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Analysis of UK domestic building retrofit scenarios based on the E.ON Retrofit Research House using energetic hygrothermics simulation – Energy efficiency, indoor air quality, occupant comfort, and mould growth potential

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A B S T R A C T

The work forms part of the CALEBRE project (2008–2013), the aim of which was to investigate a suite of technologies and staged approaches for retrofit upgrades for 'hard-to-treat' solid/thin cavity masonry-walled UK domestic buildings that would i) reduce operational energy demand/carbon emissions, and ii) be acceptable and appealing to the building occupants. The E.ON Retrofit Research House (Nottingham, UK) was used as an instrumented test platform as part of this study. The retrofitting phases (and technologies) have been used as the basis for the modelling methodology in this paper, together with the corresponding envelope assemblies, material properties, climate, and internal load parameters. The approach to retrofit was to increase air tightness (reduce ACH), decrease static *U*-values of the external envelope (wall, floor and glazing), and upgrade heating system efficiency. This was complemented by a combination of options that included a whole-building system of mechanical ventilation with heat recovery (MVHR). These interventions were analysed alongside simulated passive buffering of variations in indoor air psychrometric conditions using conventional (clay, timber) and advanced (mesoporous silica) wall surface treatments. Each retrofit scenario was modelled using an energetic hygrothermics building performance simulation (BPS) approach to determine the combined effects of retrofit packages on indoor air psychrometric conditions, external envelope (dynamic) heat transfer, operational energy efficiency, occupant comfort, and mould growth potential. It is proposed that this approach can provide the basis for an intelligent risk management strategy to inform both the design and deployment of retrofit upgrade packages intended for residential buildings.

1. Introduction

In many industrialised countries more than 40% of carbon emissions are the result of energy consumption by buildings, of which domestic dwellings are responsible for more than two thirds [1]. The replacement rate of existing buildings by new-build is approximately 1.0–3.0% per annum [2,3], which means that effective solutions of a retrofit nature are needed [4], especially within the UK context if it is to meet its 2050 carbon reduction target. Energy use in many types of existing buildings can be reduced significantly through proper retrofitting or refurbishment [5–9], i.e. a package of measures to upgrade the energy efficiency of an existing building. It is logical that any technological intervention must not only be cost-effective, but also be acceptable to the stakeholder/end-user in terms of providing a comfortable and healthy indoor living environment. Of the 25 million dwellings in the current UK housing stock, it has been estimated that 8.1 million (34%) can be considered 'hard-to-heat, hard-to-treat' in terms of retrofit options and which are responsible for about 50% of total UK domestic sector carbon emissions [10]. Of the five key phases in a building retrofit programme recently identified by Ma et al. [4], the work presented in this paper relates to Phase III; specifically building performance simulation (BPS), risk assessment, and technology prioritisation. The typical approaches towards selection of retrofit technologies (for maximised energy efficiency enhancement) are to calibrate against the results of a building energy audit [4] or against the results of detailed and validated BPS.

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Nomenclature

A_c	coefficient of capillary absorption, kg/m^2 s$^{0.5}$
c_p	specific heat capacity at constant pressure, J/kg K
n	bulk porosity, %
w	specific moisture content, kg/m^3
λ	dry-state thermal conductivity, W/(m K)
μ	water vapour diffusion resistance factor, –
ρ	density, kg/m^3

Subscripts

f	at saturation
20	at 20% relative humidity ($\varphi = 0.2$)
50	at 50% relative humidity ($\varphi = 0.5$)
80	at 80% relative humidity ($\varphi = 0.8$)
dry	in the dry condition ($\varphi = 0$)

A number of transient whole-building energetic BPS models have been used to assess the efficacy of retrofit measures including: EnergyPlus, IESve, eQUEST, DOE-2, ESP-r, BLAST, HVACSIM+, TRNSYS, and TAS [6,11–13]. The heat balance method (HBM) has been widely applied, for example to large sets of multiple buildings to support both decision-making and optimisation of retrofit strategies using uncertainty analysis [14]. As several studies that have used hygrothermal BPS have shown, the accurate simulation of coupled heat and moisture transport/storage is essential in order to both quantify and understand the implications for occupant comfort [15–17], indoor air quality and mould growth [18] (leading to occupant health), and whole-building operational energy use [15–17,19]. Consideration of these factors in combination is considered important with respect to the expected growth in demand for domestic energy efficiency refurbishment, so as to gain understanding of the potential 'unintended consequences' that could arise as a result of today's refurbishment practices.

In the UK climate, space heating is a dominant component of total annual energy consumption and so a large proportion of the existing housing operational inefficiencies are often attributed to high thermal transmittance through the external envelope and adventitious ventilation. Notwithstanding the generic issue of lighting technology efficiency, three of the principal components of 'hard-to-treat' domestic building retrofit can be categorised as: i) external envelope insulation technologies, ii) boiler replacement technologies (inc. heat pumps, biomass and micro CHP), and iii) ventilation/operational energy management methods. Cavity fill insulation (if possible) and/or internal wall insulation (IWI) are often preferred to external (EWI) as they satisfy the commonly-applied planning law requirements to maintain the external appearance of older/existing buildings (especially historic), are much less expensive, and require less surface area coverage. The further challenge of creating high-performance IWI with a low thickness (~≤25 mm) can potentially be addressed via advanced (though perhaps less durable) technologies such as vacuum insulation panels (VIPs) and also Aerogel-based composite insulation panels. For the case of internal wall treatments, the resulting lack of thermal inertia and hygric response within the building can mean that heating/cooling loads and humidity levels may have to be controlled by active mechanical systems (with associated energy penalty) in order to maintain adequate occupant comfort and to mitigate the risks of mould growth and/or condensation-related damage to the envelope fabric. The purpose of this study was to test this hypothesis using a BPS approach with a validated energetic hygrothermal modelling tool (see Section 2).

The results presented in this paper emerged as part of the CALEBRE (Consumer-Appealing Low Energy technologies for Building REtrofitting) project; an E.ON/Research Councils UK-funded programme from 2008 to 2013 involving a partnership of six UK universities (Loughborough, Nottingham, Oxford, Heriot Watt, Ulster and Warwick). The aim was to establish a suite of staged approaches to the retrofitting of 'hard-to-treat' UK domestic buildings that would i) reduce operational energy demand/carbon emissions, and ii) be acceptable and appealing to the building occupants. The E.ON Retrofit Research House (Nottingham, UK) is a replica 1930's–1960's semi-detached house (representing ~60% of UK housing stock) that was used during the CALEBRE project for real-time monitoring of indoor environmental conditions, energy use and occupant behaviour throughout several phases of retrofit upgrades [20]. The retrofitting phases (and technologies) have been used as the basis for the modelling methodology in this paper, along with the corresponding envelope assemblies, material properties, climate, and internal load parameters. The approach to developing retrofit scenarios was to increase air tightness (reduce air changes per hour; ACH), upgrade heating system efficiency, and decrease static *U*-values of the external envelope (wall, floor and glazing). This was complemented by a combination of options that included installation of a whole-building system of mechanical ventilation with heat recovery (MVHR). These practical refurbishment interventions to the test house provided information to support the simulation of different wall surface treatments for passive buffering of variations in indoor air psychrometric conditions using conventional (clay, timber) and advanced (mesoporous silica) materials. Each retrofit scenario was modelled using an energetic hygrothermics approach to determine the relative effect on indoor air psychrometric conditions, external envelope (dynamic) heat transfer, operational energy efficiency, occupant comfort, and mould growth potential.

