Exposure to indoor air pollutants in a deep energy retrofit of block of flats in the UK

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SUMMARY

Large-scale retrofit projects are necessary to meet UK net zero emission targets, but better insulated and airtight homes potentially risk increasing exposure to indoor air pollutants due to reduced indoor-outdoor air exchange This paper examines indoor air pollutants in four flats of a low-rise block of flats that underwent a deep energy efficiency upgrade. Indoor air quality in terms of temperature, relative humidity, carbon dioxide, particulate matter $PM_{2.5}$ and PM_{10}, formaldehyde, ethanol and isobutylene were measured using plug-in Airthinx sensors in living rooms: four flats captured post-retrofit data (May-December 2021), one flat also captured retrofit and early post-retrofit data (October 2020-April 2021). Ethanol, isobutylene and formaldehyde levels were found to be high from October to December 2020 corresponding to specific retrofit works (plastering, painting). Post-retrofit, these levels dropped significantly, but $PM_{2.5}$ and PM_{10} consistently exceeded recommended limits. Retrofit projects must consider indoor air pollutants since air-tightness may prevent pollutants originating from within the building from escaping.

KEYWORDS

Retrofit, indoor air quality, housing, particulate matter, formaldehyde

1 INTRODUCTION

The climate emergency requires large-scale energy retrofitting in the UK, particularly in the domestic sector. Air pollution may be the world's largest single environmental health risk (WHO, 2014), but though outdoor air quality has been extensively studied and regulated, indoor air quality (IAQ) has been relatively neglected. IAQ is strongly dependent on outdoor air pollution, but there are many sources of air pollutants within buildings: building materials, consumer products and occupant activities. To reduce the heating energy demand, homes are becoming better insulated/more airtight, minimising unwanted heat loss/gain and infiltration of outdoor air pollutants. However, it also reduces the exfiltration of indoor air pollutants.

Studies of IAQ often measure air temperature, relative humidity (RH) and CO_2 levels over varying amounts of time (Baborska-Narozny and Stevenson, 2015, Jimenez-Bescos and Prewett, 2018, Perisoglou et al., 2019). While CO_2 is thought to serve as an effective proxy for IAQ (Ramalho et al., 2015), measuring individual pollutants directly would provide a more focussed analysis of the IAQ and provide opportunity to address any issues in a more bespoke way. Many IAQ studies depended on short term IAQ monitoring less than two weeks, making it difficult to determine more long term trends and seasonal variations (Moreno-Rangel et al., 2020).

Against this context, the empirical approach in this paper measured IAQ in a low-rise block of flats that underwent a deep energy retrofit. This longitudinal monitoring provided detailed insight into the flats' IAQ (including formaldehyde, VOCs and PM's) during a post-retrofit period rarely studied in depth.

2 METHODS

The deep retrofit was conducted on a low-rise block of six flats located in an east coast town of the UK. The fabric-focused retrofit provided a wrap-around layer of insulation covering the roof, external walls and into the ground. Each flat was provided with their own mechanical ventilation with heat recovery (MVHR) system, with units in the loft space and external ducting. Windows were upgraded to highly efficient triple-glazed but were kept openable in line with occupant preferences. The 1950's council-owned flats had east and west facades, gas boilers for heating/hot water and a floor area of 70m^2 (Figure 1). Occupants remained within their flats throughout the retrofit. Of the six flats, four (A, B, D and E) contributed to the research study. Each flat had unique occupancy: Flat A – two working adults; flat B – one working adult and three school-aged children; Flat D – one retired adult; flat E – one working adult and two school-aged children. All flats had pets: A and D had cats; B and E had a dog each. Flats A, B and D had at least one occupant who smoked. Prior to the retrofit, all flats had damp and mould issues, particularly in the bathrooms and bedrooms, some occupants linking this to regular coughs and chest infections.

Figure 1 Case study flats (post-retrofit): east facade (left), representative floor plan (right).

The retrofit works began in October 2019 and were completed in December 2020, with delays due to Covid-19. Pre- and post-retrofit airtightness tests were conducted in accordance with industry standards ATTMA TS1 Issue 2, BS EN13829:2001 and Passive House. IAQ monitoring began in October 2020 (flat E, capturing the final months of retrofit works) and in May 2021 (flats A, B and D) and continued until December 2021. Readings were averaged at 15-minute frequency. Airthinx IAQ monitors (specifications in Table 1) were deployed in the living rooms of each flat, transmitting data to a secure cloud-based portal. These devices were susceptible to being unplugged by the flat occupants occasionally, requiring prompting by the researchers to reconnect them.

