domestic/content/solid-wall.

[xxii] Ofgem (2011), *Factsheet 96: Typical Domestic Energy Consumption Figures.* London. Office of Gas and Electricity Markets.

[xxiii] DECC (2012), *Statistical Release: Experimental Statistics – Estimates of Home Insulation Levels in Great Britain.* London. Department of Environment and Climate Change.

[xxiv] The Golden Rule principle is that the bill should not exceed the expected savings and the length of payment period should not exceed the lifetime of the measures. See, DECC (2010), *The Green Deal, A Summary of the Government's Proposals.* London. Department of Energy and Climate Change.

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Wingfield, J., Johnston, D., Miles-Shenton, D. & M. Bell (2010), Whole-house Heat Loss Method, Leeds Metropolitan University

NOTE:

Historic England

A RETROFIT OF A VICTORIAN TERRACE HOUSE IN NEW BOLSOVER

A WHOLE HOUSE THERMAL PERFORMANCE ASSESSMENT

Prepared for Historic England by Dr. Paul Baker

School of Engineering & the Built Environment

Glasgow Caledonian University

CONTENTS

FIGURES AND TABLES

1. INTRODUCTION

This report presents the results and analysis of the thermal performance measurements made in a brick built end terrace house in New Bolsover, Derbyshire. The house (Figure 1), constructed in 1891 has a total floor area of 88m^2 and comprises a living room, kitchen/dining room and bathroom on the ground floor and three bedrooms on the first floor. The work was carried out by Historic England and Glasgow Caledonian University, before and after the installation in December 2011 of a package of interventions, including internal wall insulation, improved loft insulation, insulation of the suspended timber floor and reinstatement of single-glazed timber framed windows with high specification secondary glazing systems behind them. Before the intervention, the house had only loft insulation of varying thicknesses and a variety of single and double glazed replacement aluminium framed windows.

The overall aims of the project were:

- To determine the improvement in thermal performance of the building envelope of an end terrace house after interventions to improve its insulation.
- To investigate the risk of condensation and moisture problems within the walls after intervention for the two insulation systems selected, one of which represent a vapour permeable approach and the other a more conventional vapour control approach to manage moisture in buildings. This work is continuing and will be the subject of a future report.
- To use the results to inform a strategy for implementing energy efficiency in the house type.

The main objectives of the thermal performance assessments were to:

- Measure the *in situ* U-values of the various building envelope elements as follows
  - > Front, rear and gable end elevations exposed to external climate.
  - > Party walls (note: unable to measure U-values as no access to neighbouring house).
  - > Ceiling to loft space.
  - > Ground floors to front (suspended timber) and rear (concrete).
  - > Glazing.
- Measure the whole house heat loss coefficient value by a “co-heating” test.
- Carry out air tightness measurements by building pressurisation testing before and after the co-heating test.
- Calculate the whole house heat loss coefficient using the results of the *in situ* U-value and air tightness measurements, with supplementary information on thermal bridges and whole window and door U-values obtained by calculation or from recognised databases.

The measurements reported here were performed over the periods March-May 2011 (before interventions) and March-April 2012 (after interventions).

Figure 1: The New Bolsover house front elevation

Construction pre- interventions

Prior to the interventions the walls consisted of nominally 9 inch brick and mortar with an internal plaster finish, except for the gable-end wall in the living room which was finished with plasterboard on timber studs.

The living room floor was suspended timber. The floor of the rest of the ground floor had been replaced with concrete, although the actual construction details are unknown.

The loft space was insulated with mineral wool or glass fibre, however the insulation had been disturbed probably as the result of electrical works and was unevenly distributed.

The original timber windows had been replaced with a combination of single and double glazed aluminium framed windows and one PVC-u window in the bathroom. The front door was solid timber with a fixed single glazed timber window above and the rear door was timber with single glazed panels.

Internal Wall Insulation Systems

The specification and schedule of work for thermal upgrading works to 113 New Bolsover specified two insulation systems as follows:

1. On the ground floor PIR (polyisocyanurate) insulation was used (schematic diagram Figure 2 and plan view Figure 4), with aluminium foil/kraft paper facings on both sides, finished with plasterboard in two variants:

   Type A: Plasterboard directly bonded to 65mm insulation. Note that the original specification was to use insulation with taped joints and separate plasterboard.

   Type B: 55mm insulation, with all joints taped, battens to provide service zone and plasterboard.

   The PIR insulation was fixed to the inner face of the wall using timber battens leaving a small air gap.

   In both cases, the intent was to retain the original plaster finish and fix the insulation to this, however the building contractors removed all original plaster before installing the insulation.

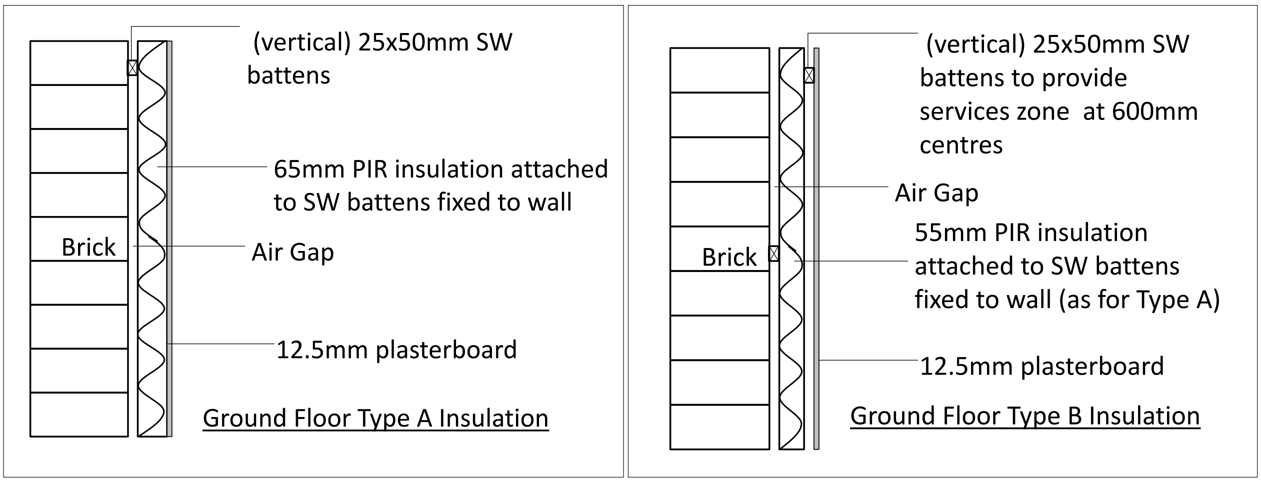


Figure 2: Ground floor insulation systems

2. The first floor used a vapour permeable system based on wood fibreboard insulation:

   Type C: lime plaster applied to brick, 100mm wood fibre insulation, finishing coat of lime plaster (schematic diagram Figure 3 and plan view Figure 4).

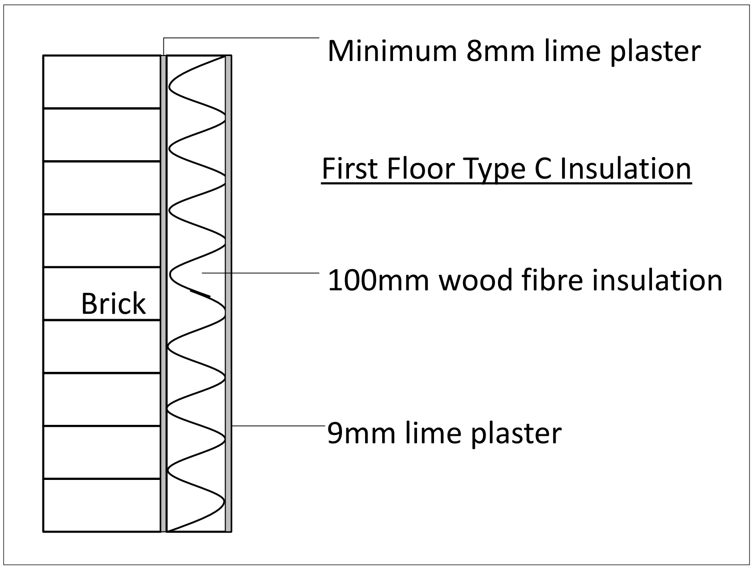
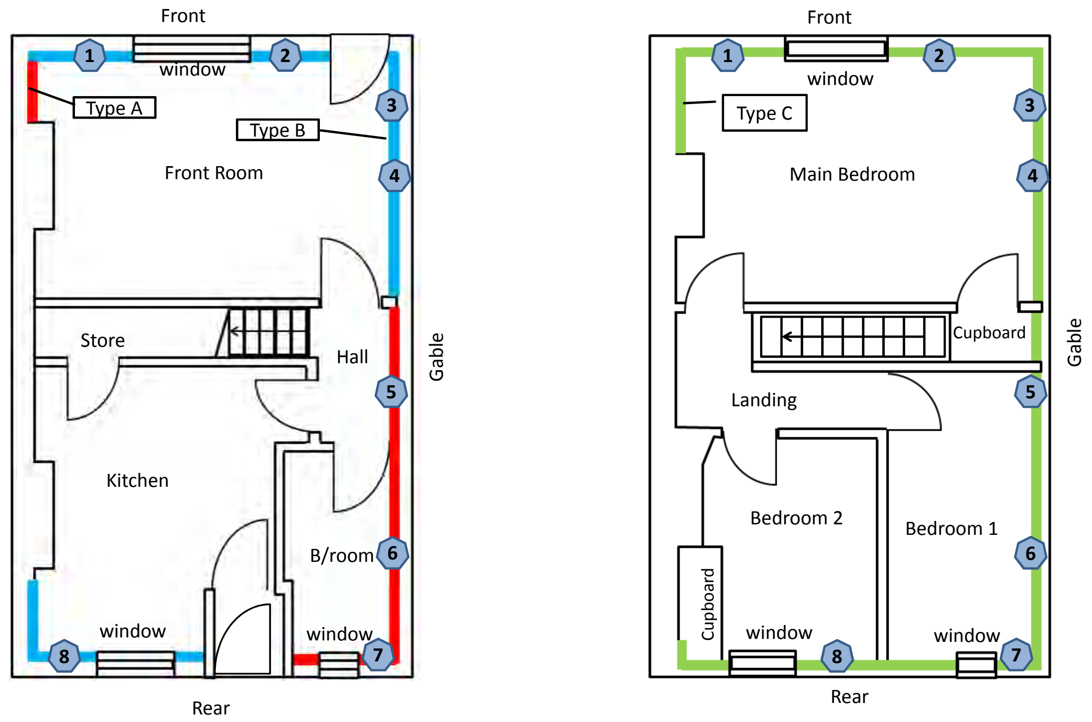


Figure 3: First floor insulation system

Types A and B represent the more conventional vapour-checked solutions, as used in new buildings with internal insulation; and as recommended in the Energy Saving Trust's Good Practice Guide 138 "Internal wall insulation in existing housing – a guide for specifiers and contractors" (EST, 2002) to reduce condensation risk.

Type C represents an approach which some perceive as being more 'sympathetic' for use in traditional solid-walled buildings, benefiting the absorption, transport and release of moisture through the use of hygroscopic materials.

Calculations of heat and moisture transfer through internally-insulated solid walls indicate that the greatest risk of condensation occurs at the interface between the cold face of the insulation and the masonry. Relative humidity, temperature and wood block moisture content sensors were therefore installed here for all three types of insulation. Monitoring started in December 2011 and will continue for 5 years until 2017. The interim results will be published in late 2015. Full results will be published at the end of the monitoring period in 2018.



Type A: Plasterboard directly bonded to 65mm PIR insulation.

Type B: 55mm PIR insulation, with all joints taped, battens to provide service zone and plasterboard.

Type C: lime plaster applied to brick, 100mm wood fibre insulation, finishing coat of the lime plaster.

Figure 4: Location of the two internal wall insulation systems – left: ground floor with PIR; right: first floor with wood fibre system.

Other improvements to the thermal performance of the building included:

- Insulating (i) between the joists of the suspended timber floor with 100mm wood fibreboard insulation and (ii) the perimeter of the front wall to the depth of the joists with 100mm PIR insulation. Insulating the perimeter of the first floor void using wood fibreboard insulation to the depth of the joists (170mm) and extending 300mm from front wall.
- Removing the loft insulation and replacing it with glass fibre insulation in two layers, one between and one over the joists, to give a total depth of 300mm. The loft hatch was insulated, and brush draft seals fitted to its perimeter.
- Partial insulation of the party walls, as shown in the plan view Figure 4.
- Replacing aluminium windows with timber windows of the original pattern, supplemented by high specification secondary glazing, including a sample using slim profile vacuum glazing, in aluminium frames.
- Effecting airtightness measures including taping of ground floor insulation joints, at ceiling abutment and at window and door reveals.

2. METHODOLOGY AND TEST PROCEDURES

2.1 *IN SITU* U-VALUES

2.1.1 Test Method

The test methodology for opaque elements (walls, floors and ceilings) is described in Baker & Rhee-Duverne (2013) and Historic Scotland Technical Paper 10 (Baker 2011), using heat flux sensors and internal and external temperature measurements. The measurement and analysis of centre-of-pane glazing U-values is described in Heath et al (2010); only the night-time data are used for analysis to exclude the influence of solar radiation on the heat flux meters.

A thermal imaging survey and visual inspection were carried out on 3rd February 2011 to identify possible representative locations for the heat flux sensors, i.e. approximately in the centre of each element avoiding thermal bridges. The locations selected for installation of sensors pre-intervention in March 2011 and follow-up measurements post-intervention in March 2012 are given in Table 1; approximately the same locations were used before and after intervention. Figures 5 & 6 show typical examples of heat flux sensor installation on walls and windows.

Figure 5: In situ U-value measurements in main bedroom: front elevation, gable wall and ceiling.

Figure 6: In situ U-value measurement on secondary glazing and adjacent wall in bedroom 2.

Table 1: Heat flux sensor locations

ROOM	LOCATION	CONSTRUCTION / COMMENTS	
		Pre-intervention	**Post-intervention**
Living room	• External wall at front elevation between window and party wall	• Wall construction is brick and plaster.	• Wall with insulation system type B (55 mm PIR, service zone, plasterboard).
	• Gable end.	• Brick wall drylined with plasterboard.	• Wall with insulation system type B (55 mm PIR, service zone, plasterboard).
	• Boarded up fireplace forming part of party wall	• Brick and plaster with cavity.	• No change
	• The surface of the suspended timber floor	• Un-insulated. • The external reference temperature is a ground temperature measurement approximately 61cm below ground under the floor. A temperature sensor is also located on the ground directly underneath the floorboards.	• Insulated. • The external reference temperature is a ground temperature measurement approximately 90cm below ground under the floor. A temperature sensor is also located underneath the insulation.
Hall between kitchen and living room	• Gable end wall.	• Wall construction is brick and plaster.	• Wall with insulation system type A (65 mm PIR and plasterboard).
Bathroom	• Gable end wall.	• Wall construction is brick and plaster. Not measured.	• Wall with insulation system type A .
Kitchen	• External wall at rear elevation.	• Wall construction is brick and plaster.	• Wall with insulation system type B (55 mm PIR, service zone, plasterboard).
	• Surface of concrete floor.	• The external reference temperature is the ground temperature under the suspended timber floor.	• No change. The external reference temperature is the ground temperature under the suspended timber floor.
	• Party wall to right of old fireplace.	• Brick and plaster.	• No change.
	• Party wall to left of old fireplace.	• Brick and plaster. ***Not measured.***	• Wall with insulation system type B (55 mm PIR, service zone, plasterboard).

Main bedroom front elevation	• Wall on front elevation.	• Wall construction is brick and plaster.	• Wall with insulation system type C (lime plaster, 100 mm wood fibreboard, lime plaster).
	• Gable end.	• Wall construction is brick and plaster.	• Wall with insulation system type C.
	• Ceiling.	• Two locations. The plaster ceiling is insulated with glass fibre or mineral wool of varying thickness. A temperature sensor was laid on top of the insulation material in a position approximately in the centre of the ceiling over the bedroom.	• Two locations. Insulation upgraded to uniform thickness. A temperature sensor was laid on top of the insulation material in a position approximately in the centre of the ceiling over the bedroom.
	• Glazing.	• Double glazed unit. External glazing surface temperature measured.	• Single glazed window with secondary glazing. Heat flux sensor mounted on warm side of secondary glazing. External glazing surface temperature measured.
Small bedroom 2 rear elevation, adjacent to neighbouring house.	• External wall.	• Wall construction is brick and plaster.	• Wall with insulation system type C (lime plaster, 100 mm wood fibreboard, lime plaster).
	• Glazing.	• Single glazing. External glazing surface temperature measured.	• Single glazed window with secondary glazing. Heat flux sensor mounted on warm side of secondary glazing. External glazing surface temperature measured.
Small bedroom 1 rear elevation / gable end.	• External wall, gable end	• Wall construction is brick and plaster. *Not measured*	• Wall with insulation system type C (lime plaster, 100 mm wood fibreboard, lime plaster).
	• Glazing on rear elevation.	• Single glazing. *Not measured.*	• Single glazed window with Vacuum secondary glazing. Heat flux sensor mounted on warm side of secondary glazing. External glazing surface temperature measured.
Landing	• Party wall.	• Brick and plaster.	• No change.

External air and surface temperatures were measured on the front and rear elevations and the gable end wall.

It was not possible to install temperature sensors in the neighbouring house for estimation of the party wall U-values.

All *in situ* U-value measurements were carried out during the co-heating tests.

