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Lessons learnt from design, off-site construction and performance analysis of deep energy retrofit of residential buildings

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ABSTRACT

The article introduces the process of deep energy retrofit carried out on a residential building in the UK, using a 'TCosy' approach in which the existing building is completely surrounded by a new thermal envelope. It reports on the entire process, from establishing the characteristics of the existing building, carrying out design simulations, documenting the off- site manufacture and on-site installation, and carrying out instrumental monitoring, occupant studies and performance evaluation. Multi-objective optimisation is used throughout the process, for establishing the characteristics of the building before the retrofit, conducting the design simulations, and evaluating the success of the completed retrofit. Building physics parameters before and after retrofit are evaluated in an innovative way through simulation of dynamic heating tests with calibrated models, and the method can be used as quality control measure in future retrofit programmes. New insights are provided into retrofit economics in the context of occupants' health and wellbeing improvements. The wide scope of the lessons learnt can be instrumental in the creation of continuing professional development programmes, university courses, and public education that raises awareness and demand. These lessons can also be valuable for development of new funding schemes that address the outstanding challenges and the need for updating technical reference material, informing policy and building regulations.

1. Introduction

This research draws its primary data from a Retrofit Plus project, funded between 2014 and 2017 under a grant from Innovate UK within the scheme for 'Scaling-Up Retrofit of the Nation's Homes'.

The general context of this research was set several years before, when in 2009 a five year 'Retrofit for the Future' programme was initiated and funded by Innovate UK [1]. The programme aimed to catalyse retrofit market by developing innovation in carbon emissions reduction. In the first phase, nearly 200 projects were funded to develop strategies for reductions of 80% of carbon emissions in existing homes. Subsequently, 86 projects were funded to enact successful strategies in over 100 retrofit demonstration projects [2]. Although significant reductions of carbon emissions were achieved and good practice identified, the programme identified considerable challenges for the retrofit market. These included a range of issues, including lack of competition, thus driving up the prices of high specification products; lack of skills of site operatives; disruption to residents; unexpected changes to project teams due to businesses going into administration; unexpected site issues causing delays; unexpected issues when obtaining planning permissions; increasing costs and delays; and others [2]. In order to overcome these challenges, a new programme on 'Scaling-Up Retrofit of the Nation's Homes' was launched in 2013 [3], of which Retrofit Plus project reported in this article was one of ten funded projects.

Retrofit Plus project worked on transforming an existing poorly performing building into a zero carbon building. The building was owned by Birmingham City Council, and was provided to the project for the purpose of deep energy retrofit under this scheme. The retrofit was carried out using a 'TCosy' approach that completely surrounds the building with Passivhaus type envelope [4].

The building comprised of two semi-detached houses (Fig. 1), with a common party wall. The construction type was 'Wimpey no-fines', which was common in the UK after the Second World War. This was a cast concrete construction without the 'fine' sand aggregate, thus explaining its name. This particular type of construction was a response to a rapid increase in housing demand and was aimed to help alleviate the shortage of materials and skilled labour in the late 1940s. Wimpey design was quicker and cheaper to produce, and some 300,000 dwellings were built us-

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Fig. 1. Houses to be retrofitted.

Fig. 2. Solid concrete in the external wall revealed during the retrofit process.

ing this method [5] between late 1940s and early 1950s, leaving a legacy of poor energy performance under the current regulations. A photo taken during the retrofit process with the external door frame removed shows the 300 mm solid concrete in the external wall (Fig. 2).

Thermal images taken before the retrofit during a cold winter day show high heat loss through the external walls below windows, in the positions that correspond to the locations of central heating radiators in the building (Fig. 3).

This article introduces the entire process of retrofit, from establishing the characteristics of the existing building, carrying out the design simulations, documenting the off-site construction and installation, and carrying our post-retrofit performance evaluation, using instrumental monitoring, user interviews and numerical analysis.

Dynamic simulation and multi-objective optimisation were used throughout the process, from establishing the existing building model, developing the design, and carrying out the evaluation physical parameters of the completed retrofit.

In addition to the comparison of energy consumption before and after the retrofit, the article investigates the change of building physics parameters through retrofit. This is achieved by establishing accurate simulation models of the building before and after the retrofit through calibration, and subsequently by carrying out dynamic heating tests with the calibrated simulation models. Information on the building time constant, effective thermal capacitance and the overall thermal transmittance is obtained on the basis of this analysis.

Economic analysis of the completed retrofit investigates sensitivity of payback period to investment cost and energy inflation. A monetary value of occupants' health improvement was used as an additional variable in calculating return on investment.

Initial work on this retrofit was previously reported by the author ([6–8]), however this article introduces additional and substantial new material and the final and complete analysis of the process and the performance.

The results of this research give new insights into the effect of retrofit on building performance, on building physics, and on retrofit economics.

2. Method

The method consists of the following steps before the retrofit:

1 Create dynamic simulation model of the building before the retrofit ('existing building model)' using information from technical surveys
2 Calibrate the existing building model using energy consumption information
3 Run design simulations and optimisation of the existing building model until objectives for achieving zero carbon performance are met and pass the parameters of the optimum model ('as designed retrofit model') to the construction delivery company (please see the Acknowledgements section).

After the retrofit, the method consists of the following:

1 Calibrate the 'as designed retrofit model' using data from the instrumental monitoring system and thus obtain 'as built retrofit model'.
2 Conduct simulations of dynamic heating tests with the existing building model and the as built retrofit model and obtain the building time constant, effective thermal capacitance, and overall thermal transmittance before and after the retrofit.

Details of the above steps are introduced in the text below.

2.1. Creating the existing building model

The choice of the simulation tool in this research is influenced by the required tasks that the tool is required to do. As the existing building model needs to be calibrated with reference to energy consumption data, the ultimate simulation tool needs to be capable of running dynamic simulation and specifying the functions for reducing simulation error in respect of gas and electricity energy consumption, the main sources of energy use in this building. As the simulation error needs to be the closest to zero, rather than just minimised, an absolute value is used to express the minimisation function:

$$\varepsilon = abs(Measured - Simulated)/Measured \times 100\ [\%] \qquad (1)$$

where 'measured' and 'simulated' are corresponding annual energy consumptions obtained from measurements and simulation respectively. Each energy source, gas or electricity, needs to have this error function assigned as an objective for minimisation, and therefore the simulation tool needs to be capable of multi-objective minimisation (minimisation being a special case of optimisation). Additionally, such minimisation needs to be achieved by varying relevant building energy consumption parameters within a certain range, and choosing a parameter set that generates errors that are the closest to zero. Hence the tool needs to be also capable of parametric simulation.

Although there are numerous simulation tools capable of parametric simulation and multi-objective optimisation, not many of these tools enable the user to write own objective functions. For this reason the ultimate tool chosen for this analysis was

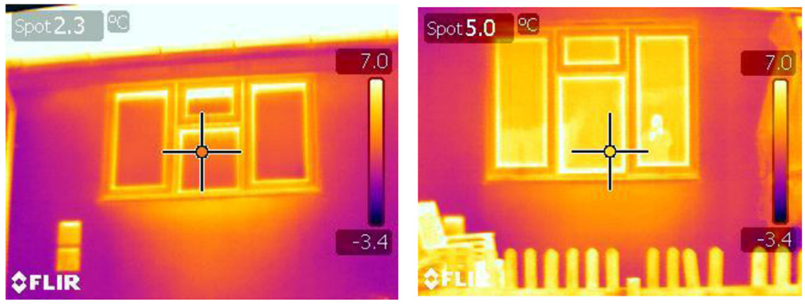

Fig. 3. Thermal images taken before retrofit showing high heat losses through external wall in positions corresponding to the locations of central heating radiators inside.

JEPlue+EA [9], running the underlying EnergyPlus simulation engine, as it fulfils all these requirements. However, due to the involvement of students in the initial survey [6], the initial model was created by them in IES Virtual Environment [10]. The model then had to undergo a number of transformations to obtain JEPlus+EA from IES Virtual Environment. First, the IES model was exported in gbXML format, and subsequently imported into DesignBuilder. As DesignBuilder uses an underlying EnergyPlus simulation engine, just like JEPlus+EA, it automatically creates EnergyPlus model from the gbXML import into DesignBuilder. The resultant EnergyPlus model was subsequently exported from DesignBuilder and the type and frequency of its outputs adjusted in EnergyPlus IDF file, in order to fulfil JEPlus+EA requirements. The resultant model was then inserted into JEPlus+EA, and the ranges and search strings for energy consumption parameters were created in order to enable parametric simulation and multi-objective optimisation. Thus the existing building model was created.

2.2. Calibrating the existing building model

The existing building model was calibrated using Eq. (1) from the previous section. Gas energy consumption calibration was achieved by varying heating set temperatures and infiltration rates through parametric simulation and minimising the error between measured and simulated consumption using Eq. (1) on an annual basis. Electricity energy consumption calibration was carried out by parametric simulations in which the lighting power density and miscellaneous gains power density were varied, both in W/m^2, and using Eq. (1) to calculate and minimise the error on an annual basis. This has resulted in the calibrated model of the existing building, which was then taken forward into design simulation and optimisation process, explained in the next section.

2.3. Design simulations and optimisation

The calibrated model of the existing building introduced in the previous section, was upgraded from double to triple glazing, and new objective functions were set: carbon emissions and discomfort hours. The parameters that were varied in order to minimise the objective functions were:

- TCosy wall insulation: 100 mm 150 mm, 200 mm, 225 mm, and 270 mm combined in pairs with the identical TCosy roof insulation thicknesses;
- infiltration air changes per hour;
- fuel type (gas or biomass);
- lighting power density;
- miscellaneous gains power density;
- two different PV arrays (east side of the roof only, and east and east side combined).

This approach resulted in a range of results, which will be discussed in the Results section. The simulation case that appeared on a Pareto front of the results scatter plot and fulfilled the design aims of being below zero carbon emissions and below a number of discomfort hours chosen in advance, was taken as the final design, and the parameters of that model were passed on to the construction delivery partner. The result of design simulation and optimisation was the as designed retrofit model.

2.4. Calibrating the as designed retrofit model

After the completion of retrofit, the houses were monitored for a year, and the results of monitoring were used to calibrate the as designed retrofit model, thus creating a calibrated as built retrofit model. The parameters that were used in this calibration were similar as in Section 1.2, but they were varied in slightly different respective ranges than those used in the design optimisation. The reason was that the results of construction were already known after the retrofit, including the wall and roof insulation thickness and the results of air tightness tests, and the end ranges of the parametric simulation were chosen to be both above and below the actual construction parameters, so that the effective value of the actual parameters could be determined. Thus:

- Wall and roof construction pairs were varied from insulation thickness between 216 mm and 324 mm, so that the actual thickness of 270 mm was in this range
- Infiltration air changes per hour between 0.6 and 6.0 air changes per hour (ACH). The measured air tightness n50 = 1.78 ACH was initially used as a fixed parameter, but calculated errors with that value were exceeding the acceptable error threshold of 0.5% by a significant amount. Hence the choice of the parametric change of ACH, from below to above this value.
- Internal set temperatures were varied between 16 °C and 21 °C in 0.5 °C steps. Unlike in the pre-retrofit calibration, in which living room temperatures and temperatures of other areas were varied separately, in the case after the retrofit a single temperature for the whole building was varied, taking into the consideration that deep energy retrofit results in more uniform temperature distribution throughout the building.
- Lighting power density was varied from $2\,W/m^2$ to $8\,W/m^2$ in steps of $0.5\,W/m^2$.
- Miscellaneous gains power density was varied in the same range as lighting power density.

Both calibrated models, the calibrated as built retrofit model and the calibrated model of the existing building were subsequently subjected to simulations of dynamic heating tests explained in the next section.