Table 1 Specifications for Airthinx IAQ monitor.

Parameter	Range	Accuracy	Resolution
Temperature (°C)	0-99	± 0.5	0.1
RH (%)	0-99	± 2	0.1
CO_2 (ppm)	0-3000	± 50 +5% FS	1
CH_2O (mg/m^3)	0-1	± 5% FS	0.001
PM1/PM2.5/PM10 (μm/m^3)	0-500	± 10% @100-500μm/ m^3	1
EtOH (ppm)	0-10	± 15%	0.01
Isobutylene (ppm)	0-1	± 15%	0.01

Research suggests that relatively low-cost IAQ monitors such as Airthinx have a tendency to under-report levels of indoor air pollutants, in particular PM's, and would benefit from calibration (Zamora et al., 2020). The Airthinx devices recorded concurrently with higher specification Hobo MX1102A's for at least two months during the monitored periods, allowing temperature, RH and CO_2 data streams to be validated and calibrated accordingly. Our analysis of indoor air pollutants focusses more on the trends observed over time rather than definitive levels recorded. Throughout the project, feedback was gathered from occupants through formal surveys and interviews and informal conversations, providing insight into their experiences of the retrofit, typical behaviors patterns and perceptions of their indoor environmental conditions.

3 RESULTS

3.1 Airtightness

Pre- and post-retrofit airtightness tests found a reduction from 3.2 ach@50Pa to 0.67 ach@50Pa post-retrofit, well below EnerPhit (Passivhaus standard for retrofits) threshold of 1 ach@50Pa. Feedback from the occupants indicated that the flats were much warmer through the winter and heating bills significantly reduced.

3.2 Post-retrofit temperature, CO_2 and RH (all four case study flats)

Post-retrofit IAQ monitoring covered the non-heating season (May-Sep 2021) and the heating season (Oct-Dec 2021) (Table 2). Temperatures varied from flat to flat, but remained within the occupants' comfort ranges for much of the time – flat E's non-heating season peak of 29.9 °C due to occupants being on holiday for 3 weeks during a summer heatwave, and therefore not regulating solar gains with cooling strategies. During the heating season, temperatures cooled with medians 1.8-4.3 °C lower than during the non-heating season. Interquartile ranges (IQRs) were 0.8-2.9 °C, and diurnal profiles showed stable temperatures with very few high or low extremes. Occupants perceived their flats to be warmer with more stable temperatures in the post-retrofit period.

Monitored CO_2 levels varied significantly between flats. Flat E's occupants habitually opened windows, giving them significantly lower CO_2 levels than their neighbours. Flat D (single occupant) showed little change between non-heating and heating seasons, whereas flats A and B had much wider seasonal variation, with heating season lower quartiles higher than upper quartiles in the non-heating season. Nevertheless, with the MVHR providing continuous infiltration and exfiltration, overall CO_2 levels were much lower than would have been expected in the pre-retrofit flats.

Table 2 Descriptive statistics for temperature, CO_2 and RH

		Temperature (°C)				**CO_2 (ppm)**				**RH (%)**			
	Flat	**A**	**B**	**D**	**E**	**A**	**B**	**D**	**E**	**A**	**B**	**D**	**E**
May-Sep 2021	Mean	24.0	23.2	26.2	29.1	975	778	820	486	49	52	47	35
	Median	24.2	23.3	26.3	29.2	954	718	811	433	50	52	48	35
	Min	13.4	13.1	11.5	22.6	616	461	492	402	21	31	31	24
	Max	38.5	26.9	33.6	33.7	4737	4665	5000	1564	71	87	82	57
	1st Q	23.2	22.5	25.5	28.4	865	637	754	406	45	47	44	32
	3rd Q	24.9	24.3	27.1	29.9	1048	859	870	520	53	56	50	38
Oct-Dec 2021	Mean	21.3	21.4	22.1	25.8	1199	1305	815	531	39	47	44	30
	Median	21.4	21.5	22.0	25.6	1181	1304	821	471	39	47	44	29
	Min	19.4	14.0	16.3	18.2	887	588	501	402	27	31	36	15
	Max	24.4	26.4	25.8	30.8	2032	3522	1538	1865	60	78	64	48
	1st Q	21.0	20.8	21.0	24.4	1077	1014	771	406	34	41	41	26
	3rd Q	21.8	22.2	23.1	27.3	1300	1574	866	611	44	52	47	34