2.1.2 Calculation of whole house heat loss coefficient based on *in situ* U-value measurements

The estimate of the whole house heat loss coefficient based on the elemental U-values derived from the measurements is, in its simplest form, the sum of each individual component U-value multiplied by its area (A):

$$\sum UA \qquad \textit{Equation 1}$$

The UK convention is to measure the areas internally. The UA-values for the walls, insulated ceilings and the solid kitchen floor are straightforward to obtain as these envelope elements can be considered to be homogeneous. However, some adjustment to the suspended timber floor UA-value was made to allow for the joists. The whole window UA-values were calculated to include the frame using the BRE U-value calculator software. Appropriate default values for the two doors were also included.

Estimates of the thermal bridges for each element (ΨxL) and a ventilation heat loss term (H_V) were also included.

$$\sum UA + \sum \Psi L + H_V \quad \text{(W/K)} \qquad \textit{Equation 2}$$

The ψ-values can be estimated by using a program such as TRISCO (www.physibel.be) or applying a standard correction as used in SAP calculations (Appendix K, SAP 2009, 2011). The SAP method has been used in this report since a more detailed analysis of the thermal bridges was beyond the scope of this work.

H_V can be derived from the building pressurisation test results (see below) as follows:

$$H_V = \rho \cdot C_p \cdot q_V \quad \text{(W/K)} \qquad \textit{Equation 3}$$

Where **ρ** is the density of air (kg/m^3), Cp is the specific heat capacity of air (J/kgK) and q_V is the estimated volume infiltration/natural ventilation rate (m^3/s). q_V is derived from the measured air change rate per hour in the building measured at 50 Pa pressure difference from the building pressurisation test (ACH_{50}):

$$q_V = \frac{ACH_{50} \times HouseVolume}{N \times 3600} \quad \text{m}^3\text{/s} \qquad \textit{Equation 4}$$

N is a factor derived from correlations between building pressurisation tests and tracer gas tests used to measure infiltration rates, allowing an average infiltration/natural ventilation rate to be predicted from the ACH_{50} measurement. For domestic buildings, a value of 20 is commonly used (for example see: Meier, 1986) and is implemented in the SAP2009 calculations of infiltration. However, the Lawrence Berkeley Laboratories, for example, have derived factors ranging from N=11.2 to 23.5 for 2 storey building in different US climate zones and levels of exposure (LBL 2001).

A corrected value of H_V can be calculated using the procedure in SAP2009 which allows for infiltration due to chimneys, flues and fans, and a shelter factor for the house.

2.2 BUILDING PRESSURISATION TESTING

A building pressurisation test is carried out to give the overall airtightness of a building, from a series of volume flow rate measurements carried out at different pressure differences between the inside of the building and outdoors. The airtightness at a reference pressure differential of 50Pa can expressed as:

- The air changes per hour, ACH_{50}= Volume flow rate ÷ Volume of air inside building, and alternatively as
- The air permeability ($m^3/(h.\ m^2)$) = Volume flow rate ÷ Area of building envelope, which includes all walls, roof and floor bounding the volume being tested, measured internally. For example, the Building Regulations Approved Document Part L1A 2010 (HMG, 2010) states a maximum permissible air permeability values of $10m^3/(h.m^2)$ at 50 Pa.

A device known as a 'blower door' is used for measuring the airtightness of small buildings. It includes a calibrated fan, some means of controlling air flow rate, and instrumentation for measuring pressures, fitted within an adjustable frame with a flexible covering impermeable to air (Figure 7), that can be clamped and sealed to the frame of an external doorway. By adjusting the fan speed the air flow rate (m^3/h) is measured for a range of pressure differences, measured using a manometer over the range 10-50+ Pa at approximately 5Pa intervals. For the best results, measurements should be carried out under calm conditions, with wind speed less than about 2m/s. Pressure differences lower than 10Pa are not usually used, as the measurements can be disturbed by wind effects. Measurements can be carried out with the building both pressurised and depressurised, as differences may occur due to air leakage paths opening or closing under positive or negative pressure.

Figure 7: Blower door assembly for building pressurisation test.

The results are usually plotted as shown in Figure 8 and a power law fitted applied (Equation 5):

$Q = a \times \Delta P^c$ *Equation 5*

Where Q is the volume air flow rate (m^3/h), ΔP is the pressure difference (Pa), and a and c are constants determined by analysis of the data. The correlation coefficient, R^2, which shows the goodness of fit, is usually expected to be better than 0.99.

From Equation 1, ACH_{50} is calculated as the air flow rate Q at 50Pa divided by the internal volume of the house in cu. m.

Note that all designed ventilation openings (e.g. extractor fans and trickle vents) are temporarily sealed during the period of testing.

2.3 CO-HEATING TEST

A co-heating test is a method of measuring the heat loss (W/K) through the fabric and from background air infiltration in an unoccupied dwelling. It involves measuring the energy used to heat the inside of the dwelling to an elevated mean temperature (typically 25°C) over typically between 1 and 3 weeks.

The term co-heating originated in the USA, where initially the building's own heating system was supplemented by electric heaters. Normal practice today (Wingfield et al, 2010) is to use electrical heating alone, as the electrical energy use is relatively easy to measure.

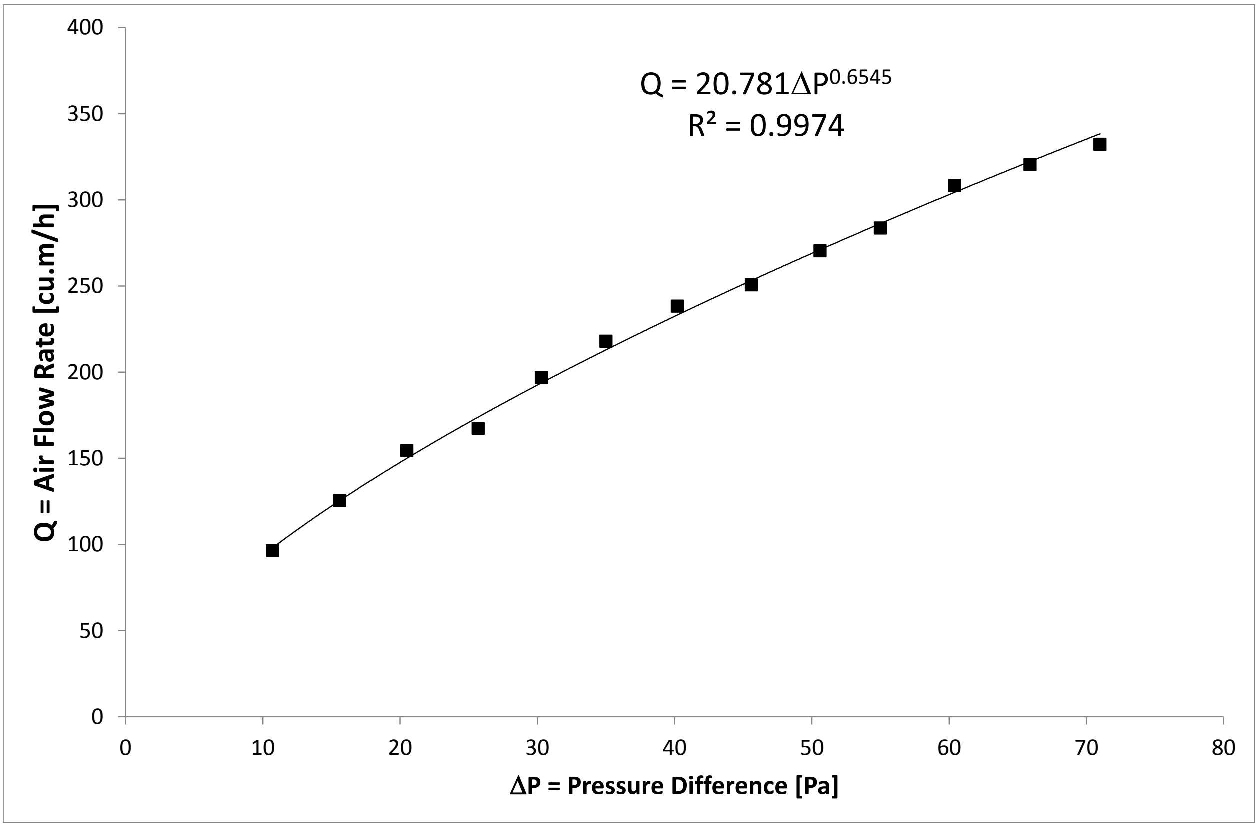


Figure 8: Example of building pressurisation test data with power law curve fit

The simplest method of calculating the heat loss coefficient of the dwelling is to plot the daily heat input against the daily average difference in temperature between the inside and outside of the dwelling. The resulting slope of the plot gives the heat loss coefficient. However, the analysis can be refined to account for the influence of solar radiation, since the solar radiation will vary daily and seasonally and the dwelling has a *solar aperture* which can vary seasonally. The solar aperture can be defined as the heat flow rate transmitted through the building envelope to the internal environment under steady state conditions, caused by solar radiation incident at the outside surface, divided by the intensity of incident solar radiation (Baker & van Dijk, 2008). The solar aperture embodies both the effects of direct solar transmission (e.g. through glazing, including any absorbed/re-radiated quantities) and of solar radiation falling on opaque parts of the building envelope. It can be regarded as equivalent to a totally transparent area which lets in the same solar energy as the whole building.

At New Bolsover, heating was provided by free standing 2kW electric radiators and circulation fans in the main rooms of the house (Figure 9). The heaters were controlled by thermostats to maintain a constant temperature, 25°C to increase the internal-outdoor temperature difference, and hence the accuracy of the calculated heat loss coefficient.

Figure 9: Co-heating test set-up with heater, fan & thermostat.

2.3.1 Measurement requirements

Measurement requirements were as follows:

- Electrical power was monitored using Historic England's Eltek remote monitoring system, which was also used to measure shielded external air and room temperatures, relative humidity and wind speed.
- Shielded room air temperatures and external air temperatures were measured as part of the *in situ* U-value tests.
- In order to determine the influence of solar radiation, solarimeters were mounted on the front and rear elevations, which contain the windows. The solarimeter outputs were measured using the Campbell data loggers used for *in situ* U-value testing.
- It was not possible to measure temperatures in the adjacent house, so heat flows through the party wall were calculated by multiplying the measured heat flux by the party wall area.
- A test duration of 4 weeks was considered desirable to maximise data and allow for any unforeseen problems.

2.3.2 Analysis of co-heating test data

A detailed discussion of the analysis methods used to obtain the whole house heat loss coefficient and solar heat gain factor is given in Appendix A.

The principle of the analysis methods is to represent the data as three main parameters:

1. The electrical heat input (H)
2. The incident solar radiation (Gsol)
3. The indoor-outdoor temperature difference (ΔT).

These are represented in Figure 10 below. For steady state conditions, the electrical heat input to maintain a constant internal temperature within the house, will increase when the outside temperature falls and decrease when the solar radiation rises (in actuality these are always fluctuating, but dampened by the thermal inertia of the building). However, neither the heat loss coefficient, nor the solar heat gain factor of the building envelope can be measured directly. The simplest approach is to obtain the whole house heat loss coefficient or heat loss coefficient (Ω-value) and the solar aperture (gA) from the steady state heat balance:

$$H = \Omega \times \Delta T - gA \times Gsol \qquad \textit{Equation 6}$$

The symbol Ω is used as it includes the fabric heat loss through all the building elements, thermal bridges and heat loss by air infiltration (which is a function of both wind speed and temperature difference). This avoids confusion with the UA-value which is commonly used as a measure of the heat loss coefficient of a component.

Improvements to the analysis can be achieved by including other parameters such as wind speed and considering the thermal inertia.

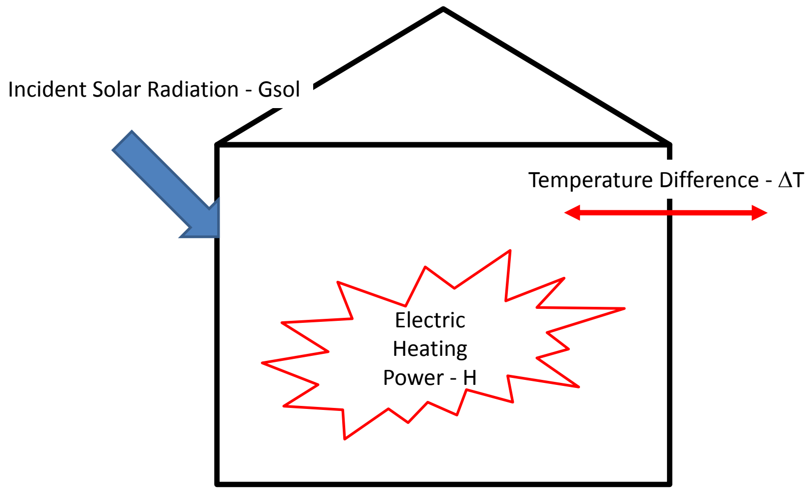


Figure 10: Schematic diagram of main parameters for analysis of co-heating test data using simplified analysis.

Three methods of analysis were used: two are based on linear regression analysis of daily average data and the third is a dynamic technique, which uses hourly average data. The methods, as follows, are explained in detail in the Appendix A.

Linear regression analysis of daily average data:

- Siviour analysis (Siviour, 1981; Everett et al, 1985)
- Leeds Metropolitan University method (Wingfield, 2000)

Dynamic technique:

- LORD program (Gutschker, 2004).

For the Bolsover house, since the temperature of the neighbouring house is unknown, the heat flux measurements on the party wall were area weighted and subtracted from the total heat input.

2.4 SUPPORTING CALCULATIONS

Design values may be used by a building professional to determine the insulation requirement prior to refurbishment in order to meet a specific target, e.g. current regulatory standards. Software such as BuildDesk is used to calculate U-values from manufacturer's data or from a generic database. In order to compare the *in situ* measured U-values post intervention with the 'design' for the walls, floor and ceiling, BuildDesk calculations were performed using available thermal conductivity data for the insulation systems and default brick thermal conductivities from the BuildDesk database.

The BRE U-value calculator was used to estimate whole window U-values based on the centre-of-pane U-values measured. It is possible to do more accurate calculation of the whole window U-values using more sophisticated software (for example TRISCO, www.physibel.be and FRAME, 1993), but this was considered to be beyond the scope of this project.

3. RESULTS

3.1 *IN SITU* U-VALUES

The results are summarised below in Table 2 for measurements made before and after the interventions.

Before intervention:

- The results for the solid brick and plastered walls are consistent across the six measurement locations, except for the kitchen wall which appears to have a significantly lower U-value. In this location, after the plaster was removed prior to installation of insulation, it was noted that part of the internal brick leaf had be removed and filled with plaster or filler, which may account for the lower U-value.
- The measured U-value of the gable wall in the living room is consistent with the calculated value (using BuildDesk) for a solid brick wall with plasterboard on timber studs forming an air gap.
- The variation in the measured ceiling U-value in the main bedroom is consistent with observed variation in the depths of insulation in the loft space.
- The measured centre-of-pane results for the windows are consistent with calculated values for single glazing and an air-filled sealed double glazing unit without low-e coatings (BS EN 673:2011).

After the insulation measures were carried out:

- The type C (wood fibre) system gave similar results in all four measurement locations, with an average U-value of 0.33 ± 0.03 W/m^{2}K.
- On the ground floor, the average U-value for type B insulation (PIR with service void) was 0.27 ± 0.03 W/m^{2}K, excluding an anomalously high result of 0.67 W/m^{2}K from the rear elevation (kitchen wall). Inspection here revealed a probable thermal 'by-pass' from a poorly sealed wall vent, allowing external air to enter the service gap between the plasterboard and insulation.
- Only one result was obtained for type A insulation, from the bathroom wall, 0.20 ± 0.02 W/m^{2}K, since the heat flux sensor fell off the hall wall soon after the start of the test.
- The bedroom ceiling results show more consistency than before improving the loft insulation: average 0.15 ± 0.02 W/m^{2}K.
- Insulation between the joists of the suspended timber floor in the living room results in a significant improvement in U-value from 1.2 to 0.32 W/m^{2}K.
- The centre-pane U-value for the low-e single pane secondary glazing applied to the single glazed timber windows (1.6 W/m^{2}K) is similar to that measured in the laboratory for Historic England (Baker et.al., 2009), and to modern sealed double-glazing units.
- Using vacuum double glazing in the secondary glazing system gives further significant improvements in the centre-of-pane U-value (0.8 W/m^{2}K).
- All the measures tested show substantial reductions in U-values in comparison with the pre-intervention values.