2. Methodology

2.1. Building description

The E.ON Retrofit (1930's–1960's semi-detached) research house was the scenario upon which the building performance simulation was based. Since all rooms within the building were retrofitted using the same materials and technologies, a notional simulation of a single room, under each retrofit scenario, was conducted to maximise model efficiency (avoiding duplication)

Table 1
Constant building parameters used in the simulation.

Internal room parameters:			
Length	5 m	Wall surface area	56 m^2
Width	5 m	Ceiling surface area	25 m^2
Height	2.8 m	Floor surface area	25 m^2
		Room volume	70 m^3
Window parameters:			
Length	2 m	Inclination	90°
Height	1.5 m	Orientation	South (100%)
Surface area	3 m^2	Frame factor	0.7
Single glazed window *U*-value	5.00 W/m^2 K		
Double glazed window *U*-value	1.99 W/m^2 K		
Vacuum glazed window *U*-value	0.70 W/m^2 K		
MVHR system parameters:		**Comfort limits:**	
MVHR SFP	1.20 W/L/s	RH upper limit	70 %RH
Flow rate	8.25 L/s	RH lower limit	30 %RH
MVHR rating	9.90 W	T_{db} upper limit	N/A
For 1 year (at 70 m^3)	86.72 KWh	T_{db} lower limit	18 °C

Table 2
Summary of building retrofit phases.

Retrofit phase	Envelope description	ACH	Scenario number
Phase 1 (Base Case)	Single glazed windows, un-insulated (walls, floor and roof space), no draught-proofing	0.74	1 – Glow worm boiler 2 – Electric heaters
Phase 2a	Double glazing installed, insulation applied to walls and loft. Low quality draught-proofing applied to windows (excluding kitchen, bathroom and WC) and doors	0.68	3 – Worcester boiler 4 – MS
Phase 2b	Draught-proofing applied to kitchen, bathroom, WC windows and under-croft trap-door. High quality draught-proofing applied throughout the house.	0.47	5 – Boiler only 6 – MS
Phase 3	Window trickle vents sealed, service risers sealed, pipe work envelope penetrations sealed (radiators, water pipes etc.), sealing around boiler flue, covers fitted to door locks, kitchen fan removed and sealed. Under-croft insulated. MVHR system installed.	0.41	7 – Boiler only 8 – MVHR 9 – MS 10 – MVHR + MS
Phase 4	Suspended timber floor (ground floor) sealed using breather membrane.	0.25	11 – Boiler only 12 – MVHR 13 – MS 14 – MVHR + MS
Phase 5 (Passivhaus)	Building infiltration reduced to give 0.1 ACH. Windows upgraded to vacuum glazing	0.10	15 – Boiler only 16 – MVHR 17 – MS 18 – MS + MVHR 19 – Clay 20 – Clay + MVHR 21 – Spruce 22 – Spruce + MVHR
Phase 6 (Realistic)	Insulation and infiltration as outlined in Phase 4 but with vacuum glazing. Increased internal moisture loading to represent occupation (inc. showering and cooking)	0.25	23 – Boiler only 24 – MVHR 25 – MS 26 – MVHR + MS

whilst keeping the results representative. The building parameters (see Table 1) remained constant for all simulations with the exception of minor increases in wall cross-section thickness due to the added depth of internal insulation and wall surface treatments. Increases in envelope thickness were added without altering the interior room volume, and the internal surface area/window surface area ratio was 106 m^2/3 m^2 = 35.33′.

2.2. Retrofitting phases and technologies

All retrofit scenarios simulated are based on proposed staged upgrade packages applied to the E.ON Retrofit Research House. Phases 1–4 had all been installed at the time of writing whilst Phases 5 and 6 are hypothetical cases based on future intended upgrades. Airtightness levels as indicated by ACH values were either determined experimentally for each applied airtightness upgrade using the blower door method in accordance with ATTMA TS1 'Measuring Air Permeability of Building Envelopes' [21], or were assumed based on target design code parameters, e.g. Passivhaus [22,23]. A summary of all retrofitting phases with corresponding hourly air change rate (ACH) is given in Table 2. Phase 1 (Base Case) was designed to represent an un-insulated house with low airtightness and an inefficient 1980s boiler, i.e. pre-retrofit intervention. The windows were single glazed (U = 5 W/m^2 K) with timber framing, and heating was supplied using either electric heaters or a commercially-available conventional (non-condensing) Glow-worm™ gas boiler [24] (Heat I/P 15.59 kW; heat O/P 11.72 kW) with traditional radiators (O/P limited to 0.8 kW). The U-value of the walls, ceiling and floor were 1.44, 3.64 and 1.71 W/m^2 K, respectively. In Phase 2 the single glazed window panes were upgraded to double glazing using an assumed (typical) window U-value of 1.99 W/m^2 K. Insulation was applied to the wall cavities and loft space giving wall and ceiling U-values of 0.54 and 0.13 W/m^2 K, respectively. In Phase 2a, low quality draught-proofing was applied to windows and doors to reduce air infiltration down to a value of 0.68 ACH. In Phase 2b the draught-proofing was enhanced to further reduce to 0.47 ACH. The heating system was upgraded to a commercially-available (condensing) Worcester boiler [25] (Heat I/P 24.75 kW, heat O/P 24 kW) with new radiators providing higher heat O/P (limited to 1.5 kW).

Phase 3 gave further reductions in air infiltration by sealing the window trickle vents, service risers, pipe work envelope penetrations (radiators, water pipes, etc.) and fitting covers to door locks. The under-croft was also insulated giving a revised floor U-value of 0.12 W/m^2 K. A Titon HRV2 Q Plus whole-house MVHR system (see Table 1) [26], assuming the (optimum) manufacturer's-stated heat recovery rate of 90%, was installed to provide replacement fresh air to the room. The glazing and heating system remained identical to Phase 2. In Phase 4 the suspended (softwood) timber ground floor was tightly sealed using a taped 'Vario' vapour membrane (Saint-Gobain Isover, Gotham, UK) resulting in a revised ACH of 0.25. The preceding air tightness interventions were practically implemented on the test house and provided useful data to aid simulation. The following retrofit phases were not physically implemented on the test house and analysis was undertaken using modelling only. Phase 5 was a hypothetical scenario in which additional IWI (with vapour barrier) was installed with reductions in fabric U-values and air infiltration rates that met/exceeded those required for Passivhaus standard (0.15 W/m^2 K and >>0.6 ACH) [22,23]. The timber-framed windows were upgraded to SPACIA 21 vacuum insulated glazing with an assumed U-value of 0.7 W/m^2 K [27]. Phase 6 represented a 'realistic' occupancy scenario used the same configuration as for Phase 4 but with the addition of vacuum glazing and additional moisture loads to represent showering and cooking.

