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The impact of airtightness and low ventilation on air quality in domestic buildings and their effect on occupants.

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The impact of airtightness and low ventilation on air quality in domestic buildings and their effect on occupants

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Abstract. One of the facets of responding to climate change is energy conservation which has become so imperative to both domestic and non-domestic buildings. The increasing idea of better insulation and airtightness in a bid to save energy in buildings tended to lead to higher risks of low ventilation and low air quality of the indoor environment. Furthermore, the resulting impact on occupants' thermal comfort and well-being are often untested.

The aim of this paper is to examine how to balance airtightness with energy consumption and low ventilation to enhance good indoor air quality to meet carbon emission reduction targets in accordance with World Health Organisation (WHO) stipulated guideline to satisfy occupants comfort and wellbeing. The focus will be on domestic dwellings in Scotland.

A mixed method approach was used to carry out an assessment of the perception and satisfaction of occupants. In addition to a survey of occupants, measurements of indoor air quality indicators of the sample dwellings, including carbon dioxide, relative humidity, air temperature, air velocity and other pollutant such as benzene, formaldehyde, TVOC, PM2.5, PM10. An assessment of the building fabric performance was also conducted to establish levels of energy efficiency and carbon emissions.

Preliminary findings seem to indicate that the CO_2 level in some of the sample dwellings are above the WHO recommendations for occupant and the level of the PM2.5 are not suitable for human habitation. Hence, there may be health implication for occupants in those buildings due to the elevated level of CO_2 and PM2,5. Further analysis of the data collected will be carried out before final conclusions are established.

Key words: energy conservation, Indoor air quality, Low Ventilation, Carbon Emissions, Thermal Comfort, Wellbeing.

1. Introduction

The growing awareness of the impact of the indoor environment on occupants' health in passive buildings is of great importance, with respect to indoor air pollution. Recently conducted research shows that energy efficient buildings tend to put the emphasis on low energy consumption and thermal comfort. However, the impact of pollution on indoor air quality in passive buildings is still not adequately discussed in these research due, often, to lack of technical knowledge and skills to address the issue (Alejandro,et al 2018).

Notwithstanding the increased airtightness in the construction of building envelopes, primarily for energy efficiency reasons, results in low natural ventilation rates. The latter necessitate the application of modern technologies and use of building material which may reduce the indoor environmental quality, if proper and adequate measures are not taken into consideration (Howieson et al., 2014).

The effect of reducing the rate of natural ventilation in passive buildings combined with increased insulation, to improve energy efficiency, and hence reducing the rate of carbon emissions, without adequate consideration of alternative means of ventilation measures or strategies may result in pollution of the indoor environment. As this may be hazardous, toxic, and negatively impact occupants' health and wellbeing in the long-term (Howieson, et al 2013).

There are several indoor pollutants that may impact occupant health, with long term and short-term effects, thereby causing different health problems such as respiratory complications, runny noses, potentially cancer, cardiovascular problems, and hypertension. Such pollutants are identified as Particulate matter such as PM2.5, CO_2, CO, VOC etc. (Azuma et al., 2016) The short-term health effect of indoor pollutants includes the irritation of the eyes, nose and throat, headaches, dizziness, and fatigue. These are easily treated either by removing the affected person from the pollution sources. Although, symptoms of some diseases such as asthma develop immediately if one is exposed to the indoor pollutant. The long-term health effect of indoor pollutant includes respiratory diseases, hearts diseases and cancer which can be so serious. These show after a long time of exposure to the indoor pollutants or frequent exposure to the indoor pollutants. However, ensuring adequate and clean indoor air quality is paramount for occupant health and comfort despite symptoms not manifested, as reactions differ when exposed to the indoor pollutants (EPA, 2022).

In domestic buildings the indoor sources of pollution are mostly due to exposure exposed to surface dampness or condensation due to low ventilations (Jesica Fernández-Agüera, 2019). Other sources also vary, either from the occupant's behaviour and activities and the building materials and furnishing such as product for household cleaning, carpet, furniture etc. The effect of these pollutants to occupants/human health is on the rise, most especially in passive building, as different threshold has been set for each pollutant, according to the world Health Organization (WHO, 2021).

The basic understanding of air exchange and building airtightness is a vital decision to be incorporated during the design and operation of a building. Hence, adequate performance of the ventilation system in a building will significantly impact the internal thermal comfort and the indoor air quality of that buildings (Kisilewicz et al., 2019).

To achieve a full energy saving potential, airtightness is a crucial factor affecting energy consumption in buildings. While, on the other hand, the rate of ventilation either natural or mechanical has a major effect on the quality of air in the indoor environment it is also an important criterion for an effective building performance (Eskola et al., 2015).