Table 2: Summary of in situ U-values

	Before		After	
Element/Room	**Detail**	**U-value W/ m^2K**	**Detail**	**U-value W/ m^2K**
Front elevation east wall (Living room)	Brick & solid plaster	1.75	Type B	0.28
Gable wall (Living room)	Brick & plasterboard on studs	1.21	Type B	0.25
Suspended timber floor (Living room)	Un-insulated	1.19	100mm wood fibre insulation between joists	0.32
Gable wall (Hall/Bathroom)	Brick & solid plaster	1.65	Type A	0.20
Rear elevation west wall (Kitchen)	Brick & solid plaster	1.36	Type B	0.67
Solid floor (Kitchen)	Concrete/ Screed/vinyl floor covering	0.82	No change	0.82
Ceiling (Main bedroom)	Insulation various thicknesses	0.17 & 0.45 (Adjusted values for the roof space resistance)	300mm glass fibre between & over joists	0.15 & 0.16 (Adjusted values for the roof space resistance)
Front elevation east wall (Main bedroom)	Brick & solid plaster	1.76	Type C	0.33
Gable wall (Main bedroom)	Brick & solid plaster	1.78	Type C	0.35
Rear elevation west wall (Bedroom 2)	Brick & solid plaster	1.74	Type C	0.32
Gable wall (Bedroom 1)	Brick & solid plaster	Not measured	Type C	0.32
Glazing Main bedroom (centre of pane U-value)	Double glazing	2.71	Single glazing + low-e secondary glazing	1.63
Glazing Bedroom 2 (centre of pane U-value)	Single glazing	5.23	Single glazing + low-e secondary glazing	1.64
Glazing Bedroom 1 (centre of pane U-value)	Single glazing	Not measured	Single glazing + Vacuum secondary glazing	0.81

3.1.1 Comparison of measured, calculated and default U-values

A comparison is given in Table 3 of the *in situ* U-values, BuildDesk calculations, which give the design values, RdSAP default values (RdSAP 2009 with amendments version 9.9 from SAP 2009 *Appendix S: Reduced Data SAP for existing dwellings)* and Building Regulation U-values from Table 2 Part L1A (2010).

Concerning RdSAP default values, Appendix S (SAP 2009) states

> *a) Reduced data SAP assigns default insulation on the basis of the age band of the part of the property concerned (main dwelling, extension, room in roof). Except for loft insulation which should be measured wherever possible, in most cases the construction elements will be indicated as "as-built" or "unknown insulation".'*
>
> *b) Where it can be established that a building element has insulation beyond what would normally be assumed for the age band, this can be indicated if adequate evidence exists. 'Evidence can be:*
>
> *- 'what is observed in the site inspection (e.g. loft insulation, rafter insulation, cavity wall insulation), and/or*
>
> *- 'on the basis of documentary evidence.*
>
> *'Acceptable documentary evidence includes certificates, warranties, guarantees, building regulation submissions and official letters from the applicable Registered Social Landlord (RSL). The assessor must be confident, and able to demonstrate, that any documentation relates to the actual property being assessed and that there is no physical evidence to the contrary.'*

For Table 3, RdSAP option (b) has been chosen for the walls, assuming a U-value of 0.35 W/m²K on the basis of the specification of the wall insulation (Anderson 2013). The second approach, option (b) is more appropriate for a refurbishment such as New Bolsover house, where the relevant evidence is available and would be the preferred option for a correct assessment. The BuildDesk calculated U-values use a more accurate specification of the insulation systems than RdSAP.

Table 3: Comparison of in situ, BuildDesk calculations, RdSAP 2009 default and Part L1A 2010 Building Regulation U-values.

Element/Build-up	*In situ* U-value, W/m²K	BuildDesk U-value, W/m²K	RdSAP 2009 U-value, W/m²K	Part L1A, W/m²K
Brick wall with insulation type A	0.20 ±0.02	0.28	0.35	0.30
Brick wall with insulation type B	0.27 ± 0.03	0.29	0.35	0.30
Brick wall with insulation type C	0.33 ± 0.03	0.34	0.35	0.30
Ceiling/Roof	0.15 ± 0.02	0.14	0.13	0.20
Suspended timber floor	0.32 ± 0.03	0.31	0.18	0.25

Generally, there is agreement between the BuildDesk values and the *in situ* measurements in Table 3, except for the type A wall. A sample of the insulation used for type A had an aluminium foil backing which would face the original brick wall: depending on the method of fitting used by the contactors, the foil may be considered as forming a low emissivity cavity thus reducing the calculated U-value. It can be demonstrated using a U-value calculator that, for a well insulated wall, the U-value is largely insensitive to the brick properties used, since the thermal resistance of the insulation is significantly greater than that of the brick.

The RdSAP defaults for the insulated walls slightly overestimate the actual values, whilst the ceiling and floor values are more optimistic. It is clear that where the evidence exists (for example in the case of New Bolsover, the Specification and Schedule of Work which details all insulation measures), the appropriate U-values should be used rather than default U-values.

Except for the walls insulated with type C insulation and the suspended timber floor, the other insulation systems meet or exceed the requirements of Part L1A.

3.2 BUILDING PRESSURISATION TESTS

The pressurisation tests were carried out before and after the improvement measures, with vents such as extractor fan inlets and wall vents sealed with masking tape.

The results are shown in Figure 11. Table 4 shows the standard air changes per hour (ACH_{50}), and the Air Permeability or Envelope Air Leakage Index at 50 Pa pressure difference.

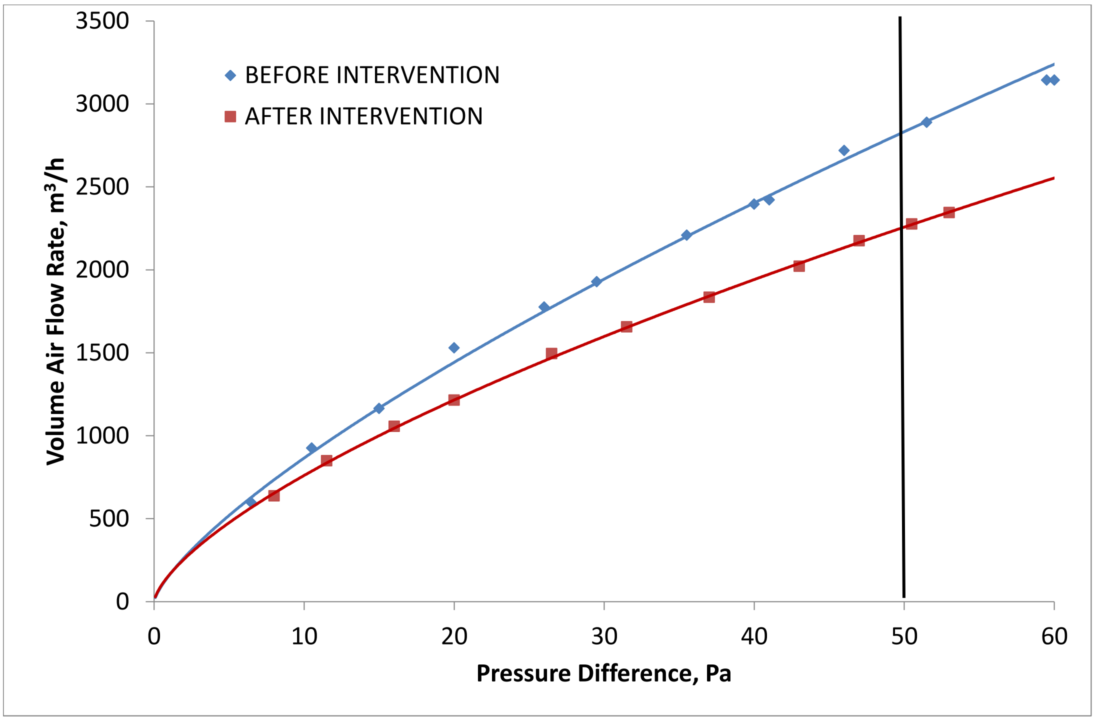


Figure 11: Building pressurisation test results before and after improvement measures for New Bolsover

The BRE's database of air leakage of UK dwellings (Stephen, 2000) gives the relationship between dwelling age and air leakage based on 471 dwellings of different age, size, type and construction. For pre-1900 dwellings an average value of 12.5 air changes per hour @ 50 Pa is given. The value obtained for the New Bolsover house before interventions is similar to the BRE value. However, the results after the interventions show a significant improvement, with the air permeability values just meeting the maximum permissible of $10 m^3/(h.m^2)$ at 50 Pa given in the Building Regulations

Approved Document Part L1A 2010 (HMG, 2010).

Table 4: Summary of building pressurisation test results at 50Pa pressure difference

		Volume air flow rate m^3/h @50Pa	Air Changes per hour @ 50Pa	Air permeability $m^3/(h.m^2)$
Before Intervention June 2011 (SEALED)	Vents, etc. sealed	2832	13	13
After Intervention March/April 2012 (SEALED)	Vents, etc. sealed	2157	10	10

3.3 CALCULATION OF WHOLE HOUSE HEAT LOSS COEFFICIENT BASED ON *IN SITU* U-VALUE MEASUREMENTS

The envelope areas (A) related to each of the *in situ* U-values in Table 2 were estimated from the plans and dimensions provided by Historic England and further measurements made after the post-intervention co-heating test. The U-values of the windows and doors were estimated using the BRE U-value calculator with the measured centre-of-pane U-values. The UA-value of each component was calculated (Table 5).

Equations 3 & 4 are used to calculate the ventilation heat loss term (H_V). H_V has been corrected for infiltration due to chimneys, flues and fans, and a shelter factor for the house according to SAP (2009) of 0.85.

Adding H_V to the sum of the UA-values and a default value for thermal bridges of 0.15 x total area of external elements as recommended in for RdSAP calculations in Appendix S of SAP (2009) gives a whole house heat loss coefficient value (Table 5). This value excludes the party walls. An error estimate is given at the end of the table calculated assuming that the U-value measurements are made to ±10%, dimensions to ±5mm and the building pressurisation test to ±10%, W/K and these errors are random (i.e. unrelated to each other). The uncertainty of the thermal bridge estimates is unknown.

Table 5: Calculation of the whole house heat loss coefficient from in situ U-values. Notes: 'W' and 'D' refer to window and door; 'SG' and 'DG' are single and double glazing, respectively

BEFORE	Area m^2	U-value W/ m^2K	UxA W/K	**AFTER**	Area m^2	U-value W/ m^2K	UxA W/K
Living room							
W1 (DG Aluminium frame)	2.56	3.90	9.98	W1 (SG timber + secondary glazing)	2.56	2.1	5.38
D2 (Timber)	1.65	2.50	4.13	D2 (Timber)	1.65	2.5	4.13
W2 (SG timber)	0.29	3.70	1.07	W2 (SG timber)	0.29	3.7	1.07
Front elevation solid wall area	8.66	1.75	15.16	Front elevation solid wall area	8.49	0.28	2.38
Gabe End	9.70	1.21	11.74	Gable End	9.48	0.25	2.37
Hall							
Gable wall	5.39	1.65	8.89	Gable wall	5.39	0.2	1.08
Bathroom							
W3 (DG PVCu)	0.53	4.50	2.39	W3 (SG timber + secondary glazing)	0.53	2.1	1.11
Rear elevation solid wall area	3.07	1.75	5.37	Rear elevation solid wall area	2.90	0.2	0.58
Gabe End	8.20	1.65	13.53	Gabe End	8.04	0.2	1.61
Porch							
D7 including W5 & W6 (SG timber)	1.63	2.90	4.73	D7 including W5 & W6 (SG timber)	1.63	2.9	4.73
Rear elevation solid wall area	0.96	1.75	1.68	Rear elevation solid wall area	0.96	0.2	0.19
Kitchen							
W4 (SG Aluminium frame)	1.59	6.20	9.86	W4 (SG timber)	1.59	4.5	7.16
Rear elevation solid wall area	4.97	1.36	6.76	Rear elevation solid wall area	4.75	0.67	3.18
Main bedroom							
W7 (DG Aluminium frame)	1.94	3.90	7.57	W7 (SG timber + secondary glazing)	1.94	2.1	4.07
Front elevation solid wall area	11.39	1.76	20.05	Front elevation solid wall area	10.86	0.33	3.58
Gable	9.83	1.78	17.50	Gable	9.58	0.35	3.35

Small bedroom 1							
W8 (SG Aluminium frame)	1.32	6.10	8.05	W8 (SG timber + vacuum secondary glazing)	1.32	1.2	1.58
Rear elevation solid wall area	4.25	1.74	7.40	Rear elevation solid wall area (bed1)	3.99	0.32	1.28
Gable	11.37	1.78	20.24	Gable	11.11	0.35	3.89
Small bedroom 2							
W9 (SG Aluminium frame)	1.30	6.10	7.93	W9 (SG timber + secondary glazing)	1.30	1.8	2.34
Rear elevation solid wall area	6.21	1.74	10.81	Rear elevation solid wall area	5.91	0.32	1.89
Bedroom Ceilings	38.32	0.34	13.03	**Bedroom Ceilings**	35.48	0.16	5.68
Ground Solid Floor	22.47	0.82	18.43	**Ground Solid Floor**	21.71	0.82	17.80
Ground Suspended Floor	17.25	1.19	20.53	**Ground Suspended Floor**	16.62	0.32	5.32
Fabric Heat Loss, excluding thermal bridges, ΣUA W/K			246.80				85.74
Default thermal bridging value, ΣΨL W/K			26.23				25.21
Total Fabric Loss =ΣUA + ΣΨL W/K			273.03				110.95
Ventilation heat loss, Hv W/K (adjusted for infiltration due to chimneys, flues and fans, and shelter factor SAP2005)			50.11				40.66
Whole house heat loss coefficient = ΣUA + ΣΨL + Hv W/K			323.14				151.61
Estimate of total floor area, m^2			87.84				84.51
Heat Loss per unit floor area, W/m^2K			3.68				1.79
The estimated errors of the Whole house heat loss coefficient values, assuming the U-value measurements are made to ±10%, dimensions to ±5mm and the building pressurisation test to ±10%							
Before			*±25W/K (8%)*	*After*			*±9 W/K (6%)*

Table 6 shows the reduction in the main thermal performance parameters due to the intervention.

Table 6: Improvement in the thermal performance parameters due to the intervention

	Percentage Reduction due to intervention
Fabric Heat Loss, ignoring thermal bridges, ∑UA W/K	65%
Total Fabric Loss, including thermal bridges =∑UA + ∑ΨL W/K	59%
Ventilation heat loss (adjusted for infiltration due to chimneys, flues and fans, and shelter factor SAP2009), Hv W/K	19%
Whole house heat loss coefficient = ∑UA + ∑ΨL + Hv W/K	53%
Heat Loss per unit floor area, W/m^2K	51%

The greatest improvement is the reduction in the fabric heat loss due to improved insulation of most of the building elements. Even replacing an aluminium window frame is an improvement. Including default thermal bridges, which may be pessimistic values, there is a reduction of 59% in the total fabric heat loss. Including ventilation heat loss, which was reduced by 19%, the overall reduction in whole house heat loss coefficient was 53%. This translates into a 51% reduction in the heat loss per unit floor area (note that the internal insulation reduced the useable floor area by about 4%).

Table 7 summarises the before and after results from Table 5 for heat loss through the building elements, and due to thermal bridges and ventilation.

Table 7: Summary of the heat losses through the building elements and due to thermal bridges and ventilation, based on Table 5 and the reductions in the heat loss due to the interventions.

	Heat loss through element, W/K		Reduction of heat loss through element
	Before	After	
Windows & Doors	56	32	43%
Walls	139	25	82%
Floors	39	25	41%
Ceilings	13	6	56%
Thermal Bridges	26	25	4%
Ventilation	50	41	19%

Significant reductions in the heat loss through all building elements are made due to the interventions; the main reduction is through the walls from 139W/K to 25W/K (82%). Replacing the aluminium windows frames with timber and installing high specification secondary glazing reduces the overall heat loss through windows and doors by 43%. Insulating the accessible suspended timber floor, which comprises about 43% of the ground floor area, reduces the heat loss through the floors by 41%. Removing the poorly laid loft insulation and replacing with 300mm glass fibre insulation reduces the heat loss through the ceiling by 56%. Ventilation heat loss is reduced by 19%. There is a small reduction in thermal bridging, due to the reduced total area following the insulation of the walls, since default values have been assumed following SAP2009; detailed calculations may produce a different result.

Figure 12 shows the heat loss through each of the fabric elements and due to ventilation and thermal bridges as a proportion of the total heat loss for before and after the interventions. Before the interventions, the walls are the major source (43%) of heat loss followed by windows and doors (17%). After the interventions, whilst the heat loss through the walls is reduced to 17% of the total, the windows and doors become more significant at 21%. Ventilation represents a higher proportion of the total heat loss after the interventions (27%) compared to before (16%). This highlights the need for identifying and improving areas of poor airtightness and implementing a well thought-out ventilation strategy, for example, installing a mechanical ventilation and heat recovery system. The change in the proportions of heat loss through thermal bridges should be considered after more detailed calculations have been carried out.