2.5. Simulations of dynamic heating tests

Equations for calculating building physics parameters from the results of actual dynamic heating tests are introduced in [6]. In this

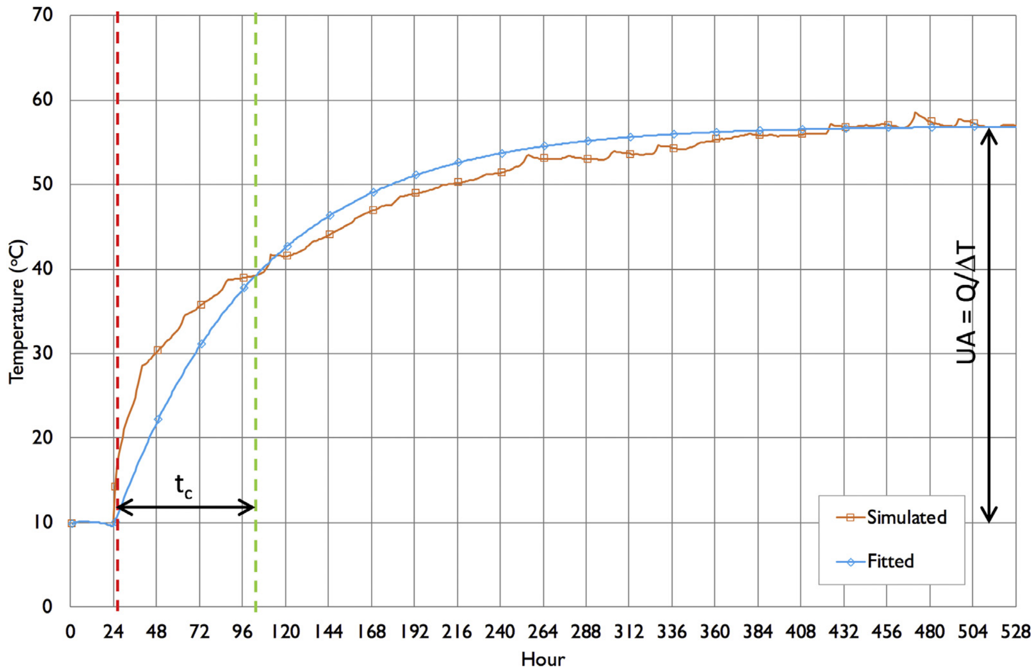

Fig. 4. Explanation of the dynamic heating test.

article, the actual dynamic heating tests are replaced with simulations of dynamic heating tests using calibrated simulation models. Although it can be argued that on the one hand the tests in an actual building would be more accurate than the simulations of these tests, the dynamic tests in an actual building are hard to carry out: the building needs to be heated up to a significantly higher temperature than typical room temperatures using additional electric heaters; the tests could last up several days during which external conditions need to be stable; and all internal heat gains need to be eliminated and occupants need to be moved out.

However, the simulation of a dynamic heating test is much easier to do, as it overcomes the difficulties associated with actual dynamic heating tests. It can be also argued that using a calibrated simulation model would be nearly as good as using the actual building.

The essence of a dynamic heating test is explained with reference to Fig. 4. The heating in the simulation model is switched on at 24:00 on 1st January. A sufficiently high heating power is chosen in order to achieve visible temperature response, and it is left on indefinitely. The pre-conditioning period that is normally used in simulation models in order to eliminate the effect of initial temperature assumptions is set to zero.

The equation that represents the change of internal temperature is as follows:

$$T_t = T_{start} + (T_{\max} - T_{start})\,x\left(1 - e^{-t/(t_c)}\right) \quad (2)$$

wheret – time

T_t – internal air temperature at time t

T_{max} – maximum internal air temperature reached as result of the heat input

T_{start} – starting internal air temperature at the time when heat input was switched on

t_c – building time constant in hours, representing the time it takes to go through 63% of the total change or internal air temperature

Building time constant from Eq. (2) is defined as

$$t_c = C/UA \quad (3)$$

where

C – effective thermal capacitance in MJ/K

UA – overall thermal transmittance-area product in W/K.

The value of building time constant is obtained from curve-fitting Eq. (2) to the simulated temperature in Fig. 4. The UA value is then obtained from the heat input Q divided by the temperature difference ΔT between internal and external temperature, after the internal temperature has reached steady state in Fig. 4. Effective thermal capacitance is then calculated from Eq. (3) as

$$C = t_c x UA \quad (4)$$

The overall thermal transmittance value UA accounts for both conductive and infiltration loss. Using the overall building surface area A calculated from building geometry, an average thermal transmittance value U is then calculated in W/(m^{2}K) as

$$U = UA/A \quad (5)$$

The average U value calculated in this way accounts for thermal transmittance of all elements of the building envelope, including walls, windows, ground floor slab, as well as infiltration heat loss.

The method introduced in this section will be applied to the analysis in the Results section.

3. Production, construction and monitoring

3.1. Production

The production of external building envelope was carried out in a factory of the construction delivery partner. In addition to on-site measurements of the existing building geometry, a 3D laser scan of the building was prepared by the research team and provided to the construction delivery partner for off-site measurements (Fig. 5). As the construction delivery partner was based a considerable distance away from the construction site, this reduced unnecessary travel to the site and increased the quality of the off-site production.

The production steps are documented in Fig. 6. First, the basic segment for the external insulation panel is created from timber (Fig. 6a) and its position on the wall is demonstrated (Fig. 6b).

Fig. 5. 3D laser scan of the building used for off-site measurements.

Subsequently, panel segments are linked together to create a complete frame (Fig. 6c). Before the panels are injected with insulation on site, ducting for MVHR (mechanical ventilation heat recovery) is inserted into them, as shown on the test façade in Fig. 6d. Fig. 6e shows a completed panel resting on the brackets on the test façade, and a damp proof membrane that will be wrapped around the bottom of the panel when installed on the building.

3.2. Construction

The completed panels are subsequently delivered to the site (Fig. 7a) with triple glazed Passivhaus standard windows preinstalled (Fig. 7b). The panels are lifted by a crane (Fig. 8a) and carefully slid down between the building façade and the scaffolding (Fig. 8b), until they reach the brackets alongside the perimeter trench (Fig. 8c), where they are secured. Thermal insulation beads are subsequently blown into the hollow panels (Fig. 8d), where a glue additive sets the insulation and prevents its leakage through the openings. Fig. 8b also shows old windows on the ground, which had been removed before the new insulation panels with preinstalled windows were put into place.

The completed retrofit is shown in Fig. 9, and is specified by the envelope characteristics in Table 1, shown side by side with the corresponding characteristics before the retrofit.

Further details of the external wall and roof constructions are shown in Fig. 10. The surface finish on the external walls is made from fiberglass-reinforced composite polymer panels with surface of aggregated natural stones. These panels, which are installed for ease of maintenance as they can be jet-washed, are completely ventilated. As they do not contribute to the thermal properties of the wall, they are not shown in Fig. 10a. The 300 mm air gap in

a) b) c) d) e)

Fig. 6. Production steps: a) creation of external insulation panel segment; b) panel segment provisionally attached to a wall; c) partially competed panel; d) panel with inserted MVHR duct attached to a test facade; e) bottom of the panel ready to be wrapped with a moisture barrier to prevent moisture ingress from the ground (a, b, d, and e source [7]).

(a) (b)

Fig. 7. (a) Prefabricated panels delivered to site (b) with pre-installed windows.

Fig. 8. Installation of the retrofit thermal envelope: (a), (b) and (c) – Stages of installation of an external prefabricated envelope panel; (d) Injection of thermal insulation into the installed external panel (source [7]).

Fig. 9. A photo of the completed retrofit (source [7]).

Table 1
Envelope characteristics before and after retrofit (source [7]).

	Before retrofit U value W/(m^2.K)	After retrofit
External walls	1.48	0.11
External glazing	1.60	0.79
External door	2.56	0.78
Ground floor slab	1.49	0.26
Roof	0.47	0.10
House	Air tightness 1/h at 50 Pascal	
A	6.05	calibrated 0.8 measured 1.78*
B	10.74	calibrated 0.8 measured 1.78*

* Please see Discussion section

the roof construction in Fig. 10b represents a much larger air gap in the pitched roof. The ground floor insulation was achieved by placing the same amount of external insulation in a 0.7 m vertical trench around the slab perimeter. Thus, the U value of the ground floor slab in Table 1 was calculated according to a CIBSE procedure for vertical edge slab insulation [11, pp. 3–16.]

3.3. Monitoring

Internal conditions were monitored using a wireless data logger and the corresponding temperature sensors were placed away from

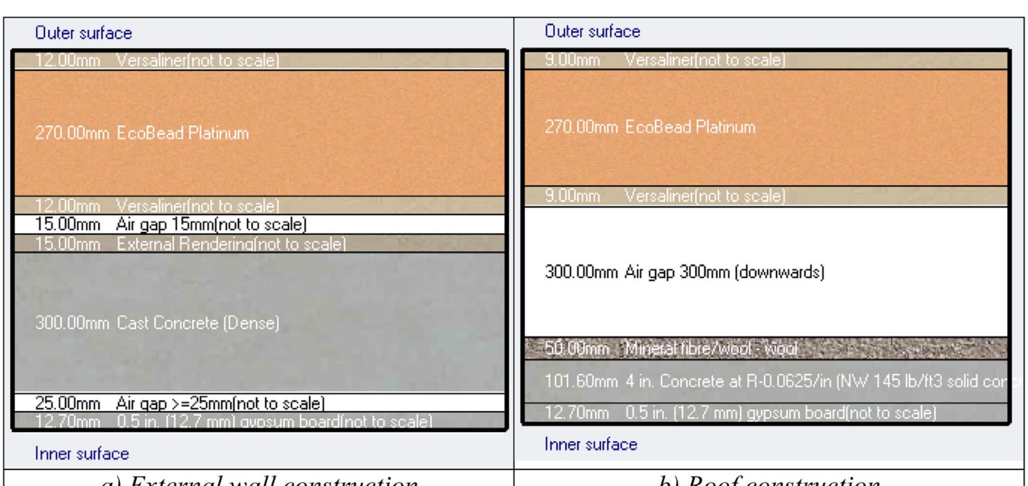

Fig. 10. Details of wall and roof constructions.

(a) (b)

Fig. 11. Internal conditions are monitored with (a) wireless room temperature sensors connected to (b) wireless data logger.

(a) (b)

Fig. 12. (a) Smart electricity meter; (b) smart gas meter.

heat sources at 1.5 m height in the living room and the larger of the two bedrooms.

Gas and electricity energy consumption were monitored with smart meters and data were obtained directly from the energy supplier.

External conditions were monitored with a weather station installed locally on the roof of a university building. The weather station recorded in intervals of 15 minutes the solar radiation on the horizontal surface, external air temperature and relative humidity, wind velocity and direction, and rainfall.

4. Results

4.1. Existing building model

The calibration process in JEPlus+EA was set using parameters that influence electricity and gas consumption. For calibrating electricity consumption the lighting power density and miscellaneous gains power density were set as parameters to be varied. For gas energy consumption the heating set temperatures and infiltration rates were set as parameters to be varied. Eq. (1) was used for both gas and electricity objective functions.

After the completion of the optimisation process, the JEPlus+EA scatterplot gives interactive access to the results (Fig. 14). In the case of calibration, we are not interested in the minimum values as we would be in the case of optimisation, but we are interested in the points that are the closest to the origin of the coordinate system. Thus placing the cursor on that point brings up a popup window with the calibration parameter set, the ‘chromosome’ that determines the values of parameters that resulted in the most accurate simulation. The results show that the errors of the calibrated model are 0.17% in respect of electricity consumption and 0.33% in respect of gas consumption, meaning that the model is 99.83% accurate in respect of electricity consumption and 99.67% accurate in respect of gas consumption. This calibrated model was subsequently carried forward into design simulations and optimisation analysis reported in the next section.

4.2. Design simulation and optimisation

Design simulations and multi-objective optimisation were subsequently carried out in order to minimise discomfort hours and carbon emissions, using a range of technical and behavioural parameters. The technical parameters were: five different thicknesses

Fig. 13. Weather station.

of TCosy wall insulation: 100 mm, 150 mm, 200 mm, 225 mm, and 270 mm, combined in pairs with the identical TCosy roof insulation thicknesses; infiltration air changes per hour; fuel type (gas or biomass); lighting power density and miscellaneous gains power density; and two different PV arrays (East side of the roof only, and East and West side combined).

