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Indoor Environmental Quality and Health Implications of Building Retrofit and Occupant Behaviour in Social Housing †

Arman Hashemi * and Mohan Dungrani

School of Architecture, Computing and Engineering, University of East London, London E16 2RD, UK
* Correspondence: a.hashemi@uel.ac.uk

† This article is a revised and expanded version of three conference papers entitled [1—*Indoor environmental quality and energy performance: Reviewing the case of council homes in London*; 2—*Assessing the effect of retrofit strategies on thermal comfort and energy performance in social housing*; and 3—*Towards energy-efficient retrofitting of social housing in the UK: Assessing the occupant behaviour and indoor environmental quality of a council block in London* which were presented at ZEMCH 2023 (Arequipa, Peru, 2–4 August 2023) and SEEDS 2023 (Ipswich, UK, 29–31 August 2023) International Conferences].

Abstract: Poor housing quality contributes to poor Indoor Air Quality (IAQ) and overheating with older adults, children, pregnant women, and those living in poverty most at risk. While retrofit strategies could help to reduce carbon emissions by improving building energy efficiency, they could simultaneously lead to 'unintended' outcomes including overheating, damp, mould, and exposure to harmful indoor air pollutants by making buildings more airtight and trapping heat and air pollutants inside. Occupants' lifestyles, attitudes, and awareness have also been identified as some of the key challenges when it comes to improving energy performance, winter/summer thermal comfort, and IAQ in buildings. This paper provides insight into the effects of energy efficient retrofit strategies and occupant behaviour on energy performance, IAQ, thermal comfort, and health, with a focus on older people living in social housing. A mixed method is employed involving: (1) physical measurements, to record actual energy consumption and indoor environmental conditions (i.e., temp., RH%, CO_2); (2) questionnaire surveys, to assess occupants' behaviours and health; (3) dynamic thermal modelling, to evaluate the effects of retrofit strategies; and (4) thermal imaging, to assess the building fabric performance and identify possible defects. The results revealed that although retrofit strategies reduced energy consumption by up to 60%, some resulted in significant risk of overheating. Occupants' behaviours combined with debatable building management practices also contributed to risks of overheating and poor IAQ that could negatively affect health and wellbeing of building occupants in the long-term.

Keywords: social housing; retrofit; thermal comfort; indoor air quality; energy performance; public health

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1. Introduction

In the wake of population growth, technological advancements, and the pursuit of higher living standards, the global landscape has witnessed a substantial surge in energy consumption over the past decade. In response, the UK has taken significant strides in implementing energy efficiency policies and regulations, resulting in a noteworthy decline in energy consumption from 150 million tons of oil equivalent in 2010 to 120 million tons in 2021 [1]. A critical sector contributing to the UK's energy demand is buildings, responsible for almost 30 percent of the country's total energy demand. In 2021, the residential sector in the UK contributed to approximately 16 percent of greenhouse gas emissions, with an overwhelming 97 percent of these emissions attributed to carbon dioxide [2]. Amidst a housing stock of approximately 28 million, the annual replacement rate of 180,000 signifies the paramount role of retrofitting in improving energy performance [3]. With nearly half of emissions originating from existing housing stock, comprehensive retrofitting strategies are imperative to meet the UK Government's targets for achieving net-zero carbon by 2050 [4]. Mitigating domestic energy use in London faces significant challenges due to limited uptake of energy-efficient measures in older housing stock. Most of the social housing stock predates energy efficiency standards, with the vast majority built between the end of WWII and the early 1980s [5], leading to issues such as thermal discomfort and poor Indoor Air Quality (IAQ) affecting the health and wellbeing of building occupants.

Space heating is the predominant driver of energy consumption in existing dwellings, constituting 63% [6] of the annual energy demand. Initiatives targeting a reduction in energy demand for space heating have been instrumental, emphasising improvements in building envelopes to minimise heat loss and enhance overall thermal efficiency. Numerous studies have explored the impact of retrofitting measures on energy performance. Evangelisti et al. [7] reported a 40% reduction in energy consumption through retrofits (e.g., utilizing double-glazed windows and adding thermal insulation to roof and walls). Similarly, El Darwish [8] reported a 33% reduction in annual energy consumption in a case study. However, although retrofits could improve the energy performance of buildings, defective retrofit strategies, combined with poor occupant behaviour, could lead to 'unintended' outcomes such as increased risk of overheating and exposure to indoor air pollutants. This could significantly affect occupants' health and wellbeing in the long term [9–11], given that individuals in developed countries spend around 90 percent of their time indoors, with two-thirds of this time allocated to residential buildings [12,13].

According to the World Health Organization, 3.2 million deaths in 2020 were attributed to household air pollution [4]. The ramifications extend to the UK where air pollution leads to 28,000 to 36,000 premature deaths annually, accompanied by a substantial financial burden on the healthcare system [12,14,15]. As the gravity of the health impacts caused by indoor air pollution becomes evident, the urgency to address indoor environmental quality (IEQ) and energy efficiency in residential buildings intensifies.

In this context, effective ventilation is crucial to avoid excessive heat loss, prevent pollutant build-up, remove excess moisture, and ensure an adequate supply of oxygen in buildings [16]. This intricate balance between minimising heat loss for energy efficiency, improving thermal comfort, and safeguarding occupants' health necessitates a nuanced approach to determine optimal ventilation rates. Some studies, for instance, suggest mechanical ventilation with heat recovery (MVHR) systems to improve occupants' health while reducing heat losses [17], yet the high initial and maintenance costs of such systems may limit their application in social housing.

On the contrary, efforts to improve energy efficiency, while well-intentioned, have inadvertently led to increased airtightness and reduced ventilation rates, exacerbating IAQ issues. The connection between IAQ and health outcomes is well-established, with poor IAQ linked to respiratory problems, allergies, asthma, and more serious illnesses such as lung cancer [18]. Although building airtightness and thermal insulation play crucial roles in reducing energy consumption and improving thermal comfort [16,19], they can simultaneously result in elevated concentrations of water vapour and indoor air pollutants. These byproducts, coupled with residents' activities such as cooking with open flames, contribute to compromised indoor air quality [19]. Moreover, improved building performance, while enhancing thermal insulation and airtightness, can result in over-insulated envelopes prone to overheating during warmer seasons, especially when exposed to direct solar radiation [11].