2.3. Envelope assemblies and material props

The external envelope wall assemblies used in each simulation scenario are detailed in Fig. 1 and represent those used (or intended to be used) in the E.ON Retrofit Research House. Based on the results of previous studies [28,29], the 8.3 nm mesoporous silica (MS) material (developed as part of the CALEBRE project) was selected as the advanced surface treatment suitable for humidity buffering in this scenario. The small effect of thermal bridging due to joists in the floor and ceiling construction assemblies are not represented but is likely to have little effect since they are perpendicular to the

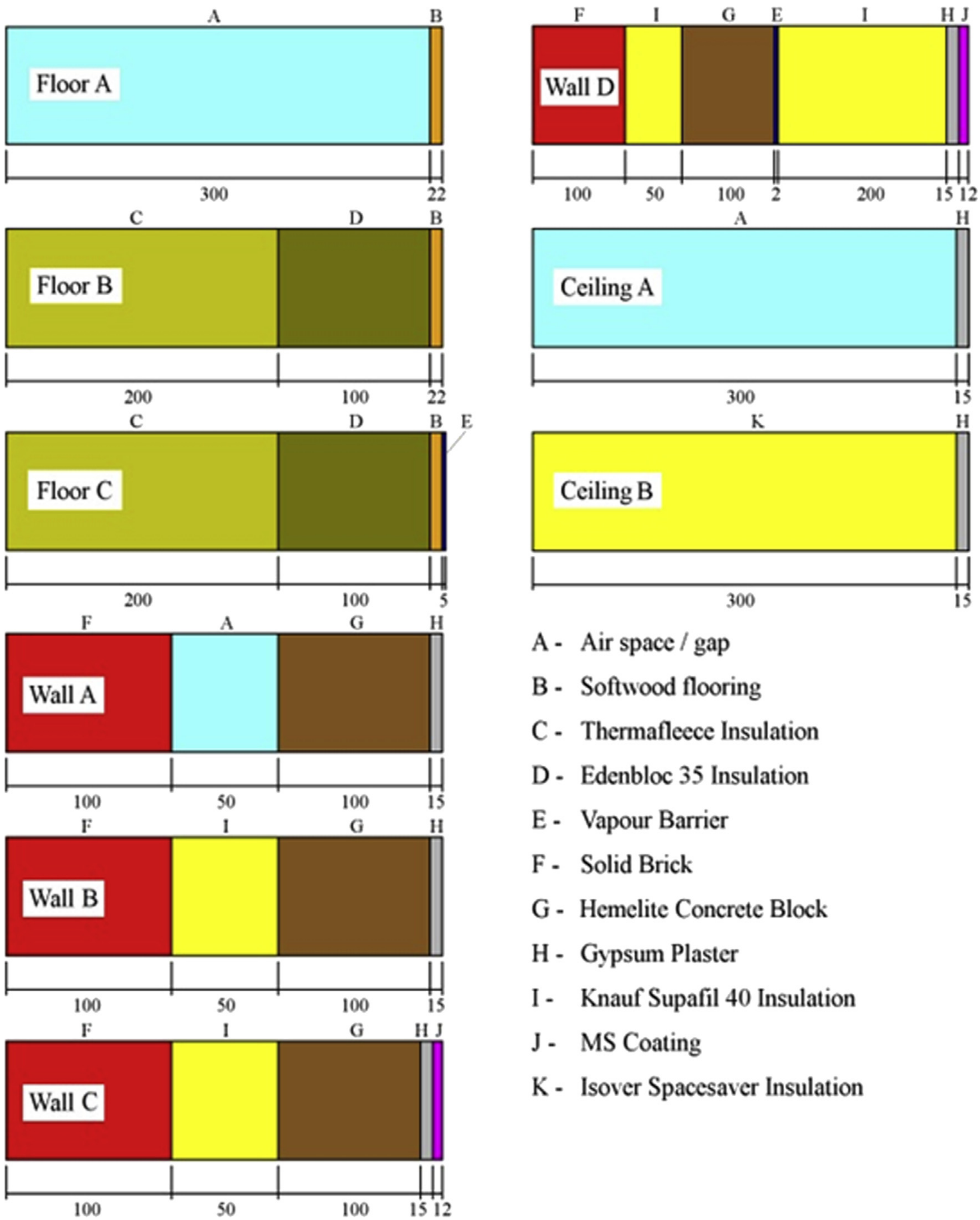

Fig. 1. Cross-sectional assemblies of wall, floor and ceiling elements.

1D hygrothermal (heat and moisture) transfer plane under consideration and represent ~8% of the floor/ceiling surface area, i.e. assuming ten joists with dimensions 0.04×5 m = 2 m^2. Interior surface vapour permeation resistance, S_d values for gypsum were set at 0.5 m to represent a painted surface finish. All other interior S_d values were set according to component type, where $S_d = 0$ m for unpainted MS, clay and spruce surfaces. In Phases 2–6, the surface treatment were assumed to cover 100% of interior wall surface area with depth, $d = 12$ mm for the MS coating, and $d = 15$ mm for clay coating and spruce timber cladding. The dry-state thermophysical and basic hygrothermal material properties for all the materials simulated for use in the building envelope (and as model input parameters) are contained in Table 3.

2.4. Numerical modelling

Feist et al. previously used TRYNSYS (heat balance method (HBM)-based) to model and design the MVHR system for an energy efficient building as part of the CEPHEUS project [23]. However, they only measured 'thermal' comfort with respect to dry bulb temperatures and did not consider RH. Regarding perceived comfort, Schnieders et al. interviewed the occupants of numerous

Table 3
Dry-state thermophysical and basic hygrothermal material properties.

Material	ρ_{dry}	n	c_p	λ	w_{20}	w_{50}	w_{80}	w_f	A_c	μ
	kg/m^3	–	J/kg K	W/m K	kg/m^3				kg/m^2 s$^{0.5}$	–
Air gap[a]	1.3	–	1000	0.28	–	–	–	–	–	0.32
Softwood flooring[a]	400	0.73	1500	0.09	14	32	60	575	–	200
Thermafleece[a]	50	0.95	1600	0.038	0.1	2	5	35	0.027	10
Edenbloc[a]	45	0.95	2000	0.04	–	–	–	–	–	1.1
Vapour barrier[a]	130	0	2300	2.3	–	–	–	–	–	15×10^5
Solid brick[a]	1900	0.24	850	0.6	1	5	18	190	0.110	10
Hemelite block[a]	1360	0.45	925	0.45	46	67	75	214	0.098	10
Gypsum plaster[a]	850	0.65	850	0.2	–	4	6	400	0.287	8.3
Knauf supafil[a]	60	0.95	850	0.04	–	–	–	–	–	1.3
8.3 nm MS[b]	618	0.76	1691	0.05	5	86	295	865	0.550	10.5
Isover spacesaver[a]	60	0.95	850	0.043	–	–	–	–	–	1.3
Clay coating[a]	1568	0.41	488	0.484	9	23	38	370	0.183	11
Spruce cladding[a]	455	0.73	1500	0.09	30	45	80	600	0.007	4.3

Note: The moisture storage function (adsorption isotherm) can be plotted from the w_x values, where the subscript corresponds to φ. The moisture-dependency and temperature dependency of the thermal conductivity, $\lambda(w, T)$ were taken from the WUFI Plus database,[a] along with the liquid transport coefficient (where applicable). The complete set of hygrothermal functional properties for the MS 8.3 nm material are available in a separate publication.[b]
[a] IBP Fraunhofer material data base – WUFI Plus v2.1.1.73.
[b] Ref. [17].

passivhauses to obtain subjective opinions on thermal comfort including RH levels [30] but did not experimentally measure RH in these houses. HBM-based models such as TRYNSYS, TAS, IES, etc) are generally only capable of determining indoor RH with respect to changes in dry bulb air temperature and so ignore the important mass transfer component dealt with in hygrothermal models; hence air enthalpy is not accurately considered. In a recent study by Dodoo et al. on the primary energy implications of ventilation heat recovery in residential buildings, they also focused on dry bulb air temp and energy efficiency but ignored internal RH and hence air enthalpy [31]. This approach has implications for the accuracy of operational energy efficiency predictions in buildings in particular where, for example, MVHR has been installed on conjunction with a low ACH/high fabric insulation design.