The parameters that were left to the occupants to adjust were deemed to be behavioural parameters as follows: room set temperature and clothing level.

The results of multi-objective optimisation are shown in Fig. 15. Placing the cursor above individual points reveals the ’recipe’ or the ‘chromosome’ for the corresponding design, and was the basis for making the recommendation to the construction delivery partner.

4.3. Monitoring results

Instrumental monitoring was carried out before and after the retrofit and the results of internal conditions are shown in Fig. 16. Energy consumption results are shown in Fig. 17 and weather conditions in Fig. 18. A point to note on the horizontal axis of these figures is 19th January 2017 when the retrofit was completed. Before that date, internal conditions fluctuated significantly, and went down to 15 °C in November 2017. After the completion date, internal conditions rose steadily, despite the cold weather immediately after the completion. After the completion date, there is a significant reduction in gas heating energy consumption, so that consumption levels from before the retrofit are never reached. Energy savings are analysed in detail in Section 4.4 and in Table. 2.

It is noted in Fig. 17 that House B peaks in gas energy consumption in the post-retrofit period are not much lower than peaks for the pre-retrofit period. Electricity consumption in the pre-retrofit period in House B is at the same time higher than in the post-retrofit period. Interviews with occupants revealed that in the pre-retrofit period not all rooms were heated continuously with

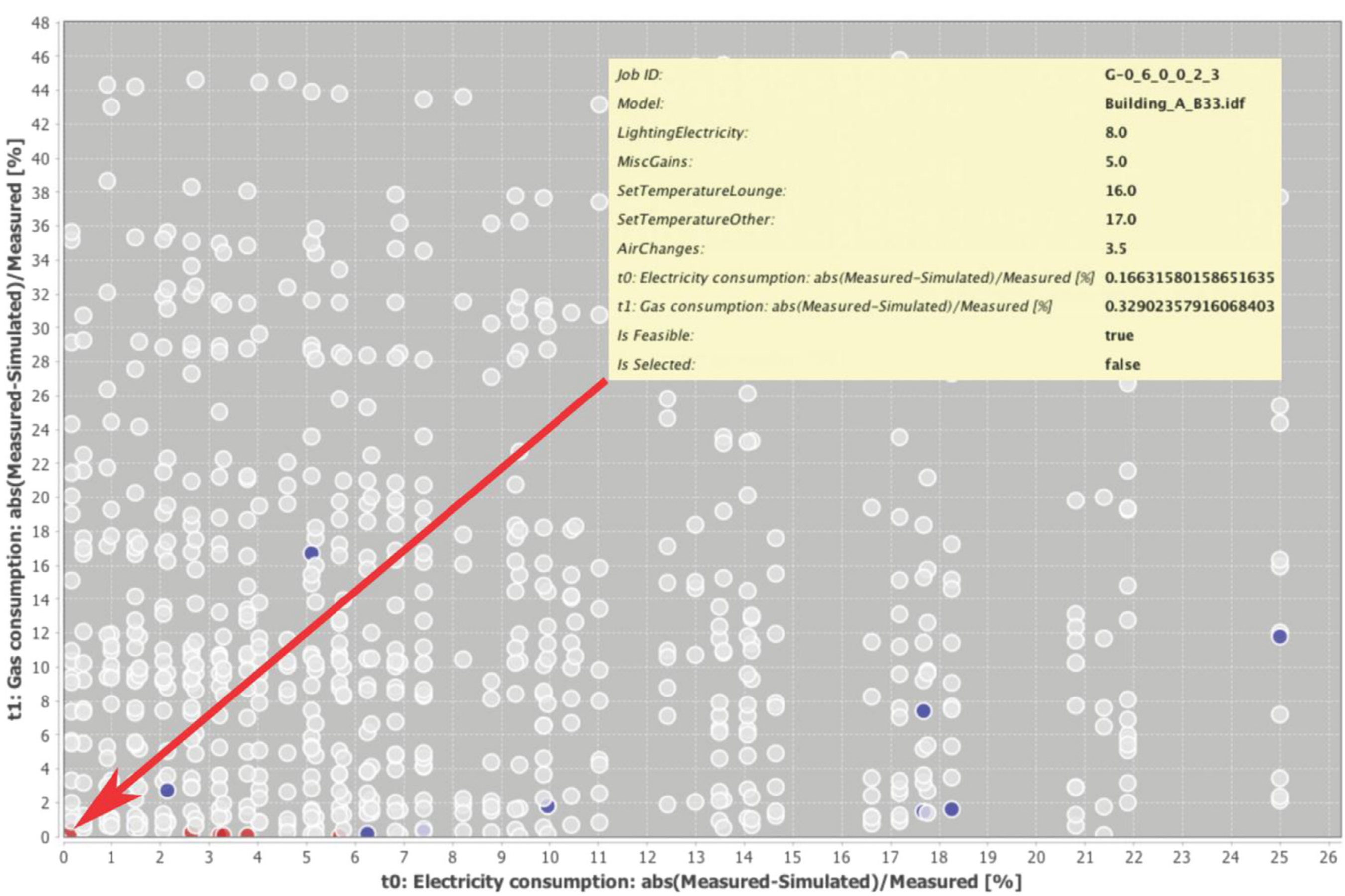

Fig. 14. Results of calibration of the existing building model (source [8]).

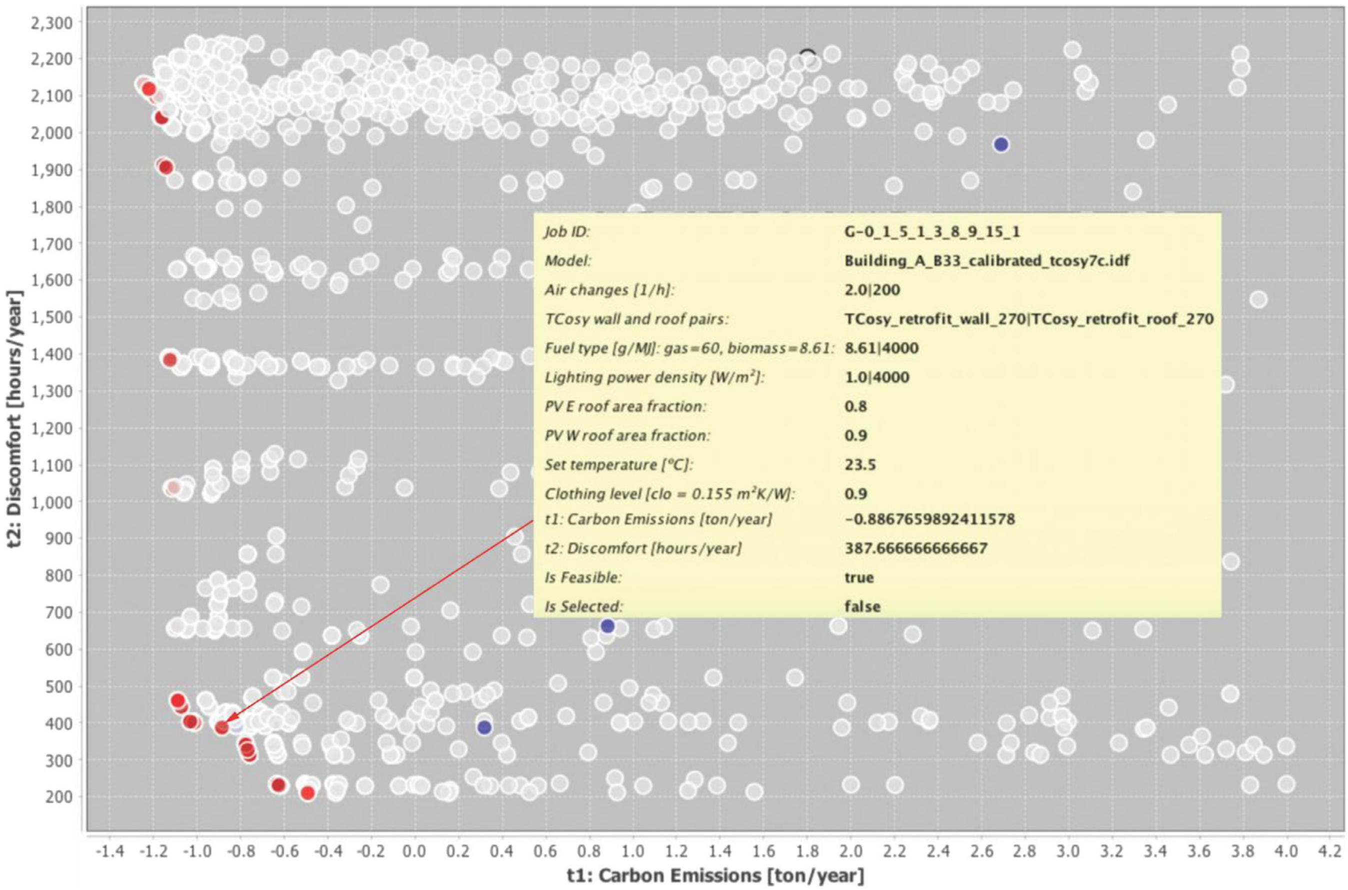

Fig. 15. Results of design optimisation.

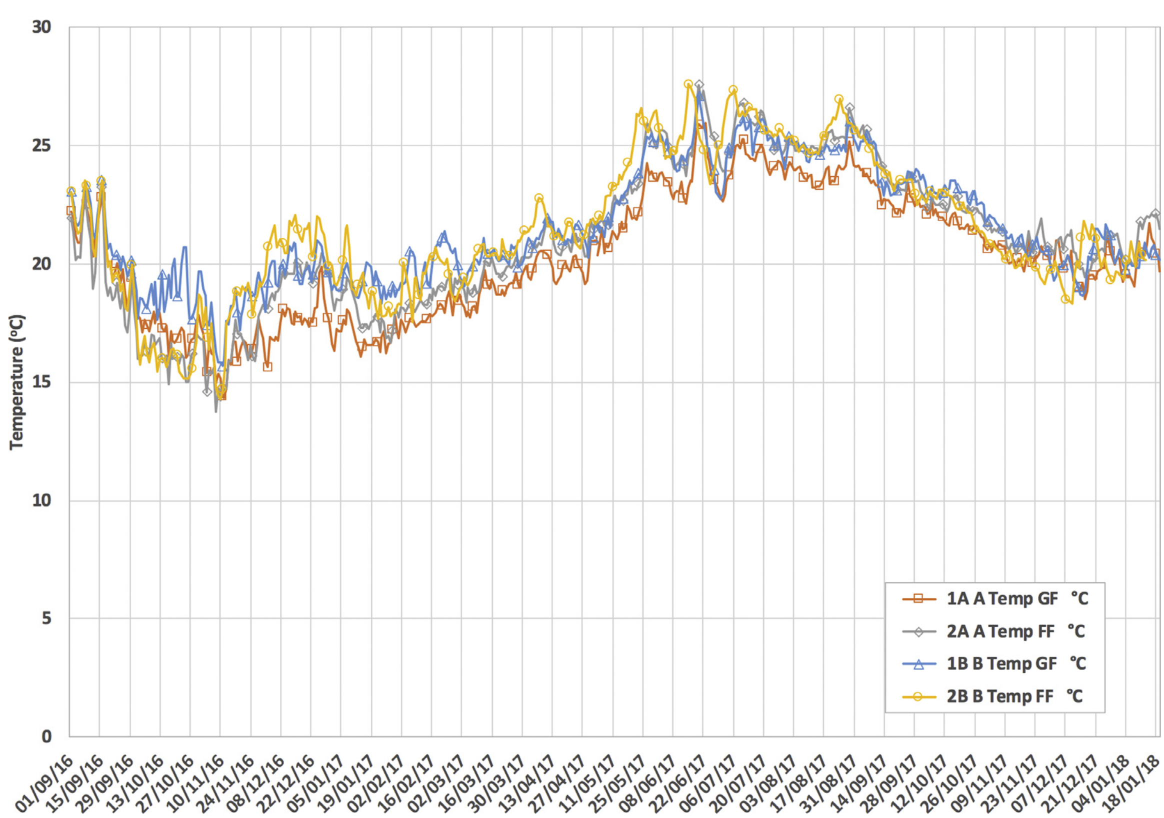

Fig. 16. Monitoring results - internal conditions.