The importance of addressing IAQ in retrofit plans is increasingly emphasised, considering the potential trade-off between energy efficiency and natural ventilation [20] in addition to challenges faced by residents, including fuel poverty and adverse health effects associated with winter conditions [21]. Vulnerable groups, including the elderly, those with chronic conditions, and children, are particularly susceptible to the effects of poor IAQ and thermal discomfort [22]. These individuals, mainly living in social housing, are often constrained by smaller living spaces and higher population densities in areas marked by elevated outdoor air pollution, and face compounded health and well-being challenges.

Social housing in the UK, primarily constructed between the post-World War II era and the early 1980s, faces a critical challenge of inefficiency regarding energy performance [5]. The introduction of Energy Performance Certificates (EPCs) in 2007 revealed that a substantial portion of the housing stock fails to meet modern energy efficiency standards, with only 40% achieving an EPC rating of A–C [23]. However, while the EPC provides an efficiency rating, it often does not evaluate user behaviour, a crucial determinant of energy consumption [24]. The complex nature of occupant behaviour necessitates a combination of user-reported findings and technology-led monitoring for a comprehensive understanding. Energy consumption, as outlined by the International Energy Agency (IEA), is influenced by climate, building characteristics, services and systems, operation and maintenance, indoor environmental quality, and occupant activities and behaviour [25]. The impact of air pollution on indoor environments arises from household activities, inadequate ventilation, exposure to disease vectors, dampness, and the utilization of unsafe construction materials [26,27]. Recognising the stochastic nature of occupant behaviour, strategies must account for varied behaviours over time and among individuals for robust retrofitting solutions.

Achieving a balance between energy efficiency, indoor thermal comfort, and indoor air quality is particularly challenging for low-income groups in council homes, residing in densely populated areas with elevated air pollution levels. The London Councils plan emphasises education, advice, and incentives to alter occupant behaviour, aiming for a collaborative effort across local authorities and key stakeholders [17]. The World Health Organization also emphasises the impact of poor-quality housing on health and the need to prioritize thermal comfort in retrofit strategies, particularly for vulnerable groups and those facing fuel poverty [28]. Previous studies, however, highlight the challenges when it comes to occupant behaviour change in residential buildings. A study on social housing properties in the UK found that despite alarming poor indoor air that was communicated to tenants, followed by tailored recommendations for behaviour change, the occupants returned to their normal practices after a few weeks [9]. The same study revealed the positive impact of technological interventions (e.g., air purifiers with digital IAQ indicators) on improving occupant behaviour. The behavioural and technological interventions should therefore be considered together to achieve the best results.

Moreover, the significant impact of occupant behaviour on energy consumption, often deviating from predicted building performance, is not consistently considered in retrofit strategies [29,30]. Building energy simulation tools show a significant discrepancy (up to 300%) between predicted and actual energy consumption, with under-recognition of occupant behaviour listed as the leading source of this performance gap [30]. Occupants' energy-related behaviours, both active and passive, are not fully considered in simulation tools, impacting alignment with energy-efficient strategies [31,32]. Various objective and subjective factors, including environmental conditions, age, habits, and social interactions, influence occupants' behaviours. Adaptive and non-adaptive behaviours must be considered to attain targeted efficiency levels [33]. A comprehensive understanding of occupant behaviour, obtained through a mix of user-reported findings and technology-led monitoring, is therefore crucial for effective retrofitting plans [34,35].

To this end, this paper seeks to assess the correlations, synergies, and trade-offs between occupant behaviour, indoor air quality, energy performance, thermal comfort, and health. Focused on a case study social housing block of apartments in London, the analysis considers the diverse factors contributing to overheating and elevated levels of indoor air pollution in low-income households. The analysis integrates insights derived from various models and studies, emphasising the profound impact of occupant behaviour on the above-mentioned issues and providing a nuanced perspective on the challenges. The overarching goal is to contribute to evidence-based retrofitting guidelines, considering the intricate connections between occupant behaviour, energy performance, indoor air quality, and the health and well-being of building occupants.

2. Methods

The study's focus lies within the unique context of an older population residing in a thermally/energy inefficient building. A mixed-method approach was employed encompassing questionnaires and building surveys, physical measurements, Dynamic Thermal Modelling (DTM), and thermal imaging, explained below.

The questionnaire, with 31 questions in total, covered five main parts, as summarised in Table 1, addressing behaviour, lifestyle and energy, hygrothermal issues, health issues, and social characteristics. All residents were invited to take part in the survey out of which 26 properties participated, representing 21% of total households. The majority (75%) of respondents lived in single-occupancy households, with 22% under-occupying larger properties. Gender distribution showed 62.5% female and 37.5% male while residency duration spanned from 6 months to 29 years, with a median of 10 years.

Table 1. Questionnaire survey.

Questionnaire Parts	Questions Covered
Behaviours	Natural ventilation; window opening patterns and durations; extractor fan usage.
Lifestyle and Energy	Heating usage patterns and durations; cooking; showering/bathing; clothes drying; time spent indoors.
Hygrothermal Issues	Damp and mould.
Health Issues	Hay fever; asthma; dryness of the eyes; itchy or watery eyes; blocked or stuffy nose; dry throat; runny nose; lethargy and/or tiredness; headache; dry or itching or irritated skin; other.
Social Characteristics	Gender; number of occupants.

HOBO MX1102 data loggers were installed to measure indoor air temperature, Relative Humidity (RH%), and Carbon Dioxide (CO_2) levels in three typical 1-, 2-, and 3-bedroom case study flats. Two data loggers were installed in each flat, one in the master bedroom and the other in the living room (Figure 1). The data loggers' technical specifications are as follows: Temperature range, 0° to 50 °C (accuracy ±0.21 °C); RH% range, 1% to 90% (accuracy ±2% from 20% to 80%); and CO_2 range, 0 to 5000 ppm (accuracy ±50 ppm).