In the work reported here, all simulations were carried out using the energetic (whole building) hygrothermal simulation software package WUFI Plus v2.1.1.73. This model simulates interaction between the 1D hygrothermal behaviours (i.e. coupled transient heat & moisture transport/storage) of all external envelope components (walls, floors, ceilings) with resulting indoor air psychrometric conditions of a closed environment. The indoor (closed environment) can also include additional loads resulting from internal occupancy patterns, heating/cooling, humidification/dehumidification, adventitious ventilation (infiltration), and ventilation systems (including MVHR). This allows detailed and realistic analysis of indoor air quality, occupant comfort, and whole-building operational energy efficiency, in addition to the transient storage and transport of heat & moisture in each component of the external envelope [15]. WUFI Plus has been well validated against physical testing data in several previous studies [15–17,19], whilst the room model used in this study was previously validated by physical modelling in a climatic simulation chamber [17,29]. The post-processing package WUFI Bio v3.1 was used in conjunction with WUFI Plus for predictive analysis of internal surface mould growth risk and potential growth rates over an extended time period of ten years. WUFI Bio compares the measured or simulated transient hygrothermal conditions inside a closed environment with the critical water content at which a spore will germinate [18]. This is strongly affected by the ambient indoor environment temperature, T_{ie}, indoor relative humidity, RH_{ie} and substrate properties. Germination growth curves are then estimated over the extended period to map the subsequent spreading of the mould [18].

2.5. Model parameters

The simulated room volume was selected as a 'heated space' with indoor climate and infiltrating air calculated based on the outdoor climate. The volume above the ceiling (roof/attic space), with dimensions $h_1 = 0.5$ m, was selected as an 'unheated space' and set to the outdoor climate. It was implicitly assumed that air infiltration in the unheated loft was sufficiently high to assume that psychrometric conditions were the same as those of the exterior climate when the model was initiated. The volume below the floor was selected as an 'unheated cellar' to represent the under-croft of the building, i.e. the void below the suspended softwood timber (ground) floor with its climate also set to the outdoor climate. All model numerics were set to have increased accuracy and adaptive convergence with grid spacing set to 'medium'. The exterior climate file used for the simulations was generated from the CIBSE test reference year (TRY) file for Nottingham [32]. This is a weather data file that represents averaged hourly weather values for a given location over a 25-year period. It is available for almost all major UK towns and cities and is the standard climate data used to allow direct comparisons between separate studies based in the UK. The calculation period was for one year from 1st January 2012 to 1st January 2013 with time steps $t = 1$ h. Note that for the mould growth predictions using WUFI Bio, this modelling period was extended to ten years to assess mould growth risk/potential. Initial T_{ie} and RH_{ie} were set at 20 °C and 55%, respectively, with a minimum accuracy of calculation of $T_{ie} = 0.5$ °C and $RH_{ie} = 0.5\%$. Heat input to the room volume was added using the HVAC controls with heat source output start-up and shutdown lag times (i.e. $Q_{zero} \rightarrow Q_{max} \rightarrow Q_{zero}$) of 0.2 and 0.7 h, respectively, for all heating appliances except the electric heaters (assumed instantaneous with zero lag time).

In Phases 1–5 occupancy was set to represent two adults resting for a period $t = 8$ h from midnight to 8AM with the room unoccupied for the remainder of the day (see Fig. 2). This was not intended to accurately reflect the actual occupancy patterns recorded for the E.ON Retrofit Research House; rather it was fixed so that internal loads were constant to allow direct comparative analysis between all retrofit scenarios. Convective and radiant heat output from each occupant was assumed to be 65 W and 36 W, respectively, with a moisture (generation) load of 43 g/h. In Phase 6 a more realistic occupancy and internal loading scenario was created to account for additional moisture load peaks due to showering and cooking, as shown in Fig. 2.

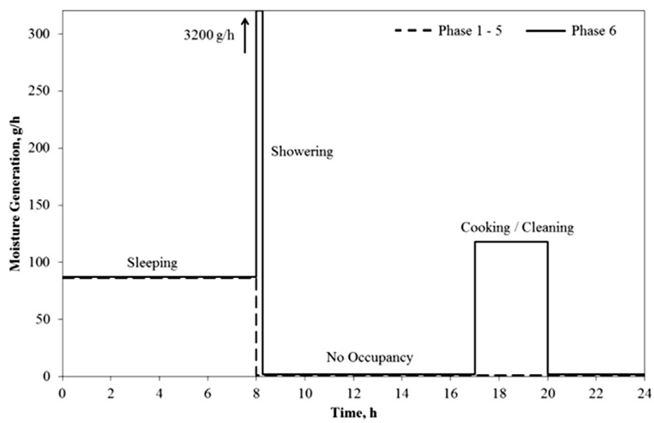

Fig. 2. Occupancy schedules and associated moisture generation loads.

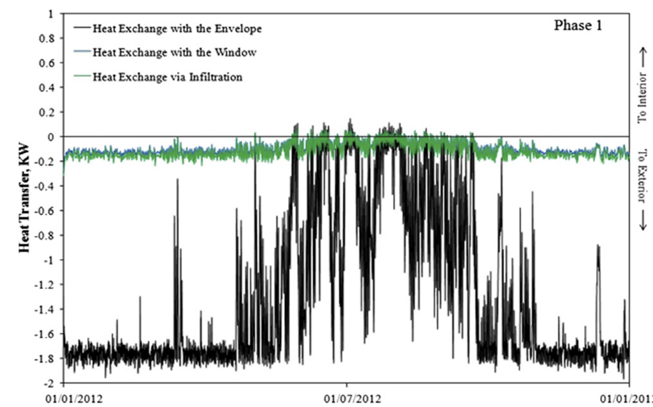

Fig. 4. Annual distribution of fabric, infiltration and glazing heat transfer for Phase 1 retrofit (base case).

3. Results and discussion

3.1. Phase 1 retrofit

Fig. 3 shows that the indoor air psychrometric conditions indicated very poor levels of occupant comfort, where for the vast majority of time they were significantly outside the ASHRAE thermal comfort envelope (defined in Table 1). RH_{ie} levels exceeded the upper comfort limit (70%RH) for both the 'boiler scenario' and 'electric heater scenario' (scenarios 1 and 2) throughout the summer period. Very high levels of heat transfer through the building external envelope ($\approx$1.8 kW, radiator capped at $\approx$ 0.8 kW) occurred during the winter months. The vast majority of heat transfer, calculated with reference to the O/P of radiators (electric heater case shown, see: Fig. 4), occurred through the wall fabric, with comparatively minor heat losses due to infiltration and even less through glazing.

3.2. Phases 2a and 2b retrofit

The results for Phase 2a showed a significant improvement in occupant comfort levels with a high proportion of psychrometric conditions occurring within the ASHRAE thermal comfort envelope (see: Fig. 5). This was principally due to the increased fabric thermal resistance from retrofit cavity insulation, although floor surface temperatures still remained uncomfortably low ($T_{min} = 9.2$ °C). The T_{ie} and RH_{ie} levels frequently increased beyond ASHRAE comfort limits during the summer months, and decreased below them during the winter months. This suggests a high degree of thermally-driven (natural) air infiltration where heating of incoming winter air (low absolute humidity) results in low relative humidity, whilst there is no dehumidification control to handle the incoming (high absolute humidity) summer air. The relative improvements in draught-proofing carried out in Phase 2b gave a slight reduction in infiltration heat transfer, compared to Phase 2a, as shown by Figs. 6 and 7, but had no significant effect on the psychrometric conditions of indoor air (RH_{ie} and T_{ie}).