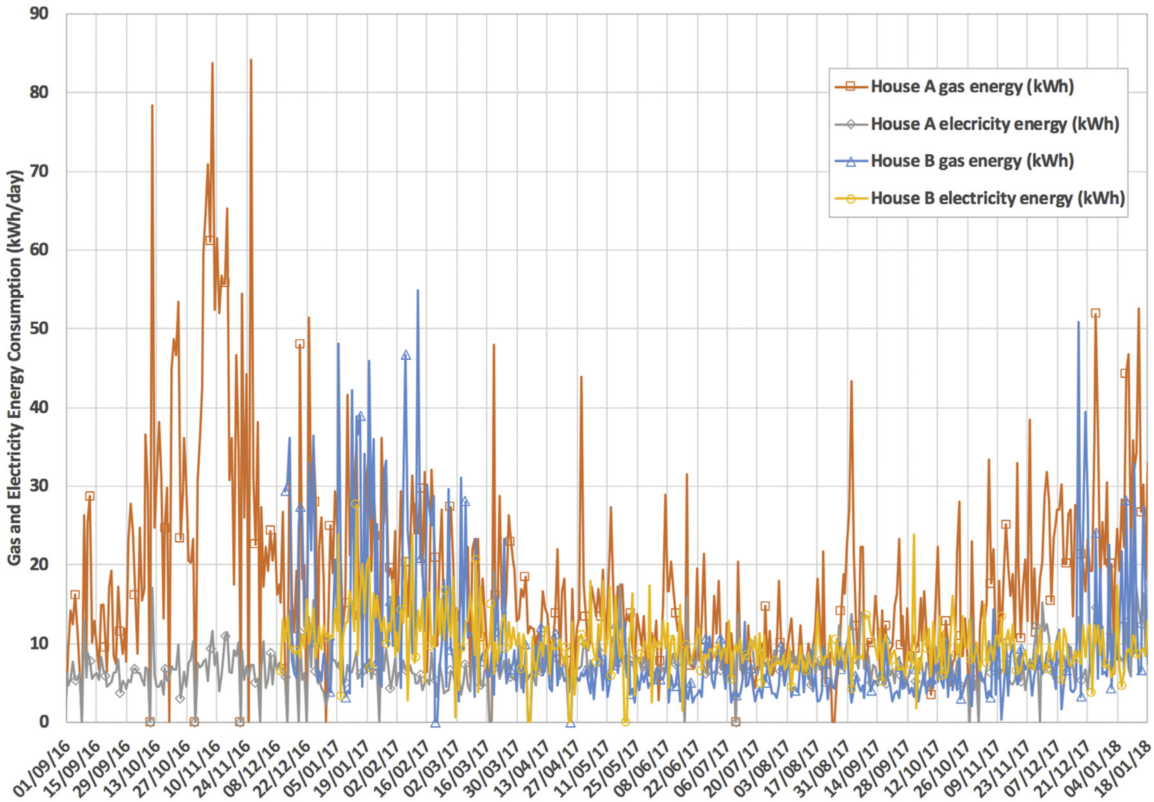

Fig. 17. Monitoring results – energy consumption.

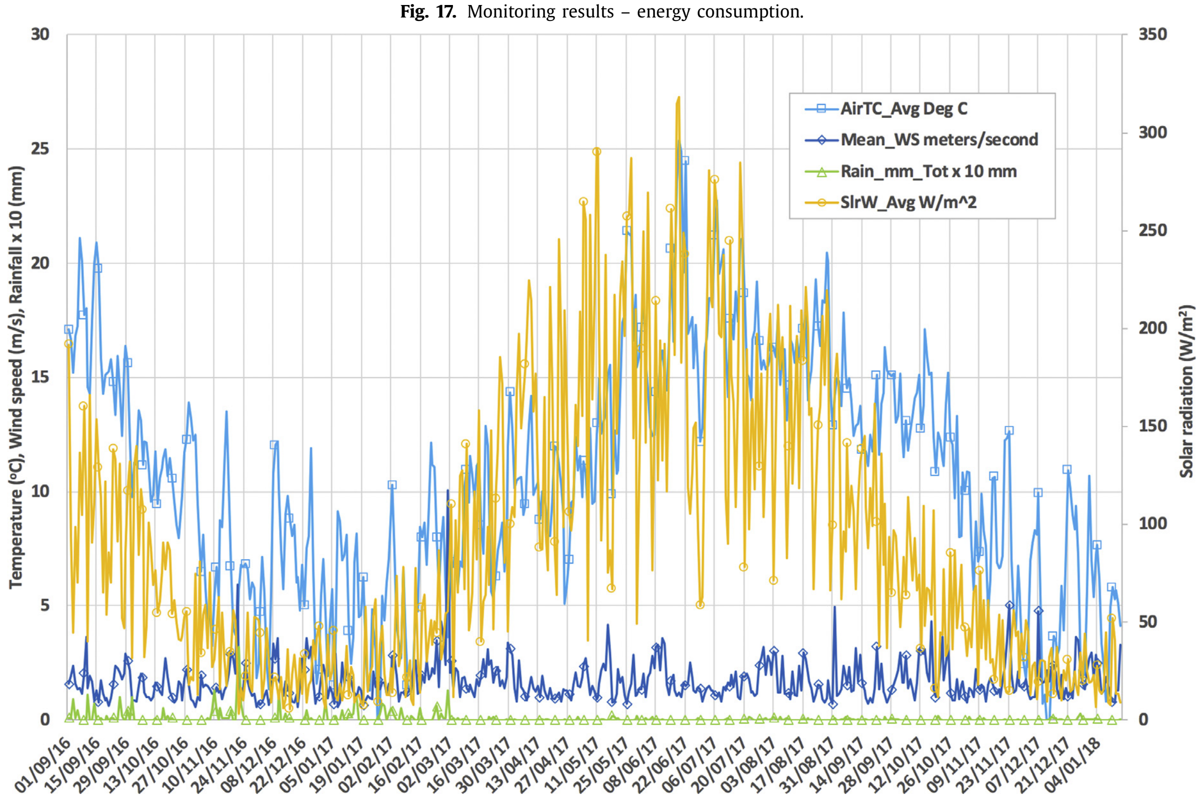

Fig. 18. Monitoring results – weather data.

gas central heating, and that the living room was heated with electricity. Gas heating was switched intermittently during that period, often to dry clothes after washing. The gas energy peaks in the pre-retrofit period were therefore mainly associated with evaporating moisture from washed clothes and inadvertently heating up the cold walls. After the retrofit, and electricity consumption halved in House B. Central heating was used more, thus potentially representing a manifestation of the 'rebound effect' [12], a "*phenomenon that improving energy efficiency may save less energy than expected due to a rebound of energy use*" [13].

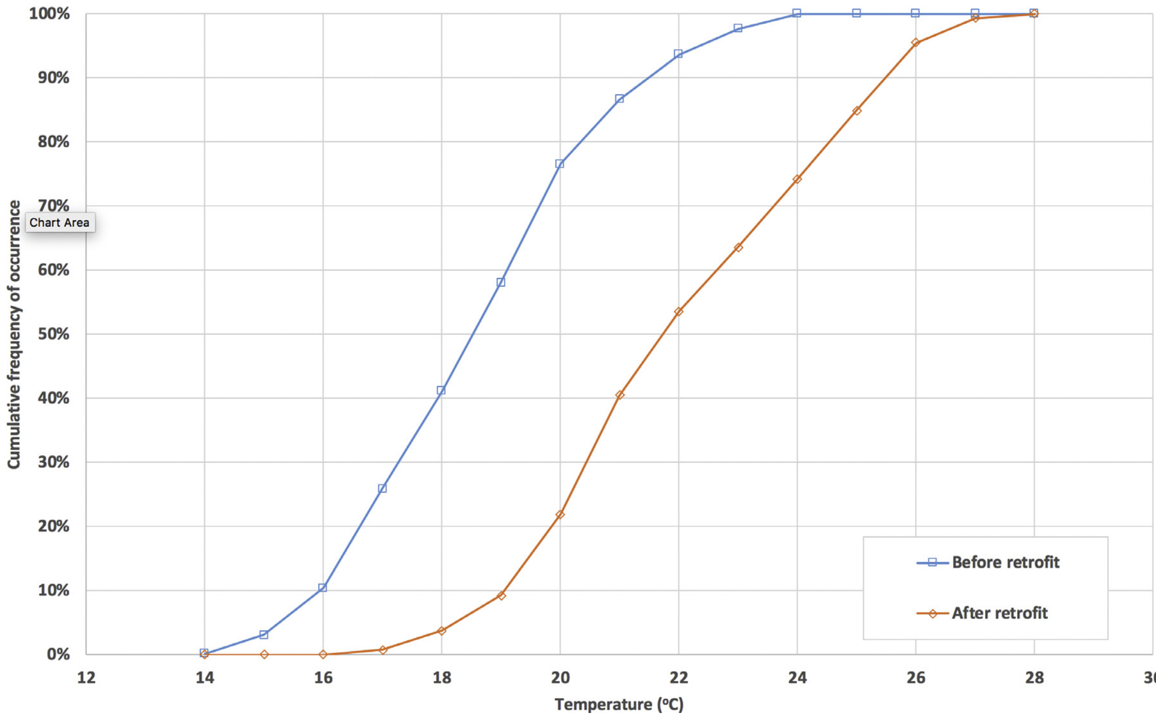

Fig. 19. Frequency of occurrence of internal air temperatures before and after retrofit.

The odd peaks in gas consumption in House A are attributed to cooking.

In order to ascertain internal thermal comfort conditions, frequency of occurrence internal air temperatures was calculated before and after the retrofit (Fig. 19). The results show that 87% of all internal temperatures are less than or equal to 21 °C before the retrofit, and only 41% of temperatures are less than or equal to 21 °C after the retrofit. This indicates a considerable improvement in internal conditions during the heating season. The same figure also shows a general elevation of internal temperatures by 3 °C after the retrofit, and that no overheating occurs after the retrofit, despite this temperature elevation. However, some of the temperature elevation during the space heating period may be attributed to the occupants becoming more relaxed about their energy bills.

4.4. Energy savings resulting from retrofit

Energy savings are calculated on the basis of records of energy consumption before and after the retrofit. The records before the retrofit were based on annual energy bills for year 2014–2015. The records after the retrofit were based on annual energy consumption recorded by smart meters. The analysis focuses on one out of the two semi-detached houses, due to better energy records before the retrofit. The heating energy consumption reduction HECR is calculated as

$$HECR = \frac{Q_{post}}{Q_{pre}} \tag{6}$$

where
Q_{post} – heating energy after the retrofit
Q_{pre} – heating energy before the retrofit.

In order to estimate longer term savings, heating energy consumption reduction is normalised using Degree Days as follows:

$$HECR_{norm} = \frac{\frac{Q_{post}}{DD_{post}}}{\frac{Q_{pre}}{DD_{pre}}} \tag{7}$$

where
DD_{post} – Degree Days after the retrofit
DD_{pre} – Degree Days before the retrofit.

Rearranging the expression (7) leads to weather-normalised heating energy consumption reduction:

$$HECR_{norm} = HECR \times \frac{DD_{pre}}{DD_{post}} \tag{8}$$

and the unadjusted heating energy saving HES after the retrofit is calculated as

$$HES = 1 - HECR \tag{9}$$

After We define the term from Eq. (8)

$$\frac{DD_{pre}}{DD_{post}} = ECNF \tag{10}$$

as Energy Consumption Normalisation Factor ECNF. The weather-normalised hating energy saving is calculated as:

$$HES_{norm} = 1 - HECR_{norm} \tag{11}$$

Energy consumption and savings are shown in Table. 2. The savings figures are shown as a direct comparison between before and after the retrofit, as well as weather-normalised using two sources for Degree Days (Table 3).