Pre-retrofit flats had persistent damp and mould, particularly during the heating seasons. Lowering RH was therefore a priority in the retrofit design. Post-retrofit, RH was kept well below the recommended upper limit of 60% in most flats in both heating and non-heating seasons. Mean RH was 35-52% (non-heating season), falling to 30-47% (heating season), consistently lowest in flat E. In all flats, RH was lower during the heating season, with radiators serving to dry the air. As with CO_2, the flat with the smallest difference between non-heating and heating season RH was flat D, whose occupant said that he had rarely needed to turn on the heating at all since completion of the retrofit. Although post-retrofit flats did not experience the pre-retrofit high RH evidenced by damp and mould, levels below the recommended 40% were widespread, particularly in flat A during the heating season and flat E during both monitored seasons.

3.3 Post-retrofit Formaldehyde, VOCs and particulate matter (all four case study flats)

Formaldehyde levels in all four flats were below 0.001 mg/m^3 for between 54% (flat A) and 99% (flat D) of monitored readings (Figure 2). However, occasional spikes were measured in flats A, B and E. WHO guidelines recommend formaldehyde levels do not exceed 0.1 mg/m^3 30-min avg. (WHO, 2010). Converting the data to 30-min avg. revealed this limit to be exceeded 5.6% (A), 1.2% (B) and 0.5% (E) of the monitored non-heating season and 0.7% (A), 1.5% (B) and 0.5% (E) of the monitored heating season.

Ethanol and isobutylene levels exceeded the Airthinx device's upper range in flats A, B and D. Both pollutants had much lower levels in the heating season compared to non-heating season. Flat D stood out as having significantly higher levels of both ethanol and isobutylene in both seasons: ethanol medians of 9.44 ppm (non-heating season) and 3.81 ppm (heating season); isobutylene medians of >1 ppm (non-heating season) and 0.51 ppm (heating season). Neither ethanol nor isobutylene have regulated/recommended upper concentrations. Public Health England describe one hour exposure to ethanol <1800 ppm would result in no more than mild transient adverse health effects (PHE, 2015). Industry recommendations for isobutylene exposure are in the order of 250 ppm averaged over 8 hours (TCP Group, 2012). These levels are far beyond Airthinx's monitoring range, and unlikely to be close to those experienced within the flats.

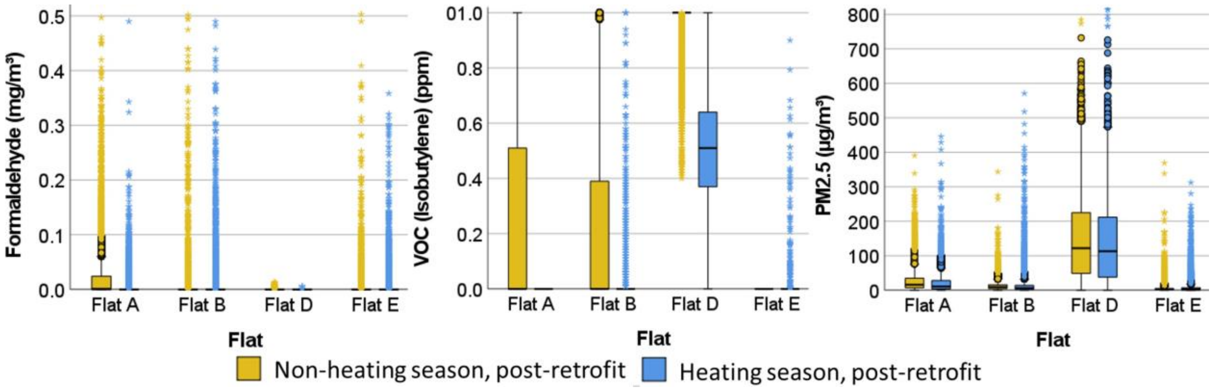

Figure 2 Boxplots showing distribution of formaldehyde, isobutylene and $PM_{2.5}$ in each flat during the post-retrofit non-heating and heating seasons.