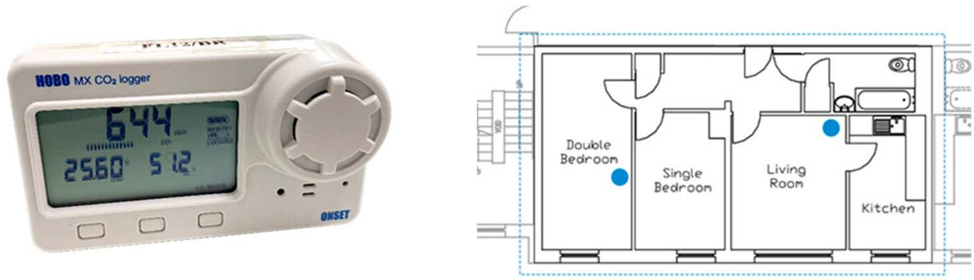

Figure 1. HOBO MX1102 data logger (**left**). Installation in the case study flats (**right**).

The FLIR E96 thermal camera was also used for the assessment of building fabric and heat losses during winter. Four weekly meter readings (between 24 March and 20 April) were collected for each flat during the installation period. Each flat was equipped with two energy meters—one supplied and paid for by the council, providing electricity between 11 pm and 6 am (mainly for heating), and the other a private meter for excess consumption.

DTM was also conducted using IES (VE) 2023 software to assess the energy performance as well as summer (CIBSE TM59 [36]) and winter thermal comfort conditions (CIBSE TM52, PMV method [37]) in one of the case study flats for the base case (as-built) and retrofitted scenarios. The heating set points for different zones were considered based on the CIBSE Guide A recommended comfort criteria (i.e., dwellings' living rooms at 22–23 °C, bedrooms and kitchen at 17–19 °C, relative humidity 40–60%) [38], ensuring a balance between energy efficiency and occupant wellbeing.

CIBSE TM59 provides a standard method to assess the risk of overheating during summer (May to the end of September) in naturally ventilated residential buildings. The following criteria must be met:

1. For the living room, kitchen, and bedrooms, the number of hours during which operative comfort temperature is greater than or equal to one degree (K) should not be more than 3%;
2. For bedrooms, the operative temperature between 10 pm and 7 am should not exceed 26 °C for more than 1% of annual hours. Internal doors are also modelled as open during daytime and are assumed to be closed during sleeping time.

The guidelines specify that windows should be opened when a room is occupied and internal temperature exceeds 22 °C. The use of the Predicted Mean Vote (PMV) approach [37] for thermal comfort analysis from October to the end of April, in addition to TM59, ensures a comprehensive evaluation of occupant satisfaction covering both summer and winter periods. This method considers various parameters, including air velocity, temperature, mean radiant temperature, and relative humidity, as well as clothing and metabolism rate. The PMV index, ranging from +3 to −3, with a thermal acceptability criterion between 0.5 to −0.5, provides valuable insights into the comfort levels experienced by occupants. For the winter simulations, windows were supposed to be closed (windows opened when indoor temperature reached 25 °C [36]) and clothing levels were assumed to be 1 'Clo'. CIBSE Design Summer Year (DSY1) and IES London City Airport weather files were utilized to assess summertime overheating analysis and PMV index, respectively.

In the context of retrofit strategies, two sets focusing on building fabric, airtightness, and windows' thermal transmittance were considered to assess the effects of retrofit. Three scenarios were modelled as follows: (1) Base Case (current conditions); (2) Retrofit to the current UK building regulations (Approved Document L (APL) [39]); and (3) Retrofit to Passive House (PH) standards [40,41]. APL is the minimum requirement in the UK while PH is the higher side of the spectrum in terms of building fabric performance. The details of building characteristics before and after retrofit strategies, including U-values, G-values, airtightness, and roof values, are summarised in Table 2. These retrofit scenarios provide a basis for assessing the potential improvements in energy efficiency and thermal performance within the case study building.

Table 2. Building fabric assumptions for the current and retrofitted scenarios.

Building Element	Passive House	Part L	Current Situation
External wall U-value (W/m^2·K)	0.15	0.3	2.2
Windows U-value (W/m^2·K)	0.77	1.4	2.29
Internal ceiling (W/m^2·K)	1.25	1.25	1.25
Roofs (W/m^2·K)	0.15	0.15	2.1
Windows G-value	55%	40%	40%
Air Change Rate (airtightness)	0.05	0.5	0.7

Case Study Building

This study is the first phase of a broader research project aiming to assess both pre- and post-retrofit conditions in council homes within the London Borough of Newham (LBN). The initial phase, known as pre-retrofit, focused on evaluating the existing state of Indoor Air Quality (IAQ), energy, Thermal Comfort (TC), and health-related issues in designated case study buildings (CSBs). The overarching objective is to understand the current conditions based on which retrofit and behavioural intervention strategies could be developed. The chosen properties are situated in the Hamara Ghar sheltered housing complex, mainly occupied by older and vulnerable residents (Figures 2 and 3). Hamara Ghar is a flagship retrofit project for Newham Council with UKP 10M allocated to address both fuel poverty and climate-related issues [42].

Figure 2. The case study building, designed for the over-50s demographic, is depicted, providing a visual representation of the study's focus.

The case study building was built in 1965 and was renovated during the 1990s. The building is a nine-story block of apartments featuring 124 flats, two lifts, communal spaces, and on-site offices for council staff. All flats are naturally ventilated, relying on electricity for cooking, space heating, and water heating. Three typical case study flats (CS-1, CS-2, and CS-3) were selected for physical measurements (monitoring) and a 2-bed, southwest-facing, naturally ventilated flat (69 sqm) was selected as the case for simulation purposes (Figure 3).

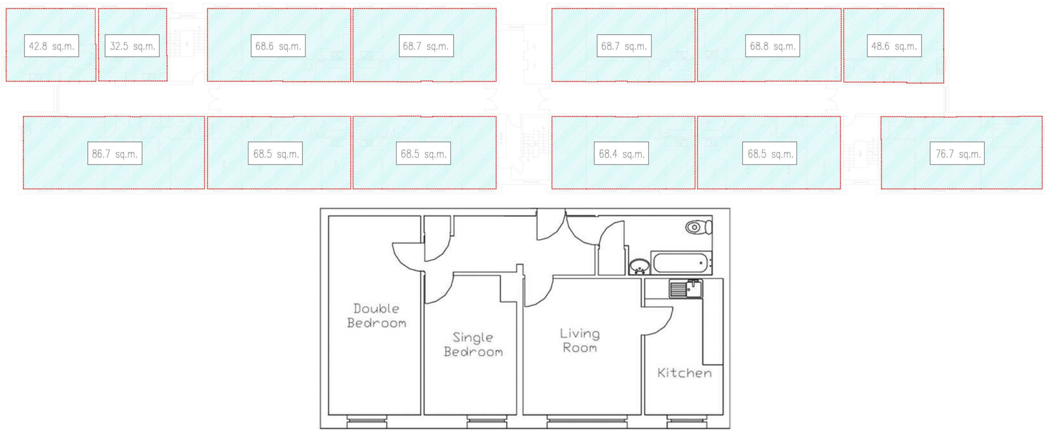

Figure 3. Level 3 floor plan with floor areas (**top**). Simulated CSB (**bottom**). Source: Newham Council, edited by the authors.