As it can be seen from Table 2, heating energy saving based on gas consumption is 53% with base load taken into account. However, as gas was used for cooking as well as for heating, base load was estimated from gas consumption during June and July 2017 and deducted from overall gas consumption, thus representing heating energy consumption. This has resulted in a 3% increase in the estimate of the heating energy consumption saving, from 53% to 56%. When heating energy consumption is weather-normalised, the savings are reduced to 45% and 42% depending on the degree Days used for calculation (Table 2). Electricity consumption comparison after the retrofit shows a 3% increase, and with electricity base load removed using similar calculation as for gas energy, electricity consumption after the retrofit increased to 4%.

Table 2
Energy savings resulting from retrofit.

	Pre-retrofit consumption	Post-retrofit consumption	Unadjusted savings	Degree day normalised saving (weather file DD)	Degree day normalised saving (CIBSE DD)
Energy consumption and savings	(kWh)	(kWh)	HES (%)	HES_{norm} (%) (see Table 3)	
Including base load					
Gas	12,179	5699	53%	41%	38%
Electricity	2530	2613	−3%		
Excluding base load					
Gas	11,511	5032	56%	45%	42%
Electricity	2071	2155	−4%		

Table 3
Energy consumption normalisation factors.

Degree days calculation (base temperature 15.5 °C)		Energy consumption normalisation factor (ECNF)
Post retrofit (source: monitoring system weather station)	1826	1.00
Pre-retrofit (source: weather file GBR_Birmingham.035340_IWEC.EPW)	2300	1.26
Pre-retrofit (source: CIBSE for Birmingham-Elmdon)	2425	1.33

Table 4
Carbon emissions performance resulting from retrofit.

Energy consumption	Pre-retrofit consumption	Post-retrofit consumption—unadjusted	Post-retrofit consumption—degree day normalised (weather file DD)	Post-retrofit consumption—degree day normalised (CIBSE DD)
Space heating (kWh/y)	11,511	5032	6337	6682
Electricity consumption increase due to MVHR ($kWh/m^2/y$)		83	83	83
Carbon emissions				
Gas ($kgCO_2/y$)	2486	1087	1369	1443
Electricity ($kgCO_2/y$)	0	43	43	43
Total emissions ($kgCO_2/y$)	2486	1130	1412	1487
Reduction of emissions (%)		55	43	40

This increase is most likely to be due to the operation of the MVHR system. As electricity was not used for heating, the electricity consumption figures were not weather-normalised.

4.5. Overall performance metrics

How does this retrofit compare with other performance standards, and has it reached zero carbon emissions as originally aimed?

The results are discussed in the context of Fig. 15 and Table 5. Despite the application of Passivhaus type retrofit envelope in this project [4], the original aims of the project were to retrofit to zero carbon performance and not to Passivhaus standard. This is how design simulations were carried out, as shown in Fig. 15, from where it can be seen that the selected design was below zero carbon emissions and below 400 discomfort hours. The selected design from that figure includes two PV arrays, on the east side and west side of the roof, covering 80% and 90% of the respective roof surface areas. The selected design also includes the change of an existing gas boiler into biomass heating.

The project was awarded funding by Innovate UK over a three-year period and started in 2014. Although the funding did not include renewable energy systems, the UK Government Green Deal was in operation at that time, and funding for renewable energy systems was expected to come from that source. However, in 2015, Green Deal was discontinued [14], and this change of external funding circumstances meant that the project could not achieve zero carbon performance. However, a significant reduction of carbon emissions was achieved, as shown in Table 4. The space heating figures in this table are taken from the part of Table 2 that excludes the base load attributed to cooking. Instead of representing the figures as percentage savings in Table 2, these were expressed as absolute values in kWh. Electricity consumption from Table 2 is expressed in Table 4 as consumption increase due to the MVHR operation. Energy consumption figures were subsequently multiplied by the corresponding emission factors, 0.216 kgCO2/kWh for gas and 0.519 kgCO2/kWh for electricity and shown separately in this table, together with the total emissions and emission reductions with reference to the pre-retrofit case.

Although the project did not specifically target Passivhaus performance, it is useful to compare its performance with Passivhaus and EnerPHit standards, the latter being a slightly more relaxed Passivhaus standard for low energy retrofit projects [15]. The comparison is shown in Table 5. The space heating figures in this table are taken from Table 4 and are normalised to the floor area to make them comparable with Passivhaus and EnerPHit standards.

As it can be seen from Table 5, neither Passivhaus or EnerPHit standards have been achieved, bearing in mind that these performance standards were in fact not the aims of this project. What can be said however is that the project has placed the retrofitted building onto a trajectory to zero carbon, as actual zero carbon performance could not be achieved in practice due to the change of external funding circumstances referred to above. If or when that funding becomes available in the future, a further retrofit that

Table 5
Energy performance resulting from retrofit.

	Pre-retrofit consumption	Post-retrofit consumption—unadjusted	Post-retrofit consumption—degree day normalised (weather file DD)	Post-retrofit consumption—degree day normalised (CIBSE DD)
Space heating (kWh/y)	11,511	5032	6337	6682
Space heating (kWh/m²/y)	153	67	84	89
Passivhaus space heating demand (kWh/m²/y)			≤ 15	
EnerPHit space heating demand (kWh/m²/y)			≤ 25	

involves the installation of PV and biomass heating could change the performance of this building into zero carbon.

It is worth noting that the space heating consumption figures in Tables 4 and 5 may also be influenced by the rebound effect [12], as the occupants become more relaxed about their energy bills, as already discussed in Section 4.3. This is a complex issue, which requires a further detailed investigation that is beyond the scope of this article and will be subject of a follow up research.

4.6. Improvements of wellbeing of occupants

Regular questionnaires were issued to the occupants after the retrofit and were followed by interviews in order to establish the user experience. The questionnaires were based on visual analogue scales, which reduce the chances of remembering the answers from previous questionnaires and thus ensuring higher accuracy of user feedback. Thus, all occupants were consistent in their perception of heating energy use being high before the retrofit, and being low after the retrofit. The perception of thermal comfort is also consistent, low before the retrofit and high after the retrofit. The buildings were not very air tight before the retrofit and became much tighter and with mechanical ventilation with heat recovery after the retrofit (see Table 1), and hence the perception of internal air quality was consistently low before the retrofit and consistently high after the retrofit. The perception of the general performance of systems after the retrofit and of the mechanical ventilation system was consistently high, and so was the perception of the overall performance of the house, including comfort and energy.

I addition to the questionnaires, the following comments were received from the occupants:

"I did not need heating when outside temperature dropped below freezing yesterday";

"The house feels like home now – no damp, no dust, no noise.";

"I have stopped using my asthma puffer".

The above indicate significant improvements of wellbeing and health, the value of which is generally not taken into account when evaluating retrofit projects. This will be addressed in more detail in Section 4.8.

4.7. Retrofit payback period

Although the project discussed in this article was fully funded through industrial research (please see the Acknowledgements section), it is useful to establish economic performance of the retrofit and a direction for similar interventions in the future.

The analysis in this section therefore seeks to establish a payback period of the actual retrofit cost, taking into account weather-compensated energy consumption, inflation rate, borrowing interest rate, and energy cost inflation rate. A comparison will be made with weather-uncompensated savings and uninflated energy costs.

The figures of energy cost inflation of 1.5% for gas and 8.6% for electricity were obtained from the UK energy prices statistics [16].

The total cost of retrofit and energy consumption before after the retrofit is calculated as follows:

$$C_{post} = I + \sum_{0}^{N} \Big(Q_{pre} \times C_Q \times HECR \times (1+i_g)^n + E_{pre} \times C_E \times EECR \times (1+i_e)^n \Big) \times \frac{(1+i)^{n-1}}{(1+d)^n} \quad (12)$$

$$C_{pre} = \sum_{0}^{N} \Big(Q_{pre} \times C_Q \times (1+i_g)^n + E_{pre} \times C_E \times (1+i_e)^n \Big) \quad (13)$$

and the objective is to find payback period n that satisfies the following criterion:

$$C_{post} = C_{pre}, \; N > n > 0 \quad (15)$$

where
C_{post} – running energy costs after the retrofit in £
C_{pre} – running energy costs before the retrofit in £
Q_{pre} – running heating energy consumption before retrofit in kWh
Q_{post} – running heating energy consumption after retrofit in kWh
E_{pre} – running electricity energy consumption before retrofit in kWh
E_{post} – running electricity energy consumption after retrofit in kWh
EECR-Epost/Epre (HECR has already been defined in Section 4.4)
C_Q – Unit cost of heating energy provided by gas central heating in £/kWh
C_E – Unit cost of electricity energy in £/kWh
i_g – price inflation of gas expressed as a fraction
i_e – price inflation of electricity expressed as a fraction
N – time horizon in years
n – number of years.

The results of this analysis are shown in Fig. 20 for weather-uncompensated energy consumption and uninflated energy costs. Fig. 21 shows the results for weather-uncompensated energy consumption and inflated energy costs. Retrofit payback periods for weather-compensated energy consumption and uninflated energy costs are shown in Fig. 22 and retrofit payback periods for weather-compensated savings and inflated energy costs are shown in Fig. 23. In addition to the analysis with the actual costs of £85,000 per house, these figures show a range of other lower investment costs for the purpose of testing the sensitivity of payback periods. Thus, in an uncompensated and uninflated case (Fig. 20), the payback period is just under 120 years, but when energy inflation is taken into account, this reduces to 38 years (Fig. 21). If it was possible to reduce the cost of retrofit to £10k whilst achieving the same energy performance, applying the low end of the sensitivity testing range referred to above, then the same figure shows that payback period would be reduced to 17 years.

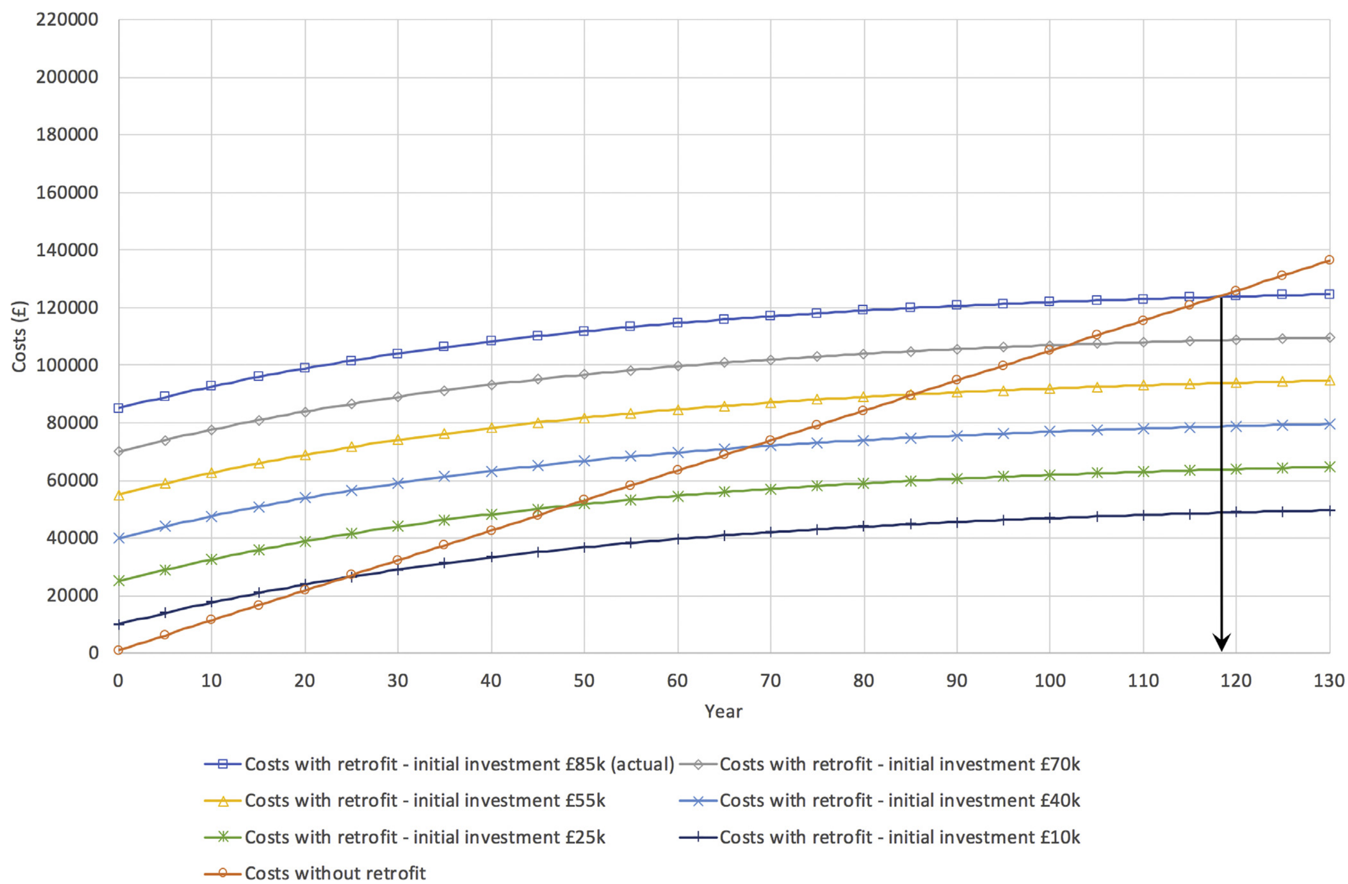

Fig. 20. Retrofit payback periods for weather-uncompensated energy consumption and uninflated energy costs.