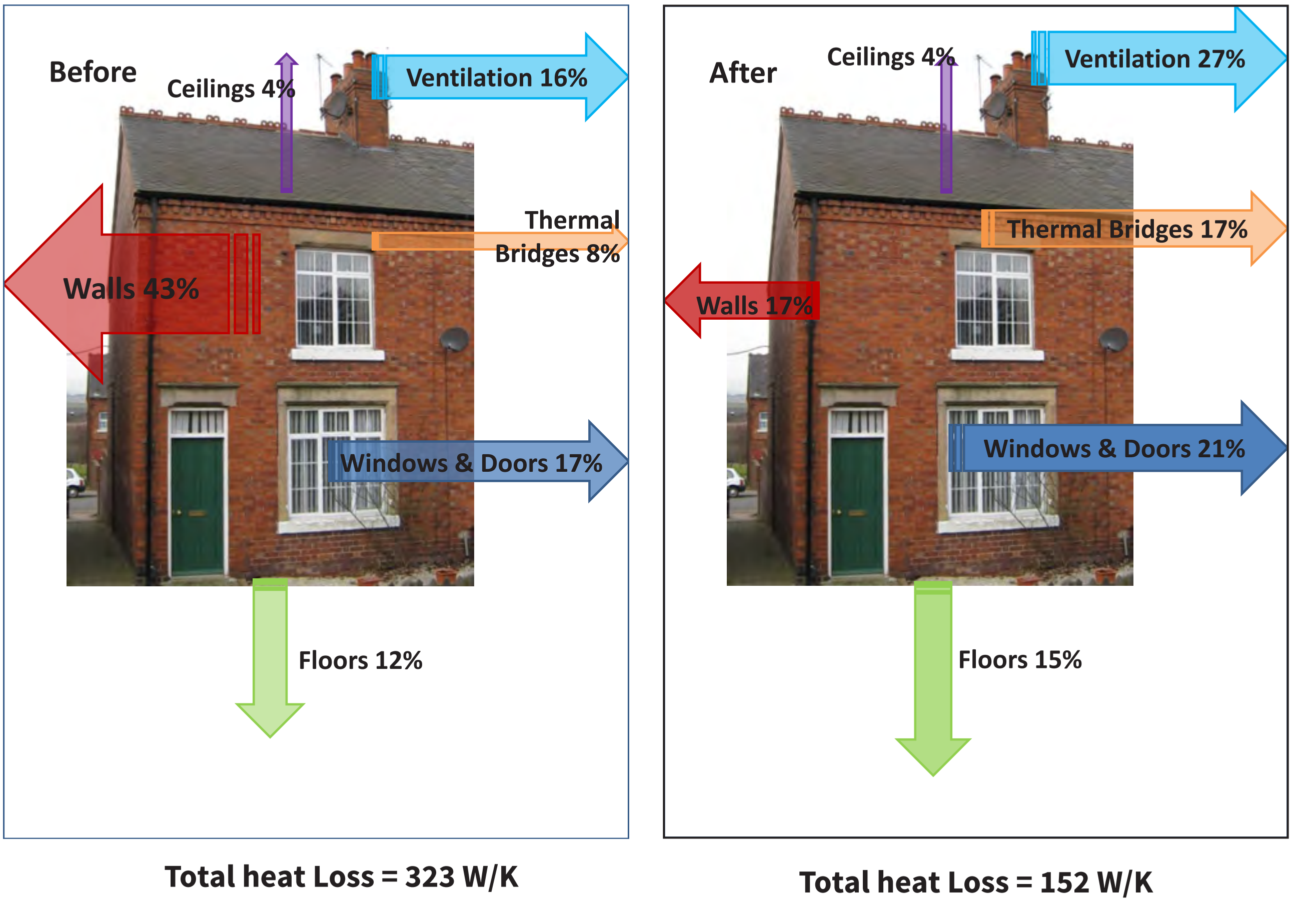


Figure 12: The proportions of heat loss through the building elements, thermal bridges and ventilation before (left) and after (right) the interventions.

The results from Table 5 can be used as input into a SAP calculation to determine the SAP and CO2 emission ratings. STROMA FSAP 2009 (www.stroma.com/certification/software/sap-software-fsap) was used to determine the ratings, annual CO2 emission rate and energy consumption, given in Table 8.

Table 8: SAP 2009 results based on the measured in situ U-values Table 5.

	Before	**After**
SAP rating	46	65
SAP Band	E	D
CO2 Emission Rate $kgCO_2/year/m^2$	70	43
EI Rating	41	62
EI Band	E	D
Total fuel used kWh/ year $/m^2$	347	210
Total primary energy used kWh/ year $/m^2$	365	225

It should be noted that no other improvements were included in the calculations other than the fabric intervention carried out, i.e. improvements to insulation, windows and airtightness. Compared to the 'before' case, the calculated CO2 emissions are reduced by 38%; and the total fuel consumption and primary energy use are reduced by 40% and 38%, respectively. These are reflected in the improvement in the SAP rating by 41%. The EI rating improves by 51%. However, the bands only improve by moving from E to D.

For comparison (see Table 9) the SAP ratings were calculated using Rd SAP default values for U-values. The 'after' ratings were also calculated using the U-values estimated by BuildDesk (Table 3) using default values for brick thermal conductivity and manufacturers' data on insulation and finishes.

Table 9: Using default values in SAP2009 calculations and BuildDesk (post-intervention only) compared to measured values.

	Before		**After**		
	Default using Rd SAP	Measured	Default using Rd SAP	Measured	BuildDesk
SAP rating	42	46	60	65	63
SAP Band	E	E	D	D	D
CO2 kg/m2/year	77	70	50	43	45
EI Rating	38	41	56	62	60
EI Band	F	E	D	D	D
Total Fuel $kWh/year/m^2$	379	347	243	210	218
Primary Energy $kWh/year/m^2$	398	365	259	225	235

Table 9 shows that in the pre-intervention case the SAP rating using the *in situ* measurements is 10% better than using default values for the wall construction. Band E is achieved with both the default and *in situ* values.

In the post-intervention case the SAP rating using the *in situ* measurements is 8% better than using the default Rd SAP values. Band D is achieved with both the default and *in situ* values. The default values result in about 15% higher CO2 emissions, and fuel and energy consumption than using the measured values.

However, the absolute differences between the 'before' and 'after' CO2 emissions and fuel and energy consumptions are similar using only *in situ* or default Rd SAP values. For example, using *in situ* values before and after results in a 19 point increase in the SAP rating and predicted primary energy reduction of 140 kWh/year/m^2; using default values results in a 18 point increase in the SAP rating and 139 kWh/year/m^2 primary energy reduction. The impact of using measured values in terms of SAP calculations is more apparent if, for example, a condensing boiler is installed as part of the intervention strategy: using *default* values for fabric insulation improvement with a condensing boiler results in a SAP rating of D67 and a primary energy use of 205 kWh/year/m^2, whereas using *measured* values plus a condensing boiler gives a SAP rating of C73 and a primary energy use of 165 kWh/year/m^2.

Using BuildDesk U-values gives CO2 emissions and fuel and energy consumptions about 4% higher than measured values for the post-intervention case. A plausible scenario when assessing a refurbishment project by a Green Deal assessor, without before and after measurements, would be to survey the house and assign default Rd SAP values prior to intervention and use BuildDesk values post-intervention to determine SAP ratings and energy and CO2 savings, which would be allowable for SAP calculations since the insulation properties and construction details are known post-intervention. This approach tends to overestimate savings compared with using only *in situ* or default Rd SAP values and would result in a 21 point improvement in the SAP rating for the post-intervention case compared with the pre-intervention value and a 163 kWh/year/m^2 primary energy reduction.

3.4 CO-HEATING TEST

The results are based on the analysis of the measurements, which were undertaken between 1st April and 11th May 2011 for the pre-intervention test and between the 10th March and 12th April 2012 post-intervention.

The average values of the main parameters are given in Table 10. Since the temperature in the neighbouring house was not known, the heating power (H) was calculated by subtracting the heat into the party walls from the recorded total heat input (W). The party wall heat loss was estimated by multiplying the measured heat flux by the relevant party wall areas. The average "heat requirement" ($H/\Delta T$) has been calculated, which gives an estimate of the heating power required to maintain the room temperature (at a nominal set point) per degree temperature difference above the external temperature. The calculated elemental heat loss values are somewhat higher than the $H/\Delta T$ values, however the latter are influenced by solar gains and the ventilation rate. The variation of the *daily* average values of $H/\Delta T$ with solar radiation and wind speed is shown in Figures 13 & 14, for before and after the intervention.

Table 10: The average values of the main parameters for the co-heating test.

	Before Intervention (2011)	After intervention (2012)
Electricity Consumption = Heating Power [W]	2588.8	2170.6
Heating Power excluding estimated heat loss through party wall - H [W]	2379.3	1933.9
Estimate of heat loss through party wall [%]	8%	11%
External Temperature [°C]	12.0	8.4
Average Room Temperature [°C]	24.5	25.0
Ground Temperature under suspended timber floor [°C]	13.7	12.1
Incident Solar Radiation Gsol [W/m2]	94.6	98.6
Wind Speed [m/s]	1.3	1.1
Temperature Difference - ΔT [K]	12.5	16.7
Heat requirement - H/ ΔT [W/K]	**190.7**	**116.0**

Figure 14 shows clearly that the heat requirement is lower after the intervention. There is some correlation between the heating requirement and solar radiation, i.e. on days when solar radiation levels are high, the heating requirement tends to reduce and *vice versa*. This effect is more noticeable before the intervention because afterwards the high specification secondary glazing and thicker profile timber framed windows reduce the solar gains. On days when wind speed is high, notably the first few days in April 2011, the heating requirement increases (Figure 13).

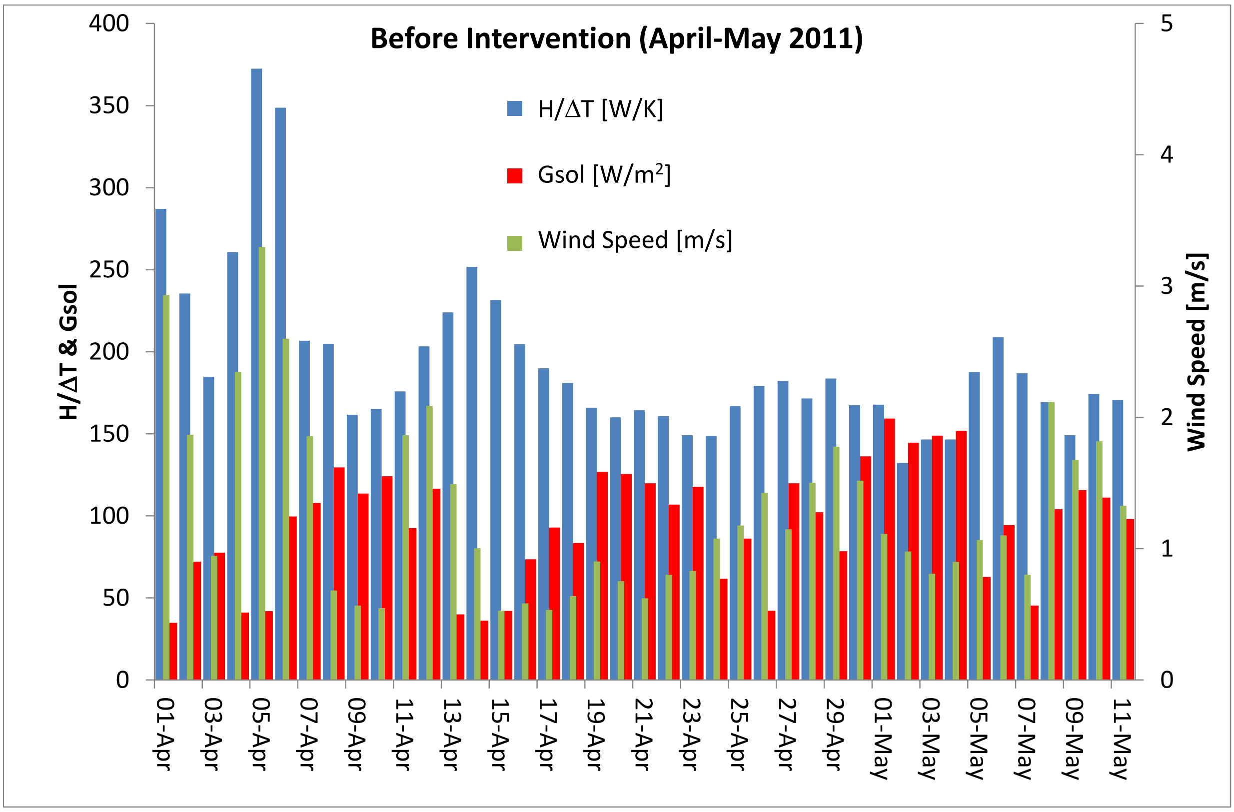


Figure 13: Before Intervention. The daily average values of H/ΔT, Gsol and wind speed during the co-heating test.

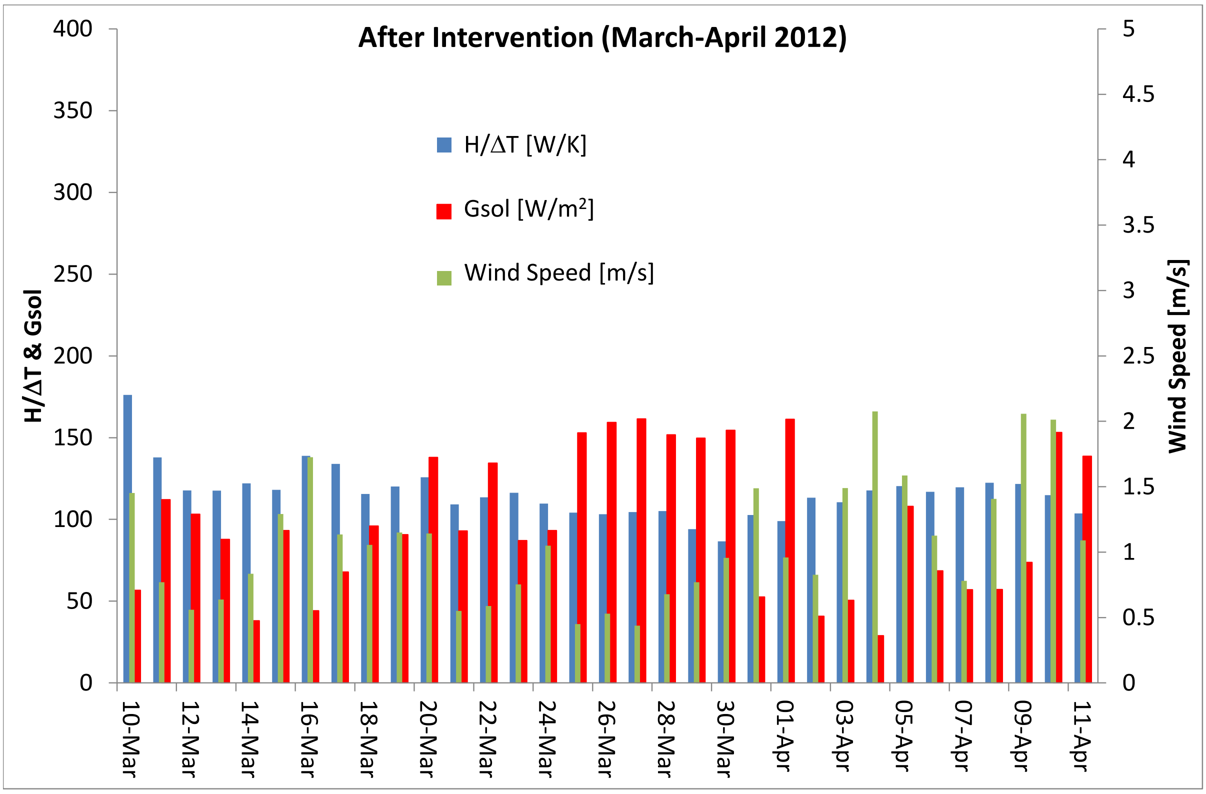


Figure 14: After Intervention. The daily average values of H/ΔT, Gsol and wind speed during the co-heating test.

The results, the whole house heat loss coefficient and solar aperture, using the three methods of analysis are given in Table 11. A more detailed discussion of the results and the differences between the analysis methods is given in Appendix A.

Table 11: Co-heating tests results summary and calculated whole house heat loss coefficients from Table 5

	Before		After	
Analysis Method	Whole house heat loss coefficient, W/K	Solar aperture, m^2	Whole house heat loss coefficient, W/K	Solar aperture, m^2
LORD ('dynamic' analysis with hourly data)	251.1 ± 44.3	10.6 ± 1.3	143.0 ± 16.2	4.8 ± 0.7
Siviour analysis : H/ΔT vs. Gsol/ΔT (linear regression with daily average data)	241.0 ± 42.3	7.3 ± 1.9	126.5 ± 16.1	2.0 ± 0.8
LMU (linear regression with daily average data)	240.7 ± 41.1	7.7 ± 1.7	125.5 ± 15.8	1.9 ± 0.8
Calculated whole house heat loss coefficients from Table 5	323.1 ± 25.1	-	151.6 ± 9.5	-

The LORD results are higher, for both whole house heat loss coefficient and solar aperture, than those obtained using regression analysis on daily average data. Baker & van Dijk (2008) suggest that the regression (steady state) analysis using daily average data tends to give a 'flattened' response, resulting in lower whole house heat loss coefficient and solar aperture values, since thermal storage effects due to changes in the external temperature and solar radiation are ignored (see Appendix A). LORD is able to account for thermal mass effects.

Compared with whole house heat loss coefficient values calculated in Table 5 from the *in situ* U-values and building pressurisation test results, reasonable agreement is achieved for the post-intervention results using LORD with the estimated uncertainties. However, the pre-intervention calculated value is somewhat higher than the LORD estimate for the co-heating test. It should be noted that the uncertainties associated with the pre-intervention test may be higher due to wind speed variations over the test and the poor airtightness.

The co-heating tests should be considered as snapshots of the building's performance for a particular set of climate conditions and combine both the heat loss coefficient and ventilation heat loss. It is not straightforward to separate out the ventilation heat loss from the total heat loss measured by the co-heating test, without measuring the actual ventilation rate over the test period.

The main issues with regard to comparison of co-heating tests with SAP whole house transmittance calculations are:

- The actual ventilation rate during the test compared to the estimate of ventilation in SAP derived from pressure test results. Is the factor of N=20 appropriate for calculating the natural infiltration rate from the pressure test result at 50Pa?
- The estimate of the thermal bridges used in the SAP calculation. Detailed thermal bridge calculations are perhaps required rather than using the SAP default.

The dynamic analysis procedure is recommended, since the method can easily deal with the other parameters, such as wind speed, and, in particular, account for thermal capacitance of the building. Modifications to the co-heating test procedure, for example using a dynamic heating sequence internally as recommended by Baker and van Dijk (2008) may give improved analysis, by 'de-coupling' solar gains entering the building via the windows from the electrical heat input.