3. Results

This section has been divided into five subsections to assess various issues including thermal comfort, IAQ, energy consumption, occupant behaviour, and health-related issues within the case study building.

3.1. Thermal Comfort and Energy Consumption (Simulations)

Summer/winter thermal comfort and energy consumption for the current situation and after implementing Part L and Passive House retrofit strategies, with different building fabric assumptions (summarised in Table 2), were assessed. The operative temperature in the living room, kitchen, and bedrooms during May–September is shown in Figure 4. The maximum operative temperature in the living room for the base-case scenario reached 33 °C, which is similar to the Part L and passive house scenarios. However, the average operative temperature was lower in the base-case scenario. For instance, the average operative temperatures in the bedroom for the base-case, Part L, and passive house are around 21, 22, and 23 °C, respectively.

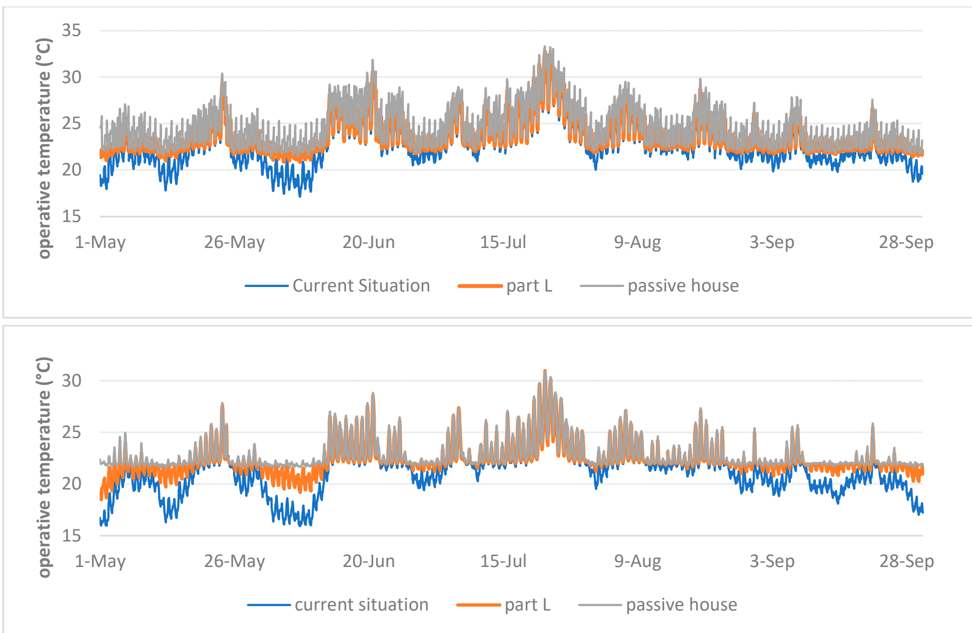

Figure 4. Operative temperature in (**top**) living room and (**bottom**) bedroom during May–September.

In the kitchen, due to higher internal gains, the maximum operative temperature reached 35 °C in July while the average temperature in both Part L and Passive House was around 24.5 °C. Additionally the operative temperature in nearly 12% of hours was greater than or equal to one degree (K), demonstrating high risk of overheating particularly in the Passive House scenario. Overall, the results demonstrate that the living room and kitchen do not meet the CIBSE TM59 requirements in the Passive House scenario while the results were more promising for the Part L in the living room with 1.1 percent of hours reported as overheated. Bedrooms were found to be the least problematic zones with less than 1 percent of hours overheated for all scenarios.

The PMV index, for the winter thermal comfort assessment, showed that the base case does not provide a thermally comfortable indoor environment being too cold. The PMV index was reported to be less than −0.5 for 20% of times in the living room and 50% of the hours in the bedrooms (Figure 5). The situation improved for the Part L scenario where the PMV index in bedrooms and living room was reported to be between 0.5 and −0.5 in around 85% of times demonstrating a thermally comfortable condition. For the Passive House scenario, the occupants are likely to experience a relatively warm sensation with a PMV index of around 1. Although windows were opened when the indoor temperature reached 25 °C (according to CIBSE TM59 guidelines), a high level of insulation combined with low air permeability resulted in overheating during winter.

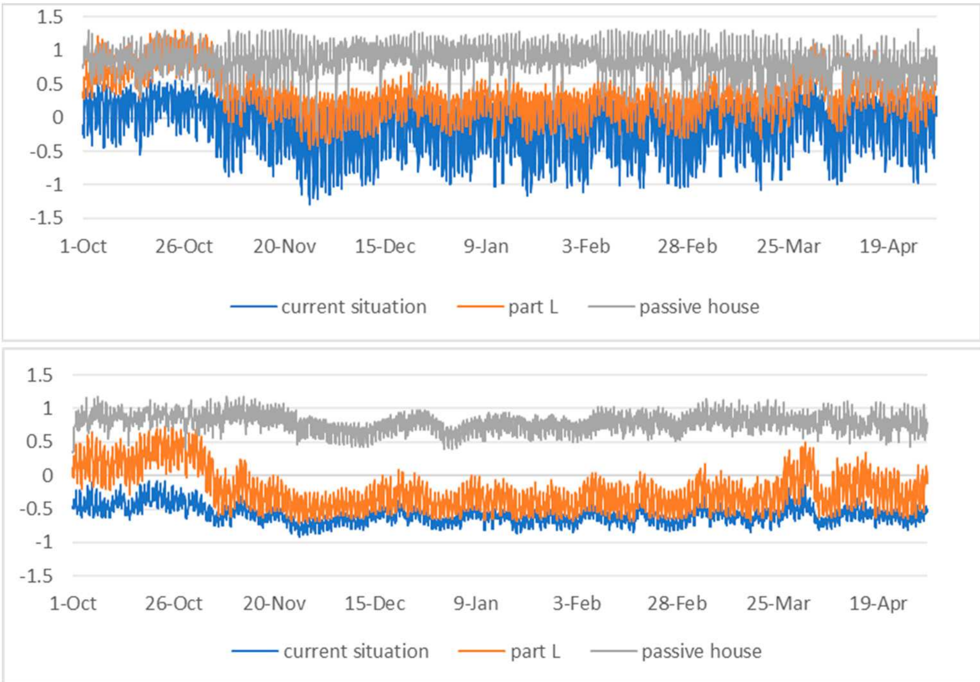

Figure 5. PMV index in (**top**) living room and (**bottom**) bedroom from October to the end of April.