The corresponding weather compensated figures are slightly worse, by a year or two, as it can be seen in Figs. 22 and 23, however the same scale of reduction occurs between the figures without energy inflation and with energy inflation, so that the minimum payback period for a £10k retrofit investment cost would be 18 years.

As it can be seen from the comparison of charts in Figs. 21 and 23, energy price inflation reduces the influence of the difference between weather-uncompensated and weather-compensated energy savings on the payback period.

4.8. Retrofit return on investment

Considering that retrofit payback periods are substantially longer than what is normally considered to be acceptable, a different approach is investigated based on the return on investment (ROI). A return on investment of an intervention is generally expressed as

$$ROI = \frac{(Benefit - Cost)}{Cost} \times 100\ [\%] \tag{16}$$

As there is evidence of immediate health improvement in the retrofitted properties discussed in 4.6, the question arises whether these benefits can be quantified and used for financial assessment of the retrofit. Eq. (16) can therefore be expressed as

$$ROI = \frac{(E + H - C)}{C} \times 100\ [\%] \tag{17}$$

where

E – Energy benefit, $E = C_{post} - C_{pre}$ and

$$H = \sum_{1}^{P} \left[\sum_{1}^{Y} \left(QALY_{after} - QALY_{before} \right) \right] \times V \tag{18}$$

where

$QALY_{after}$ – Quality-adjusted life year per occupant after retrofit
$QALY_{before}$ – Quality-adjusted life year per occupant before retrofit
P – Number of occupants
Y – Number of years for each occupant
V – Monetary value of QALY = £12,905
and where QALY – quality adjusted life year, was established to be £12,905 for thermal insulation intervention only, without changing the heating system [17].

The results of this analysis are shown in Fig. 24 using time horizon of 40 years. Without health benefits taken into account, ROI yields 26% at 40 years and payback period occurs where the ROI curve crosses the horizontal axis. The chart shows ROI improvements taking into account 10% QALY improvement for one person, two people and four people. As it can be seen from this figure, adding QALY to the calculation of retrofit benefits for one, two and four people, increases the ROI to 86%, 147% and 269% and reduces the payback period from 38 years, to 32, 25, and 16 years respectively. Given the scale of this improvement, we can ask ourselves why are we not taking the monetary health benefits into account on a regular basis in deep energy retrofit projects?

4.9. Calibrated as built retrofit model

In order to evaluate the change of building physics parameters through simulations of dynamic heating tests, calibrated

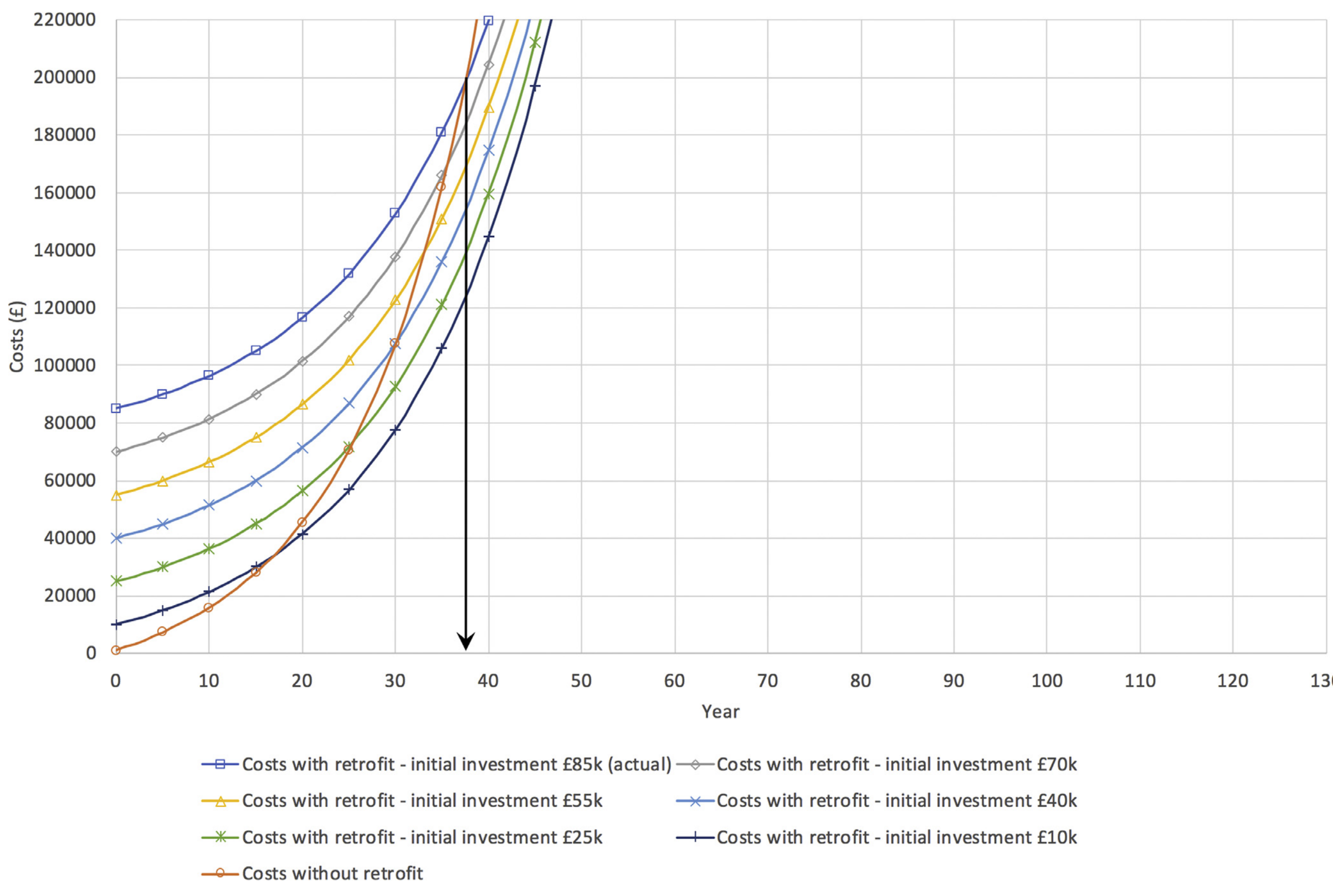

Fig. 21. Retrofit payback periods for weather-uncompensated energy consumption and inflated energy costs.

Table 6
Numerical results of dynamic heating test simulations.

Building physics parameter	Post-retrofit	Pre-retrofit	Ratio post-retrofit/pre-retrofit
Time constant C/UA (h)	78.4	21.9	3.58
Overall transmittance-area product UA (W/K)	147.3	328.7	0.45
Effective thermal capacitance C (MJ/K)	41.6	25.6	1.63
Overall thermal transmittance U (W/m^2.K)	0.69	1.54	0.45
Theoretical transmittance-area product UA (W/K)	88.7	309.4	0.29

simulation models of the building before and after the retrofit are required. The calibrated model before the retrofit was obtained before the design simulations commenced, and is reported in Section 4.1, showing accuracy of 99.83% in respect of electricity consumption and 99.67% in respect of gas consumption. The same calibration procedure was subsequently applied to the as built retrofit model, and the results are shown in Fig. 25.

The calibrated model corresponds to the point that is the closest to the coordinate system and has the coordinates of t0 = 0.05% and t1 = 0.42%, representing relative errors in respect of electricity consumption and gas consumption. This indicates high accuracy of the calibrated as built model, namely 99.95% in respect of electricity consumption and 99.58% in respect of gas consumption. Both calibrated models: the model of the existing building before the retrofit, and the model of as built building after the retrofit were subsequently taken forward into the analysis of building physics parameters before and after the retrofit using simulations of dynamic heating tests, reported in the next section.

4.10. Evaluation of building physics parameters before and after retrofit using simulations of dynamic heating tests

The results of simulations of dynamic heating tests before and after the retrofit are illustrated in Fig. 26. In both cases, the heat input into the model before and after retrofit was identical. Despite of that, the pre-retrofit case reached temperatures of around 26 °C after the heating was switched on, which was considerably lower than the temperature reached by the post-retrofit case of around 57 °C. These differences were due to different envelope characteristics: uninsulated solid concrete in the pre-retrofit case, and heavily insulated with 270 mm thermal insulation in the post retrofit case.

The numerical results of dynamic heating test simulations with a series of different heating rate inputs are shown in Table 6. The pre-retrofit case reached the time constant time much sooner than the post retrofit case. As it can be seen from Table 6, there is nearly 3.6 times increase in the time constant, from 21.9 hours to 78.4 hours as result of the retrofit. The overall transmittance-area product was reduced from 328.7 W/K to

