PRESIDENT'S AWARDS FOR RESEARCH 2016

Shortlisted 2016

Annual Theme – Learning from Projects

Low-energy, in-situ refurbishment and building performance evaluation of a historic town council building

Prof Rajat Gupta, Oxford Brookes University
Dr Adorkor Bruce-Konuah, Oxford Brookes University
Adrian Kite, Ridge & Partners LLP
Alex Towler, Bioregional
Nicole Lazarus, Bioregional
Susan Mackrell, Bicester Town Council

RIBA
Architecture.com

> This is a highly relevant work in relation to historic buildings, an issue which will increase in the near future, with an impressive range of the work and comparative assessment of elements of building performance.
>
> 2016 Judging Panel

Low-energy, In-situ Refurbishment and Building Performance Evaluation of a Historic Town Council Building

Professor Rajat Gupta Oxford Brookes University
Dr Adorkor Bruce-Konuah Oxford Brookes University
Adrian Kite Ridge and Partners LLP
Alex Towler Bioregional
Nicole Lazarus Bioregional
Sue Mackrell Bicester Town Council

Historic buildings usually come with high fuel use and low comfort levels for building users. Refurbishment of these buildings in an attempt to improve their energy efficiency, pose a number of challenges, including the need to preserve the historic character and building features. To tackle these challenges, it is important that reliable information is available related to their physical characteristics (construction, energy, environmental performance) and actual experience of occupants, so as to select appropriate refurbishment measures. This research project deployed and evaluated an innovative low energy refurbishment of a historic town council building (Garth House) in Bicester (Oxfordshire), underpinned by a systematic building performance evaluation approach pre- and post-refurbishment. Pre-refurbishment monitoring established the baseline performance and revealed issues of 'chilliness' from low surface temperature walls and low response times to heating the spaces, despite heating being on 24 hours a day. The innovative refurbishment addressed the challenges of maintaining the historic character, minimising disruption for building users while improving comfort, by deploying an innovative internal insulation technology on the internal face of external walls, integrated with secondary glazing and ventilation systems. The central strategy was to create a new airtight and continuous thermal envelope that integrated with the existing structure. The key innovation was WHISCERS™ (Whole House In-Situ Carbon and Energy Reduction System), a technique to rapidly apply internal wall insulation while the building remains occupied and applied to a non-domestic historic building in the UK for the first time. Post-refurbishment monitoring showed 58% reduction in energy consumption, in line with the design target, while indoor temperatures ranged between 15-23°C during winter and 20-26°C during summer, although airtightness doubled. Most users found the spaces comfortable all year round. The project demonstrates that it is possible to make significant energy-savings in a historic building in continuous occupation.

Context

Non-domestic buildings account for 17% of UK CO_2 emissions (UKGBC, 2016). Also, about 50% of the commercial and industrial buildings were built before 1940 and only 9% were built after 1990 and a significant (Pout & MacKenzie, 2005).

By 2050, a majority of the non-domestic buildings that were built before concerns about CO_2 emissions were raised will still be standing. Although the primary focus of energy efficiency and carbon reduction has been on new buildings, with the UK target of reducing greenhouse gas emissions by 80% by 2050 (UK Parliament, 2008), existing buildings present an opportunity to achieve this target. As well as this, the 2011 UK Carbon Plan states that all buildings will need to have an emissions footprint close to zero by 2050 (DECC, 2011). This goal cannot be achieved without significant energy retrofit of existing buildings.

Historic buildings usually come with high energy use and low comfort levels for building users and the refurbishment of these buildings, in an attempt to improve their energy efficiency, often pose a number of challenges. The need to preserve the historic character and the building features, both internal and external, are likely

to prevent the environmental upgrade of the building fabric particularly in relation to the use of external insulation or replacing windows. As well as this, some low energy options or renewable energy systems, although technically viable, may not deemed as appropriate or cost effective. These are systemic challenges which are due to factors such as material choice and approaches to installation which can hinder refurbishment of historic buildings.

One other challenge associated with refurbishment projects in general is the disruption to building users. Typically, a major refurbishment project will require the building to be emptied and for the occupants to be relocated for the duration of the refurbishment works. For many businesses, this may not be practical or an affordable possibility.

In response to the two major challenges, it is essential that refurbishment of historic buildings is underpinned and supported by useful and reliable information. A thorough understanding of the physical properties (construction and current conditions) and use of the building (user needs) are understood so as to select appropriate improvement measures. An appropriate balance between building conservation and energy efficiency improvement measures has to be achieved, considering factors such as ease of installation of the improvement measures and cost and time constraints. As a result, innovative solutions in all aspects of the refurbishment (e.g. technology selected, method of installation and interaction with technology and the building performance post refurbishment) will be essential.

The building performance evaluation approach

To evaluate the real impact of the improvement measures in buildings, it is also important to monitor the performance of the building for a period of time. This can be done using the building performance evaluation (BPE) approach where data on the performance of building fabric and systems, energy consumption, indoor environmental conditions, building management and occupant feedback are collected and analysed in a methodical way. In refurbishment projects, BPE ideally includes a pre- and post-refurbishment study where the main purpose is to maximise the intended efficiencies of the improvement measures and minimise any unintended issues they can present. The pre-refurbishment study is undertaken ideally before the design stage of the refurbishment so that the findings can be used to inform the choice of appropriate improvement measures and estimate the effectiveness of each of the measures. This will also help reduce the 'performance gap' (between design intent and actual outcomes) which refurbished buildings are prone to just as much as new buildings.

Within the context of a pre-and post-refurbishment evaluation study, the delivery of the refurbishment of Garth House was evaluated in detail in order to assess the process and performance of each improvement measure as well as tackling the identified challenges of refurbishing a historic building.

Questions, aims and arguments

This report presents the findings of a two year research project funded by Innovate UK and the Department of Energy and Climate Change (DECC) as part of the Invest in Innovative Refurbishment programme. The project aimed to successfully deliver the refurbishment of a historic building through the application of a before and after-refurbishment study using the BPE approach in order to meet the challenges identified, minimise the performance gap and provide learnings to all stakeholders and other organisations to help them implement their own projects.

Before and after-refurbishment evaluation studies were conducted with the following objectives:

1. Pre-refurbishment BPE study: determine the baseline performance of the building through a socio-technical assessment
   - Technical assessment – building fabric performance, energy assessment, review of systems and controls and indoor environmental performance
   - Social assessment (occupant's perspective) – review of occupant satisfaction feedback
   - Identify the refurbishment needs and appropriate solutions to be implements and estimate the potential savings from the refurbishment interventions
2. Post-refurbishment BPE study: determine the impact of the refurbishment works through a detailed assessment of the building performance and occupant feedback
   - Determine if there is a performance gap between the designed and actual performance
   - Measure the savings from the refurbishment work against the baseline performance

Resources, data and methodology

With funding administered by Innovate UK, a government agency which backs the development of promising new technologies and the Department of Energy and Climate Change, the process was led by the Garth House owners, Bicester Town Council and the project was managed by sustainability charity Bioregional. Ridge and Partners LLP were the architects while researchers from Oxford Brookes University's Low Carbon Building Group delivered the monitoring and evaluation of the performance of the building both before and after the refurbishment. The project started in August 2013 and was completed in July 2015 with the refurbishment work carried out over the winter of 2013/2014. Evaluation of the refurbishment project was underpinned by the systematic BPE approach.

Garth House

Garth House (Figure 1) is an 1830s Victorian hunting lodge, located in the Southeast of England and owned by Bicester Town Council. It is of significant local importance but has no formal protection as a listed building. The main linear building has two arms extending at either end in opposite directions and is laid out over three storeys which includes and an unused second floor attic space. Typical of its era, the construction of the Garth House is an un-insulated solid brick and stone on the ground floor, timber frame with vertical hung tiles on the first floor with a cut timber plain tile roof. In 2013, the building underwent a re-roofing programme to insulate it to modern standards and prevent water ingress damaging the interior of the building. There are built-in timber shutters in windows reveals and mouldings around the windows. Single glazed sash and casement windows were installed throughout and there is a modern conservatory on the southeast elevation. There are original features in all the rooms, including timber panelling in the corridors and in most of the window reveals as well as timber shutters and decorative mouldings around the windows. Many of the windows had been painted shut reducing opportunities for window opening and ventilation, resulting in overheating issues in parts of the building. The primary fuel used for space heating is natural gas in most of the rooms. One small office is heated by an electric storage heater.

The building is used as offices by the owners and other tenants and for social functions such as weddings. The Council offices are located on the southwest end of the first floor of the building and a Registry office and Council Chambers are located on the ground floor. The Council Chambers are used for the social events. The other tenants occupy the northeast end of the building. The refurbishment was on the half of the building occupied by the local council (17 rooms). The building remained occupied during the refurbishment works and its function remained unchanged after the works.

Methodology

Building performance evaluation was introduced in order to address feedback loops in different stages of a building's life cycle. The BPE approach requires the capture of both qualitative

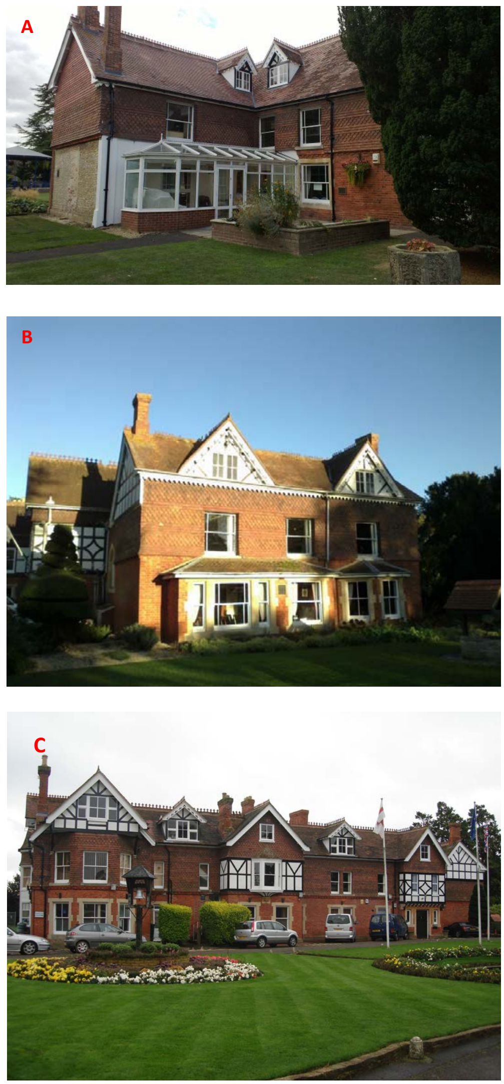


Figure 1
Garth House
(A) Conservatory on the South East elevation
(B) South West elevation with Council Chambers on the ground floor
(C) Front entrance on the North East elevation

and quantitative data with detailed analysis and interrogation in a forensic fashion informing additional data collection and lines of inquiry so as to consider and implement improvements or changes in the all phases of the building's life cycle. In all BPE projects, there is a comparison of the designed or predicted performance with the actual or delivered performance of the building. This is applicable to both new build projects and refurbishment projects. For refurbishment projects, it is ideal to conduct evaluations pre and post refurbishment in order to establish a baseline against which to assess the impact of the refurbishment works. The pre and post-refurbishment BPE study followed the methodology comprehensively covered in Gupta and Gregg (2014). Table 1 is a detailed workflow for non-domestic refurbishment evaluation revised for the refurbishment of Garth House.