Regarding energy consumption, according to the results, 155 KWh/m^2 was consumed for the base case scenario, which is around 20% higher than the figures for new domestic flats in the UK [43]. Around 60% of the energy consumption was related to space heating, which matches typical UK scenarios [6]. Retrofitting to Part L and Passive House standards reduced energy demand for space heating by up to 90 percent. Figure 6 shows that exterior wall insulation combined with triple-glazed windows can save almost 60% in total annual energy consumption. As expected, applying passive house standards further decreased total energy consumption to 63 KWh/m^2, which matches the findings of previous studies in the UK [44,45].

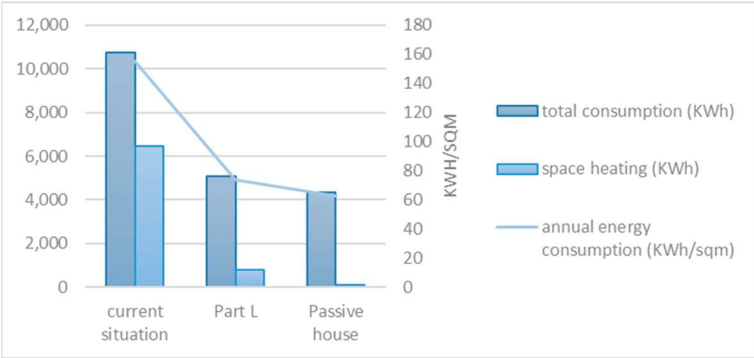

Figure 6. Yearly energy consumption and share of space heating.

3.2. Indoor Air Quality

The findings of the questionnaire survey and collected data on Indoor Air Quality (IAQ) are presented and analysed in this section. The analysis focuses on the relationship between energy consumption, indoor air quality, and health in the CSBs. Table 3 summarises the results of the questionnaire survey in the three selected case studies, highlighting variations in occupants' behaviour. These offer insights into the factors contributing to differences in the observed IEQ in the case studies. According to the observations, although mould was not observed in any of the case studies, one of the occupants in CS-1 raised issues over symptoms that indicate poor indoor air quality in the building linked to poor ventilation and lack of purge ventilation.

Table 3. Overview of the questionnaire survey results in the three case study flats in the living room (LR) and bedroom (BR).

Case Study	Area (m^2)	Occupants Number	Window Opening	Shower	Mould	Water Leakage	Daily Occupancy	Symptoms
CS-1	77	1	LR: rarely BR: once per day	No response	Not observed	No	18–24 h	Itchy eyes Dry skin Tiredness headache
CS-2	69	3	LR: 2–3 times per day BR: 2–3 times per day	2–3 times per day	Not observed	Yes	6–12 h	No
CS-3	57	2	LR: 2–3 times a week BR: 2–3 times per day	2–3 times a week	Not observed	No	No response	No

Table 4 provides a summary of temperature, relative humidity, and CO_2 concentration in the living room and main bedroom between March and April. According to the CIBSE guidelines [38], a CO_2 concentration of up to 1000 ppm is considered acceptable. For RH%, ranges between 40–60% are considered as acceptable/comfortable while for temperature, temperature ranges between 22 °C and 23 °C in the living room and 17 °C and 19 °C in the bedroom are considered as thermally comfortable.

Table 4. Summary of collected IEQ data in the main bedrooms and living rooms of the three case study flats.

Case Study	CO_2 (ppm)				Temperature (°C)				Relative Humidity (%)			
	Bedroom											
	Average	Min	Max	SD	Average	Min	Max	SD	Average	Min	Max	SD
CS-1	807	427	3117	382	22.9	18.25	27	1.48	40	28	52	4.02
CS-2	2302	445	5000	1158	21.31	19.10	23.30	0.81	59	40	73	5.45
CS-3	861	400	1795	304	23.89	20.98	26.13	0.92	39	26	51	3.9
Outdoor	400	400	400	N/A	9.17	0.00	17.22	3.72	74	31	100	17
	Living Room											
CS-1	639	400	2253	233	25.39	22.15	29.14	1.12	33	22	44	3.57
CS-2	1080	452	3420	477	23.03	19.51	30.47	1.40	46	27	62	5.97
CS-3	1025	457	2124	358	24.71	22.63	28.42	0.87	37	23	46	3.55
Outdoor	400	400	400	N/A	9.17	0.00	17.22	3.72	74	31	100	17

When it comes to IAQ, CS-2 stands out as the most problematic case study with CO_2 concentration levels reaching 3400 and 5000 ppm in the living room and the bedroom, respectively. It should be noted that the data loggers had a maximum reading level of 5000 ppm (Figure 7); hence, it is likely that the CO_2 levels would go higher than this level. Natural ventilation was therefore insufficient to provide acceptable IAQ despite occupants reporting that they open the windows two to three times per day in both rooms. It is also evident that background ventilation through the trickle vents was not providing sufficient ventilation in any of the buildings to maintain the CO_2 levels at acceptable levels. However, despite insufficient ventilation, the occupants of CS-2 did not report any health-related issues. As illustrated in Figure 8A, only 54 percent of the hours in the living room of CS-2 exhibit CO_2 concentrations below 1000 ppm, while the percentage drops to 12 percent for the bedroom. Consequently, the poor indoor air quality in CS-2 can be attributed to the number of occupants, as three individuals reside in a two-bedroom flat spanning an area of 69 m^2.