3.3. Phase 3 retrofit

The improvements in fabric insulation and draught-proofing (reduction in ACH, see Table 2), led to a 54% reduction in external envelope heat transfer from 6552 kW (Phase 2a) to 3038 kW in Phase 3. The floor temperature profiles also improved such that they corresponded directly to T_{ie} levels, along with the wall and ceiling surface temperatures. The introduction of MVHR increased RH_{ie} fluctuations (see Fig. 8), and hence the occurrence outside ASHRAE comfort limits, due to the increased quantity of outdoor air infiltration; the psychrometric conditions of which are determined by the weather. The 'Boiler only' scenario RH_{ie} levels remained the same as in Phase 2a. The application of MS 8.3 nm materials gave significant (and almost identical) reductions in RH_{ie} fluctuation both for the 'MVHR + MS 8.3' and 'MS only 8.3' scenarios (see

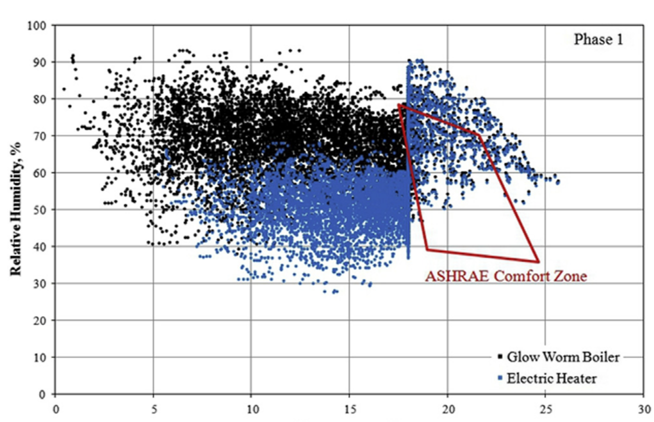

Fig. 3. Phase 1 retrofit (base case) annual plot of psychrometric variables with overlapping ASHRAE comfort parameters.

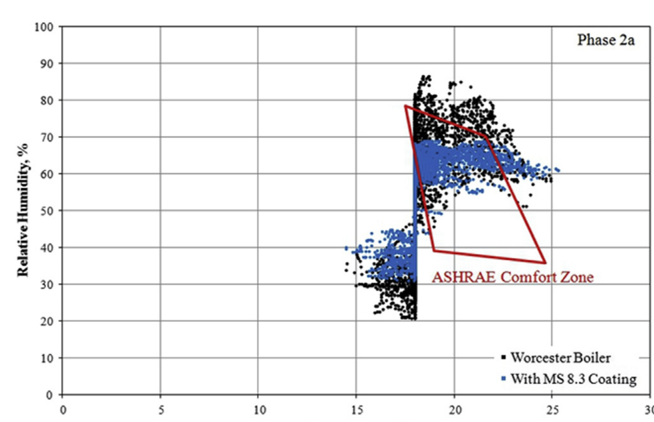

Fig. 5. Phase 2a retrofit annual plot of psychrometric variables with overlapping ASHRAE comfort parameters.

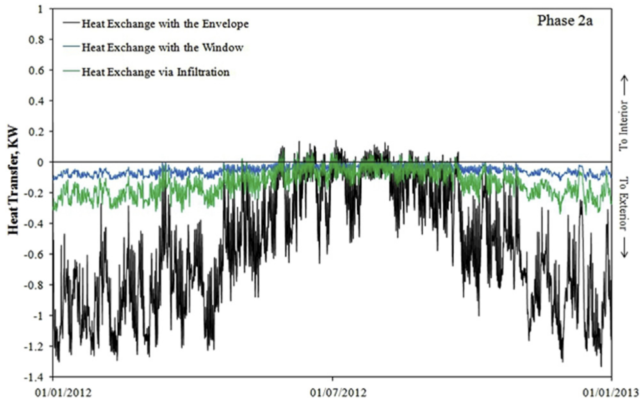

Fig. 6. Annual distribution of fabric, infiltration and glazing heat transfer for Phase 2a retrofit.

Fig. 8), with 100% occurrence within ASHRAE thermal comfort limits across the entire year.

3.4. Phase 4 retrofit

The predicted changes in indoor psychrometric conditions were insignificant compared to those for Phase 3 retrofit. A slight upward shift (typically $\leq$5%) in RH_{ie} levels was observed (see Fig. 9), most likely as a consequence of the reduction in ACH from 0.41 (Phase 3) to 0.25 (Phase 4) but with the same internal moisture loads resulting from occupancy. A significant difference was observed between the fluctuating RH_{ie} levels for the 'MS 8.3 only' and the 'MVHR + MS 8.3' scenarios; the latter showing slightly lower levels throughout the year but with increased daily RH_{ie} fluctuations (due to the larger infiltration of outdoor air). In both cases 100% occurrence within ASHRAE comfort limits was achieved throughout the year (see Fig. 9). However, the 'Boiler only' and 'Boiler + MVHR' scenarios both still have RH_{ie} levels significantly above the upper limit for thermal comfort during the summer months as for Phase 3.

3.5. Phase 5 retrofit

Despite the further reduction of ACH to 0.1 and the installation of vacuum glazing to the window, the 'Boiler only' scenario still resulted in increased summer RH_{ie} levels exceeding the upper limit, whilst the 'Boiler + MVHR' scenario resulted in RH_{ie} levels

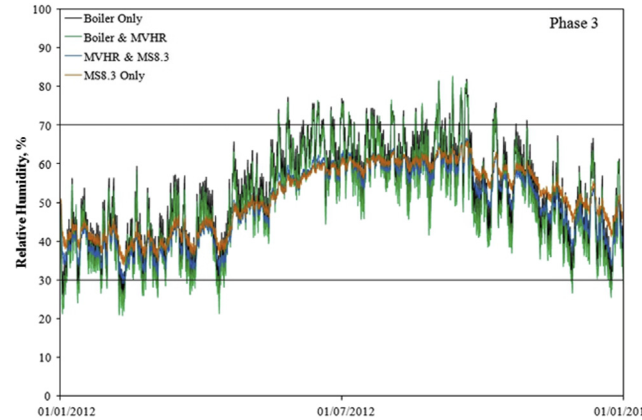

Fig. 8. Annual fluctuation of RH_{ie}, with upper/lower ASHRAE comfort limits, for Phase 3 retrofit.

exceeding both the upper limit in summer and the lower limit in winter (see Fig. 10). As with Phases 3 and 4, the 'MS 8.3 only' and 'MVHR + MS 8.3' scenarios both maintained 100% occurrence with the ASHRAE comfort limits throughout the year; the 'MS 8.3 only' case having significantly lower daily RH_{ie} fluctuations and therefore greater perceived comfort (see Fig. 10). The 'Spruce' and 'Clay' scenarios both resulted in RH_{ie} levels significantly exceeding the upper comfort limits during the summer months (see Fig. 11). This can be slightly reduced (but not eliminated) when combined with MVHR. For Phase 5 the MS coating can provide adequate RH_{ie} buffering without MVHR. The introduction of vacuum glazing resulted in the window surface temperature, T_s increasing towards T_{ie} as a result of the lower thermal resistance (compared to double glazing), but still $T_{db} - T_s \approx 2$ °C due to the assumed surface resistance that represents radiation and near-surface convection heat exchange. There is no discernible difference between Phase 4 and Phase 5 overall heat transfer through the external envelope, and the proportion of heat transfer corresponding to glazing and infiltration are at negligible levels (see Fig. 12). This is consistent with expectations, since the glazing/external envelope area ratio is typically small especially on older single-family domestic buildings.