4. SUMMARY AND CONCLUSIONS

The report presents the following results, before and after interventions to improve the energy efficiency of a brick built end terrace house in New Bolsover, Derbyshire:

1. *In situ* U-value tests on various elements of the house.
2. Building pressurisation tests to determine the airtightness of the house.
3. Estimates of the whole house thermal transmission values based on the *in situ* U-values and building pressurisation tests. These results were also applied in SAP (2009) calculations to determine the SAP and Environmental Impact ratings, CO2 emissions and energy consumption. Additional SAP calculations were made using RdSAP default U-values calculations for the insulation systems used in the improvement works.
4. Co-heating tests to determine the whole house thermal transmission values directly.

In situ U-values

- ***Pre-intervention***

The *in situ* U-values of the solid wall elements are consistent apart from one location in the kitchen.

The glazing U-values confirm expectations regarding the glazing types (single glazing and air filled double glazed units with no low-e glazing).

The two U-values results for the ceiling reflect the variations in the observed insulation depth in the loftspace.

The pre-intervention *in situ* U-values are lower (better) than the accepted default values for solid brick walls. The average measured U-value of the plastered brick walls is 1.7 W/m^{2}K compared with 2.1 W/m^{2}K as given Appendix S of SAP2009.

- ***Post-intervention***

The *in situ* U-values of the wall elements are generally consistent depending on wall type or system applied during the intervention, except at one location in the kitchen, where outside air from a poorly sealed wall vent was entering the service void behind the plasterboard, by-passing the insulation.

The post-intervention *in situ* U-values are generally in good agreement with BuildDesk calculations using manufacturers' data, except for the type A insulation system, where the *in situ* result was significantly better than the BuildDesk value. Depending on the precise details of installation by the contractor, this may be because a low emissivity cavity was formed between aluminium foil backing of the insulation and the brick wall.

The two U-values results for the ceiling before intervention reflect the variations in insulation depth in the loft space; the results after intervention are consistent with an even insulation depth.

The measured centre-pane U-values of the windows confirm expectations from other studies (Baker, 2009). Calculations were made to estimate the whole window U-values. The result for the replacement single glazed timber window with secondary vacuum glazing was 1.2 W/m^{2}K compared with 2.1 W/m^{2}K for low-e secondary glazing and 4.5W/m^{2}K for a timber window with single glazing only. The vacuum secondary glazing exceeds the Building Regulation target for windows of 2.0 W/m^{2}K. The replacement timber windows with secondary glazing outperform the double glazed aluminium windows.

Airtightness

The air permeability after intervention is reduced to 10m^3/h per m^2 of envelope area, at 50Pa pressure difference compared to 13m^3/h per m^2 before, therefore the house just meets the target required by the 2010 Building Regulations AD Part L1 for new dwellings in England & Wales.

SAP rating

The whole house heat loss coefficient values calculated from the *in situ* U-values, measured areas, building pressurisation test results and a correction for thermal bridges form the basis of the SAP2009 rating. A reduction of 53% in the whole house heat loss coefficient using the SAP calculation was achieved by the improvement measures. The full SAP calculations using *in situ* U-values show an improvement in the rating band from E before to D after improvements and the Environmental Rating from E to D, with a reduction of 38% in CO2 emissions and primary energy consumption. Further improvement would be expected if other interventions, such as central heating boiler replacement and ventilation heat recovery were made.

- ***Pre-intervention***

Before the intervention using either measured *in situ* or RdSAP default U-values give SAP ratings which fall within band E, although the *in situ* U-values produce a rating 10% higher than the default values: the average (area-weighted) measured U-values of the walls is 1.6 W/m^{2}K compared with the default value of 2.1 W/m^{2}K. Using default values for Green Deal calculations will result in an over-prediction of energy consumption compared with measured *in situ* U-values.

- ***Post-intervention***

Post-intervention, using the measured *in situ* U-values produced a SAP rating within band D, whilst the RdSAP default U-values produced a 8% lower rating in band D. The main discrepancy is due to the higher default U-value assumed for insulated wall of 0.35 W/m^{2}K compared with the average measured *in situ* U-value of 0.31 W/m^{2}K.

The comparisons indicate that the measured *in situ* are preferable to RdSAP default values in the SAP calculations post-intervention.

- ***Predicted improvements using SAP2009***

The magnitude of the predicted improvements in performance due to the interventions are similar comparing default Rd SAP and measured *in situ* U-values, however the latter result in a higher SAP rating and consequently better ratings if further improvements, e.g. boiler replacement, are implemented. The possible scenario whereby a Green Deal assessor may assess the original house using default Rd SAP values and then calculating improved U-values based on manufacturers' data for the retrofitted insulation, whilst producing similar results in the post-intervention assessment as the *in situ* U-values, over-predicts the reduction in CO2 emissions and the energy savings. This would have consequences for the Green Deal financing, since the savings would not be achieved in practice. The best option is therefore to use measured U-values if possible, or alternatively gain improved knowledge of the thermal performance of the materials used in the dwelling such as the brick thermal conductivity. Research by Baker and Rhee-Duverne (2013) indicates that, if the thermal conductivity of a brick type is known, the calculated wall U-values tend to converge with the measured *in situ* values. Whilst there is a cost for thermal conductivity measurements, these could be absorbed in a roll-out of upgrading works on estates such as New Bolsover.

The improvements to the windows and the additional loft insulation at New Bolsover are more certain and are relatively straightforward to estimate. The benefit of insulation installed in suspended timber floors is perhaps more uncertain to determine.

Co-heating tests

Whilst the co-heating tests directly reveal the differences in heat requirements before and after the intervention, there were high uncertainties associated with the pre-intervention test. It is considered that this is in part due to wind speed variations over the test and the poorer airtightness. The post-intervention results are more reliable due to the better insulation and airtightness.

The results show major reductions in the whole house heat loss coefficient following the intervention, with the more robust dynamic analysis estimating savings of 43%.

The dynamic analysis gave fair agreement for the whole house heat loss coefficient values derived from the co-heating tests and those calculated from the *in situ* U-values and pressurisation test results after intervention. Before intervention, the calculated value is somewhat higher than the dynamic estimate from the co-heating test. Note that co-heating tests are snapshots of the building's performance for a particular set of climate conditions, and combine both the heat loss coefficient including thermal bridging and ventilation heat loss. Unfortunately, it is not straightforward to separate out the ventilation heat loss from the total heat loss measured, unless the actual ventilation rate is also measured in the course of the test period. The main issues with regard to comparison of co-heating tests with SAP whole house transmittance calculations are

- The actual ventilation rate during the test compared to the estimate of ventilation in SAP derived from pressure test results. Is the factor of N=20 appropriate for calculating the natural infiltration rate from the pressure test result at 50Pa?
- The estimate of the thermal bridges used in the SAP calculation. Detailed thermal bridge calculations are perhaps required rather than using the SAP default.

On the other hand, although a co-heating test may be regarded as the most direct method of measuring heat loss, a combination of *in situ* U-value measurements together and pressurisation test results appears to be more suitable for direct inputs into SAP calculations, provided that sufficient representative measurement locations for U-values are used, determined by a knowledge of the original construction and the types of intervention carried out. *In situ* measurements can also be carried out in an occupied building, while a co-heating test requires several weeks with the building unoccupied.

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In conclusion, the works carried out at New Bolsover have resulted in significant energy efficiency improvements with predicted savings (SAP2009) of 38% in energy use and 38% reduction in $CO2$ emissions, and an improvement in SAP band from E to D, together with practical insights into the best use of RdSAP, and the most appropriate forms of test measurements.

For energy improvement schemes such as the Green Deal, with the financing of improvement measures based on the baseline thermal performance of traditional dwellings, estimates predicated on *in situ* performance measurements will result in a more realistic prediction of energy use than default values, particularly when other improvement are implemented.

Appendix A

A detailed discussion of the analysis and results of the Co-heating tests at New Bolsover

INTRODUCTION

This Appendix discusses some of the methods available to analyse co-heating test data to determine whole house heat loss coefficient. The methods can be divided into two types:

Steady State, which assumes that the system is unchanging with time - this is obviously not the case when considering changing climate conditions or indoor temperatures in a building, however by choosing a sufficiently long test period the Steady State heat loss coefficient of the house can be determined. Daily average data is used in the two Steady State methods described below.

Dynamic, which assumes that the system is changing with time – a shorter data interval, typically one hour, is used in the method described. Whilst the goal is to determine the Steady State heat loss coefficient of the house, thermal storage effects are taken into account in the method.

The treatment of the co-heating tests carried out before and after the intervention is also discussed.

ANALYSIS METHODS

Steady State

A simple way of analysing the co-heating test is to split the data into three parameters representing:

1. The electrical heat input (H)
2. The incident solar radiation (Gsol)
3. The indoor-outdoor temperature difference (ΔT).

These are represented in Figure A1 below. For steady state conditions, the electrical heat input to maintain a constant internal temperature within the house, will increase when the outside temperature falls and decrease when the solar radiation rises (in actuality these are always fluctuating, but dampened by the thermal inertia of the building). However, neither the heat loss coefficient, nor the solar heat gain factor of the building envelope can be measured directly.

The simplest approach is to obtain the whole house heat loss coefficient (Ω-value) and the solar heat gain factor (gA) from the steady state heat balance:

$$H = \Omega \times \Delta T - gA \times Gsol$$

Equation A1

Dividing by ΔT gives:

$$\frac{H}{\Delta T} = \Omega - gA \times \frac{Gsol}{\Delta T}$$

Equation A2

By calculating daily average values of the main parameters, the data can be represented graphically (Siviour analysis: Siviour, 1981; Everett et al, 1985) in an X-Y plot with Gsol/ΔT on the X-axis and H/ΔT on the Y-axis (Figure A2). The overall thermal transmittance and solar gain factor can be estimated by linear regression, where the intercept on the Y-axis is the whole house heat loss coefficient

(Ω-value) and the slope is the solar gain factor (gA). Note that the Ω-value in practice includes the effect of heat loss by air infiltration.

Leeds Metropolitan University (LMU) use linear regression analysis to determine the gA-value and UA from Equation A1 (Wingfield, et al 2000). Rather than consider only Gsol/ΔT as the independent variable and H/ΔT as the dependent variable using Equation A2, in the LMU method both the temperature difference and the solar radiation are treated as independent variables with the heating power as the dependent variable. The daily values of the heating power are adjusted for solar gains:

$$Hsol = H + gA \times Gsol = \Omega \times \Delta T$$ *Equation A3*

These values are generally presented graphically in order to demonstrate the increasing heating load with temperature difference, for example see Figure A3.

Both treatments of the data using either Equation A1 or Equation A2 should yield similar results. The advantage of the X-Y plot (Figure A2) is that all three parameters (H, Gsol and ΔT) are shown together and the influence of solar radiation on performance is clearly demonstrated. However, the LMU approach is statistically better, since Gsol and ΔT are independent variables.

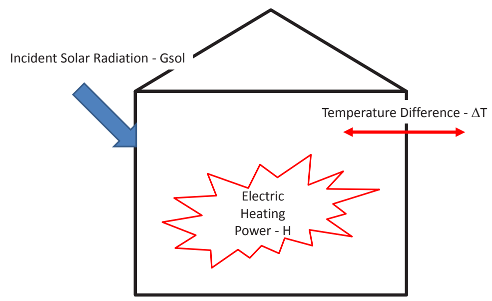

Figure A1: Schematic diagram of main parameters for analysis of co-heating test data using simplified analysis

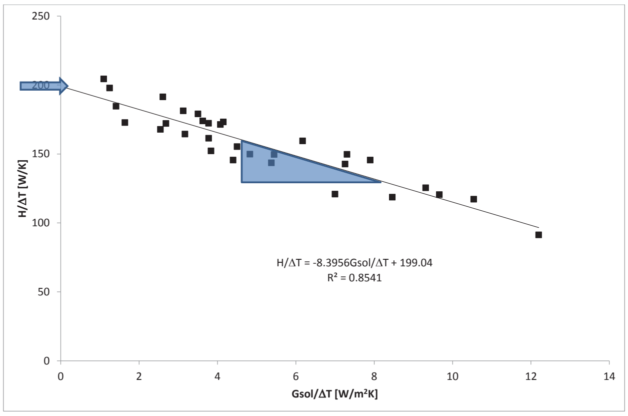

Figure A2: Example of X-Y plot of co-heating test data (Siviour analysis). The intercept of the linear regression line is the whole house heat loss coefficient and the slope is the solar gain factor

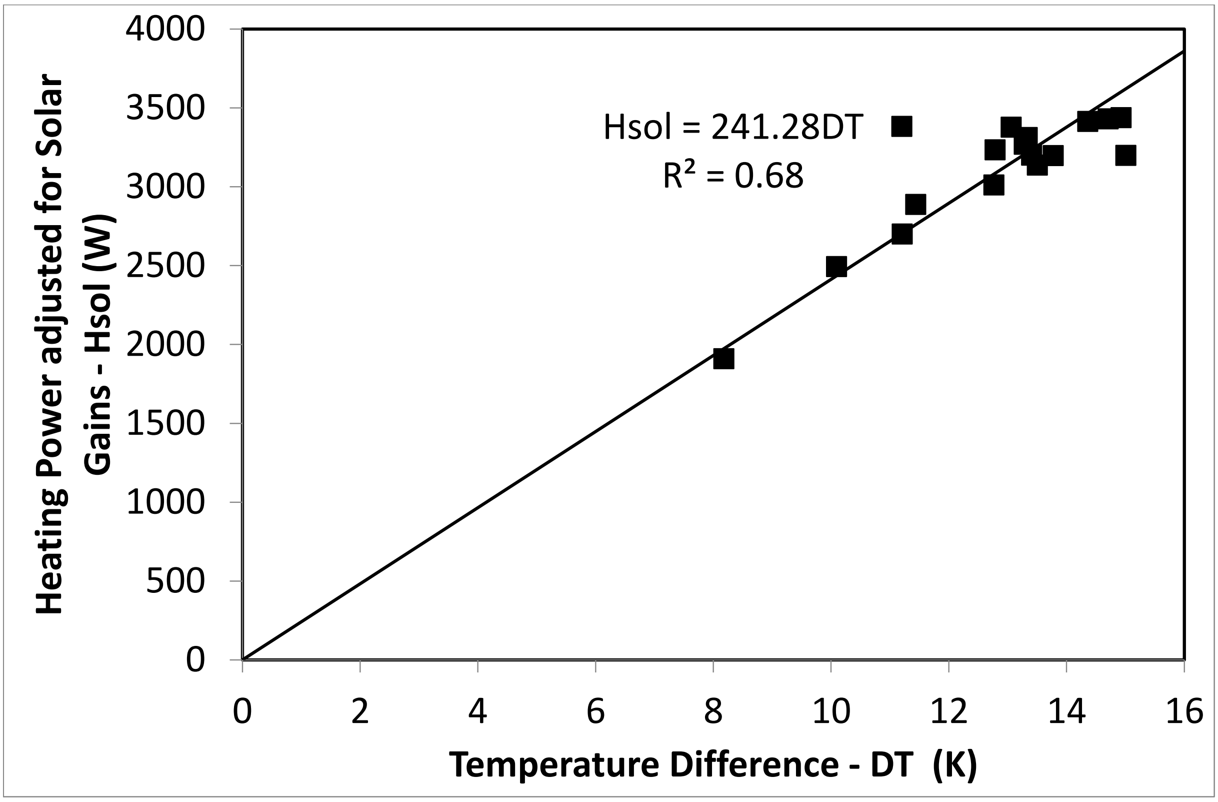

Figure A3: Example of the presentation of the data using the LMU method

THE RATIONALE FOR USING A DYNAMIC METHOD OF ANALYSIS

The disadvantages (Baker & van Dijk, 2008) of the above approaches are as follows:

- The heat balance equations are only valid for steady-state conditions.
- Under real, dynamic conditions, the steady-state equations are only acceptable if integrated values are considered over a long enough period to minimise the dynamic effects. The daily average heat loss may be strongly influenced by the history of the previous days, particularly if the building contains thermal mass which can absorb and release heat from solar gains, for example. This history is ignored in the steady-state analysis.
- The possible effects of short term weather variations on the system's characteristics are ignored, e.g. variation of cloud cover, sun position, outdoor temperature, wind speed, etc.
- The method also yields no information on the dynamics of the system, e.g. thermal capacitance and time constants.

Consider the effects of thermal mass, under test conditions where the daily average ΔT is high, but in preceding days the ΔT was lower. With the building maintained at constant temperature, the average structure temperature (and therefore the heat content) of the building envelope will be relatively high at the commencement of the test period. At the end of the test period (at high ΔT) the average structural temperature will be lower. During the transition, the duration of which depends upon the thermal capacities and insulation properties of the envelope, the stored heat lost from the envelope serves to offset the heating demand and H/ΔT values will be smaller than expected.

Figures A4 & A5 demonstrate the effect. A simple 9" brick wall was modelled using hourly time steps using MATCH heat and moisture transfer software (Pedersen, 1990), assuming a constant internal temperature of 25°C. The software was run with an external temperature of 10oC for 14 days, to reach a steady state, followed by 14 days at 5°C. There is a transition period of about two days following the change in external temperature from 10 to 5°C, during which the mean temperature of the wall decreases and the heat flux through the wall increases until a steady state is reached for the lower external temperature (Figure A7). Daily averages of the heat flux/ΔT (Figure A8) show that there is a decrease of 10% on the first day with a lower external temperature compared to the steady state value of 1.9 W/m^{2}K. The reverse effect occurs when the external temperature increases, with an increase in the daily average heat flux/ΔT of 13%.