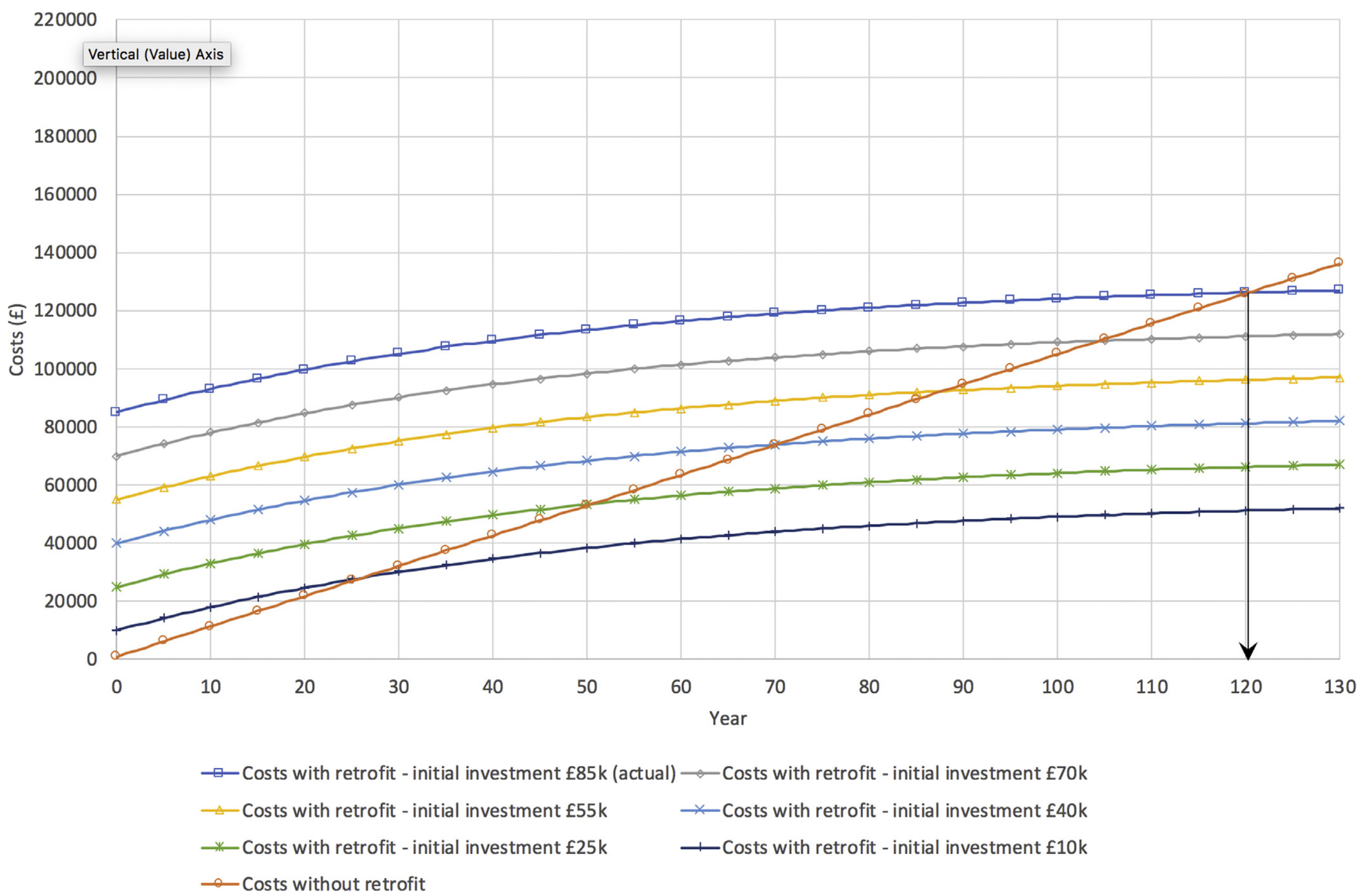

Fig. 22. Retrofit payback periods for weather-compensated energy consumption and uninflated energy costs.

147.3 W/K and the effective thermal capacitance increased from 25.6 MJ/K to 41.6 MJ/K. The overall thermal transmittance U in this table was calculated by dividing the overall transmittance-area product by a manually calculated surface area of the building. The results show that the overall U value, which included the effect of infiltration, reduced from 1.54 W/m^2.K to 0.69 W/m^2.K as result of retrofit. The theoretical UA values are shown in the same table for comparison, and it can be seen that these are 6% lower for the pre-retrofit case and 66% lower for the post-retrofit case.

This work therefore demonstrates the effect of retrofit on the building physics parameters, as well as the method for evaluating the change of building physics parameters in a retrofit project, and introduces a quality control measure for the completed retrofit.

5. Discussion

Although the retrofit approach taken in this project is innovative in comparison with typical practice, the cost of retrofit is relatively high and it leads to long payback period. However, the payback period can be considerably reduced and return on investment can be considerably increased by taking into account energy cost inflation and by quantifying health benefits arising from retrofit, as shown in Sections 4.7 and 4.8. This calls for a change of business models for retrofit, considering the scale of change introduced by this approach.

The role of multi-objective optimisation appeared to be critical in this project for establishing an accurate starting simulation model of the existing building (Fig. 14), and conducting design simulations that through optimisation create a range of trade-off solutions shown on a Pareto front (Fig. 15). Multi-objective optimisation was also instrumental in achieving accurate simulation models before and after the retrofit and evaluating building physics parameters before and after retrofit through simulations and analysis of dynamic heating tests. Due to a combined effect of multiple parameters used for parametric simulation and optimisation, the building physics parameters obtained from this analysis are considered to be ‘effective’ rather than ‘absolute’. This means that the relative change between building physics parameters shown in Table 6 reflects the actual change, however the absolute values of these parameters may not correspond to the actual building physics parameters.

It is also worth mentioning that air tightness figures after the retrofit of 0.8 1/h in Table 1 are the simulation model calibration figures. An attempt to calibrate the model with the measured air tightness value of 1.78 1/h resulted in a considerable non-convergence of the calibration process, reaching excessive non-zero values. Due to the concerns raised by the construction delivery partner in personal communication with the author about the accuracy of air tightness tests carried out by a third party, carried out in parallel with unrelated electrical installation work in the building which may have influenced the results, the calibration figures are taken as more representative of the actual building air tightness performance.

The finding that theoretical UA were 6% lower for the pre-retrofit case and 66% lower for the post-retrofit case than the measured UA values requires urgent attention, as theoretical values from reference tables and manufacturers’ specifications make the energy performance appear significantly better in the design stage. These theoretical values need to be reviewed in the context of the

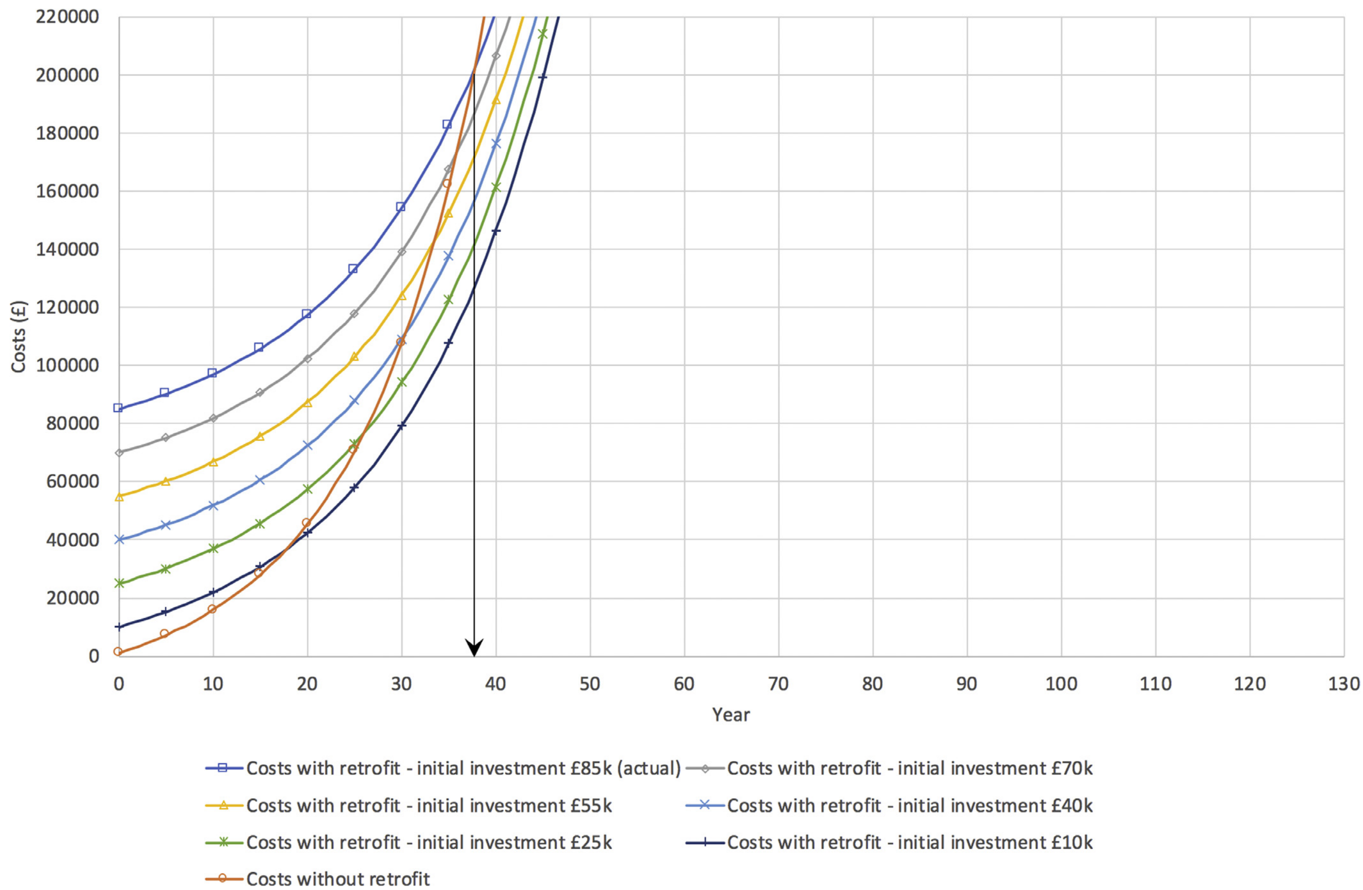

Fig. 23. Retrofit payback periods for weather-compensated savings and inflated energy costs.

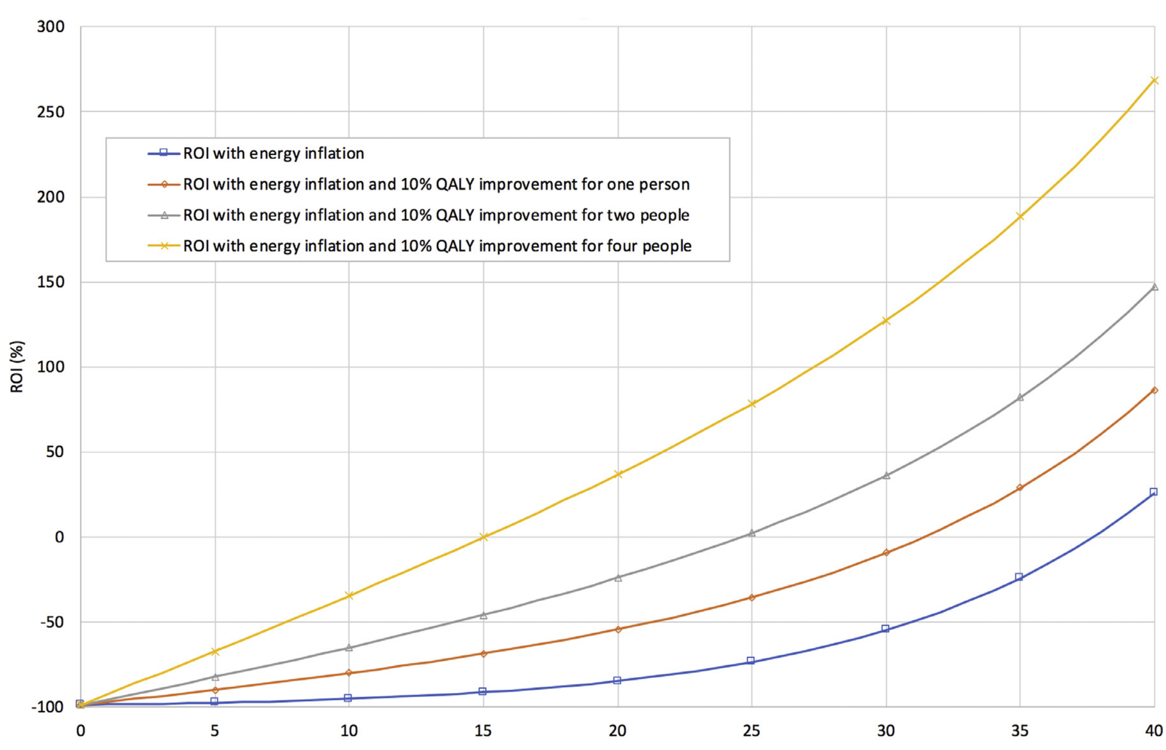

Fig. 24. Return on investment analysis.