3.6. Phase 6 retrofit

Due to the increased internal moisture loads, resulting from the 'realistic' occupancy pattern, the RH_{ie} levels for the 'Boiler only' and

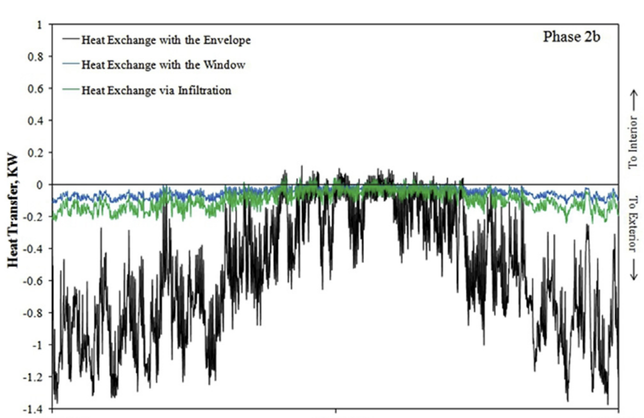

Fig. 7. Annual distribution of fabric, infiltration and glazing heat transfer for Phase 2b retrofit.

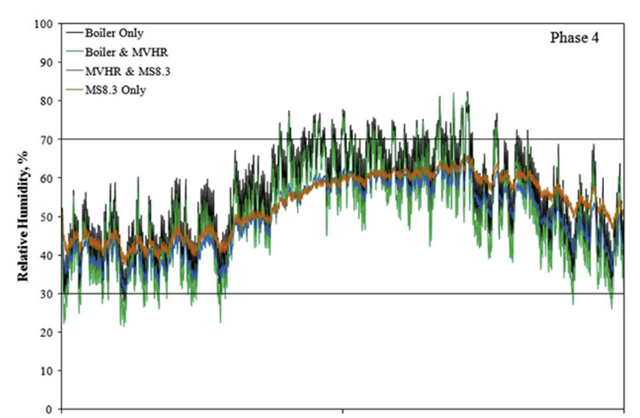

Fig. 9. Annual fluctuation of RH_{ie}, with upper/lower ASHRAE comfort limits, for Phase 4 retrofit.

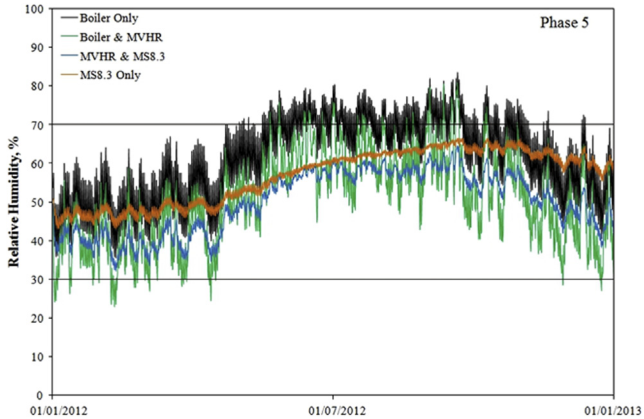

Fig. 10. Annual fluctuation of RH_{ie}, with upper/lower ASHRAE comfort limits, for Phase 5 retrofit using MS 8.3 nm RH buffers.

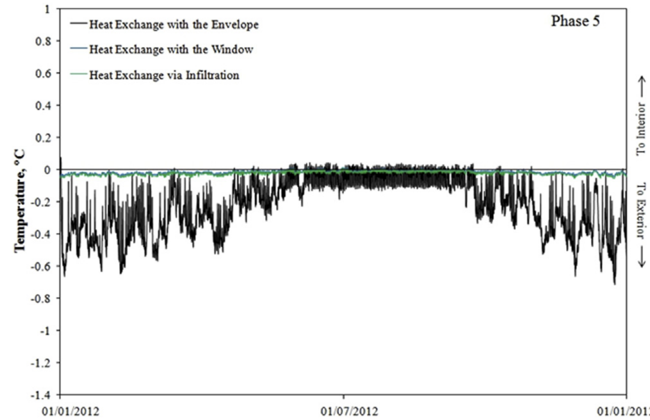

Fig. 12. Annual distribution of fabric, infiltration and glazing heat transfer for Phase 5 retrofit.

'Boiler + MVHR' scenarios now exceed the ASHRAE upper comfort limit by an even greater amount than they did in Phases 3, 4 and 5 (see Fig. 13). As in all previous phases, both the 'MVHR + MS 8.3' and the 'MS only 8.3' scenario buffer RH_{ie} fluctuations to achieve 100% occurrence within comfort limits throughout the year. Under the assumed internal loads and external climatic conditions, MVHR cannot be applied as a single solution (without RH buffering) for direct management of internal moisture loads (e.g. resulting from occupancy) in order to maintain thermal comfort since the increased air infiltration amplifies the variation in RH_{ie}, as shown in Fig. 13. This finding is in very good agreement with related recent studies where increased RH_{ie} fluctuations were observed to occur as a result mechanical ventilation technologies installed in 170 monitored domestic buildings [33], a fully instrumented research building [34], and modelled building design solutions (using a hygrothermal BPS approach) that utilise RH-sensitive ventilation systems and/or passive RH buffering materials for the building interior [35].

3.7. Psychrometrics and thermal comfort – summary analysis

For all of the scenarios listed in Table 2, the lowest indoor humidity fluctuation, $\Delta RH_{ie} = 23.6\%$ was achieved by 'MVHR + MS 8.3' (scenario #18) in Phase 5, whilst the maximum, RH_{ie} level = 93.3% was in Phase 1. This would be a very uncomfortable and potentially dangerous living environment in terms of occupant health. In all cases that use MS coating, there are no occurrences of RH_{ie} levels outside the ASHRAE comfort limits. The lowest indoor air temperature, $T_{ie} = 0.4$ °C was for the Glow Worm boiler (scenario #1) in Phase 1. The heat O/P from both the radiator (estimated at 0.8 kW for an old radiator without fins) and electric heater (2 kW) were not capable of maintaining adequate T_{ie} levels during winter due to poor envelope insulation levels. From Phase 3 onwards (floor insulated and heat loss minimised) the minimum T_{ie} level increases to 18 °C giving significant overall improvement in thermal comfort.

3.8. Mould growth potential

Figs. 14 and 15 show the calculated predictions (using WUFI Bio) of mould growth potential over a ten year period. The example in Fig. 14 shows how the water content of a 'Class K' mould spore (i.e. aspergillus fumigatus, apergillus flavus and stachybotrys chartarum), attached to a painted gypsum plaster surface, periodically exceeds the critical water content with resulting mould growth. In contrast, the example in Fig. 15 shows that the RH_{ie} buffering ability of the MS 8.3 nm coating prevents the water content of the spore from ever reaching the critical level needed for growth. Fig. 16 shows the mould growth potential for all scenarios listed in Table 2. Phase 1, Phase 5 (scenario #15) and Phase 6 (scenario #23) all result in large mould growth potential due to high RH_{ie} levels. Phase 1 (scenario #1) in particular shows dangerous levels of mould growth due to the combination of low T_{ie} and high RH_{ie}.

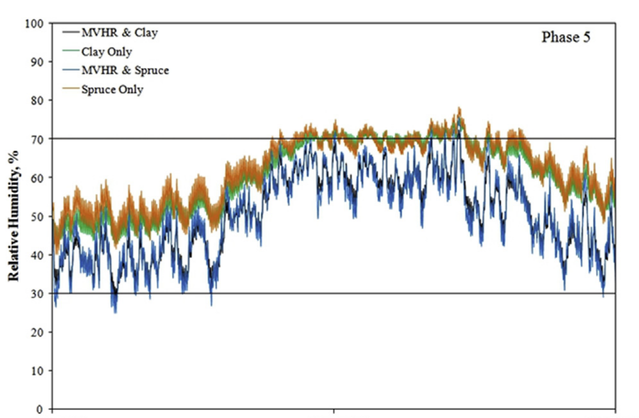

Fig. 11. Annual fluctuation of RH_{ie}, with upper/lower ASHRAE comfort limits, for Phase 5 retrofit using clay board and spruce timber RH buffers.