The effect with, for example, the normal variation in external temperature is shown in Figure A9 for simulation results over a four week period on the 9" brick wall. Daily average results are plotted as the heat flux through the wall vs. the temperature difference. The 95% confidence limits for the relationship are shown, which indicate the degree of uncertainty in the results. The U-value estimate, i.e. the slope of the linear regression line, is 1.75±0.32W/m^{2}K, whereas the expected U-value from steady state calculations is 1.87W/m^{2}K.

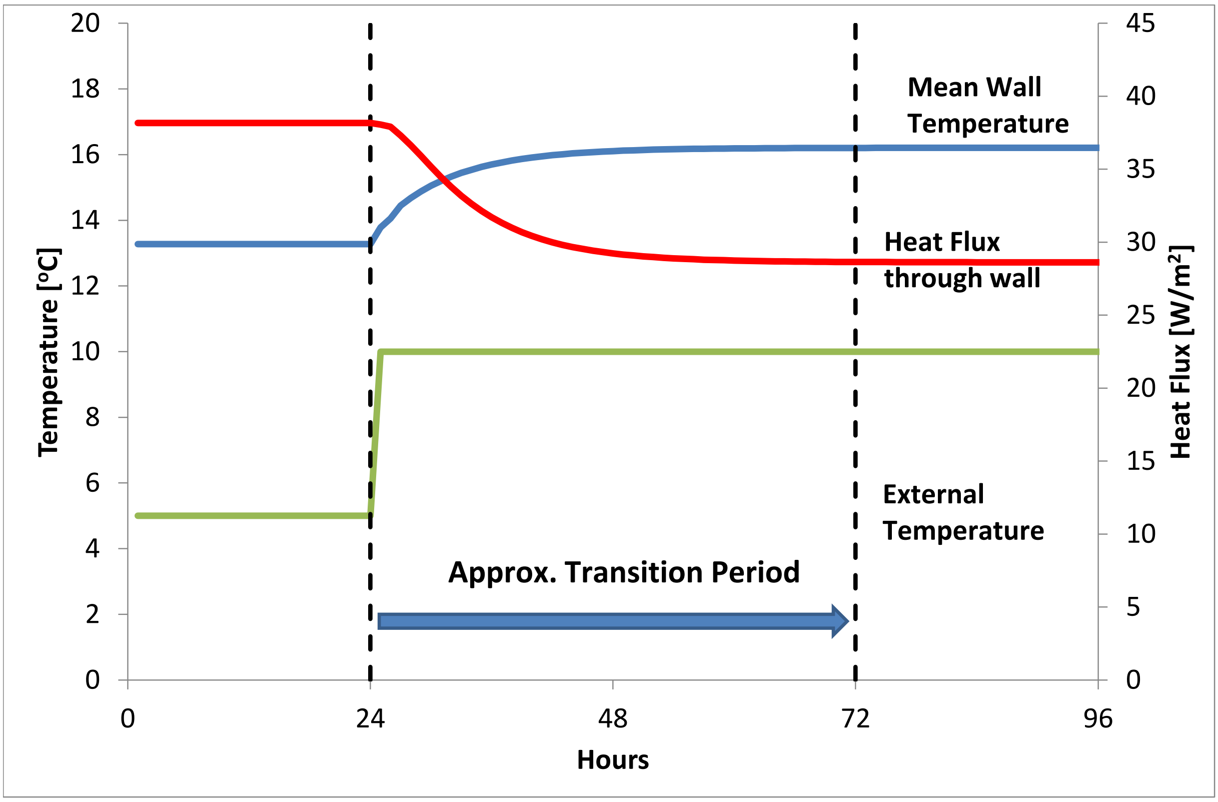

Figure A4: Simulated results for a 9" brick wall for a step change in external temperature, demonstrating the effect of thermal storage in the wall on mean wall temperature and heat flux through the wall.

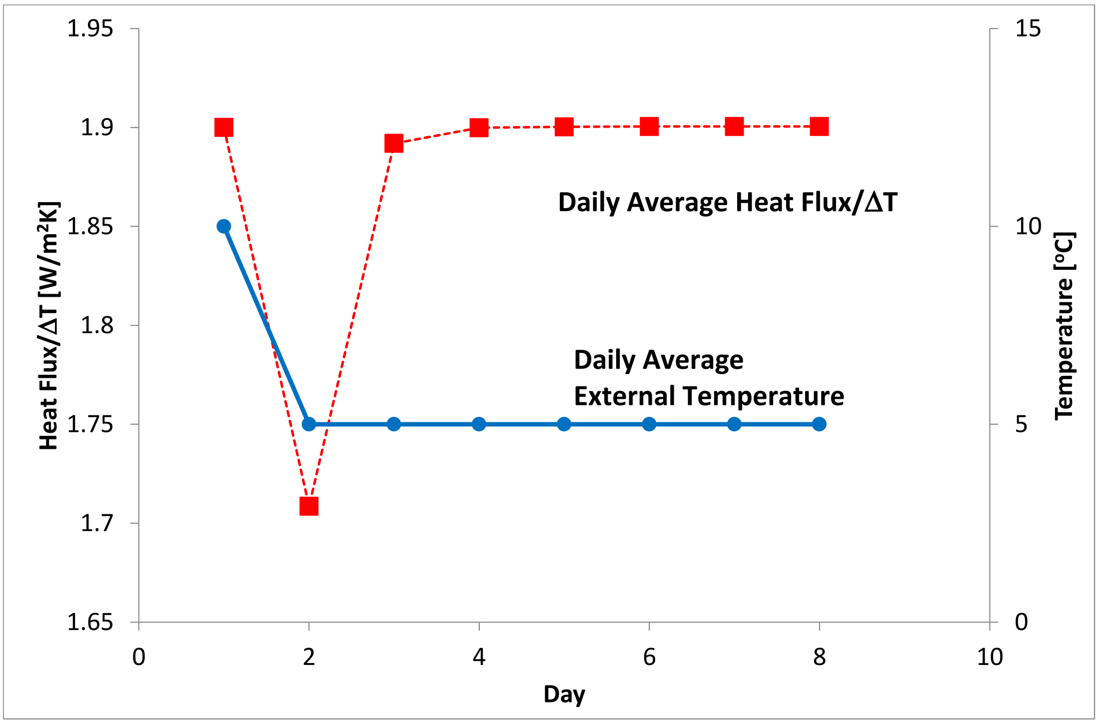

Figure A5: Demonstration of the effect of the step change in external temperature on the daily average value of the heat flux/ΔT.

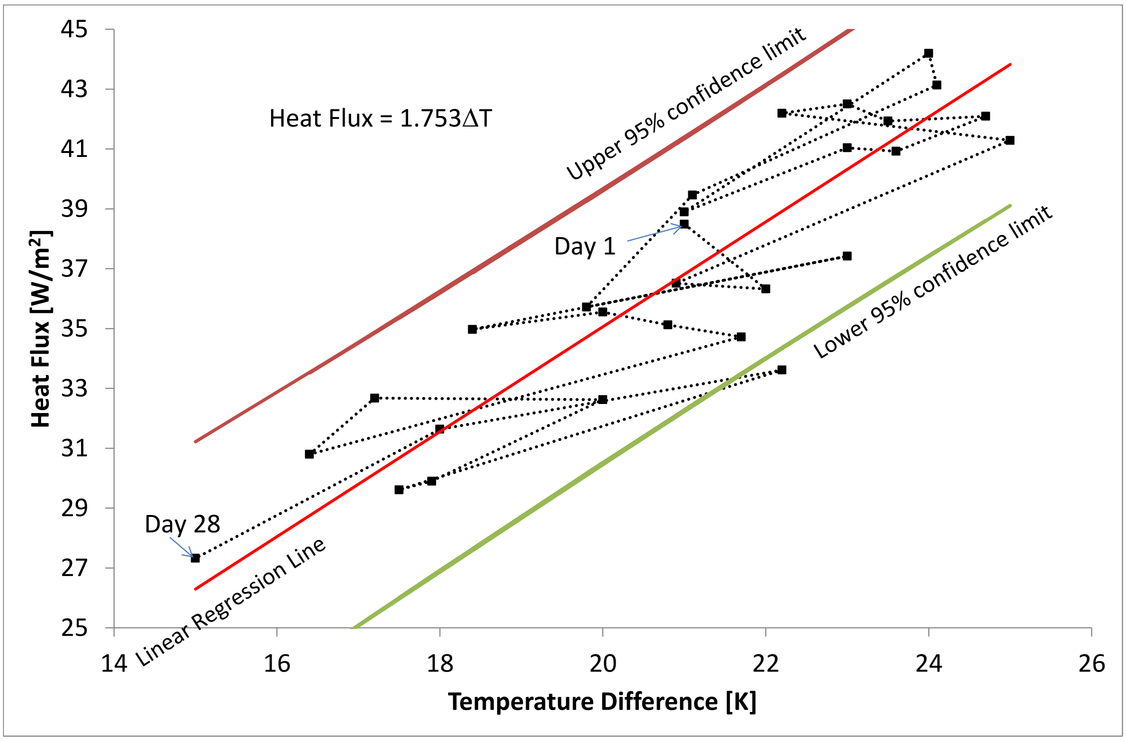

Figure A6: Daily average heat flux vs. temperature difference for simulated data using varying external temperature with 9" brick wall. The linear regression line, the slope of which gives the U-value, and the confidence limits.

Improvements to the analysis could be made by introducing a heat accumulation term ('capacity') in the analysis. From such a rudimentary first order dynamic model, it is not too great a step to a more powerful analysis method incorporating more detailed dynamic information.

DYNAMIC ANALYSIS USING LORD SOFTWARE

In reality, the building responds to the temperature of the neighbouring house and the ground temperature as well as the external air temperature. Variation in infiltration rate also occurs with wind speed and direction. Software such as the LORD program (Gutschker 2004) uses what can be described as a parameter identification approach. A transient mathematical model of the building is assumed. The parameters of the model (e.g. resistances, capacitances and heat flow admittances) essentially define the dynamic and steady-state thermal and solar properties of the system. Using LORD, the user describes the building as a network of conductances and capacitances (Figure A7) with measured input values of the outdoor temperature, the solar radiation and the heating power as functions of time. Other climate variables such as wind speed can also be included in the analysis. The full dynamic information in the data is retained; i.e. hourly data is generally used.

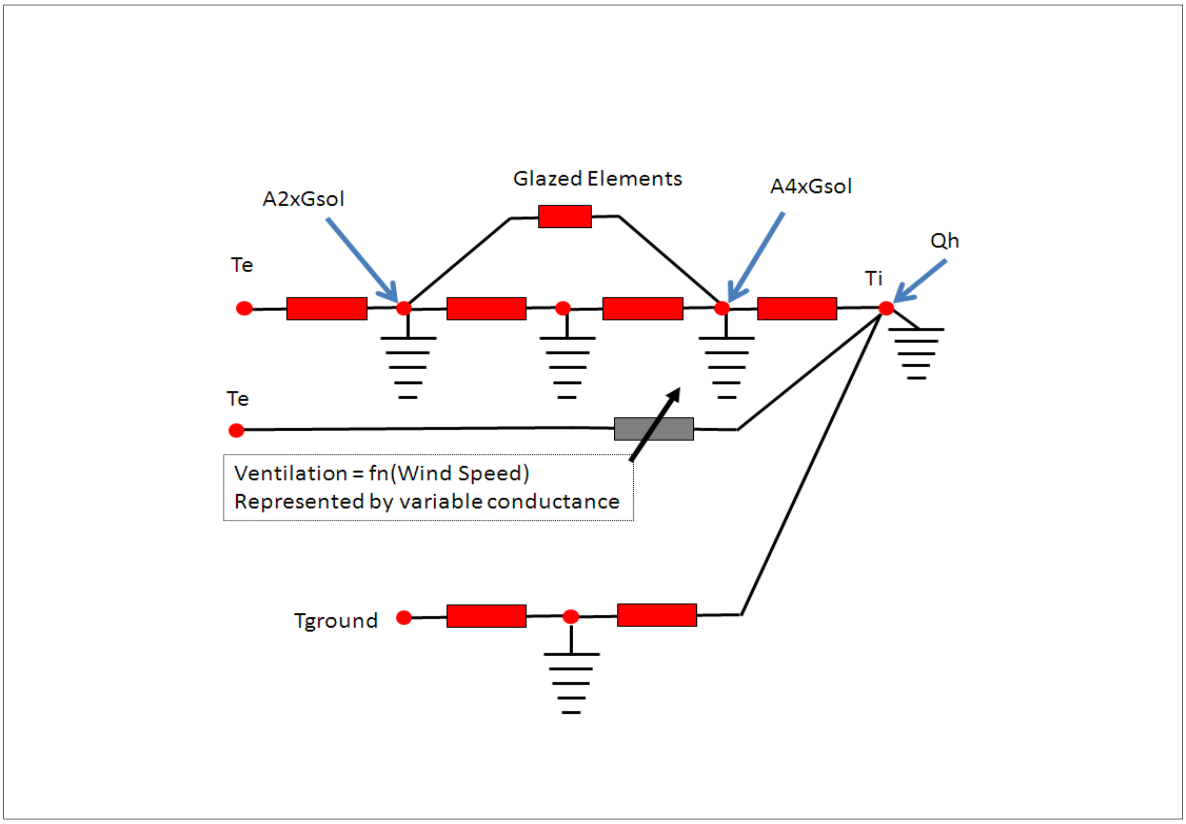

Figure A7: House modelled as a network of conductances and capacitances.

Initial guesses of the parameter values are made. The output of the actual test (for instance, the room temperature as a function of time) is compared with the output which the model produces for the same input conditions. By statistical analysis of the deviations between the calculated and the measured outputs, the parameter values are progressively adjusted in order to improve the agreement. With adjusted parameter values, the whole process of comparison of test and model output, followed by the statistical analysis, is repeated until optimum agreement is reached (Figure A8). The program produces thermal transmittance and solar gain factors.

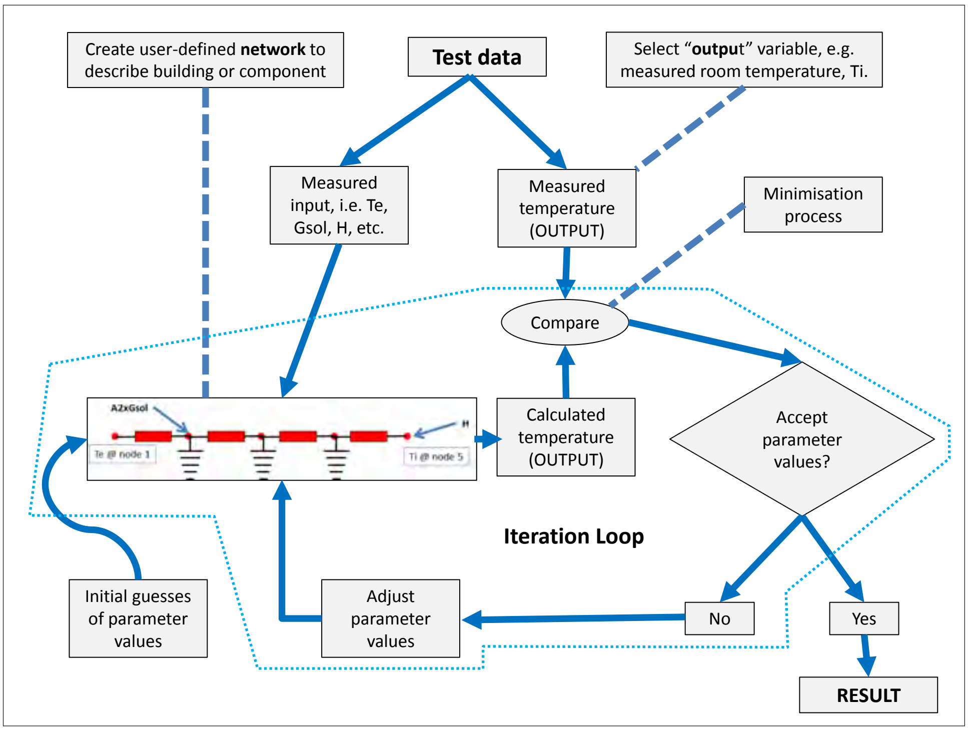

Figure A8: Parameter identification principle.

Consider the data from the 9" brick wall simulation. Analysis using LORD gives a U-value estimate of 1.91W/m²K with a confidence interval of <0.01W/m²K – close to the steady state theoretical value of 1.87 W/m²K. Figure A9 shows the simulated measured daily heat flux through the wall generated by MATCH and the estimates using linear regression and LORD. It is clear that, in comparison with the linear regression, the LORD estimates give excellent agreement with the simulated measured values, while linear regression exhibits significant discrepancies.