In both pre and post-refurbishment evaluation studies, the Building User Survey (BUS) questionnaire was used to record occupant feedback on the environment and the overall building. The BUS analysis is a quick and thorough way of obtaining feedback data on building performance through a self-completion questionnaire, the results of which can be compared against a national non-domestic benchmark database (Arup, 2016). Findings from the assessment of the indoor environmental conditions were cross-related with occupant satisfaction feedback collected through the BUS questionnaire and interviews. Energy consumption in the building was also compared with CIBSE TM46 benchmarks (CIBSE, 2008). Assessment of the performance of the building post refurbishment was monitored for a one year period, allowing the refurbishment measures, i.e. fabric and the installed systems would have stabilised and the occupants would become familiar with the building.

A variety of monitoring equipment was installed in the building for the post-refurbishment BPE to record energy and environmental data. Table 2 presents the monitoring strategy for data collection in the post-refurbishment evaluation.

Analysis and findings

Pre-refurbishment performance

The section of the building to be refurbished was monitored in the pre-refurbishment evaluation. This section is on a separate sub-meter to the other area and hence actual gas and electric used data was obtained from utility bills and manual meter readings. The bills provided six months of electricity consumption (July 2011 to January 2012) and meter readings provided six months of gas consumption pre-refurbishment (February 2011 to August 2011). An assessment of energy consumption was conducted in order to estimate annual energy consumption of the building before the refurbishment. The assessment covered a one year period, providing the closest estimation of annual energy usage before the refurbishment. The total of energy supplied to the building in this period was 81,204kWh with gas making up 79% and electricity making up the remainder 21%. The actual energy consumption and the resulting carbon emissions of the existing building were compared with the CIBSE TM46 benchmarks for

Pre-refurbishment evaluation study		
(1)	Existing building performance and existing occupancy and management evaluation	• Review of as-built drawings and specifications • Energy analysis (energy bills and TM22 assessment) • Fabric performance assessment – air permeability test, thermal imaging survey • Occupant surveys using the building user survey (BUS) questionnaires and semi-structured interviews to record habits, concerns and needs • Walkthroughs with building management team
(2)	Pre-refurbishment briefing	• Identify ideal refurbishment strategies based on the (1) and clarify design priorities
(3)	Prediction of savings from proposed refurbishment measures	• Estimate energy and carbon savings from the proposed refurbishment measures using dynamic thermal simulation • Determine a focus point for building performance analysis
Post-refurbishment BPE		
(1)	Post construction and early occupation evaluation	• Review of drawings, interviews and feedback from design and construction teams to compare design intentions to built reality and later performance • Fabric performance assessment – air permeability test, smoke pencil test, thermal imaging survey • Review of installation, commissioning and operational use of installed systems and handover processes
(2)	In-use evaluation	• Assessment of building energy consumption (monitored energy use) • Assessment of indoor environmental conditions – air temperature, relative humidity and carbon dioxide • Assessment of insulation performance – moisture content of external wall and timber studs • Review of usability of control interfaces • Occupant survey using questionnaire to record satisfaction, concerns and feedback

Table 1
Workflow for pre and post-refurbishment evaluation studies of Garth House

a general office. The resulting carbon emissions were calculated using conversion factors based on DEFRA values. Table 3 presents the annual gas and electricity consumption and emissions for the existing building and benchmarks. Electricity consumption was almost half that of the benchmark value however gas consumption was greater than the benchmark.

An examination of the relationship between weekly gas consumption and heating degree days (HDDs) (Figure 2) showed that a one HDD increase resulted in 6.8kWh increase in gas consumption. The line of best fit also shows a poor level of control of the heating system as gas consumption only explains 4.6% of the variation in heating degree days. This is confirmed by the

Table 2
Monitoring strategy in post-refurbishment BPE study

Parameter monitored	Tools
Mains gas and electricity consumption	Web-based remote system, recording at 5 minute intervals
Sub-metered electricity usage (ventilation and water heating systems)	Web-based remote system, recording at 5 minute intervals
Moisture content in building fabric	12 sensors installed recording at 5 minute intervals and data obtained from web-based remote system
Indoor environmental conditions (air temperature, relative humidity)	11 sensors installed in selected locations and data obtained from web-based remote system, recording at 5 minute intervals
Indoor CO_2 concentration	Standalone data loggers installed in selected rooms recording at 5 minute intervals
Heating behaviour (heating on/off)	Standalone data loggers installed in selected rooms recording at 15 minute intervals

Table 3
Comparison between actual energy and resulting emissions and CIBSE TM46 benchmarks for a general office

	Garth House	CIBSE TM46 (general office)
Annual electricity consumption (kWh/m^2)	51	95
Annual electricity CO_2 emissions (kgCO_2/m^2)	23	50
Annual gas consumption (kWh/m^2)	194	120
Annual gas CO_2 emissions (kgCO_2/m^2)	36	23

finding that the heating system was on for 24 hours a day during the heating season. The high gas consumption was therefore due to the heating being on all the time and poor level of control of the heating system.

The fabric performance of Garth House before the refurbishment was assessed through an air tightness test which was conducted in November 2013. The test was carried out in accordance with the requirements of the ATTMA, a TSL2, CIBSE TM23:2000, BS EN 13829:2001 method B and is UKAS accredited. Individual test areas (the Council offices) were tested using a blower door system consisting of a fan mounted in an expandable aluminium frame with a canvas blanking panel which were located with a normal door frame. The test results were as follows:

- Measured air permeability on the ground floor and first floor – **20.52 $m^3/h.m^2$ @50Pa**
- Measured air permeability on the second floor (unused attic space – 44.80 $m^3/h.m^2$ @50Pa

Air permeability in the occupied spaces was double the Building regulation benchmark of 10$m^3/h.m^2$ @50Pa and in the unused attic space, it was more than four times the benchmark. These high air permeability levels are mainly due to the lack of insulation and the air leakage paths in the building fabric.

A thermal imaging survey was conducted on Garth House also in November 2013. During the survey, there were no rapid or significant variations in weather conditions (internal temperatures ranged between 20-24°C, external temperature was 13.3°C, external relative humidity was 59.9% and there

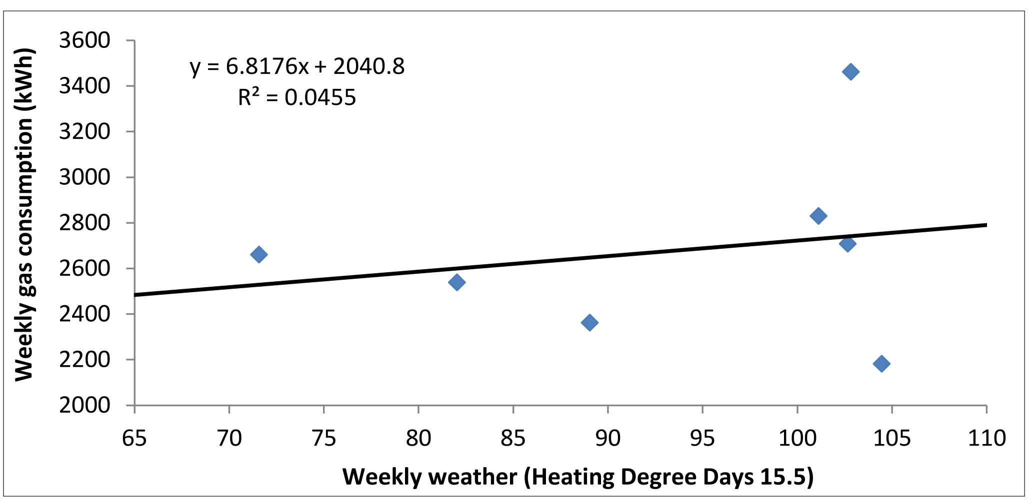


Figure 2
Relationship between weekly gas consumption and heating degree days

was no precipitation). In general the weather could be descried as a still cold winter evening with no sunshine or precipitation. The following test equipment was used during the survey:

- *FLIR T620 Thermal Imaging Camera*, 640x480 pixel resolution, 0.04K thermal resolution set on Rainbow colour palette
- *Vaisala HUMICAP®* Hand-Held Humidity and Temperature Meter HM40 with HMP113 Probe, ±0.2 °C, ±1.5% Accuracy

Figures 3 to 5 present thermograms and observations from the survey:

A detailed evaluation of occupants' feedback on the building and their comfort in the building was recorded through the BUS questionnaire and semi-structured interviews. The main concerns of the occupants were the disruptions which will be caused by the long refurbishment period as the building was to remain occupied during the works, with occupants working as normal. Another concern reported was 'cold feeling' although the heating was constantly on and high air temperatures had been recorded. This indicates that there are low surface temperatures on the walls and windows, causing thermal discomfort.

Table 4 presents a summary of the main findings from the pre-refurbishment evaluation study.

As well as the need to maintain the historic character of the building and minimise disruption to occupants during the construction stage, the issues identified to be addressed by the refurbishment were as follows:

- Heat loss through the building fabric due to lack of insulation and uncontrolled air paths and the energy required to provide a comfortable internal environment
- Lack of user interaction with the building – opening windows, adjusting radiator valves and heating controls
- Overheating in the ground floor rooms. The conservatory was found to heat up in the morning and then the sun moves around

Table 4
Summary of main findings from pre-refurbishment evaluation study

Pre-refurbishment BPE study element	Outcome
Energy consumption and CO_2 emissions assessment	Annual gas consumption was 194kWh/m^2, exceeding the energy benchmark typical of a general office
Fabric performance assessment	Air permeability of 20.52 m^3/h.m^2 @50Pa
Occupant feedback	Concerns over the length of the refurbishment period and the associated disruption and uncomfortable thermal conditions in the building
Environmental assessment	Heating on all the time to maintain comfortable indoor temperatures. Occupants found the indoor thermal conditions too hot in the summer and too cold in the winter.