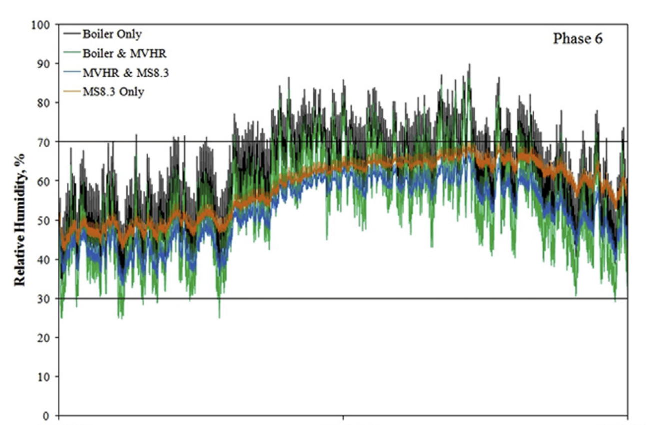

Fig. 13. Annual fluctuation of RH_{ie}, with upper/lower ASHRAE comfort limits, for Phase 6 retrofit using MS 8.3 nm RH buffers.

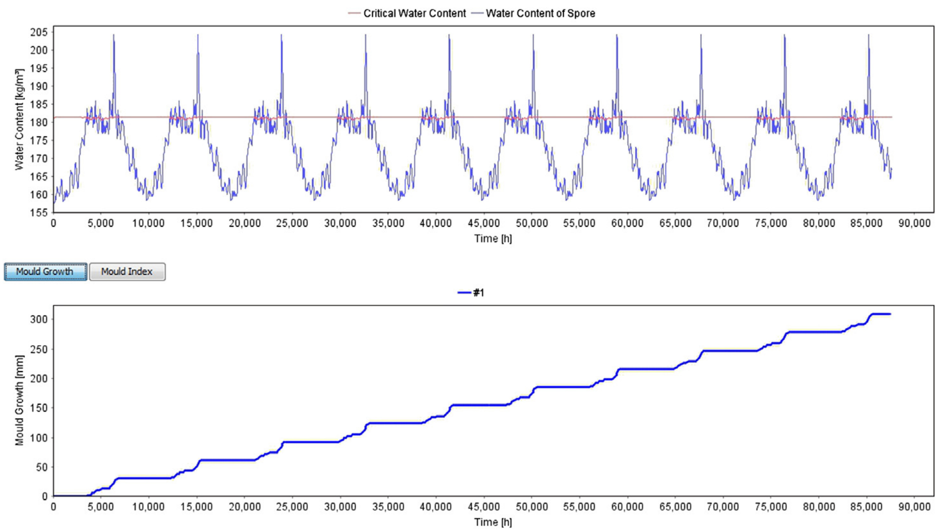

Fig. 14. Example of mould spore moisture content and growth rate (scenario #23, see Table 2).

Mould growth can lead to degradation of the building envelope materials, poor indoor air quality (affecting occupant respiratory health) and occupant discomfort. Significant mould growth potential was also observed for scenarios 3, 5, 11, 20, 22 and 24 (see Table 2), the risk of which is prone to increase during extended periods of occupant absence, i.e. leading to reduced T_{ie} levels.

3.9. Operational energy efficiency

A breakdown of annual operational energy efficiency for each scenario is given in Table 4. In Phases 1 and 2 heat loss is dominated by transfer through the building envelope, with scenario #2 (electric heater) resulting in the highest losses (11,437 kW/Yr). Heat loss through the envelope is similar for Phases 2a and 2b (4720 kW and 4932 kW, respectively) and further reduces to an average loss of 1814 kW for Phases 3–6. The ventilation heat losses reflect both the infiltration and mechanical ventilation levels through each phase. There are increased losses in each case when MVHR is operational due to the plant (efficiency = 90%) not recovering all of the heat extracted (scenarios 8, 9, 12, 13, 16, 17, 19, 21, 24, 25 – see Table 2). As with ventilation, heat losses through the glazing correspond to the type of glazing installed for each phase. Phase 1 (single glazed) has the highest losses with the electric heater (scenario #2) having a yearly loss of 861 kW. Heat gains are negligible when compared to the losses and are not shown. The highest energy demand is for Phase 1 with the electric heater (12,817 kWh), which results from the high level of heat loss (discussed above) and the proportionally higher heat O/P. The reductions in energy demand that occur in subsequent retrofitting phases correspond to several parameters and not simply fabric heat loss. The minimum predicted operational energy demand was achieved in Phase 5 using MS only (scenario #18).

4. Conclusions

In the pre-retrofit (Phase 1) condition, external fabric heat losses are so high that they dominate the overall operational energy efficiency where heat loss is capped at the radiator output (regardless of the boiler COP). A basic level of retrofit (Phase 2) results in large relative savings in operational energy and significant improvement

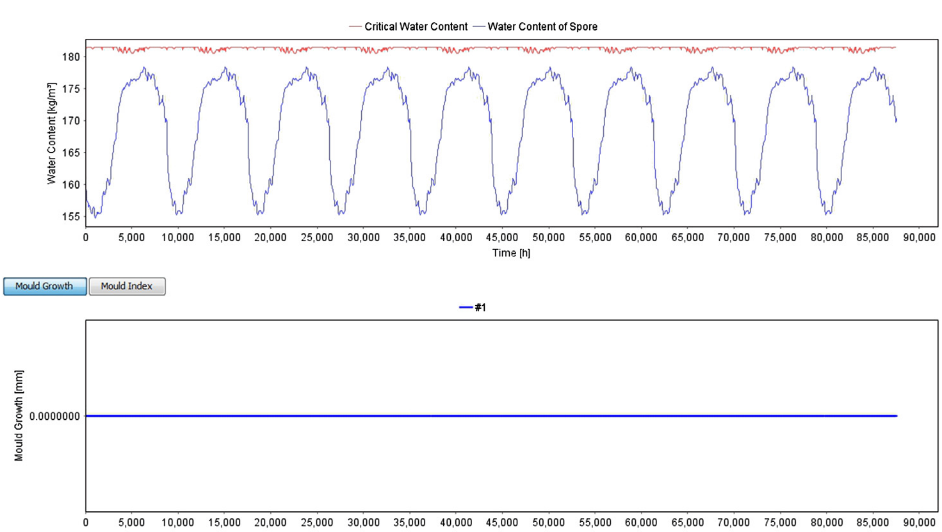

Fig. 15. Example of zero mould spore moisture content and zero growth rate (scenario #26, see Table 2).