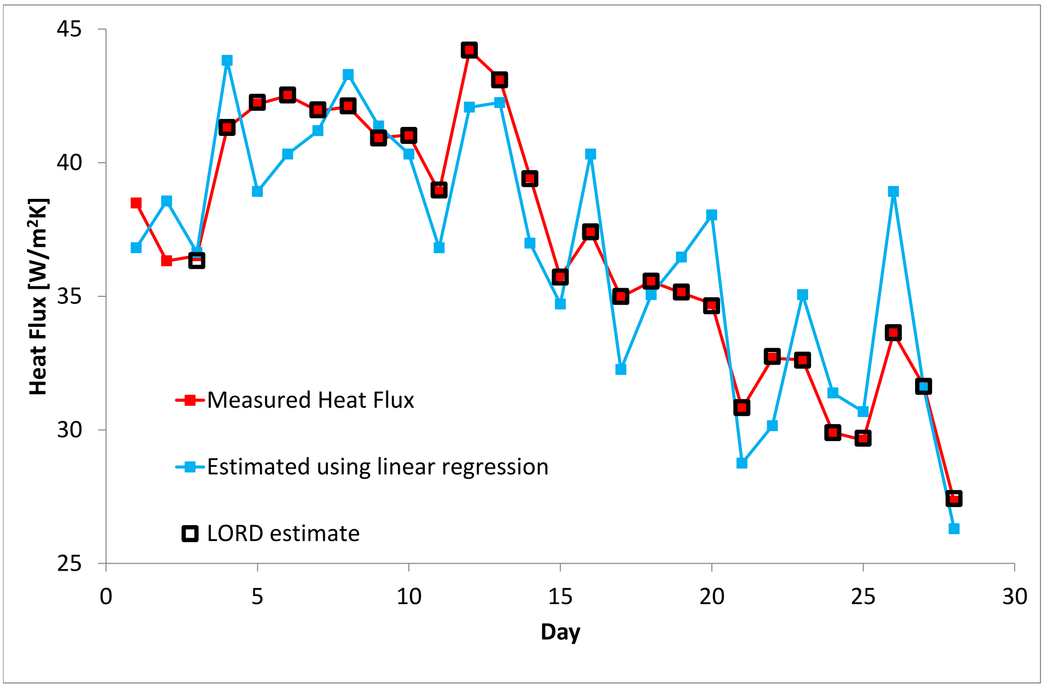

Figure A9: Comparison of the daily average heat flux estimates using linear regression and LORD with the simulated measured values for the simulated 9" brick wall. Note that the LORD estimates overlap the measured heat flux values.

CO-HEATING TEST RESULTS AND ANALYSIS USING THREE METHODS

Siviour Analysis

Figures A10 & A11 show the data plotted as in Figure A2, using Equation A2. The intercept on the H/ΔT axis gives the whole house heat loss coefficient value (Ω-value) and the slope the solar gain factor (gA-value).

By inspection it is clear that there is a considerable spread of data particularly before the intervention (Figure A10). Excluding the two days with high average wind speeds gives a Ω-value of 241.0 W/K with a correlation R2 of 0.37. Selecting only the data for daily average wind speeds below 1m/s gives improved correlation (R2 = 0.48) with a Ω-value of 234.5 W/K. However, neither an intercept nor a slope can be obtained with any confidence.

After removing the outlier from the analysis (Figure A11), the result for the co-heating test carried out after the intervention is 126.5 W/K

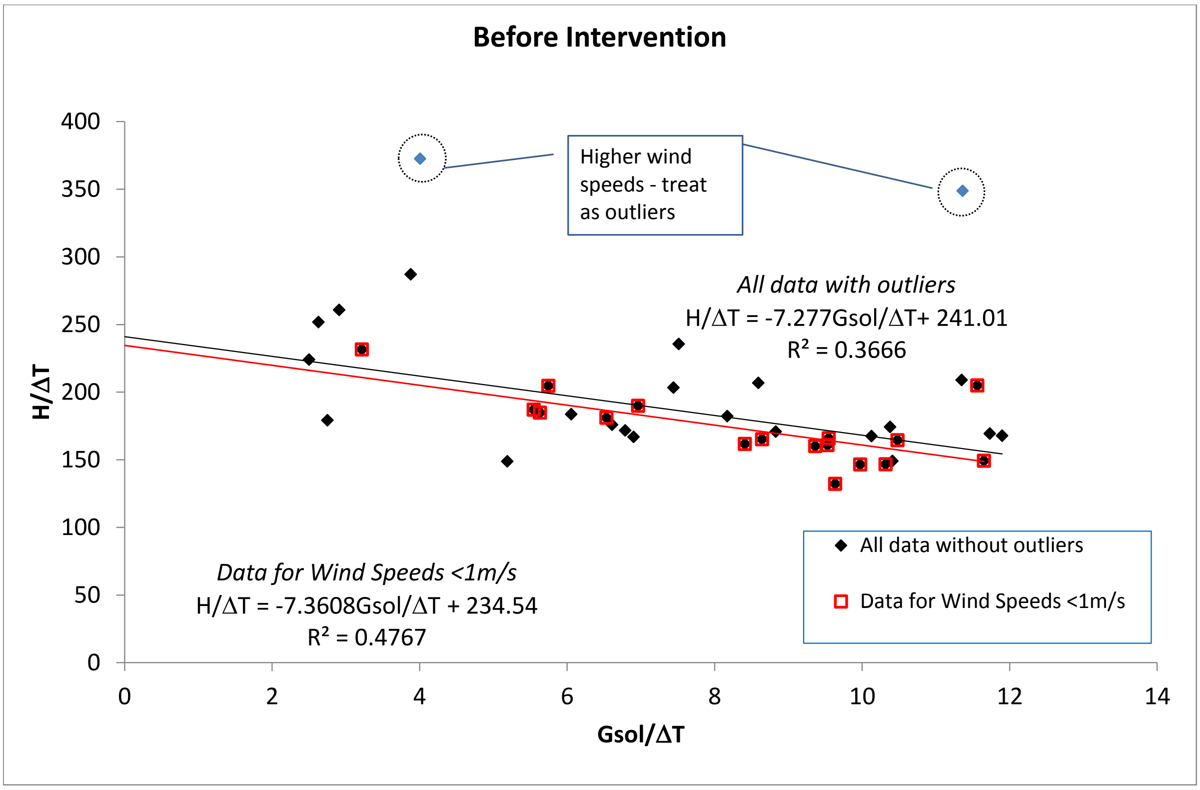

Figure A10: Before Intervention. H/ΔT vs. Gsol/ΔT plot for the daily average values from the co-heating test. The linear regression fits for all the data and only the data for wind speeds less than 1m/s are shown. The intercept on the H/ΔT axis gives the whole house heat loss coefficient value (Ω-value) and the slope the solar gain factor (gA-value).

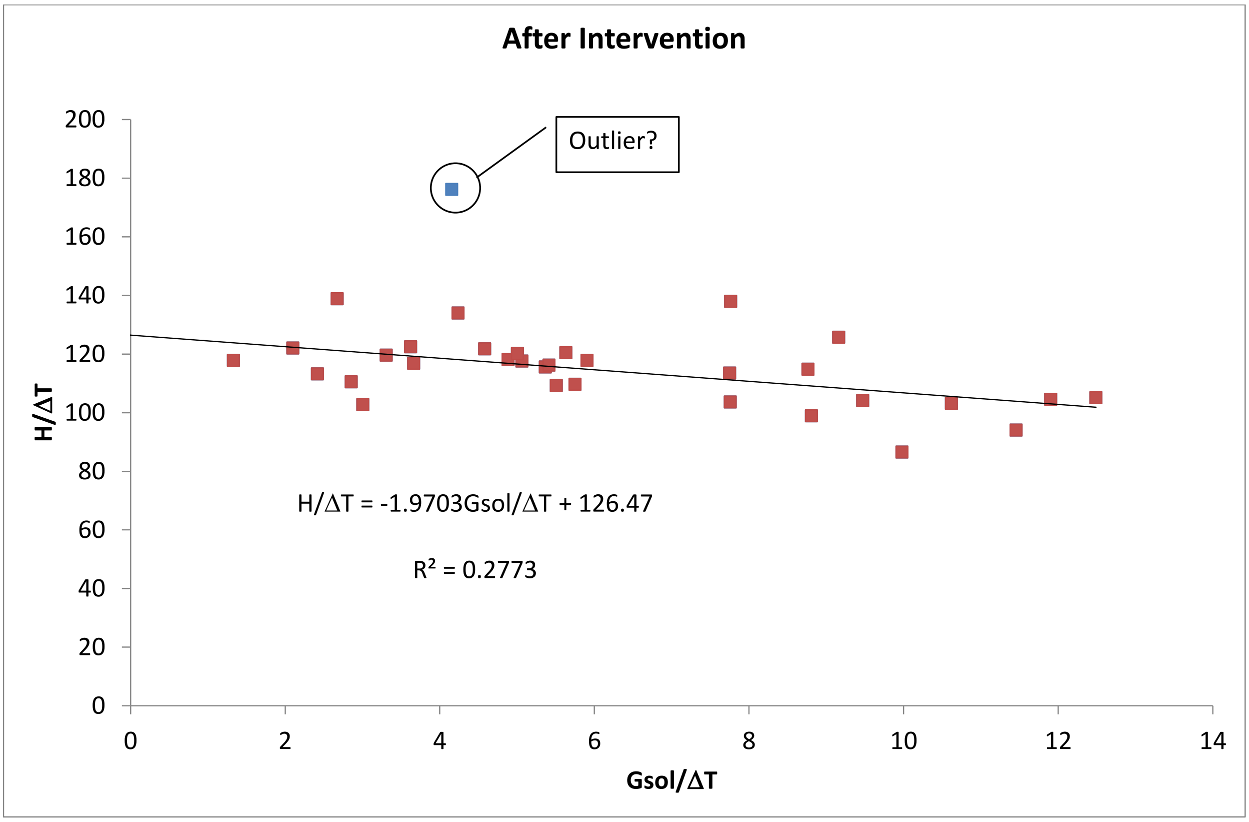

Figure A11: After Intervention. H/ΔT vs. Gsol/ΔT plot for the daily average values from the co-heating test. The linear regression fit for all the data without the outlier is shown.

LMU Regression Analysis with ΔT and solar as independent variables

Applying the LMU method gives similar results to the Siviour analysis using the data with outliers removed (Figure A12):

Before intervention: the Ω-value is 240.7 W/K

After intervention: the Ω-value is 125.5 W/K

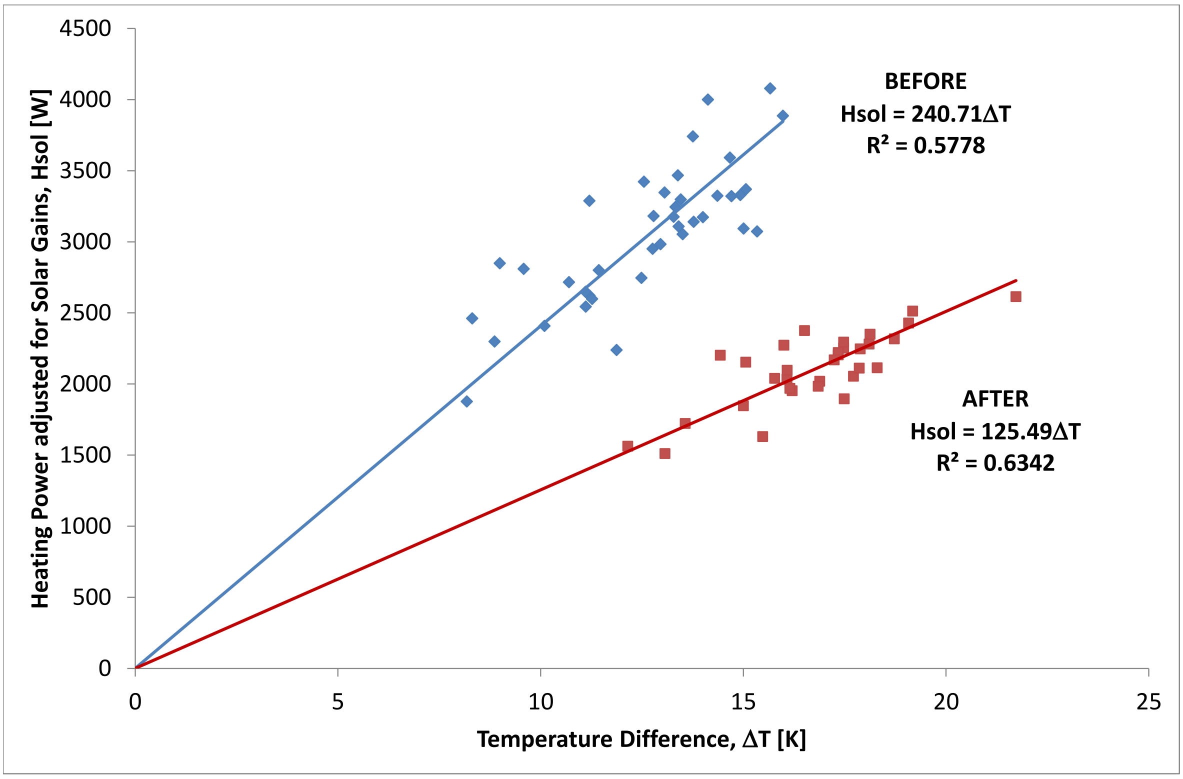

Figure A12: LMU method - heating power adjusted for solar gains plotted against temperature difference for the before and after co-heating tests.

The result for the pre-intervention test shows a high uncertainty with poor correlation coefficients. Generally, the results do not account for all the variation in the heating requirement. Additional analyses were carried out with wind speed included in the regression analysis as an additional variable in Equation A1 as follows:

$$H = \Omega \times \Delta T - gA \times Gsol + \omega \times W \cdot \Delta T \qquad \textit{Equation A4}$$

Where W is the wind speed and ω is a constant.

The term $\omega \times W.\Delta T$ should account for the variation due to the ventilation heat loss.

Figures A13 & A14 show the measured and predicted values of the heating power with and without wind speed for the before- and after-intervention cases, respectively.

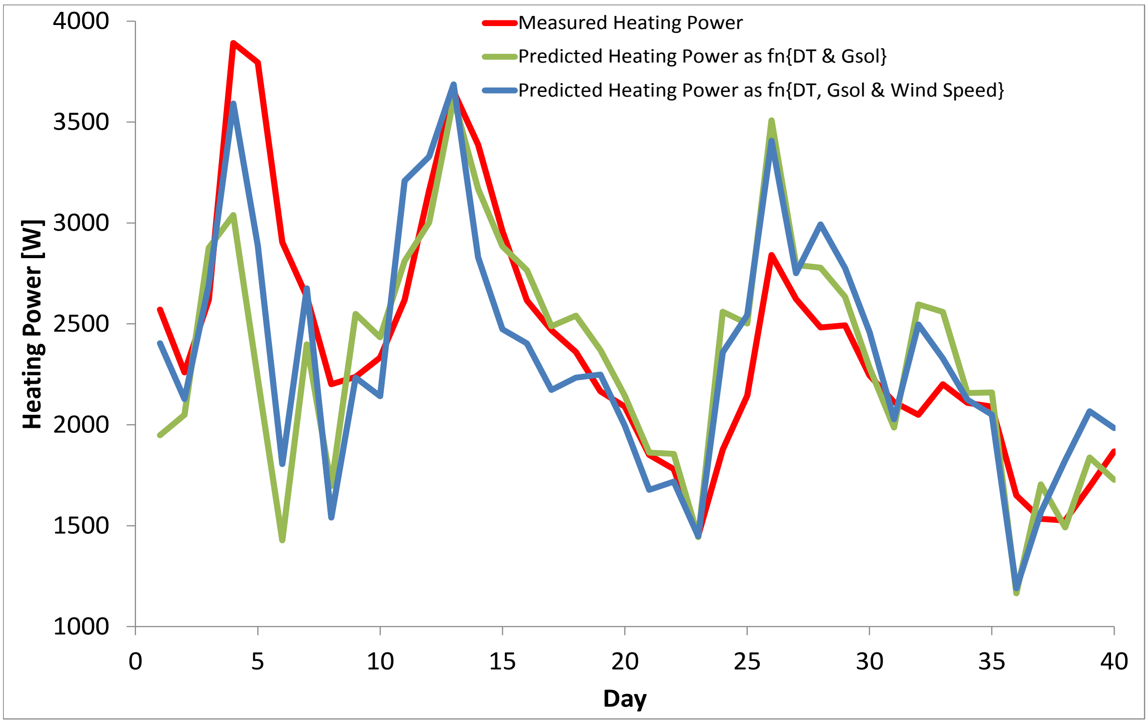

Figure A13: Before-intervention case. Measured and predicted heating power using (a) ΔT and Gsol as the independent variables (Equation A1) and (b) ΔT, Gsol and wind speed (Equation A4).