PM_{10} and $PM_{2.5}$ levels in flats A, B and E were significantly lower than those in flat D (Figure 2), whose median levels were 117-126 µg/m^3 (PM_{10}), and 113-122 µg/m^3 ($PM_{2.5}$). Regulators recommend reducing PM levels "as much as possible as no safe level is known" (WHO, 2010). Indeed, WHO lowered its recommended upper limits in 2021 (WHO, 2021) (Table 3). Only flat E had PM_{10} levels below the recommended limits over the whole monitored period, with flat D exceeding the daily mean of 45 µg/m^3 for almost every monitored day. $PM_{2.5}$ limits were exceeded in flats A, B and D. Flat E was also the only flat to be within the limits for $PM_{2.5}$, with an overall mean was 4.7 µg/m^3. The four days when flat E's $PM_{2.5}$ exceeded 15 µg/m^3 were not consecutive.

Table 3 WHO limits for PM_{10} and $PM_{2.5}$, and monitored levels in non-heating (May-Sep 2021) and heating (Oct-Dec 2021) seasons. **BOLD** text indicates recommended limit exceeded.

PM_{10}: Upper limit 15 µg/m^3 annual mean, 45 µg/m^3 24-hour mean								
	Mean µg/m^3				Days daily mean >45 µg/m^3 / total days monitored			
Flat	A	B	D	E	A	B	D	E
May-Sep 2021	**29**	14	**159**	6	**4/88**	**2/123**	**99/101**	0/125
Oct-Dec 2021	**26**	**16**	**146**	5	**2/34**	**1/57**	**57/57**	0/57
$PM_{2.5}$: Upper limit 5 µg/m^3 annual mean, 15 µg/m^3 24-hour mean no more than 3-4 consecutive days								
	Mean µg/m^3				Days daily mean >15 µg/m^3 / total days monitored			
May-Sep 2021	**26**	**13**	**150**	5	**78/88**	**39/123**	**100/101**	4/125
Oct-Dec 2021	**23**	**14**	**138**	4	**23/34**	**16/57**	**57/57**	0/57

3.4 During retrofit/early post-retrofit indoor environment (flat E)

IAQ monitoring in flat E covered the final stages of retrofit (Oct-Dec 2020) and early post-retrofit (Jan-Apr 2021) in addition to May-Dec 2021 post-retrofit. Indoor air temperature remained in comfortable throughout the monitored 15 months, and CO_2 levels followed similar trends to those observed above (MVHR commissioned in early spring, 2020). Boxplot distributions (Figure 3) cover Oct- 2020 to Dec 2021.

Throughout all periods, RH was well below the recommended 40-60% range (Figure 3), with upper quartiles never exceeding 40%, and was particularly low during the early post-retrofit heating season (Jan-Apr 2021). Formaldehyde levels tended to be very low, but with several outliers exceeding 0.1 mg/m^3. Ethanol and isobutylene levels were much higher from Oct-2020 to Apr-2021 than later on. During Oct-Dec 2020, medians were 3.09 ppm (ethanol) and 0.28 ppm (isobutylene), both peaking beyond the range of the Airthinx device.

PM_{10} and $PM_{2.5}$ had almost identical boxplot distributions, both higher from Oct-2020 to Apr-2021 compared to May-Dec 2021 (Figure 3). PM_{10} exceeded 45 µg/m^3 for 4.6% of readings (Oct-2020 to Apr-2021), compared to 1.7% (May-Dec 2021). Even during the final stages of retrofit, PM_{10} was well within WHO limits. However, $PM_{2.5}$ exceeded 15 µg/m^3 for 14% of readings from Oct-2020 to Apr-2021, falling to 5.3% from May-Dec 2021. Daily mean exceeded WHO limit of 15 µg/m^3 for several periods of 3-4 consecutive days from Oct-2020 to Apr-2021. Mean $PM_{2.5}$ over this period was 8.3 µg/m^3, exceeding WHO limit of 5 µg/m^3.