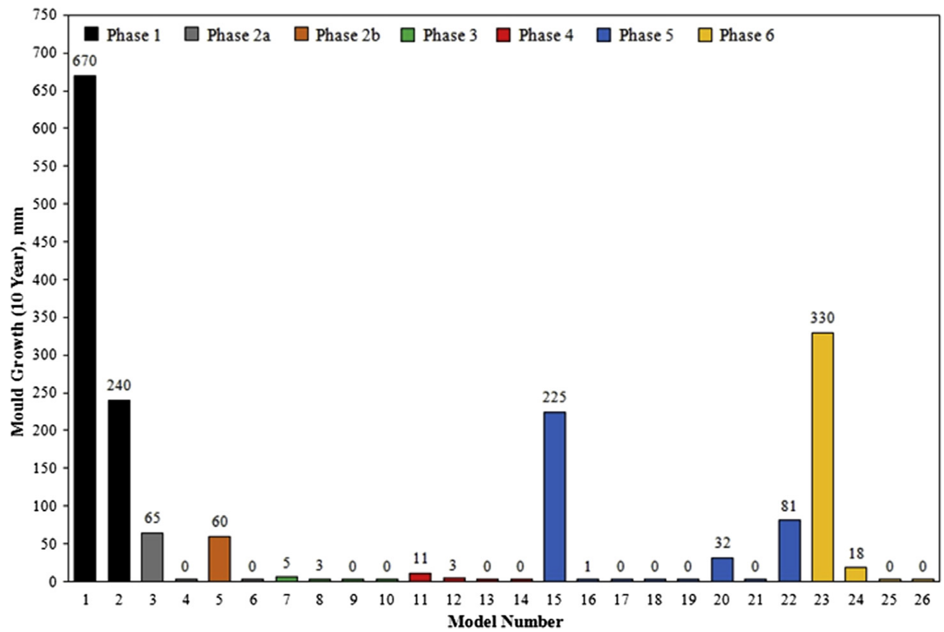

Fig. 16. Summary of mould growth potential for all retrofit scenarios listed in Table 2.

in the occurrence of psychrometric conditions within the ASHRAE-defined occupant comfort limits. This is due to i) large fabric heat loss reduction from retrofitted insulation and ii) increased isolation from outdoor psychrometric variables. These two conditions led to less output demand from the boiler, in addition to lower heating system input due to greater boiler efficiency (i.e. condensing vs. non-condensing). The enhanced draught-proofing gave a comparatively small reduction in ACH, whilst the addition of under floor insulation resulted in significantly less external envelope heat loss and better perceived occupant comfort due to the increased floor surface temperatures. MVHR decreased isolation from outside psychrometric variables (more infiltration) resulting in uncontrolled enthalpy fluctuations due to the lack of RH control. This led to i) increased occurrence of psychrometric variables outside the ASHRAE occupant comfort limits, and ii) an energy penalty associated with achieving comfort, e.g. humidification/dehumidification plant. The inclusion of RH buffering resulted in reduction of air enthalpy fluctuation and therefore control of air temperature fluctuation with associated minimisation of comfort loss, mould risk and operational energy penalties.

Table 4
Breakdown of annual operational energy demand for all scenarios.

			O/P rating	Heat O/P	Efficiency	Energy I/P	MVHR	Total
			kW	kW	%	kW	kW	kW
Phase 1	1	Glow Worm Boiler	0.8	6052	0.7	9311	–	9311
	2	Electric Heater	2.0	12,817	1.0	12,817	–	12,817
Phase 2a	3	Worcester boiler	1.5	6096	0.9	6774	–	6774
	4	MS	1.5	5909	0.9	6566	–	6566
Phase 2b	5	Worcester boiler	1.5	5747	0.9	6386	–	6386
	6	MS	1.5	5554	0.9	6171	–	6171
Phase 3	7	Worcester boiler	1.5	2579	0.9	2866	–	2866
	8	MVHR	1.5	2719	0.9	3021	87	3108
	9	MVHR + MS	1.5	2537	0.9	2819	87	2906
	10	MS	1.5	2391	0.9	2657	–	2657
Phase 4	11	Worcester boiler	1.5	2305	0.9	2561	–	2561
	12	MVHR	1.5	2443	0.9	2714	87	2801
	13	MVHR + MS	1.5	2262	0.9	2513	87	2600
	14	MS	1.5	2114	0.9	2349	–	2349
Phase 5	15	Worcester boiler	1.5	1796	0.9	1996	–	1996
	16	MVHR	1.5	1931	0.9	2146	87	2232
	17	MVHR + MS	1.5	1750	0.9	1944	87	2031
	18	MS	1.5	1595	0.9	1772	–	1772
	19	MVHR + Clay	1.5	1991	0.9	2212	87	2299
	20	Clay	1.5	1852	0.9	2058	–	2058
	21	MVHR + Spruce	1.5	1860	0.9	2067	87	2153
	22	Spruce	1.5	1724	0.9	1916	–	1916
Phase 6	23	Worcester boiler	1.5	1837	0.9	2041	–	2041
	24	MVHR	1.5	1970	0.9	2189	87	2276
	25	MVHR + MS	1.5	1790	0.9	1989	87	2076
	26	MS	1.5	1643	0.9	1826	–	1826

When infiltration is high (either where ACH >0.4, or when using MVHR), RH_{ie} fluctuations are dominated by outdoor psychrometric conditions (RH_{oe}, T_{oe}) plus any additional effects from heating the incoming air. When ACH is very low (<<0.4), internal RH_{ie} fluctuation is dominated by the internal loads, e.g. occupancy. If managed mechanically (active), this imposes an additional energy penalty but less so (or not at all) if the hygrothermal behaviour (passive) of buffering materials within the fabric can be utilised to manage these loads. Spruce timber and clay are capable of meeting relatively small RH_{ie} buffering requirements but have slow sorption rates and consequently a relatively weak buffering effect; hence they were incapable of managing the internal moisture loads for the building type/occupancy pattern modelled in this study. The mesoporous silica (MS 8.3 nm) material chosen for this application has very rapid sorption response rates and therefore a strong RH_{ie} buffering effect; it was specifically designed for managing the moisture loads in a closed environment scenario such as the ones in this study. Even with the increased moisture loading scenarios in Phase 6 and with no MVHR, the MS 8.3 coating provided 100% of the RH_{ie} buffering required to maintain psychrometric conditions inside the defined ASHRAE comfort limits throughout the year. When MVHR was used in conjunction with the MS 8.3 buffering material, to provide the necessary fresh air supply (whilst minimising energy penalties through heat recovery), thermal comfort was still maintained for 100% of the time inside ASHRAE comfort limits throughout the year despite the additional changes to air enthalpy resulting from increased infiltration of outdoor air.

Reliable prediction and quantification of energy efficiency and risk analysis are essential components of decision support in both the selection and prioritisation of building retrofit technologies. With regard to low-energy retrofit approaches, it can be concluded from this modelling study that wall and ceiling insulation appear to be the top priority followed by a reduction in ACH. The associated reductions in (fresh) air infiltration, and passive thermal & hygric buffering by the building fabric in the case of IWI, the control of RH_{ie} fluctuations becomes a critical issues from the point of view of indoor air quality, mould growth risk, and occupant comfort. These risks cannot be managed by mechanical ventilation (with or without heat recovery) since the outdoor air enthalpy is controlled by ambient weather conditions and so RH_{ie} fluctuations actually increase with more air infiltration. This demonstrates the clear need to consider RH_{ie} buffering as an essential component of building retrofit strategies in the UK climate in order to minimise the risk of deleterious 'unintended consequences'. Ultimately this should help to ensure that retrofit packages that are designed only to address envelope insulation, ventilation with heat recovery, and increased air tightness are complementary to one another and do not introduce new and more complex problems relating to poor indoor air quality, mould growth, and reduced occupant comfort. Managing these risks by mechanical humidification/dehumidification imposes additional operational energy penalties on the building that are counterproductive. This demonstrates the clear need for the development of passive approaches to humidity-buffering material/technology selection and design informed by hygrothermal BPS. Whilst it has been shown here that whole-building hygrothermal energetic modelling can output data that captures the complexity of coupled heat and moisture transport phenomena (with corresponding psychrometric conditions of indoor air), it would be impractical and prohibitively expensive to apply this on a case-by-case basis to support retrofit decision making. Therefore, future research is likely to seek integration of hygrothermal energetic model outputs with non-probabilistic optimisation under both technical and economic uncertainty, such as the methodology recently proposed by Rysanek and Choudhary (using classical decision theories: Wald, Savage, and Hurwicz) [36], to provide a practical yet robust approach towards the application of advanced BPS models.

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