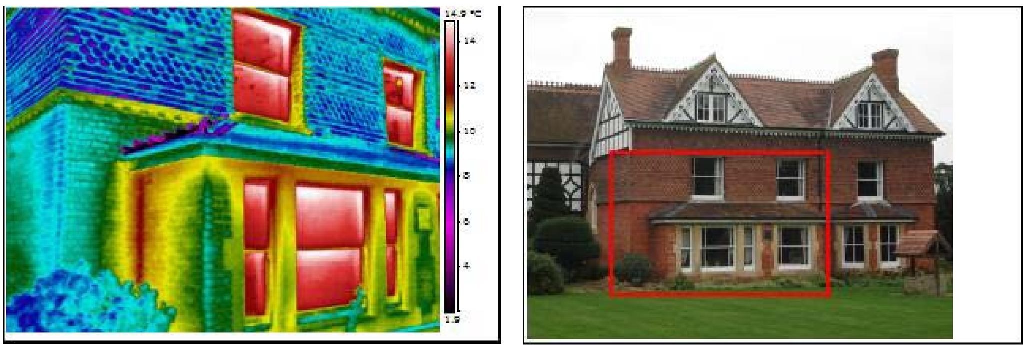


Figure 3 Southwest elevation showing significant heat loss through windows and heat loss through the wall junction

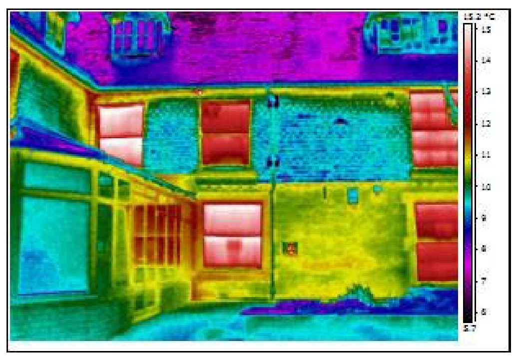


Figure 4 East elevation showing heat loss through the external wall at ground floor which is potentially due to poor insulation of the external wall

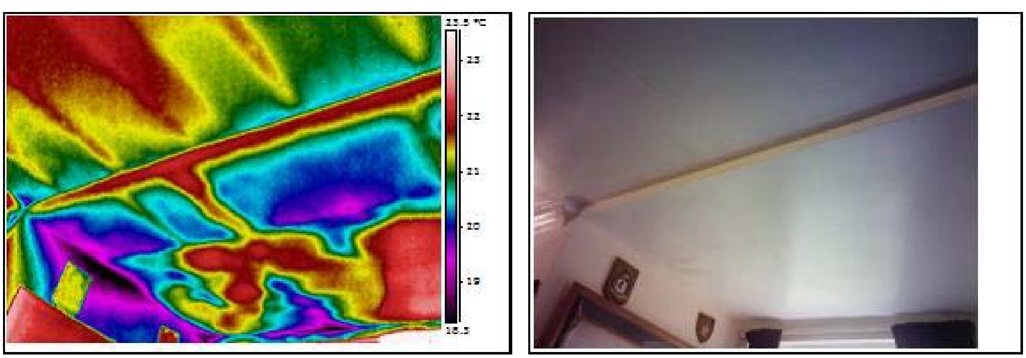


Figure 5 Ground floor room showing thermal anomalies on the ceiling which is potentially due to poor insulation of the pitched roof above the windows

the building and warms the adjacent spaces through the bay windows. However, there was no user control of the window and so they were not opened to reduce the heating. As a result there were high overheating potential.

Based in the findings of the pre-refurbishment evaluation study, the main improvement needs identified were insulation of the walls and windows. The central strategy was to create a new airtight and continuous thermal envelope that is carefully integrated with the existing structure. Due to the historic character of the building, the project's intention was to combine a number of existing products and processes to provide a replicable internal wall insulation and secondary glazing solution that will retain the historic features while ensuring a comfortable well-ventilated environment for occupants. Hence, key to the integration was the sensitive placement of the proposed elements that avoided the concealment or damage of historical features.

The refurbishment solution

The refurbishment design and process was underpinned by the findings of the pre-refurbishment evaluation study. The refurbishment work of Garth House took place between November 2013 and April 2014, during which the building was fully occupied.

A comprehensive assessment and comparison of different types of low energy improvement measures and installation solutions for different areas in the building was conducted in order to select the most appropriate yet innovative solution for the refurbishment. The following factors were considered as the criteria for selection:

- Performance (thermal and energy)
- Preservation of historic character
- Reduced disruption to occupants
- Innovation
- Cost

The primary measures selected were internal insulation and double glazed secondary glazing. An innovative installation strategy called WHISCERS™ (Whole House In-Situ Carbon and Energy Reduction System) was used to supply and install the internal insulation and its integration with the internal secondary glazing in order to retain much of the detail and character of the building. This technology has been used in hard-to-treat buildings, using a laser to survey the rooms in the building, allowing off-site cutting of the insulated plasterboards which can then be installed rapidly like a jigsaw to each internal wall. Eliminating on-site cutting of insulation material reduces waste and mess and offers a faster, less disruptive installation process, allowing building occupants to continue to work or live in their buildings throughout the refurbishment period. This technology has previously been successfully used in residential properties, ranging from single terraced properties to tower blocks. Application of this technology in this project is the first time the product has been applied to a non-domestic building and a historic building in the United Kingdom. Its use in this project therefore offered a test in the heritage building environment whilst the building was continuously occupied. Figure 6 shows the installation process of the internal wall installation.

To complete the thermal envelope the solid ground floor and internal ground floor walls were insulated. The eaves were also insulated to avoid gaps with roof insulation and heat loss at eaves level. The design intent of the insulation and the secondary glazing was to reduce the air permeability from 20.52 $m^3/h.m^2$ @50Pa to the building regulations benchmark of $10m^3/h.m^2$ @50Pa. Figure 7 shows the additional insulation and the secondary glazing installed.

To tackle the challenge of ensuring adequate ventilation, a user controlled natural ventilation strategy was developed for the first floor that included the use of the existing sash windows and some through-wall vents to allow cross ventilation into single sided rooms. A centralised, whole building mechanical ventilation with heat recovery (MVHR) system was installed to replace the existing through-wall individual vents, thus reducing the number of openings in the façade. To reduce the risk of overheating, roof lights and louvers automatically controlled by actuators linked to room thermostats were installed above the ground and first floor windows. The design intent of the combination of ventilation systems was to improve the ventilation and indoor air quality in the building. Figure 8 shows the wall vents which allow cross ventilation and the centralised MVHR system installed

Other low cost improvement measures incorporated to improve the energy efficiency of the building included sealing penetrations and redundant pipework and gaps around the existing

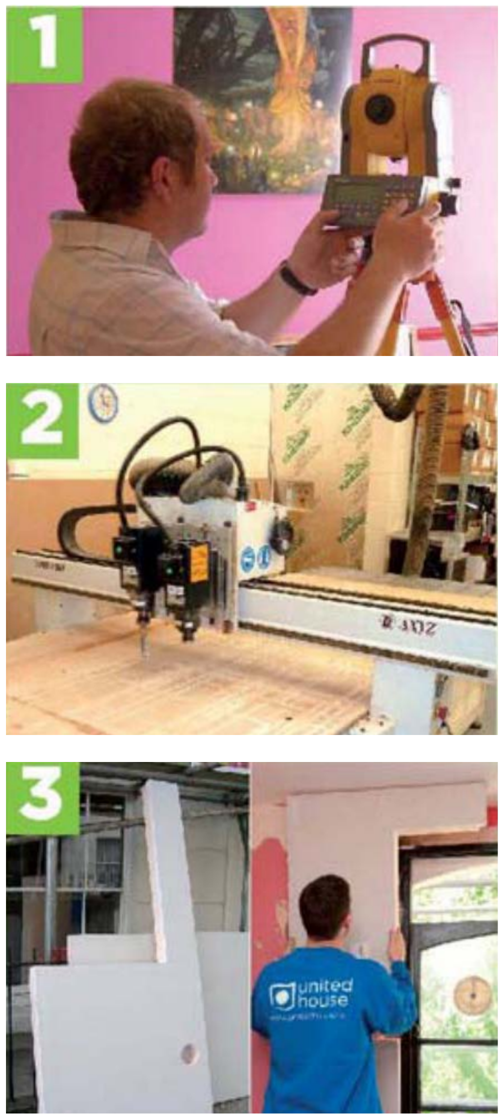
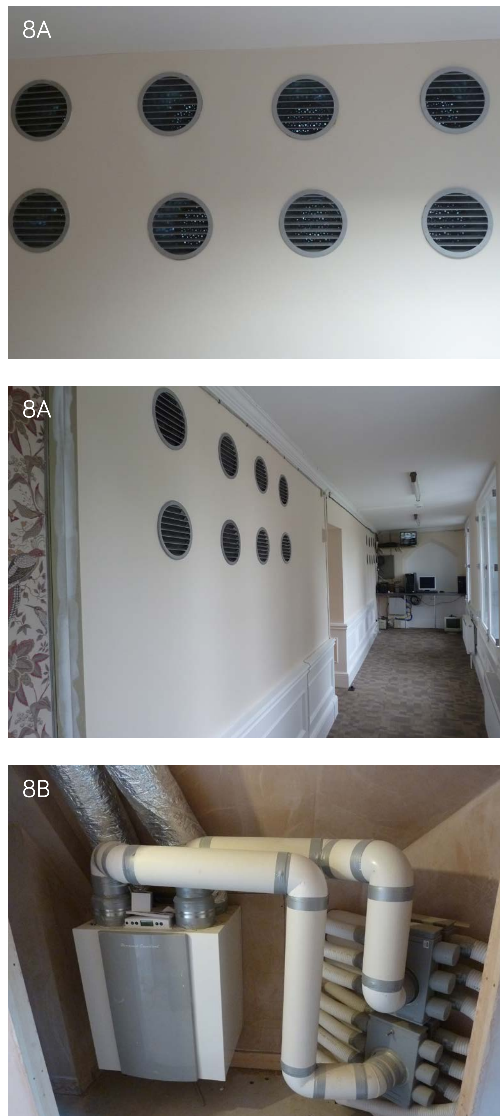


Figure 6
Stages in installation of internal wall insulation
(1) Use of 3D laser to survey the room
(2) Off-site cutting of insulation material
(3) installation of pre-cut pieces of insulation

Figure 7 (left)
(A) Floor insulation – 10mm Aerogel, 18mm chip board for floors
(B) Secondary glazing unit in the stairway
(C) Secondary glazing units in a function room

Figure 8 (right)
Ventilation systems
(A) Wall vents allowing cross ventilation
(B) Centralised whole building MVHR system



windows and in the external fabric. This was done in order to improve the air-tightness of the building envelope and providing zoning between floors and installing of wireless thermostatic radiator valves (TRV) in order to improve the control of space heating.

To estimate the energy saving potential from the refurbishment measures, a model was simulated in IES and each improvement measure was assessed. Overall, the refurbishment measures were predicted to achieve a 58% savings in energy consumption and a 37% reduction in carbon emissions.

Table 5 presents a summary of the refurbishment measures and the criteria they satisfy.