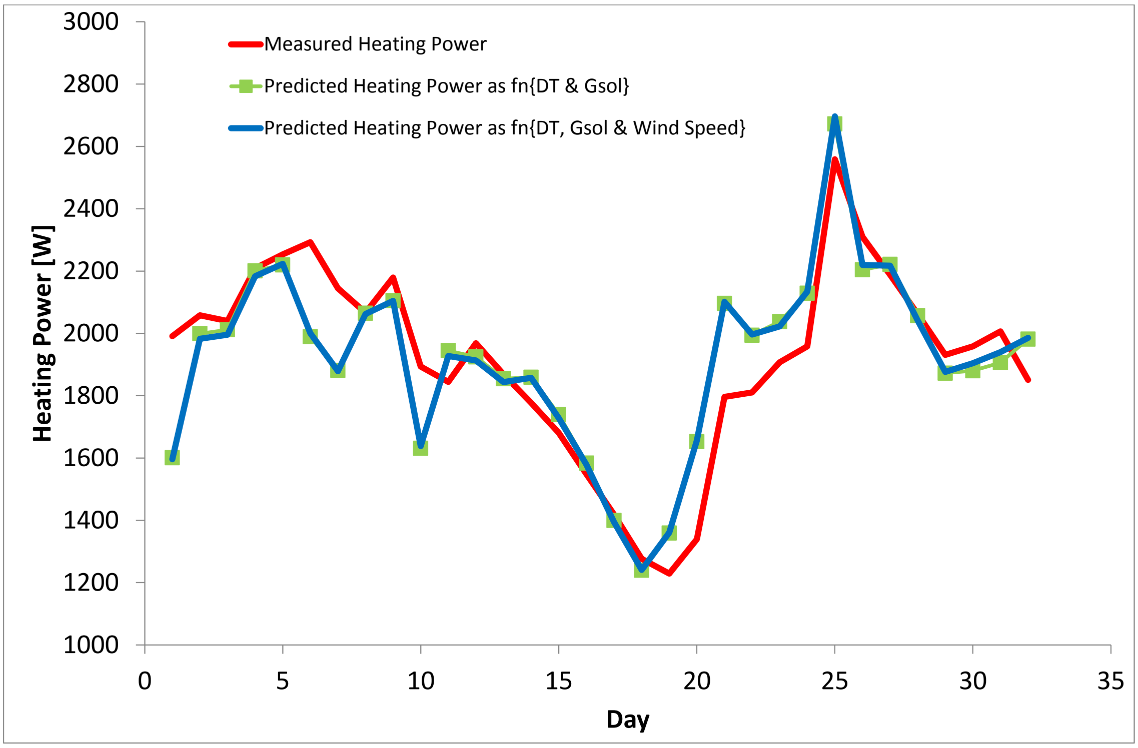

Figure A14: Post-intervention case. Measured and predicted heating power using (a) ΔT and Gsol as the independent variables (Equation A1) and (b) ΔT, Gsol and wind speed (Equation A4). Note: the line for the two predictions of heating power are effectively co-incident.

Generally, the inclusion of wind speed does not improve the regression analysis, particularly in the post-intervention case. Additional terms could be considered, however following the rationale presented above a dynamic analysis was carried out (following section) which considers thermal capacitance as well as the influence of wind speed.

DYNAMIC ANALYSIS

The LORD (Gutschker, 2004) program was used to analyse the hourly data.

Firstly the house is described as a network of conductances and capacitances which can enable the influence of both solar radiation and wind speed to be included. Various networks of varying complexity were tried. Figure A15 shows an example of one of the networks used.

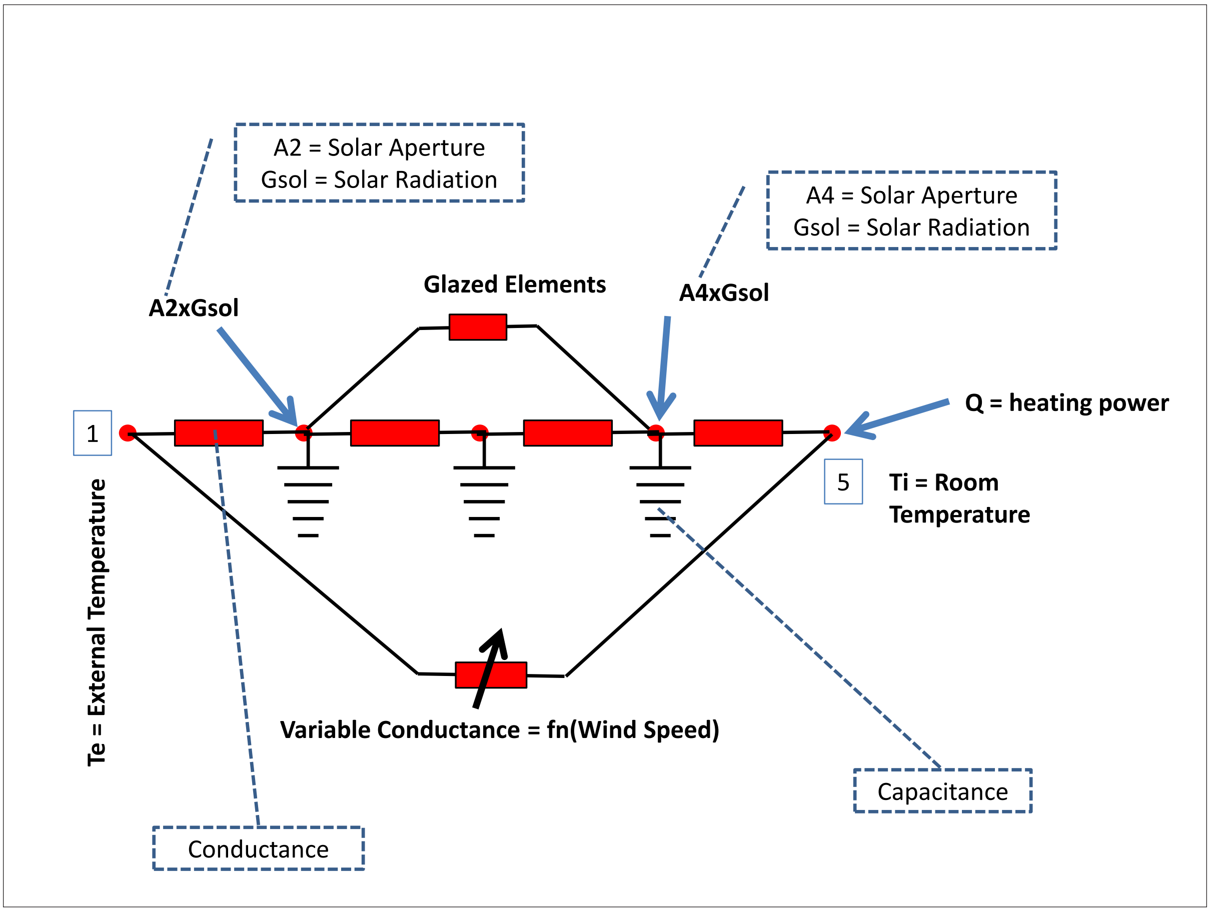

Figure A15: House modelled as a network of conductances and capacitances.

The network is a simplified description of the building with external temperature Te (at node 1) and internal temperature Ti (at node 5) connected by a series of thermal conductances and capacitances. The network considers that solar radiation (Gsol) is partly absorbed by the opaque parts of the envelope and is also transmitted through the windows and is absorbed within the building, where A2 and A4 are admittances. The influence of wind speed can be modelled using a variable conductance with connections to inside and outside temperatures. The heat input (Q) is at the internal temperature node 5.

Figure A16 shows an example of the predicted and measured output variable (chosen as the average room temperature in the house) from the analysis of the co-heating test data before the intervention. Overall agreement is generally achieved, apart from the magnitude of the temperature peaks, which corresponding to the daily peak solar radiation levels.

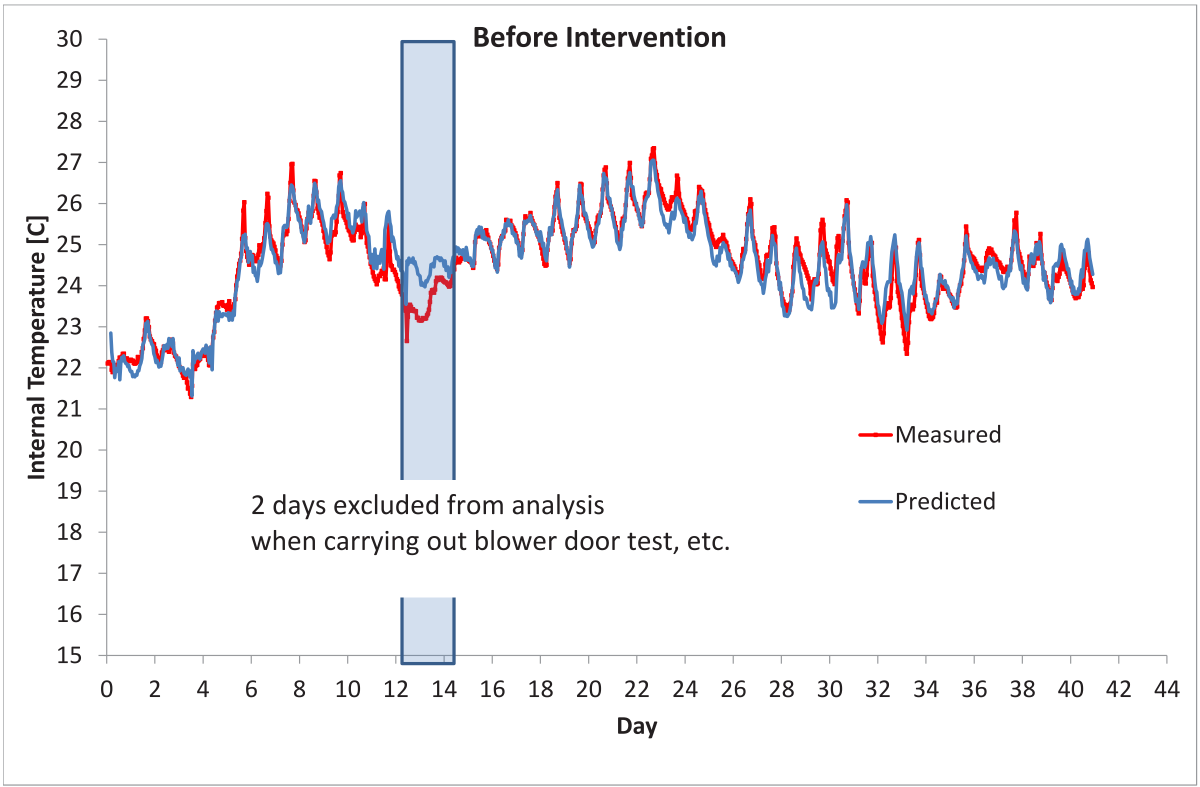

Figure A16: The predicted and measured output variable (average room temperature in the house)

RESULTS SUMMARY USING THE THREE ANALYSIS METHODS

The whole house heat loss coefficient and solar aperture estimates are given in Table A1. Uncertainty estimates are also given, based on the measurement errors and the confidence estimates of the analysis methods. The uncertainty estimate also assumes a 20% error in the estimate of the heat loss into the party wall.

Table A1: Co-heating tests results summary

	Before		After	
Analysis Method	Whole house heat loss coefficient, W/K	Solar aperture, m^2	Whole house heat loss coefficient, W/K	Solar aperture, m^2
LORD ('dynamic' analysis with hourly data)	251.1 ± 44.3 (18%)	10.6 ± 1.3 (12%)	143.0 ± 16.2 (11%)	4.8 ± 0.7 (16%)
Siviour analysis : H/ΔT vs. Gsol/ΔT (linear regression with daily average data)	241.0 ± 42.3 (18%)	7.3 ± 1.9 (26%)	126.5 ± 16.1 (13%)	2.0 ± 0.8 (40%)
LMU (linear regression with daily average data)	240.7 ± 41.1 (17%)	7.7 ± 1.7 (22%)	125.5 ± 15.8 (13%)	1.9 ± 0.8 (42%)

The LORD results are higher, for both whole house heat loss coefficient and solar aperture, than those obtained using regression analysis on daily average data. This is particularly apparent in the estimates of the solar aperture values after intervention: the Siviour and LMU results are less than half the LORD result and their uncertainties are relatively higher. Baker & van Dijk (2008) suggest that the regression (steady state) analysis using daily average data tends to give a 'flattened' response (for example see Figures A10 & A11 which show poor correlation), resulting in lower whole house heat loss coefficient and solar aperture values, since thermal storage effects due to changes in the external temperature and solar radiation are ignored.

Figure A17 compares the predicted daily average values of heating power using LORD and a regression model (e.g. LMU) which calculates the daily values using Equation A4 (including wind speed) with the measured heating power for the post-intervention test. There is generally closer agreement between the individual daily measured values and the LORD estimates than the LMU method. The greatest deviation between the measured and the regression predictions is at the start of the test, when the previous thermal 'history' of the building is unknown, however LORD is able to account for the thermal mass effects.

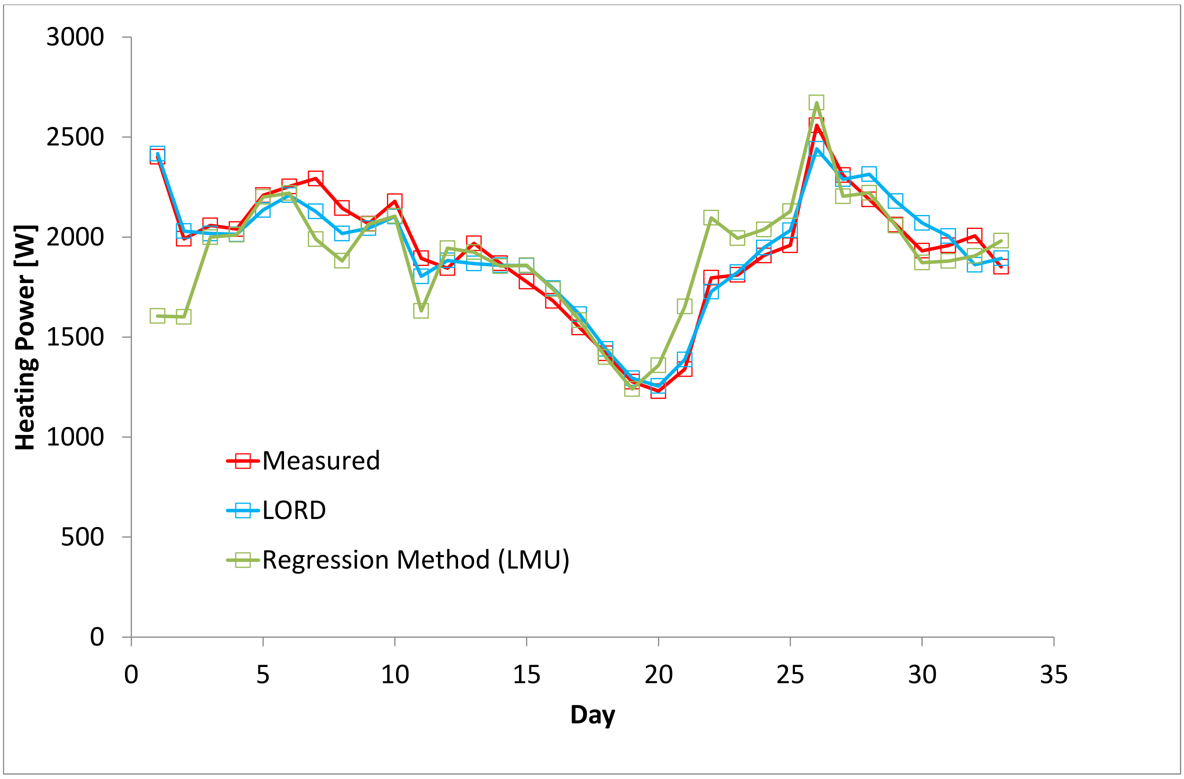

Figure A17: Comparison of measured and predicted daily average heating power for the post-intervention co-heating test.

DISCUSSION

It is not straightforward to analyse the data from a co-heating test. Both steady state methods and and the LORD analysis have their benefits and problems. The steady state methods are simple to carry out, however the dynamic response of the building to changes in weather during the test may result in poor correlation and under-estimation of the heat loss coefficient and solar aperture of the house. On the other hand LORD can deal with shorter data intervals (typically one hour) and take into account the thermal capacity of the house. It is also possible to consider, for example, wind speed linked to a variable thermal resistance representing ventilation heat loss. The main drawbacks are (i) how well does the network model describe the thermal behaviour of the house and (ii) how can the results be validated – do they 'make sense'? Of course the problem is the same for the steady state approaches which are more simplistic in describing the house. The results suggest that LORD is better able to predict the daily heating requirement than the steady state methods (Figure A17), which suggests that one can have more confidence in the LORD estimates of whole house heat loss.

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NOTE:

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Contact Historic England

East Midlands Windsor House, Cliftonville, Northampton, NN1 5BE ,
Tel: 01604 735400 Email: eastmidlands@HistoricEngland.org.uk

East of England Brooklands, 24 Brooklands Avenue, Cambridge, CB2 2BU
Tel: 01223 582700 Email: eastofengland@HistoricEngland.org.uk

Fort Cumberland Fort Cumberland Road, Portsmouth, Hampshire, P04 9LD
Tel: 023 9285 6704 Email: fort.cumberland@HistoricEngland.org.uk

London 1 Waterhouse Square, 138-142 Holborn, London, EC1N 2ST
Tel: 020 7973 3000 Email: london@HistoricEngland.org.uk

North East Bessie Surtees House, 41–44 Sandhill, Newcastle Upon Tyne, NE1 3JF
Tel: 0191 269 1200 Email: northeast@HistoricEngland.org.uk

North West Suites 3.3 and 3.4, Canada House,3 Chepstow Street, Manchester, M1 5FW
Tel: 0161 242 1400 Email: northwest@HistoricEngland.org.uk

South East Eastgate Court, 195-205 High Street, Guildford, GU1 3EH,
Tel: 01483-252000 Email: southeast@HistoricEngland.org.uk

South West 29 Queen Square, Bristol, BS1 4ND
Tel: 0117 975 0700 Email: southwest@HistoricEngland.org.uk

Swindon The Engine House, Fire Fly Avenue, Swindon, SN2 2EH
Tel: 01793 414700 Email: swindon@HistoricEngland.org.uk

West Midlands The Axis, 10 Holliday Street, Birmingham, B1 1TG
Tel: 0121 625 6820 Email: westmidlands@HistoricEngland.org.uk

Yorkshire 37 Tanner Row, York, YO1 6WP
Tel: 01904 601901 Email: yorkshire@HistoricEngland.org.uk