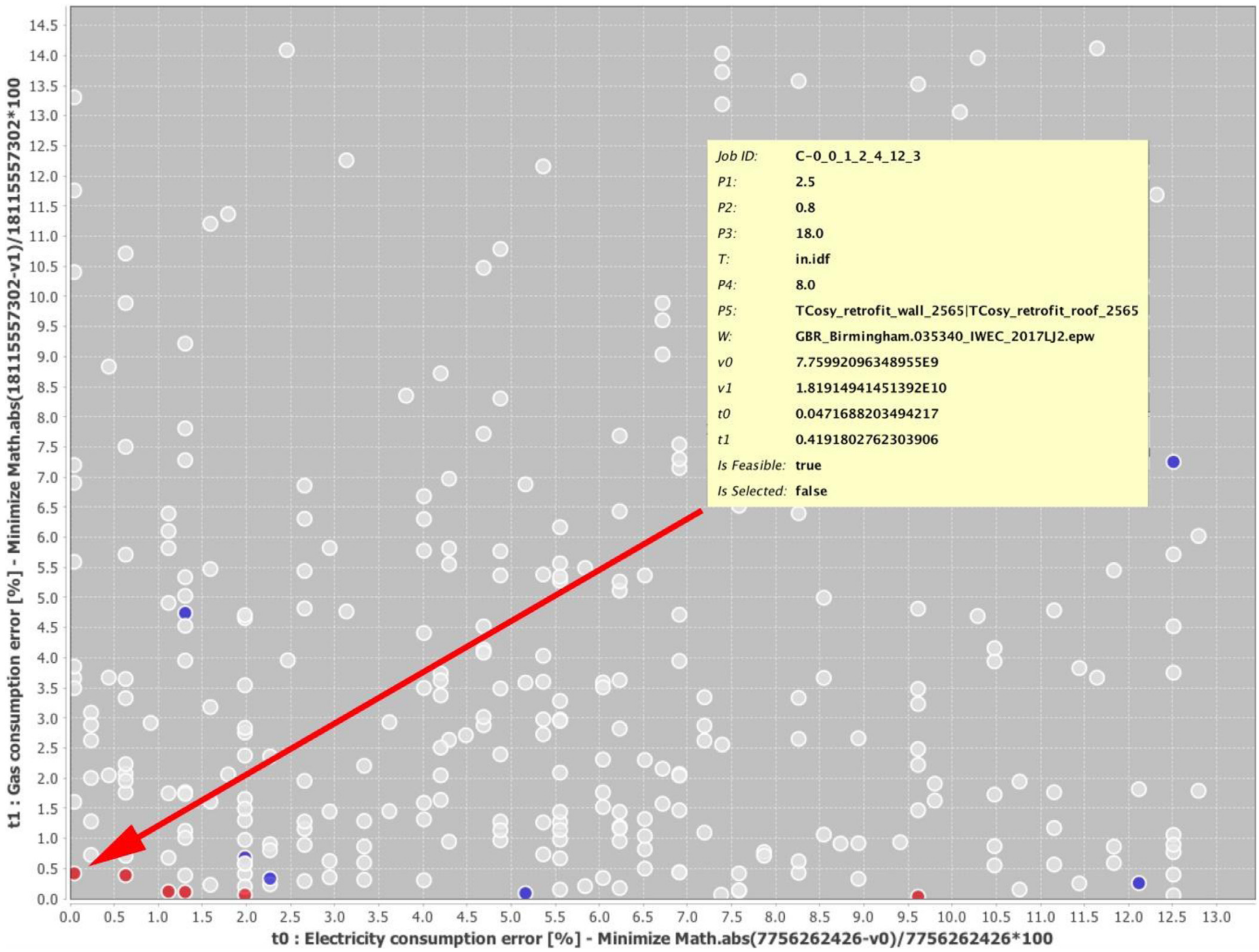

Fig. 25. Results of calibration of the as built retrofit model.

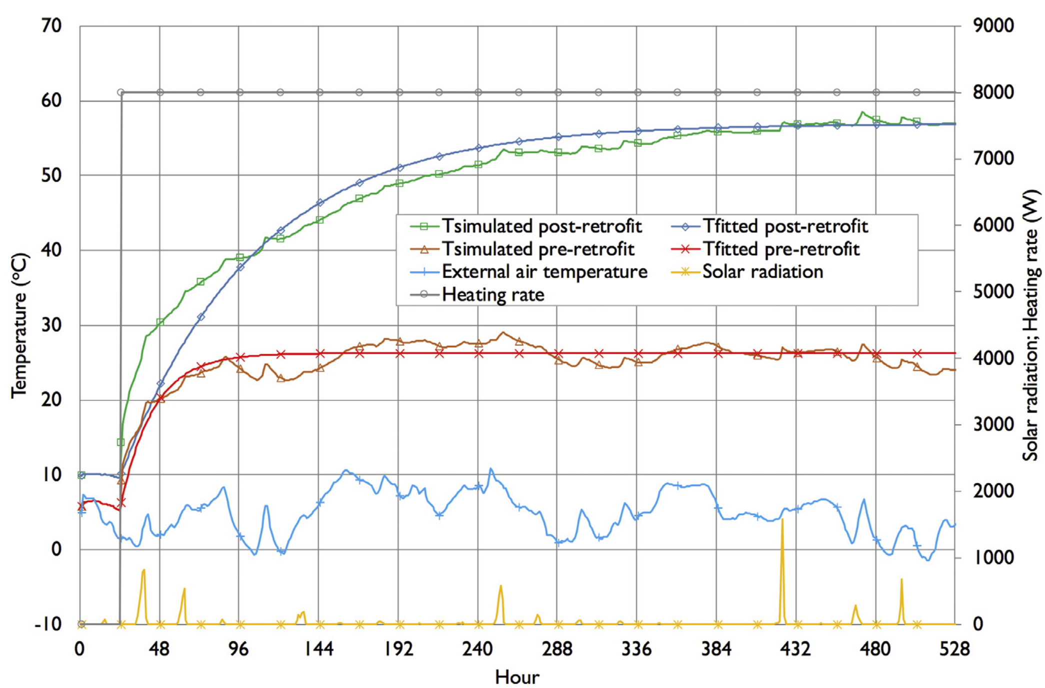

Fig. 26. Dynamic heating test simulations before and after the retrofit.

findings in this article, as they could negatively affect numerous projects in the future, and continue to cause significant performance gap between design and operation, as they appear to have done in this project.

6. Conclusions

This article documents details of a deep energy retrofit, carried out on a residential building in Birmingham, UK. The building consisted of two semi-detached houses, attached by a party wall. It was built from solid concrete based on Wimpey no-fines construction that was predominant between late 1940s and early 1950s in the UK, in response to the increased housing demand and a quicker and cheaper production. Multi-objective optimisation was used to calibrate an initial simulation model, which was subsequently used for parametric design simulations and multi-objective optimisation of design. The parameters of the optimised design were subsequently passed on to the construction delivery partner for off-site construction. Instrumental performance monitoring was carried out throughout the process, from before to after the retrofit, thus establishing a 42% improvement of building energy performance as result of the retrofit. User experience, established through questionnaires and interviews, was consistent with monitoring results, confirming considerably improved performance, and also indicating considerable health and wellbeing benefits. Building physics parameters were calculated using simulations of dynamic heating tests based on calibrated simulation models, documenting the scale of change arising from the retrofit. Thus the building time constant, the time that the building takes to go through 63% of the total change of temperature when heat is applied as a step function, has increased by 3.6 times as result of the retrofit; the overall transmittance-area product and the overall transmittance have more than halved; and the effective thermal capacitance has nearly doubled.

As a significant discrepancy in excess of 60% has been found between theoretical and measured UA values for the post-retrofit case, an urgent review of these theoretical values is needed, such as in CIBSE and ASHRAE technical guides and manufacturers' specifications. Without such a review, all future retrofit projects may underperform significantly, and present a barrier to achieving the required reduction of carbon emissions.

The payback period and return on investment were calculated using energy costs and energy inflation figures, as well as the monetary values of health improvements, considering a 40-years time horizon. Without health benefits taken into account, the ROI yields 26%. However, when health benefits for a family of four are taken into account, the payback period reduces from 38 to 16 years and the ROI increases to 269%. This article therefore clearly demonstrates the need for using a combination of energy efficiency budgets and health improvement budgets for conducting deep energy renovation of buildings. It also demonstrates the need to reduce the time on site and the cost of retrofit.

What were the challenges and how the project outcomes compare with other similar cases? One year into the project, there was an unexpected regulatory issue, a discontinuation of the Green Deal scheme [14], which required to project to re-address its objectives, from converting the existing building into a zero carbon building, to creating pre-requisites for zero carbon subject to availability of future funding.

In the 'Retrofit for the Future' programme, only three out of 37 properties achieved carbon emissions reduction of over 80%, and 23 achieved a reduction of between 50% and 80% [2]. This project falls into the second category, if long term normalisation of savings is omitted. Otherwise the savings are below 50%.

Unlike in the previous programme, in which there was no requirement to record the starting emissions and the savings were calculated with reference to the 1990 national average performance [2], the starting point in this project was to establish the existing building performance from the outset.

The project experienced other challenges similar to those in the 'Retrofit for the Future' programme referred to in the Introduction section. There have been unexpected changes to the project team, as one of the partners went into administration, and another partner pulled out after the Green Deal had been discontinued and made a detrimental impact on their business model. The project management had to work hard to replace the outgoing partners, to keep the project on track, and to justify the changes to the funding body.

There were also unexpected site issues that caused delays and resulted in increased costs. The existing windows appeared to be firmly embedded into the concrete walls, and instead of the planned removal time of all windows during a single day, it took almost a day to remove each window. The original storage sheds attached to the building on both sides, seen in Figs. 5 and 9, were not compatible with the complete wrap-around approach and had to be completely demolished and replaced with prefabricated volumetric outbuildings, which increased the cost and time on site.

Unlike some of the pitfalls in the 'Retrofit for the Future Programme' the project had very skilled site operatives, coming from the same factory of the construction delivery partner where the off-site construction took place, and very co-operative and enthusiastic occupants, who took keen interest in the process and continued living in their homes during the retrofit process without complaints.

There are three main reasons why this project did not achieve higher energy and carbon emission savings. The first is the already mentioned regulatory reason of the discontinuation of the Green Deal and the consequent unavailability of funding for renewable energy systems. The second is the significant discrepancy of over 60% between the theoretical and measured UA value, causing significant performance gap between design and operational performance. And the third is the rebound effect manifested with the occupants becoming more relaxed about their energy bills, as discussed in Section 4.3 and therefore causing diminishing returns of energy and carbon emissions savings by inadvertently using more energy.

The process introduced here could become the basis for continuing professional development programmes at CIBSE and other professional institutions and could create a model for university postgraduate programmes in retrofit design. Public education is also required to increase awareness and generate demand, and the outputs of this project, which included close participation of occupants, could be a starting point in that process. Given that there are considerable challenges yet to be addressed, new research grant funding schemes would be essential to move the state of the art forward. Funding will also be required to address the challenges concerning the accuracy of retrofit designs, due to discrepancies between theoretical and measured values of building thermal properties found in this project, and in order to review material properties reference tables, such as those published in CIBSE and ASHRAE technical guides.

Conducting deep energy retrofit of buildings in order to achieve significant reductions of carbon emissions requires consistency in policies of governments around the world. In the UK, the discontinuation of the Green Deal and the scrapping of zero carbon regulations for new homes in 2015 have created uncertainty in industry, reducing the competition and the aspiration for better performing buildings. These setbacks need to be reversed, and new Building Regulations introduced that create the conditions and requirements not only for new zero carbon homes but also for deep energy retrofit of existing homes that are currently below certain energy rating into zero carbon homes. The process introduced here and the lessons learnt could inform these new initiatives.

The article therefore introduces the process of retrofit in detail, including design, of-site manufacturing, installation, and performance evaluation. New insights are provided into retrofit economics in the context of health benefits. Building physics parameters before and after retrofit are evaluated in an innovative way through simulation of dynamic heating tests with calibrated models, and the method can be used as quality control measure in future retrofit programmes.

The future work arising from this project will focus on reducing the costs and increasing efficiency of the retrofit process by creating smaller and multifunctional external envelope panels through 3D printing, which integrate renewable energy generation and that are made suitable for automated installation, thus reducing the costs. The future work will also focus on developing collaborations between housing authorities and health authorities in order to materialise the value of health benefits arising from deep energy retrofit of buildings.

Taking into account the wide scope of the lessons learnt, it is hoped that this work would help with development of structured retrofit programs in the future.

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