Post refurbishment performance

Some study elements of the post-refurbishment BPE were conducted during early occupation of the building just after the refurbishment works (such as review of commissioning and handover processes, building fabric performance assessment), while other study elements (such as energy metering and sub-metering, remote monitoring of environmental conditions) were carried out over a period of one year, to assess the in-use

Table 5
Summary of refurbishment measures

Refurbishment measure	Performance	Preserving historic character	Reduced disruption	Reduced cost	Innovative
Internal wall insulation using an innovative installation strategy	✓	✓	✓		✓
Floor insulation using *Aerogel bonded plaster chipboard*	✓	✓			
Roof void using *blown insulation*	✓			✓	
Secondary glazing	✓	✓			
Natural ventilation	✓	✓	✓	✓	
Automated openings for natural ventilation		✓	✓	v	
Whole building MVHR	✓			✓	
Mechanical extract ventilation				✓	

performance of the refurbishment and evaluate the energy and CO_2 savings achieved.

Commissioning, handover and user training

On completion of the refurbishment works, all mechanical services installed were commissioned and a handover and comprehensive user guide and training took place during early occupation (April 2014) of the refurbished building. The aim of the building handover during the early stages of occupation was to make sure the building managers and users understand, manage and operate the building effectively. The methodology for the evaluation of the commissioning handover process comprises of the following:

1. A desktop research to thoroughly review the handover documentation.
2. A handover questionnaire survey to gather quantitative data on the handover. It involved the stakeholders (owner/occupant, architect, contractor) involved in the design, construction and maintenance of the building aimed at mapping each party's role and their contribution during and after the building's handover.
3. Structured interviews to gather contextual information from the stakeholders on each other's role during the phases of the design and construction and their understanding of the design intent.
4. A handover review workshop organised by the BPE evaluators to review the handover process and the commissioning.

The handover process included an evaluation of building logbook, operation and maintenance manuals and user guides for occupants. The user guide covered the following systems:

- MVHR
- Rooflights with automated actuator opening in the ground floor room
- Windows (passivent louvers) with automated actuator opening in the ground floor room
- Actuators in the conservatory
- Radiator controls
- New boiler controls

During the handover, training instructions and demonstrations were given to the building manager and the building users. The documentation was delivered to the building owner. The building user guide explained how the improved building will work to ensure users knew how to maintain comfortable temperatures in the building. Demonstrations were given on the use of the MVHR and controls of other installed systems such as the windows.

Observations made in the BPE study showed that there was good communication between the designer and the building user and occupants understood the ventilation strategy well. However a review of the handover documentation revealed that there was no written information on the commissioning of the MVHR system and no information about a maintenance schedule. The Building manual was incomplete and there was no building logbook. Concerns were raised about the need for having a clear handover documentation (logbook, commissioning reports, operation and maintenance manuals and user guides) which is carefully organised and kept up to date. It

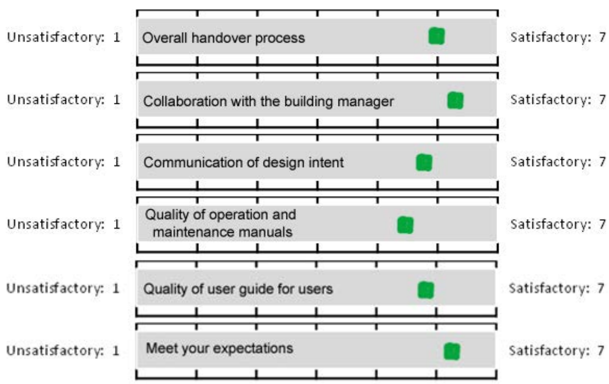


Figure 9
Feedback on the handover process

Figure 10
Images from the handover and the training sessions given to the Garth House manager and building users

was found that a schedule for seasonal commissioning and maintenance of building services be put in place and highlighted in the user guide. Table 6 presents a summary of the findings from handover and Figures 9 and 10 shows the feedback given on the handover process and some images from the handover and training sessions respectively.

Building fabric performance

After the refurbishment, a second air permeability test was conducted on Garth House to determine compliance with Part L2 of the Building Regulations. The test procedure was similar to that used in the pre-refurbishment test. The test was conducted in July 2014 on the ground floor and first sections of the building. Table 7 presents the results of the test and a comparison with the test result from the pre-refurbishment study. The results show that there was a significant improvement in the fabric performance as air permeability reduced by 52% after the refurbishment, more than half of what the air permeability was before the refurbishment. This shows that the installed insulation and secondary glazing has succeeded in improving the overall performance of the building fabric.

Table 6
Summary from handover process

Handover documents	Available on-site	Comments
Drawings (Architectural, Civil and Structural and Mechanical and Electrical)	✓	Soft copy only available
Mechanical, electrical and operations and Maintenance manuals	✓	Incomplete
Project/building fabric specifications, structural information, risk assessments and method statements	✗	
Ventilation system specifications	✓	
Strategy for energy and metering and energy assessment documents	✗	
Building logbook	✗	Not available
Maintenance schedule	✗	
Commissioning record	✗	The heating system needed to be recommissioned
Building user manual	✓	Also includes maintenance schedule
Health and Safety file	✗	

Following the air-tightness test, a smoke pencil survey was carried out in order to identify specific areas of leakage. On the ground and first floors, air leakage paths into the floor void were identified. These occurred around door frames, skirting boards and in rooms where the floor boards were exposed. Regarding secondary glazing, the seal between openable doors was often not in contact with the adjoining door and often the seals stopped short or the tops and bottoms, leaving a gap. The secondary glazing frame did not always seem to be sealed to the floor and air was drawn under the frame. On the first floor, air was drawn under the floor around the perimeter of most of the rooms. Figures 11 and 12 show some of the identified air leakage paths during the smoke pencil tests.

A second thermal imaging survey was also conducted after the refurbishment. The same equipment used in the pre-refurbishment survey was used here. The post-refurbishment survey was conducted in November 2014. During the

	Target air tightness ($m^3/h.m^2$ @50Pa)	Measured air tightness ($m^3/h.m^2$ @50Pa)
Pre-refurbishment test (November 2013)	-	20.52
Post-refurbishment (July 2014)	10.0	**9.31**

Table 7
Pre and post-refurbishment air permeability test results

Figure 11
Smoke drawn around the secondary glazing seals

Figure 12
Smoke drawn through the gap between the floor and the skirting board

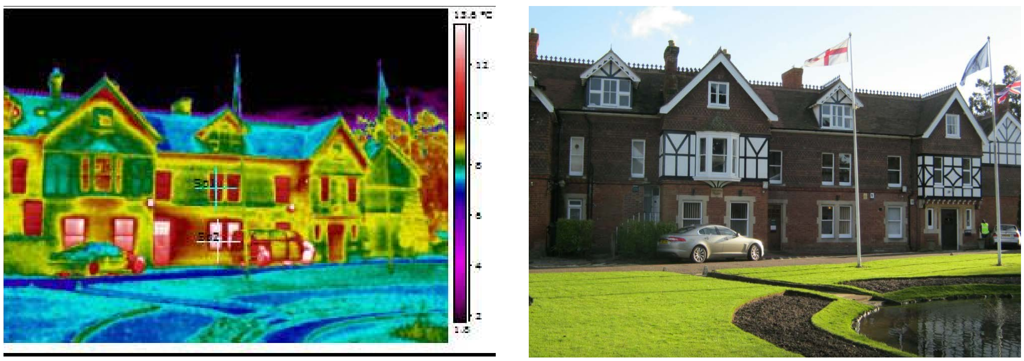


Figure 13
West elevation: The windows on the ground floor are significantly warmer than the windows at first floor as the secondary glazing was installed on the first floor

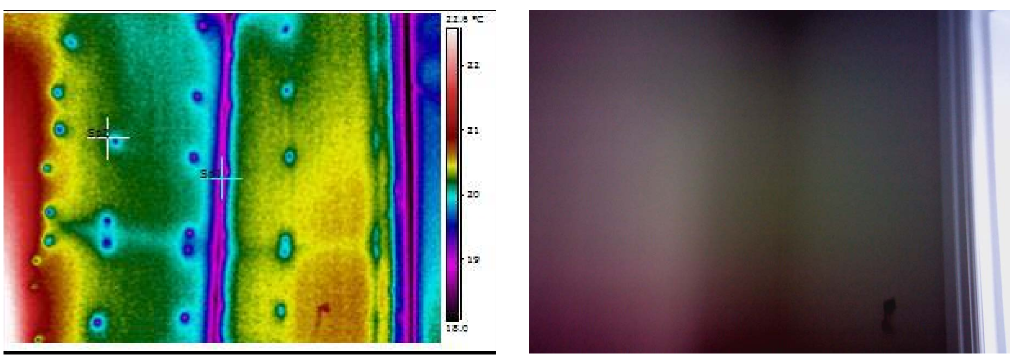


Figure 14
Office on first floor: Showing fixing points of the insulation panels and thermal bridge at the junction of the external walls

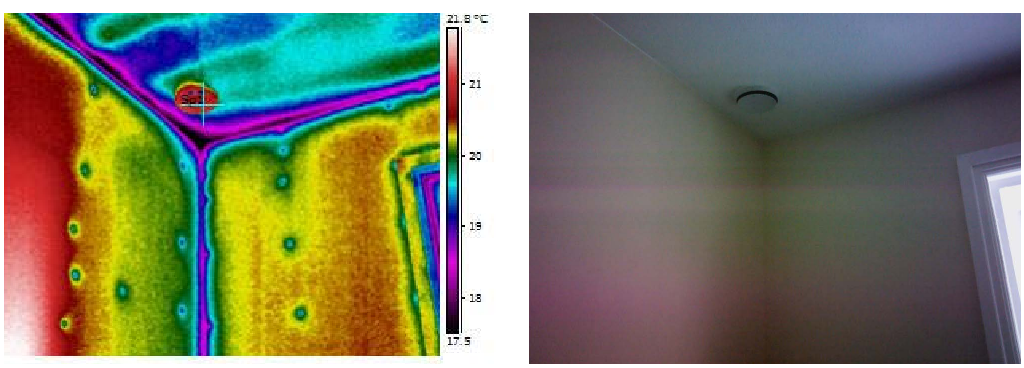


Figure 15
Office in first floor: the red spot on the ceiling is the air outlet for the MVHR system

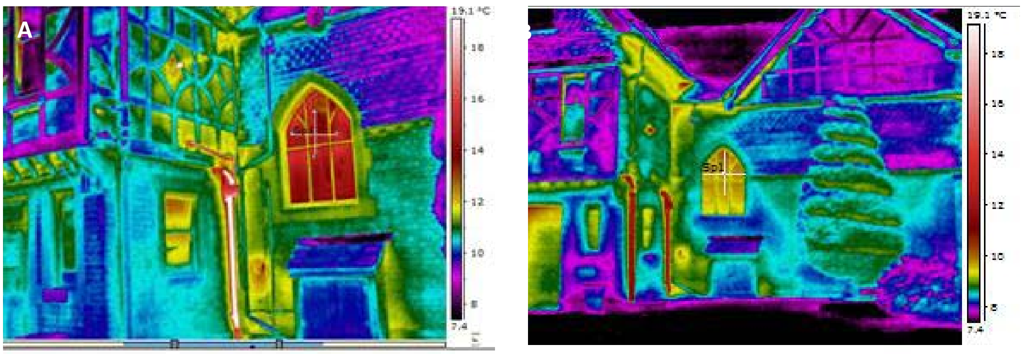


Figure 16
Thermal image showing heat loss through the window (A) Pre refurbishment (B) Post refurbishment

Figure 17
Left – gap between duct end and ceiling
Right – oversized cut outs in the plaster board

survey, there were no rapid or significant variations in weather conditions (internal temperatures ranged between 21-23°C, external temperature was 10.2°C, external relative humidity was 90% and there was no precipitation). In general the weather could be descried as a still cold winter evening with no sunshine or precipitation. Figures 13 to 15 present thermograms from the survey and the observations.