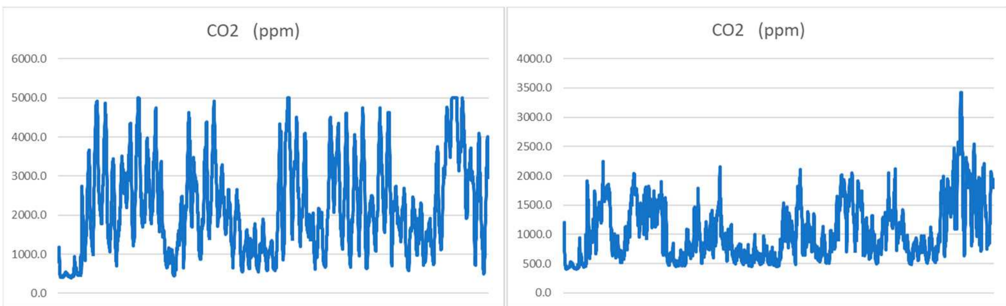

Figure 7. CO_2 concentration levels in CS-2 in the bedroom (**left**) and living room (**right**).

In CS-1, despite infrequent window opening in the living room, the larger floor plan, with one residing occupant, contributed to an acceptable air quality, with an average CO_2 concentration of 639 ppm. Although the maximum CO_2 concentration exceeded 2200 ppm, Figure 8A demonstrates that it remains within the recommended range for over 92 percent of the observed periods. Conversely, in the bedroom of CS-2, higher CO_2 concentrations were observed, with levels exceeding 3100 ppm during nighttime. This can be attributed to the smaller size of the bedroom compared to the living room, the practice of closing doors during sleeping hours, and lack of sufficient background ventilation. Overall, even in the bedroom, the CO_2 concentration remains below 1000 ppm for approximately 81 percent of the observed hours. The importance of providing fresh air for maintaining indoor air quality is highlighted by the data obtained from CS-3. In this case, window opening was reported as a few times a week, resulting in an average CO_2 concentration of 1025 ppm in the living room. Additionally, the data reveal that the CO_2 concentration remained within the acceptable range for only 54 percent of the observed hours. However, in the bedroom, daily window opening yielded more satisfactory outcomes, as depicted in Figure 8A.

Figure 8. Percentage of samples falling within the recommended range (% of the day during observation period) of: (**A**) CO_2 concentration of up to 1000 ppm; (**B**) comfort temperature; and (**C**) relative humidity (40–60%).

Moreover, high temperatures were observed across all the case studies during winter, as shown in Table 4, potentially caused by the long operation times of heating systems and insufficient window opening. For instance, in CS-1, opening windows in the living room and bedrooms only once a day for up to 30 min resulted in temperatures reaching 27 °C in the bedroom and 29 °C in the living room. In the living room, overheating was recorded in nearly 99 percent of the observed hours, with an average temperature surpassing 25 °C. Similarly, in the bedroom, the temperature exceeded 19 °C in 90 percent of the observed hours, indicating a consistent issue of overheating, as demonstrated in Figure 8B.

In CS-2, lower temperatures were exhibited compared to the other case studies. This can be attributed to the higher frequency of opening windows in both the living room and bedroom (Figure 9). However, despite this practice, overheating issues predominantly occurred in the bedroom. The average temperature in the bedroom was measured at 21.3 °C, which still exceeds the recommended limit by 2–3 degrees according to CIBSE guide A. In CS-3, despite opening windows 2–3 times a day, the issue of overheating in the bedroom was more severe compared to other case studies. The temperature in the bedroom consistently remained above 21 °C, with an average of 24 °C. This situation may arise from the continuous operation of the heating system, leading to a significant waste of energy. Anecdotal feedback from the residents highlights the practice of always keeping heating on at night during winter regardless of indoor temperatures, which was apparently requested by the facility managers.

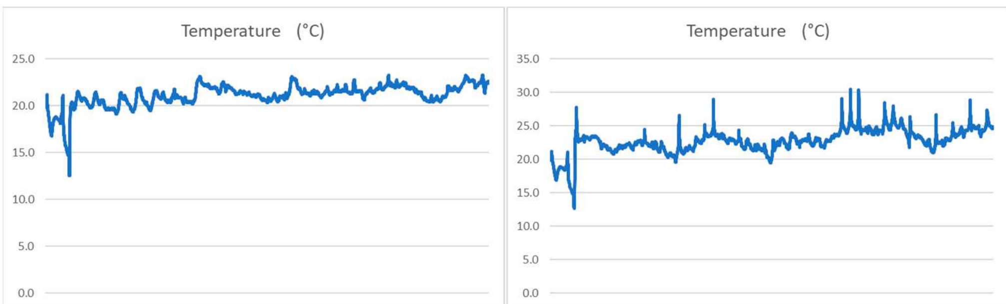

Figure 9. Indoor temperatures in CS-2 in the bedroom (**left**) and living room (**right**).

Amongst the variables investigated, relative humidity proved to be the least concerning factor in relation to IEQ. In five out of the six examined zones, relative humidity remained within the recommended range for over 80 percent of the observed hours—as shown in Figure 8C.

However, in the bedroom of CS-2, the relative humidity fluctuated between 40 to 73 percent, with an average of 59 percent, indicating a high level of moisture content in that specific area (Figure 10). The findings from the questionnaire survey indicated reported water leaks in this flat. Consequently, inadequate ventilation coupled with water leakage has led to relative humidity levels exceeding 60 percent for most of the time. Although no visible signs of mould growth have been observed thus far in CS-2, the indoor conditions in this flat are highly conducive to the growth of mould. Overall, it should be noted that a high temperature results in lower RH% and reducing temperatures to recommended standards would result in higher air water content levels that could lead to condensation, damp, and mould growth.

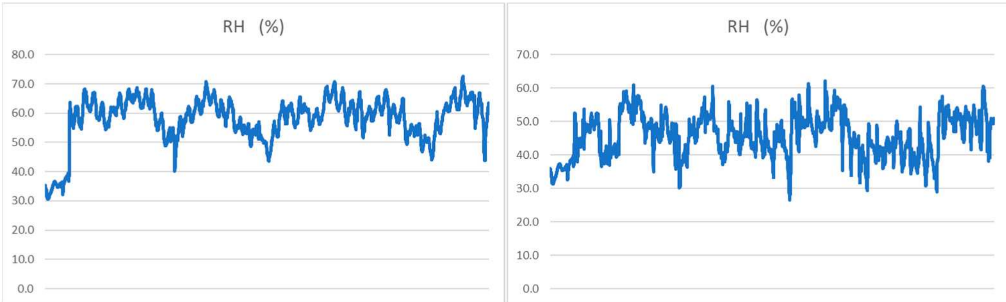

Figure 10. RH% levels in CS-2 in the bedroom (**left**) and living room (**right**).