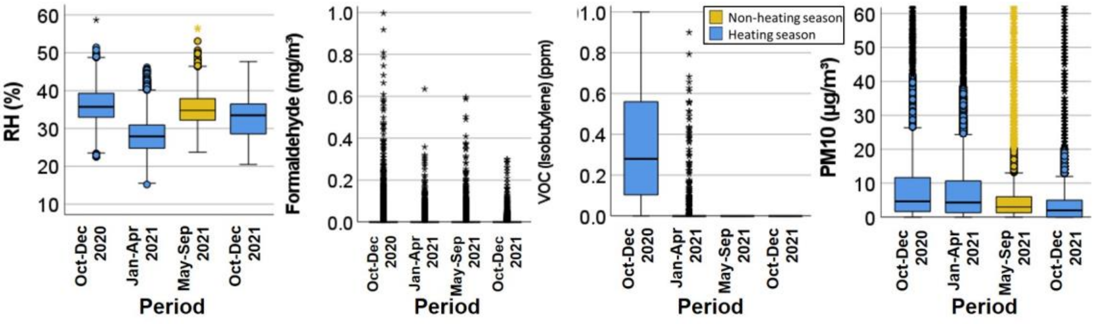

Figure 3 Boxplots showing distribution of (left to right) RH, formaldehyde, ethanol and PM10 during final stages of retrofit (Oct-Dec 2020) and post-retrofit heating and non-heating seasons.

Plotting daily averages further highlights these trends (Figure 4). Formaldehyde levels were generally very low, but spikes apparent during the final stages of retrofit exceeding the WHO recommended 0.1 mg/m^3 30-min avg., reaching as high as 1.30 mg/m^3. Isobutylene and ethanol levels were very high when monitoring began, but fell as the retrofit works came to an end. PM_{10} and $PM_{2.5}$ fluctuated daily, but trended downwards post retrofit. Spikes in monitored indoor air pollutants often corresponding to specific retrofit works conducted around the same time (Figure 4): (1) installation of windows, internal remedial decoration; (2) external balconies installed, continued redial decoration; (3) hallway ventilation installed and commissioned; (4) further ventilation installed in hallway; (5) completion of retrofit, removal of scaffolding, front access door installed.

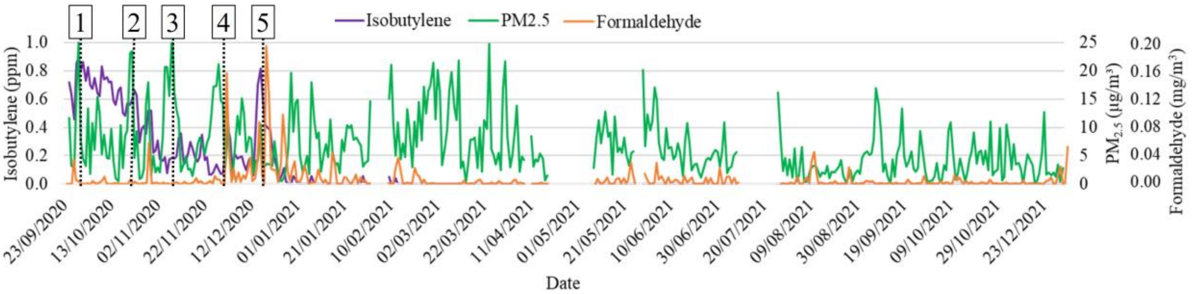

Figure 4 Daily averages over the full monitored period in flat E for isobutylene, $PM_{2.5}$ and formaldehyde, with five significant periods during the final stages of retrofit highlighted.

Overall, the trends in flat E indicated a significant improvement in IAQ post-retrofit. It is notable that only the final stages of retrofit were monitored. Major stages of retrofit – balcony removal, installing insulation cladding, MVHR and windows – were all disruptive to the occupants and likely resulted in significant periods of reduced IAQ.

3.5 Relationship between CO_2 and monitored pollutants

CO_2 is often used as a proxy for IAQ. Concurrent monitoring of CO_2 and indoor air pollutants allowed correlations to be investigated. Spearman's Rho non-parametric two-tailed correlations were calculated, disaggregated by flat and period. The results proved diverse. Flat A's CO_2 correlations with formaldehyde, PM_{10}, $PM_{2.5}$, ethanol and isobutylene were all negative (and sig. at the 0.01 level), the strongest correlations were -0.364 (ethanol/isobutylene, non-heating season). Conversely, flat D had positive correlations, strongest in the heating season: 0.505 (PM_{10}/$PM_{2.5}$) and 0.319 (ethanol/isobutylene), indicating the source of pollutants in this flat were internal rather than external. By comparison, flats B's and E's correlations were much weaker, ranging from 0.05 to 0.278.