Figure 16 is a comparison between thermal images of the external wall taken during the pre-refurbishment study (Fig 16A) and the post-refurbishment study (Figure 16B). The internal temperatures recorded at the window are 14.7°C (external temperature is 24°C) and 9.7°C (external temperature is 23.2°C) in Fig 16A and Fig 16B respectively. This indicates that after the refurbishment, heat loss through the window has reduced compared to before the refurbishment due to the installation of the secondary glazing.

Figure 18
Top left – excerpt from installation drawing
Top right and bottom left – supply air valve used as extract valve and vice versa Bottom right – terminal fitted too close to the wall

Table 8
Airflow measurements at supply terminals in selected rooms

	Measured airflow rates at given fan speed (l/s)		
Rooms	**100m³/hr**	**1000m³/hr**	**3000m³/hr**
Council office 1	2.7	5.2	7.2
Council office 2	3.3	6.5	7.7
Council office 3	3.6	6.5	8.9
Meeting room	3.1	6.5	9.3
Reception	2.3	5.7	7.7

Performance of systems and controls

The installation process and the commissioning procedure of the mechanical ventilation system were reviewed as part of the post-refurbishment evaluation study. A walkthrough observation was conducted evaluation team and this revealed some issues with the installation and commissioning of the ventilation system. The following issues were recorded:

- Supply and extract valves found in the 'unlocked' position
- Ducts were too short hence the valves were not fully engaged with the duct resulting in significant airflow bypassing the valves and flowing directly into the ceiling void (Figure 17)
- Oversized cuts in the plaster board where the distribution valves were mounted (Figure 17)
- Most of the supply and extract terminals were not installed as specified in the drawings, with the supply terminals installed in position of the extract terminals and vice versa (Figure 18)
- Some ceiling terminals had been fitted too close to the wall which resulted in ineffective air distribution (Figure 15)

To assess the ventilation rate supplied by the MVHR system, air flow measurements were conducted using three different fan speeds (100m^3/hr, 1000m^3/hr and 3000m^3/hr). The minimum ventilation rate of 8L/s/person specified by CIBSE Guide B (CIBSE, 2005) was used as the benchmark for the assessment. The results presented in Table 8 shows that the ventilation system failed to provide the minimum recommended ventilation rate even at the highest fan speed setting (3000m^3/hr) in some of the spaces.

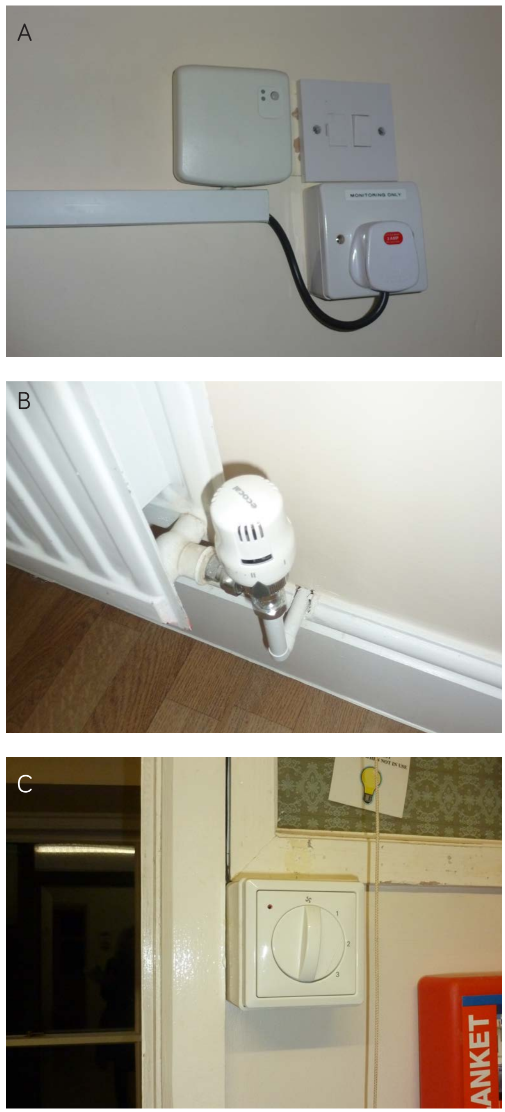


Figure 19
(A) Boiler control – not intuitive to use
(B) Radiator valves – easy to access and use
(C) MVHR boost – no labelling and no indication of system response

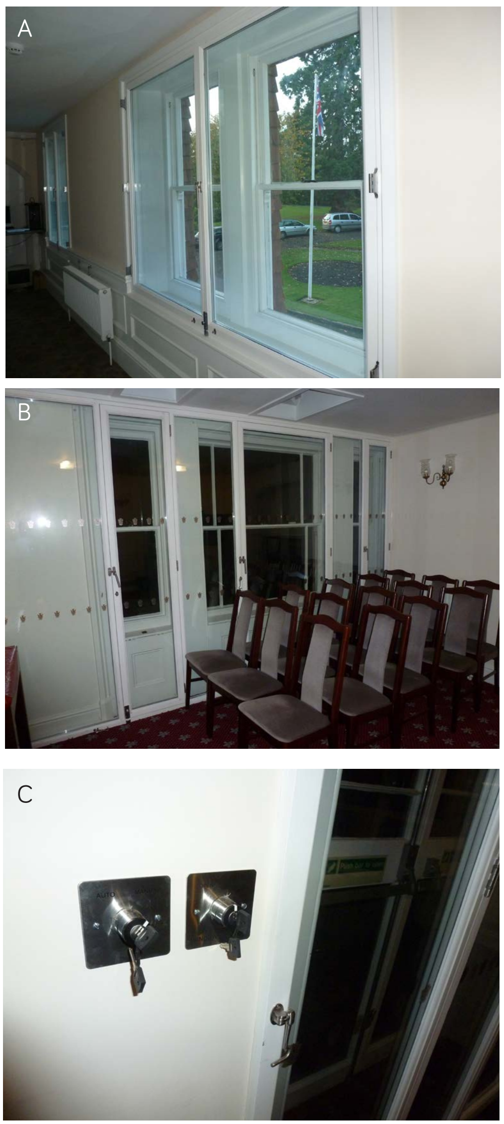


Figure 20
(A) First floor windows – fully openable giving good access to original sash windows
(B) Ceremony room windows – windows opening hindered by furniture
(C) Electric window switches – the electric windows they control are not visible from the switch location hence no indication of system response

It was also found that the unit operated noisily at the highest fan speed level. The minimum recommended ventilation rate could be achieved by additional opening of windows, although this was not likely to happen in the winter and would also cause wastage of heating. It was recommended that occupants use the higher fan speed levels in the winter. Due to the findings of this element of the BPE study, it was recommended that the system be re-commissioned (required after ductwork alterations have been made) and the fan speeds set to higher air flow rates, considering the balance between system noise and ventilation rates.

Review of the performance and usability of controls

According to the Building User Guide, the building's response to heating and cooling was expected to change and good occupant control would be of significant importance in order to achieve comfortable conditions throughout the year. The review of the usability of controls in the case study building revealed a number of issues with the control of the heating system. Even though the degree of fine control of the thermostat was good, a lack of zoning in the building meant that one temperature setting applied to all the spaces. The control strategy was also confusing as there were several controls installed in the building and the override strategy was not clear. Control over the MVHR system, the boiler, the thermostat and smoke and security alarms were not found to be intuitive and there was a lack of simple and easy to understand user guides. Figure 19 shows controls of the ventilation and heating systems

The secondary glazing units that were installed were easy to use and opened fully, allowing access to the original sash windows. However, the new windows opened into the internal space, and their opening could sometimes be prevented by furniture arrangements in the room. The electrically operated rooflights were easy to operate but they were not visible from the location of the control interface, thus limiting effective control. Figure 20 shows some control of secondary glazing installed during the refurbishment reviews of their usability

Energy assessment

The post-refurbishment energy assessment of Garth House covered a one year period from May 2014 to April 2015. During this period a

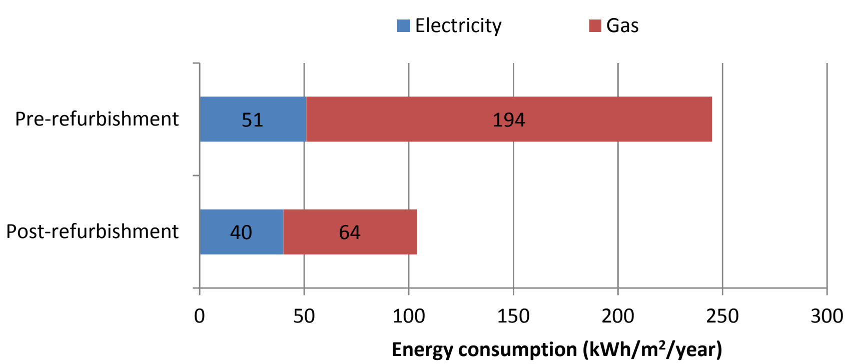


Figure 21
Comparison between annual energy consumption pre and post refurbishment