3.3. Actual Energy Consumption

Figure 11 illustrates the energy use for heating (space or water heating) as well as the overall energy consumption in the three case study flats. Notably, there is a significant disparity in energy consumption, with CS-1 exhibiting considerably higher levels, with heating accounting for over 90 percent of the total energy consumption in CS-1. This can be attributed to the elevated average temperatures observed in both the living room and bedroom of CS-1, which indicate a substantial demand for space heating in this particular flat. Indeed, maintaining an indoor temperature of approximately 25 °C during the winter season necessitates a significant amount of energy consumption. Additionally, the flat is situated at a corner position within the building, resulting in two sides of the building envelope being exposed to the outdoor environment resulting in more energy waste through the building fabric.

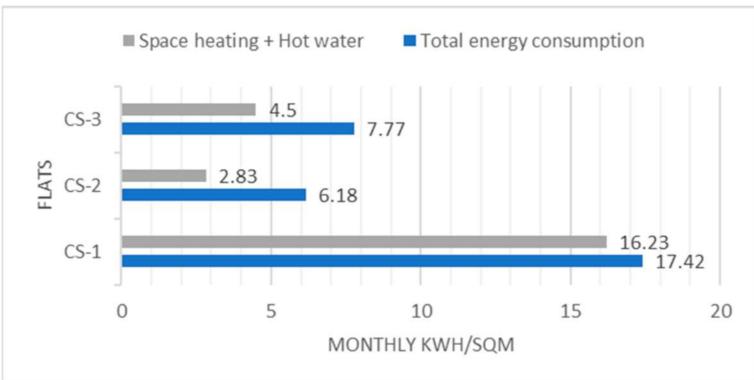

Figure 11. The total energy consumption and energy used for heating in the three case study flats.

When comparing the energy consumption between CS-2 and CS-3, it becomes evident that CS-2 reports a higher demand for domestic hot water (see Table 3), with a less energy used for space heating—this is validated by the lower recorded indoor temperature in CS-2. In the case of CS-3, the share of energy consumption attributed to both space heating and hot water is approximately 58%. Considering that domestic hot water (for taking a shower) is used 2–3 times a week, it can be inferred that a larger portion of this energy is related to space heating.

3.4. Thermal Imaging

Thermal imaging (Figure 12) was also employed to investigate the factors contributing to excessive energy consumption in certain flats. A visit was arranged between 6 am and 7 am during winter. As demonstrated in Figure 12, a notable number of flats left their windows open during this early time of the day. This practice can lead to a considerable increase in energy consumption as it necessitates additional heating requirements when the outdoor temperature is low, as it is the case during wintertime. This could be due to the observed overheating in the case study buildings. As stated above, it should be noted that the current practice of keeping the council-metered heating/radiators on during nighttime (requested by building managers), despite concerns about excessive temperatures in the flats, probably contributed to some irrational behaviours by some occupants. However, the discussions during the end of project community engagement event highlighted that some residents were suffering from cold and high energy bills while others were concerned about overheating and poor IAQ. Upgrading the building fabric and installation of heating thermostats along with ventilation systems would be effective retrofit strategies to address both thermal comfort issues and energy consumption while addressing IAQ issues in the building.

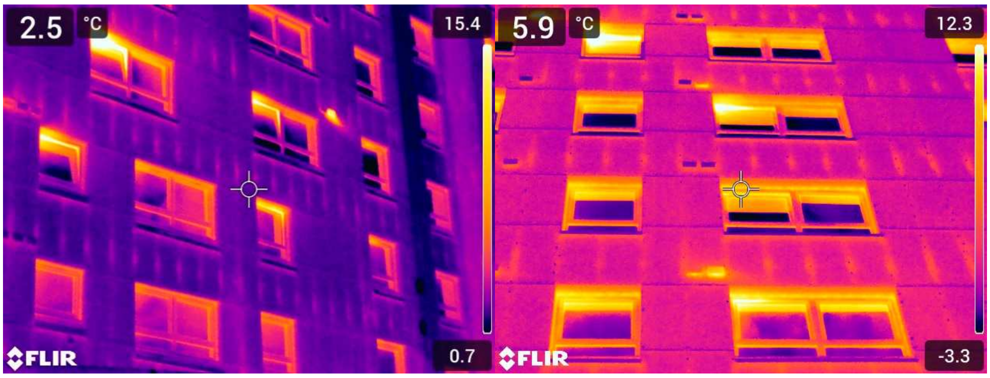

Figure 12. Thermal images show windows left open during early morning.

3.5. Occupant Behaviour, IAQ, and Health (Questionnaires)

According to Vardoulakis et al. [46], 'Household characteristics and occupant activities play a major role in exposure' to indoor air pollutants. Occupants' behaviours are also known to play a significant role in energy consumption and thermal comfort and indoor air quality. Participants were asked about the frequency of window opening across the four main living areas, living room, bedroom, bathroom, and kitchen, during winter and summer. During winter, 65% of the respondents opened their bedroom and living room windows at least once a day and 80% opened their windows less than once a day. Around 50% did not open their windows at all in their kitchen and 88% never opened their bathroom windows in winter. As expected, participants' use of windows for natural ventilation increased significantly to 96% in summer with bedroom and living room windows opened at least once a day. Similarly, this increased for both kitchen and bathroom windows with 42% of respondents opening their kitchen windows 2–3 times per week and 62.5% not opening their bathroom window at all. The primary reasons for opening the windows were to provide fresh air (87%) followed by thermal comfort (9%).

In terms of mechanical ventilation, 58% reported they use extractor fans in the kitchen at least 2–3 times per week with 33% not using any mechanical ventilation. For the bathrooms, around 62% used mechanical ventilation at least once a day and 37.5% did not use the extractor fans at all. This is while around 35% reported washing and/or cooking at least once a day. Despite relatively low use of extractor fans coupled with 88% who did not open their windows during winter, only 15% of the respondents reported damp and/or mould in their property. A possible explanation for this may be the relatively high indoor temperatures and availability of communal washing and drying facilities with 62% of residents using this as their primary facility to wash/dry clothes.