4 DISCUSSION

Analysis of the monitored indoor air parameters revealed several important features of the flats in their post-retrofit state. Resident feedback indicated they were much happier with their post-retrofit indoor environment, with more comfortable and stable temperatures, heat staying within the flats, and damp and mould all but eliminated. This concurred with monitored temperature, CO_2 and RH levels. However, MVHR had lowered RH well beyond the recommended 40% limit for long periods of time. Any installation of mechanical ventilation would benefit from incorporating sensors to help regulate RH and allow both dehumidification and humidification when necessary.

Levels of pollutants were high in the post-retrofit flats but varied from flat to flat. Ethanol and isobutylene levels exceeded the Airthinx's range, with spikes corresponding to specific retrofit works. Ethanol, isobutylene and formaldehyde will all have been components in the retrofit materials, but can also be found within the home: ethanol from soaps, cleaning products and cosmetics; isobutylene from the microscopic breakdown of a multitude of household items; and formaldehyde from tobacco smoke, detergents and cosmetics. Flat E's elevated levels during the final stage of retrofit suggested levels may have been much higher throughout the earlier retrofit works. Particulate matter generally originates from outdoor sources (car and ship repair yards and scrapyards all within 400m of the flats), but can also be produced within homes (including tobacco smoke and pets). Particulate levels were high, particularly in flat D, whose living room window was often open during the day, allowing infiltration of PM. Compared to the other flats, D was less clean, with dirt and dust evident on most surfaces. This combination of factors likely led to its much higher PM levels.

Although the retrofit protected the occupants from outdoor air pollutants, openable windows still allowed infiltration, and even during the heating season, formaldehyde and PM levels remained high, suggesting inadequate filtration with the MVHR and/or indoor sources of these and other pollutants. The probability that pollutant levels were even higher during the retrofit raises the question as to whether the convenience of occupants remaining in-situ during the retrofit outweighs the increased health risk associated with vastly diminished IAQ.

The effectiveness of using CO_2 as a proxy for indoor air quality proved to be inconclusive: correlations between CO_2 and monitored pollutants were positive in flat D, negative in flat A and mixed in the other two (B and E). The flats had the same orientation, location, design and build characteristics. Therefore, the differences in pollutant levels and the relationships between CO_2 and these pollutants were likely due to occupant behaviours. This makes it difficult to predict 'air quality' based on CO_2 levels alone and suggests more specific monitoring would be needed to quantify actual levels of each air pollutant.

The specificity of the case study flats, in particular their occupant characteristics, may appear to make generalisations more challenging. However, these occupant characteristics are representative of the variety of characteristics that may be found within the social housing population of the UK. This adds strength to applying general trends found in the results to the wider population, and highlights the influence that occupant characteristics can have on IAQ.

5 CONCLUSIONS

This paper examined exposure to indoor air pollutants in four flats of a low-rise 1950s block that received a deep energy retrofit with advanced levels of insulation and air tightness. One of the flats was monitored during the final months of the retrofit process. Pre- and post-retrofit airtightness was measured. Indoor environment (temperature, RH and CO_2) and air pollutants (formaldehyde, PMs, ethanol and isobutylene) were monitored. The retrofit was a success in terms of (1) significantly reducing the heating energy demand – airtightness going from 3.2 to 0.67ach@50Pa, (2) providing more comfortable and stable temperatures through both heating and non-heating seasons (medians 22-26°C and 21-26°C respectively), and (3) reducing RH (to means of 35-50% in the heating season and 30-48% in the heating season), and consequently reducing damp and mould within the flats.

Although CO_2 is sometimes considered to be a suitable proxy measure for indoor air quality, the results showed significant variation from flat to flat in the correlations between CO_2 and the monitored pollutants, even to the point where some correlations were positive and others were negative between the same pollutants over the same periods but in different flats. This indicates that an accurate assessment of indoor air quality requires specific pollutants to be monitored directly rather than relying on extrapolation of data from other parameters.

Large scale deep energy retrofits will need to be an integral part of any programs aimed to help meet government targets aimed at reducing domestic energy demand. While it may be possible in some cases to relocate occupants for the duration of the retrofits, in practical terms the majority of occupants will be required to remain in-situ throughout the process. The design and delivery of retrofits should take account of indoor air measurements before, during and after to quantify improvements, establish any negative impacts, and raise awareness of any risks posed to the occupants, perhaps requiring them to be relocated even for short, specific periods during the retrofit if not for the whole process.

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