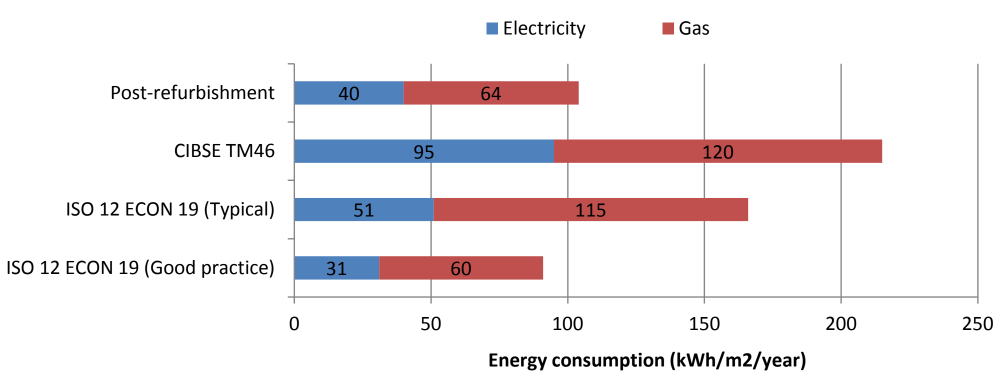
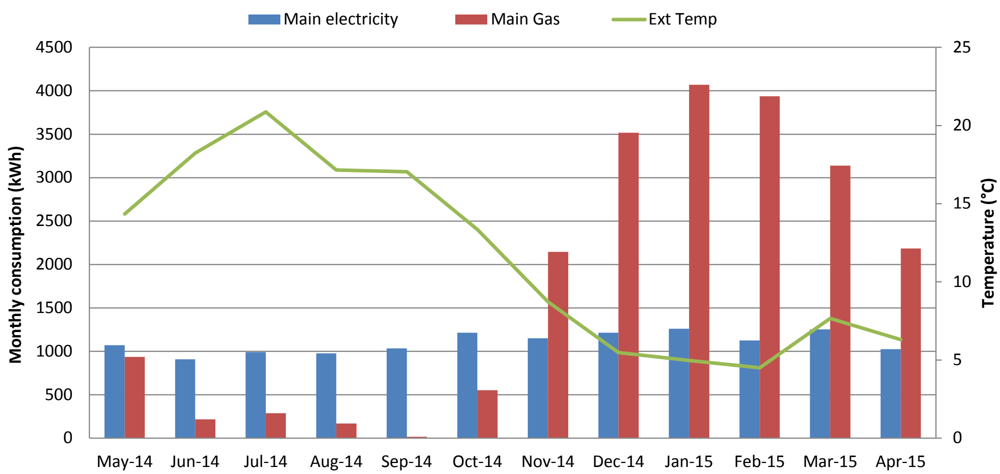


Figure 22
Comparison between annual energy consumption post refurbishment and energy benchmarks

Figure 23
Monthly electricity and gas consumption in Garth House and external temperature at the location



total of 34,387kWh of energy was used in the building with gas consumption making up 62% and electricity consumption making up 38% of the total. Post-refurbishment, Garth House achieved a 22% reduction in electricity use and a 67% reduction in gas use compared to pre-refurbishment. Figure 21 presents a comparison between energy used in the building during the periods pre and post refurbishment. There was a 58% reduction in overall annual energy consumption, matching perfectly the design prediction from the dynamic model. The overall emissions reduction achieved post-refurbishment was 48% of the pre-refurbishment figure. This is greater than the design prediction (37%) and the discrepancy was due to the fact that model did not take into account the use of electric heaters and fans post-refurbishment. Electricity consumption causes greater carbon emissions and hence a small reduction in electricity use results in significant reduction in overall carbon emissions. The post-refurbishment evaluation study showed that use of electric heaters and fans had greatly reduced, thus positively affecting the carbon footprint of the building. After the refurbishment, a strict heating schedule was applied and the heating was turned on only during occupied hours. This resulted in a significant reduction in gas consumption, corresponding to the pre-refurbishment prediction.

The annual gas and electricity consumption post-refurbishment were lower than ISO 12 ECON 19 Typical and CIBSE TM46 benchmarks and on only slightly higher with ISO 12 ECON 19 Good Practice benchmarks (Figure 22).

A more detailed assessment of electricity and

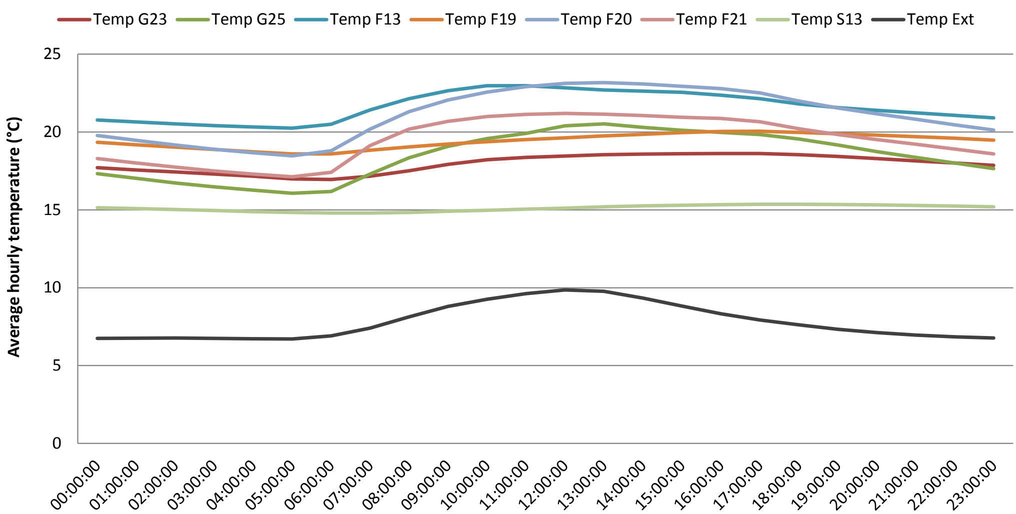


Figure 24
Daily variation of average hourly temperatures after the refurbishment during the winter season (October to April)

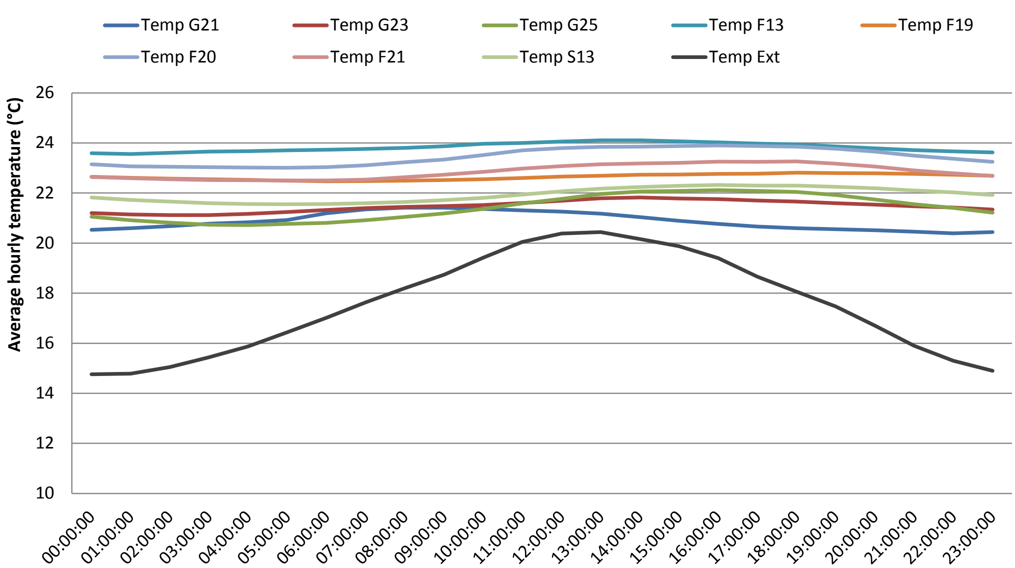


Figure 25
Daily variation of average hourly temperatures after the refurbishment during the summer season (May to September)

Figure 26
Temperatures during the hottest week in 2014 (Jul-14)

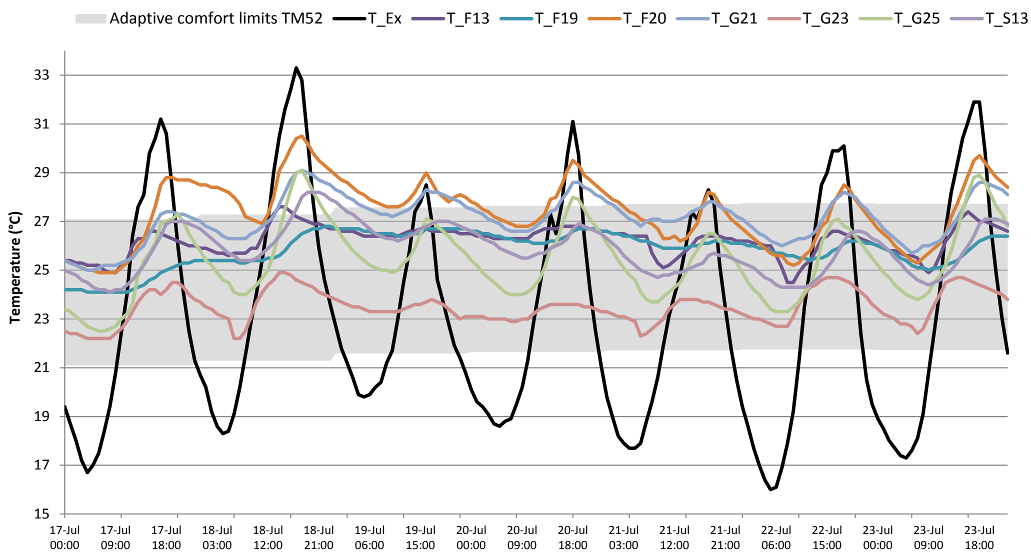
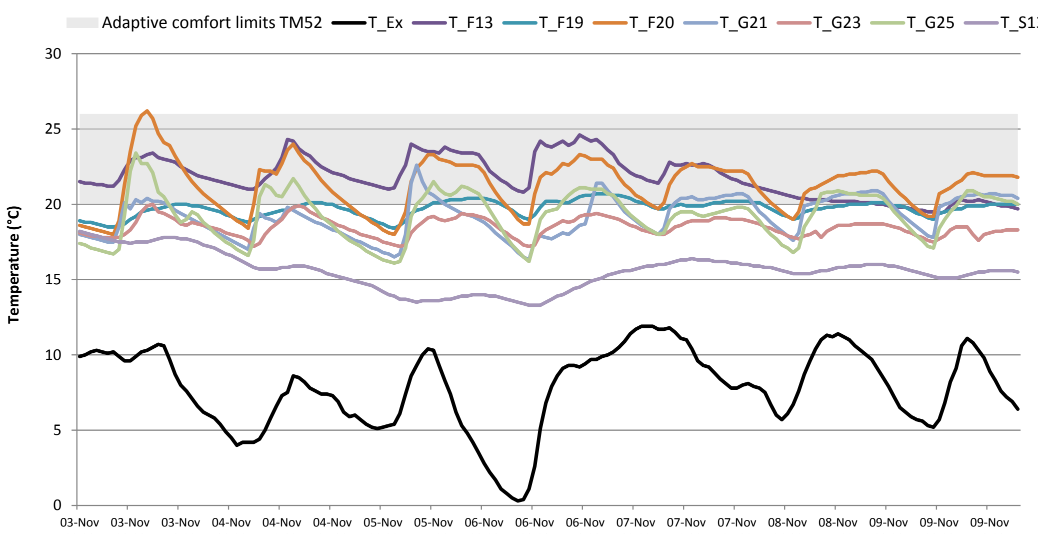


Figure 27
Temperatures during the coldest week in 2014 (Nov-14)