The survey also investigated long-term health conditions and symptoms linked to IAQ and occupant behaviour. According to the results, 5% of the respondents had asthma, 3% had hay fever, and 1% suffered from both. Of those with asthma, 40% reported damp or mould in their property. Despite the relatively low number of reported issues with damp and mould, and the low number of residents with either hay fever or asthma, a significant number of respondents reported other IAQ-related symptoms including itchy or watery eyes (56%), headache (52%), and lethargy or tiredness (44%) (Figure 13). Looking at the potential IAQ issues, 64% of this cohort cooked at least once a day and 42% cooked 2–3 times or more. Out of the 64% with itchy or watery eyes, 55% never opened their windows during winter spending 18–24 h a day inside the property. Similarly, out of the 56% who reported headaches, 76% cooked at least once a day and 60% did not open their kitchen windows at all during winter and all spent 18–24 h a day indoors. Though a direct cause and effect cannot be shown due to other potential lifestyle and health issues, a statistically significant correlation can be seen between occupant behaviour (e.g., operation of extractor fans, opening windows regularly, etc.), exposure to indoor air pollutants, and reported symptoms. Additionally, whilst around 44% of the respondents reported lethargy or tiredness, no statistically significant correlation between IAQ and the reported symptom was found. It is prevalent though that the age of the respondents (the majority of whom were from older age groups) is a potential factor. Moreover, when it comes to smoking, known as a major contributor to poor IAQ and health, due to the very low number of smokers (only one resident with no self-reported respiratory or other health symptoms) no conclusions could be drawn.

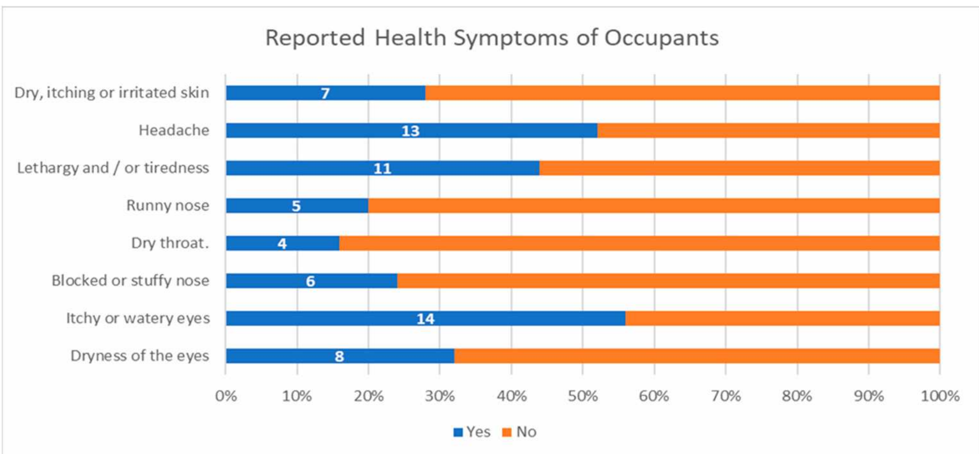

Figure 13. Reported health symptoms suffered by occupants.

4. Conclusions

The multifaceted investigation conducted in this research offers insight into the intricate relationship between occupant behaviour, retrofit strategies, indoor environmental quality (IEQ), and health within the specific context of social housing. The study focused on older and vulnerable occupants living in a social housing block of apartments in London. Given the demographics and socio-economic similarities of the social housing residents, as well as similar building archetypes, the results could be generalised to wider populations within the social housing context. A mixed method was employed involving: (1) physical measurements for actual energy consumption and IEQ monitoring; (2) questionnaire surveys on occupant behaviour and health; (3) dynamic thermal modelling to assess the effects of retrofit on energy consumption and winter/summer thermal comfort; and (4) thermal imaging for the assessment of building fabric. The simulated retrofit scenarios highlighted potential challenges including elevated risk of overheating during both summer and winter. It was evident that risk of overheating significantly increased for the highly insulated buildings (e.g., Passive House), especially in zones with increased internal and solar heat gains. Concurrently, the study revealed the profound impact of occupant behaviour on energy performance, risk of overheating, and indoor air quality. Despite these challenges, the analysis indicated that strategic retrofitting targeting building fabric improvements achieved substantial energy savings of up to 60%. However, it was revealed that defective retrofit strategies could lead to poor indoor environmental condition including overheating and poor indoor air quality that in turn would negatively affect occupants' health in the long term.

The questionnaire survey highlighted the intricate correlation between occupant behaviour, ventilation practices, and health outcomes. The study identified inadequate ventilation (either through purge ventilation through windows, or mechanical ventilation through extractor fans), particularly in conjunction with routine cooking, as a potential risk factor for concentration of indoor air pollutants, with symptoms such as itchy and watery eyes and headaches linked to poor indoor air quality. Significant risk of overheating, even during winter, combined with some debatable building management practices resulted in irrational behaviours from building occupants contributing to both overheating and significant energy waste (e.g., opening windows for long periods of time during winter while heating systems were on). The identified need for retrofitting strategies to address insufficient ventilation, particularly in critical areas (e.g., kitchens, bathrooms, and bedrooms), highlights the practical challenges that must be navigated. In this respect, some measures including improved heating schedules, automated ventilation systems, and educating residents, as well as regular and timely maintenance of buildings, are recommended to address issues such as excessive condensation, water leakage, inadequate or faulty ventilation systems, etc., that could lead to poor IAQ, mould growth, and/or overheating/cold in buildings.

The research emphasises the necessity of adopting a holistic approach that seamlessly integrates considerations of occupant behaviour into retrofit designs and strategies. Additionally, the study advocates the significance of implementing systematic educational initiatives tailored towards both building occupants and social housing providers. Examples include general knowledge on IAQ and thermal comfort in buildings, benchmarks, use of ventilation and heating systems, heating schedules and set points, etc. Such initiatives would not only increase awareness regarding the influence of individual behaviours on energy consumption and IAQ but also empower residents to actively contribute to the success of energy efficiency measures.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Anonymised raw data is available from the University of East London repository upon request.

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