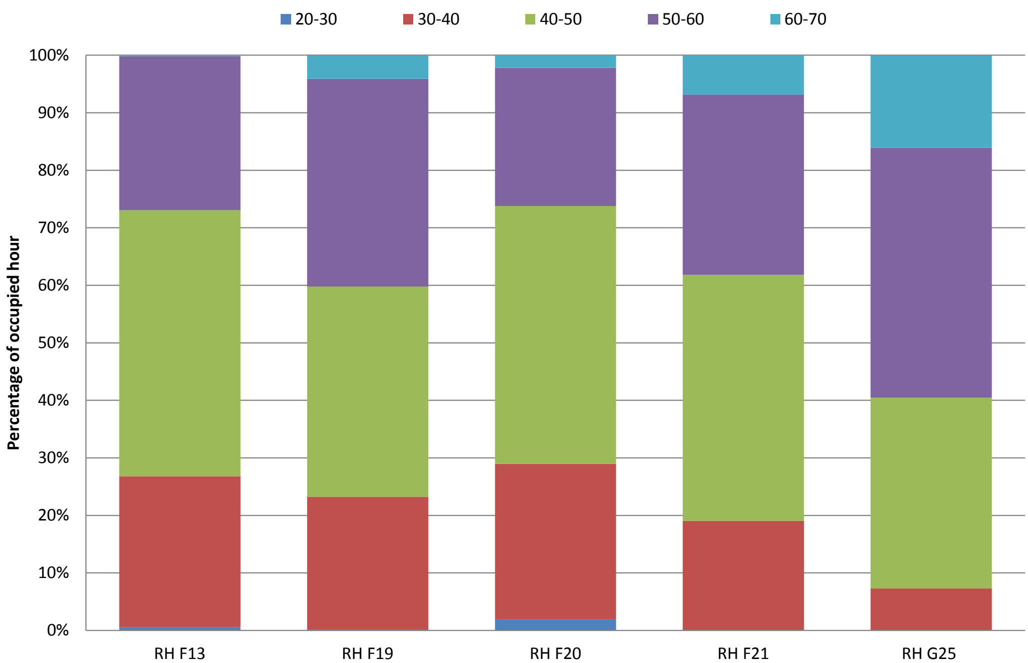


Figure 28 Percentage of occupied hours at a given RH ranges during April 2014 to March 2015

gas consumption showed that monthly electricity use was fairly constant throughout the year and gas consumption was in response to external temperature (Figure 23) indicating good control of heating in the building.

Environmental assessment

Post-refurbishment indoor environmental conditions were monitored in selected rooms for one year. The temperatures in most of the rooms ranged between 15°C to 23°C in the winter and 20°C to 26°C in the summer. The hourly indoor and outdoor temperature during winter and summer after the refurbishment are presented in Figure 24 and Figure 25 respectively. Before the refurbishment, the heating was continuously on to maintain the indoor temperature between 21°C and 24°C. After the refurbishment, higher temperatures were achieved during occupied hours even though the heating was on for a lesser amount of time than before. This was a result of the reduction of heat loss through ventilation and the building fabric. (Room S13 located on the second floor was not heated).

Thermal conditions were assessed for overheating in the summer and cold conditions in the winter using the adaptive thermal comfort range defined by CIBSE TM52. Figure 26 shows

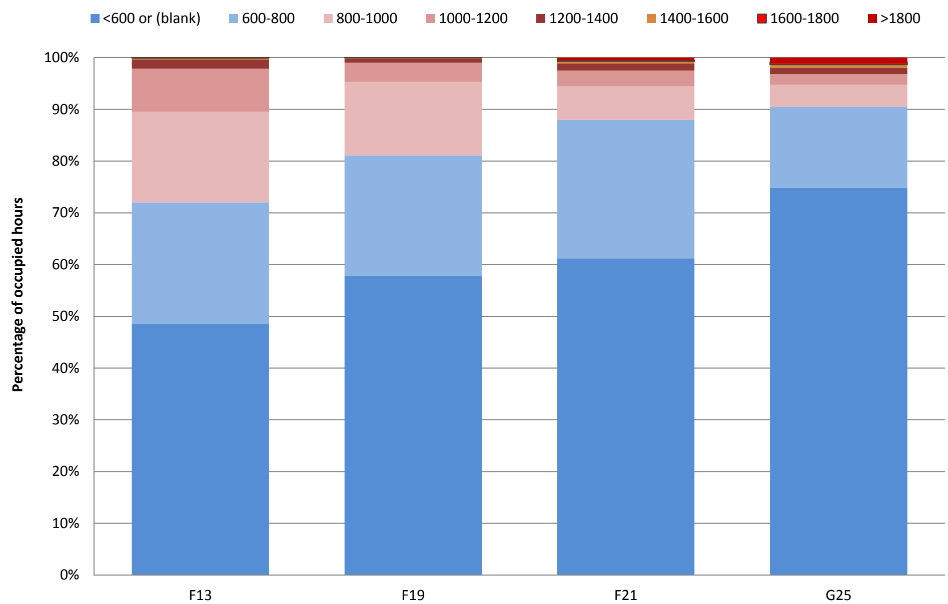


Figure 29 Percentage of occupied hours at a given CO_2 concentration range during April 2014 to March 2015

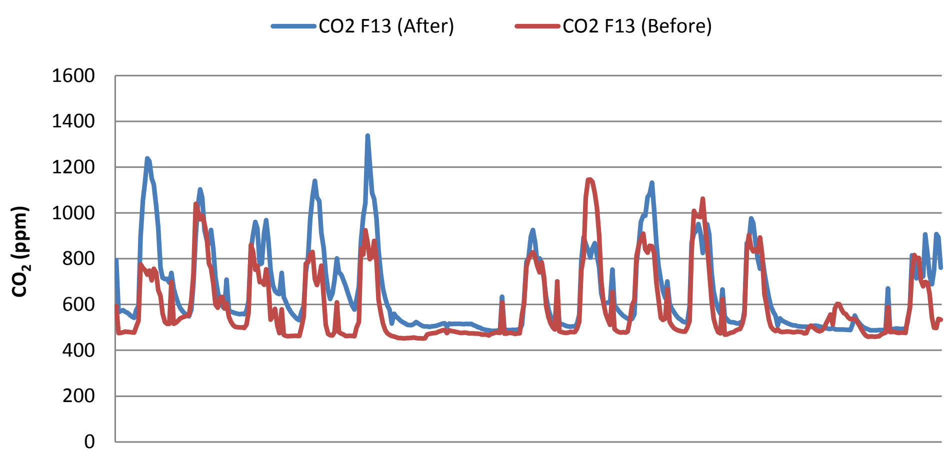


Figure 30 CO_2 concentration in room F13 before and after the refurbishment during winter (Before: Feb-13 – Mar-13 After: Feb-15-Mar-15) temperature patterns during the hottest week in the summer of 2014 (after the refurbishment). Temperatures in room F13 on the first floor exceeded the upper limit of the comfort zone in three out of the seven days. These days were all working days.

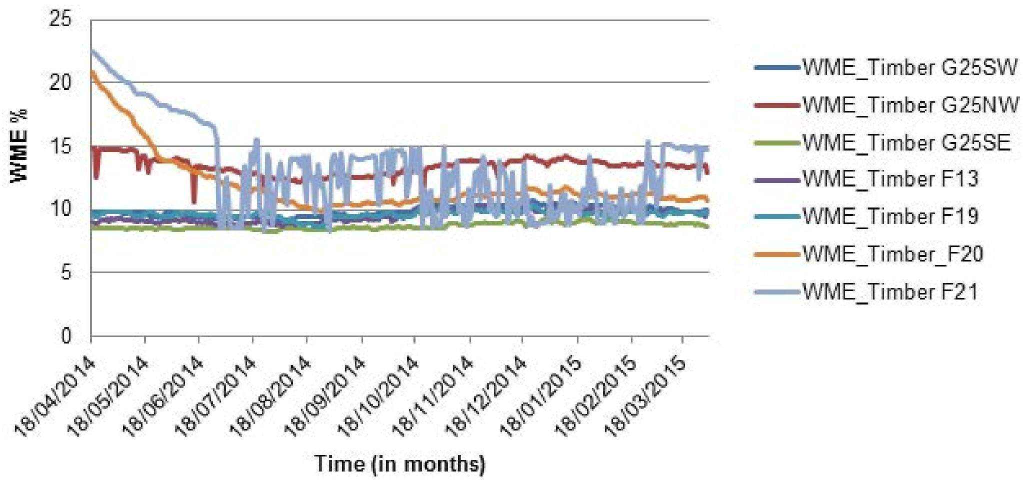
Figure 27 shows temperature patterns during the coldest week in the winter of 2014 (after the refurbishment). Room G23 on the ground floor was the coldest room however this room is not insulated as part of the project and used as a 'control' room in the assessment. The insulated room remained within the comfort band for most of the occupied hours.

After the refurbishment, relative humidity (RH) levels in most of the rooms ranged between 35-55% in the winter and 45-65% in the summer. There had been an improvement in winter RH levels as before the refurbishment it was drier, ranging between 20-40%. Overall, RH is maintained within the recommended limits of 40-70% for most of the occupied time (Figure 28)

Using CO_2 concentration as an indication of air quality, the monitored spaces experienced good air

Figure 31
Moisture sensors installed on the timber studs to record moisture content

Figure 32 Wood Moisture Equivalent (WME) of the timber studs inside the internal insulated walls



quality as CO_2 remained below 800ppm for over 70% of the occupied hours (Figure 29).

A comparison between CO_2 concentrations in room F13 on the first floor before and after the refurbishment show that higher concentrations occurred after the refurbishment than before. During both periods concentrations remained below 1500ppm, indicating adequate ventilation (Figure 30). The number of occupants in room F13 remained unchanged before and after the refurbishment. The higher concentrations after the refurbishment were probably due to the installation of insulation and lower air permeability levels. This indicates the importance of provision of adequate ventilation when the building air tightness is increased.

Moisture content of the building fabric

In addition to the standard environmental building monitoring system, sensors were installed to measure moisture content (Wood Moisture Equivalent (WME)) in the cavity construction formed behind the internal wall insulation and the timber studs at various locations (Figure 31). It is used to monitor the physical performance of behind the internal wall insulation and investigate if there was any risk of moisture related damage to the building fabric. Moisture build-up within the building fabric can result in mould growth and health risk to occupants as well as structural damage through rot.

As shown in Figure 32 moisture content of the timber studs reduced gradually from a maximum of 23% to below 16% over the first three months after the refurbishment and also remained relatively stable, well below 20% for the remainder of the monitoring period (dry rot thrives when humidity is over 90% and temperature is around

23°C. In a well maintained building, the moisture level in timber should not rise above 20% (Jenkins, 2008).

Occupant feedback and satisfaction

The BUS questionnaire method was used to obtain feedback on the building performance from the office staff members. The survey was conducted once before the refurbishment and again after the refurbishment. From both surveys, six respondents completed and returned the questionnaires. In addition to the BUS surveys, semi-structured interviews with the occupants and walkthroughs were conducted in order to further investigate any underlying issues with the building performance and overall user experience. All the occupants who participated in the surveys and interviews had been working in the building for more than one year and had a good knowledge of the building. Figure 33 summarises the key findings of the BUS survey conducted before and after the refurbishment.

The overall picture of the BUS survey conducted after the refurbishment revealed a very positive opinion of the staff members towards the building. The design, image to visitors and response to occupant needs were the most appreciated elements. The appearance of the building was reported to be smarter, tidier and more welcoming to both employees and visitors after the refurbishment. After the refurbishment, occupants found that their thermal comfort had greatly improved and they commented that the refurbishment had succeeded in making the building warmer and less draughty even though the heating system was not on as much as it used

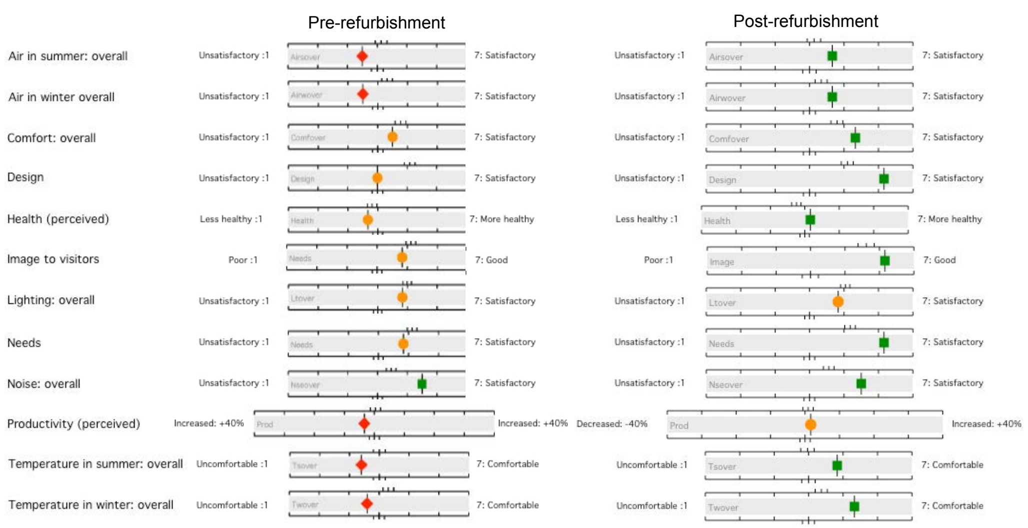


Figure 33
Occupant feedback on environmental parameters and overall comfort in the building before and after the refurbishment

it be (before the refurbishment). Air quality was also considered as improved and satisfactory after the refurbishment. The parameters rated positively before the refurbishment, were lighting and noise and these did not change after the refurbishment. On productivity, occupants acknowledged that it was a more pleasant atmosphere to work in but they had not noticed any increase or decrease in their productivity levels.

In the semi-structured interviews conducted after the refurbishment, positive comments were on the thermal conditions in the building. Occupants commented that:

> *'In the past we nearly all had an electric heater. We don't need them as much, at all now. And the heating thing has been fixed, I may not need one this winter. Before there was at least one heater per person, so probably about 4 and now there's probably one'*

> *'In the summer we used to get fans out to move the air around whereas with this summer we did notice quite a difference with opening the window. We all had a fan each (before)'*

> *'The refurbishment has succeeded in making the building warmer and less draughty'*

> *'In winter it used to be very cold and this winter was much more comfortable in terms of extremes in temperature and obviously there's not the draught through the windows'*

> *'In the winter, yes we have noticed warmer conditions. The radiators are not used on full power all the time and the heating system is not being worked as heavily as it should so we have noticed a big impact.'*

> *'In the summer it's been much nicer because we have those (new) vents so we can open the windows at the back and open the windows in our office, so it was lovely breeze coming through'*

The data environmental data recorded and analysed and the feedback from the occupants show that the refurbishment has succeeded in improving the thermal and air quality conditions in Garth House.

Key findings

Post-refurbishment monitoring data showed that there is 58% reduction in overall energy and 48% reduction in CO_2 over the pre-refurbishment level. This equates to 67% reduction in annual gas consumption and 22% reduction in electricity use over the pre-refurbishment level.

The envelope performance has very much improved after the refurbishment. The airtightness of the building improved greatly, from 20.52$m^3/h.m^2$ @ 50Pa to 9.31$m^3/h.m^2$ @ 50Pa. However, several air leakage paths were still identified around door and window frames, floor voids, skirting boards and glazing seals. Thermal imaging after the refurbishment showed some heat loss patterns through the roof-wall junction and between floors.

Although several minor problems have been identified during building handover, overall users are very satisfied about performance of the refurbishment, especially the indoor air quality.

The MVHR unit is easily accessible and is easy to operate. However, the control is not intuitive and a simple User Guide would be useful. Furthermore, the system is not installed and commissioned properly. There is a large amount of leakage into ceiling voids due to the way the ceiling terminals have been installed.

After the refurbishment, temperatures in most rooms range between 15-23°C during winter and 20-26°C during summer.

It was observed that following the refurbishment higher temperatures can be achieved in the room during occupied hours even though the heating is on for far less amount of time than before. This is a result of the reduction of heat loss through ventilation and fabric.

Overheating analysis using the Adaptive Comfort criteria (CIBSE TM 52) and following BS EN 15251 did not show any occurrence of overheating in any of the rooms.

The air quality in monitored offices is very good as over 70% of occupied hours are below 800ppm CO_2 concentration. In Room G25, 2.1% of occupied hours exceeded 1400 ppm CO_2 concentration due to the large number of occupants. These findings suggest that the MVHR system is performing well.

The moisture content of timber studs inside northwest wall of room G25, external wall of F20, southeast wall of F21 were gradually reduced from 22% to 12% over the first three months. The moisture content of external wall and floor joist stays relatively stable. They all stay below 20% moisture content above which rot does not develop.

The overall picture of the Building Use Studies (BUS) survey conducted after the refurbishment revealed a very positive opinion of the staff members towards the building with almost all elements scoring higher than the benchmark, as opposed to the findings before the refurbishment were most factors had scored below or within the benchmarks.

The BUS survey showed that most people find the spaces comfortable during winter and summer. Comments received during the second interviews pointed out that the comfort conditions in terms of temperature had greatly improved during both seasons, with the use of individual heater and fans greatly being reduced following the refurbishment.

The results are better than those from the pre-refurbishment BUS survey, which showed that before the refurbishment, temperatures during both summer and winter were not considered comfortable. Temperatures were considered 'too hot' during summer and 'too cold' during winter, leading to the use of fans to promote air movement during summer and electric space heaters during winter.

Air quality overall is also considered satisfactory, scoring higher that the scale midpoint and higher than the benchmark during both winter and summer. Results from the BUS survey conducted before the refurbishment were significantly worse with all elements and air quality overall scoring below the benchmarks

Impact, significance and outputs

The refurbishment of Garth House successfully tackled the challenges presented by refurbishing historic buildings to achieve a step-change reduction in primary energy use and CO_2 emissions primarily through the improvement of the building fabric. Additionally, there was a significant upgrade to the environment and occupant comfort making it an attractive option for organisations operating in historic buildings. The refurbishment project was delivered on time and within budget and the building's occupants responded positively to both the improvement of the internal environment and to the retention of historic features.

While no electricity-saving measures were installed, electricity use was reduced by 22% which can be partly attributed to users becoming more energy-conscious due to the works. The Garth retrofit marks the pioneering first use of WHISCERS™ (Whole House In-Situ Carbon and Energy Reduction System) on a non-domestic and historic building in the UK. This technology can now be considered for typical projects. Furthermore, with 12 months of detailed monitoring on the actual energy and environmental performance of the retrofit, the project offers significant information and the opportunity for shared learning to help other organisations implement their own projects.

This refurbishment project has a strong significance and impact as it tackled the main challenges facing refurbishments of historic commercial buildings to achieve the following:

- Minimising disruption to occupants and work routines was successfully preserved which avoided costs associated with renting alternative offices
- Garth House is now far more attractive to potential tenants due to its reduced energy bills and improved environment
- Staff wellbeing has been boosted with improved environment (e.g. better air quality and warmer in winter months)
- Bicester Town Council is involved in the delivery of NW Bicester (the UK's first eco town led by developer A2Dominion). This refurbishment has furthered its experience and reputation of pioneering sustainable development.

Communicating the success of this project could make similar installations more attractive to other project teams. The combined incentives of energy bill savings and reduction in carbon emissions as well as the improvements for occupants are compelling given the challenges of refurbishing historic buildings. While policy changes would be required to facilitate large-scale uptake, this project demonstrates how the barriers to energy-efficient retrofits can be overcome and could be used to inspire action.

Contextualising these outcomes, they can be applied to other historic buildings even though it is important to acknowledge the impact of differences between each historic building and its needs. The innovative retrofit of Garth House demonstrates the wide-ranging benefits of energy efficiency for project teams planning refurbishment projects. The project also successfully demonstrated that refurbishments do not have to impact upon building use or damage the appearance of heritage buildings – which are two recognised barriers to the uptake of energy-efficiency measures. Wider lessons and recommendations relating to the effectiveness of the BPE approach can be drawn for clients, designers, contractors and builders, the supply chain, building operators and users.

References

Arup. (2016). BUS Methodology. Retrieved from http://www.busmethodology.org.uk/

CIBSE. (2005). *CIBSE Guide B: Heating, Ventilation, Air Conditioning and Refrigeration*. London.

CIBSE. (2008). *TM46 Energy Benchmarks*. London.

DECC. (2011). The Carbon Plan: Delivering our low carbon future. *Energy*, (December), 218. Retrieved from http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf

Gupta, R., & Gregg, M. (2014). Evaluating Retrofit Performance – A Process Map. In S. Prasad (Ed.), *Retrofit For Purpose: Low Energy Renewal of Non-Domestic Buildings* (pp. 55–70). London: RIBS.

Jenkins, M. (2008). Rot in timber. *Technical Conservation Group*. Retrieved from http://conservation.historic-scotland.gov.uk/inform-rot-in-timber.pdf

Pout, C. H., & MacKenzie, F. (2005). *Reducing carbon emissions from commercial and public sector buildings in UK*. Watford.

UK Parliament. (2008). Climate Change Act 2008 (pp. 1–103). London: The Stationary Office.

UKGBC. (2016). Retrofit: Non-domestic buildings. Retrieved June 24, 2016, from http://www.ukgbc.org/resources/key-topics/new-build-and-retrofit/retrofit-non-domestic-buildings

Acknowledgement:

We would like to thank Innovate UK's Invest in Innovative Refurbishment programme for supporting this work.

Edited by Dr Kat Martindale