These are major concerns in a cold climate where daily management of energy consumption, to save energy cost, is a prime preoccupation of many householders particularly in buildings with airtight envelopes (Salehi et al., 2017). The thermal performance of residential buildings can as well be affected, due to their construction characteristics (Litvak et al., 2000).

2. Environmental Impact of Pollution on Occupants' Health and Comfort

To ascertain that occupant health and comfort are met and given priority in current buildings, fossil fuels such as heating oil, natural gas, electricity, and liquefied petroleum gas used for cooking and space heating meet the strictest environmental safety measures. The carbon monoxide gas must be effectively controlled due to its poisonous nature and adequate ventilation is provided for the appliances and care must be taken to avoid exposing Nitrogen oxide gas emitted from gas stoves. Current appliance installations safety standards cater for these requirements when adhered to. However, the burning of solid fuels such as fire wood as source of heating, which are uncontrollable cannot be compared with the gaseous fuel heating such as boiler, which are significantly controlled to emit significantly lesser amounts of pollution, comprising particulate matter (PM2.5), volatile organic compounds (VOC) such as aldehydes and carcinogenic compounds like benzene, and 1, 3 – butadiene and polycyclic aromatic hydrocarbon, which affect eye irritation (Zhang et al, 2016) .

2.1 OCCUPANTS BEHAVIOUR

Occupant behaviour means the contact and interaction with building systems to monitor their health environment and achieve environmental, visual, and acoustic comfort in buildings. The ability of humans to monitor environmental factors is not only restricted to the natural world, but also to their living areas. The improvement of air quality (in terms of fresh air, air pollution and odour elimination), acoustic conditions (with no undesirable noise and vibration), visual or lighting quality (in terms of the regulation of luminance ratios, reflection, and glaring) through their involvement and activities in the house, occupants may thus affect the indoor climate and overall well-being.

In the late 19th century, the term “thermal convenience” was introduced. The American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) defined the principal concept of thermal comfort as “that mindset that expresses thermal environment satisfaction and is subjectively evaluated." Two quantitative formulas developed by Fanger were used in their calculation, though subjective, thermal comfort: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD). PMV models include temperature, humidity, air velocity, metabolic heat rates and thermal garments worn, all of which are important for predicting the thermal comfort level. After its foundation, several researchers have investigated and updated heat comfortable applications in different building types worldwide and PMV and PPD models (Fanger, 1970).

In addition to passive metabolic heat generated by occupants in the occupancy section of energy simulation software, total energy consumption in buildings is also affected by active utilization. Occupants interact with the control systems and building components so that they achieve their ideal personal level of comfortable facilities in various ways: use of opening and closing window systems for the house, use of lighting and controls for solar shading (e.g., changing blinds) and use of HVAC systems. As illustrated in figure 1, thermal comfort in a dwelling is a function of occupants’ status, their occupancy behaviour and energy cause. The latter criteria are significant to the aim of this paper i.e., how to balance energy consumption and ventilation to be able to achieve good indoor air quality.

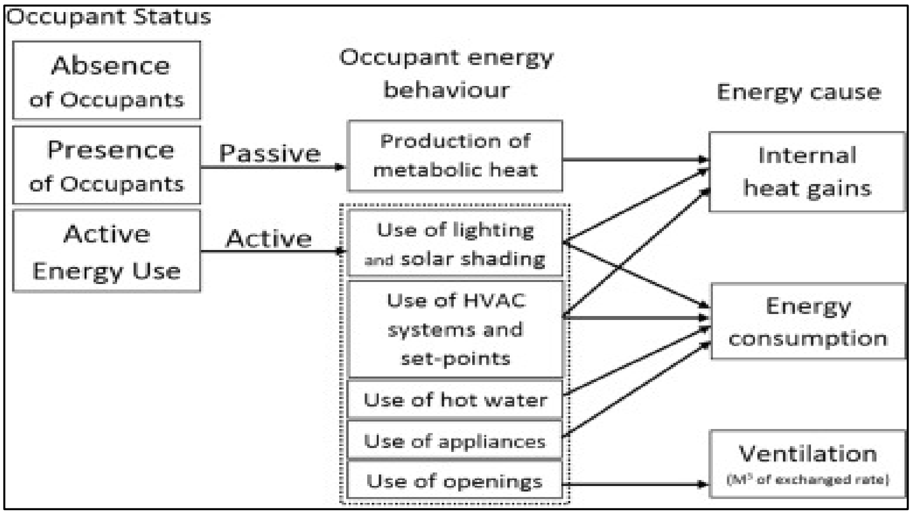

Figure 1. Occupants Status and Energy behaviour (Delzendeh et al., 2017)

2.1.1. Rationale

Airtightness of the building envelope constitutes one of the major factors of achieving energy efficiency in buildings. Furthermore, energy efficiency, reducing carbon emission and greenhouse gas emissions is one of the aims of the sustainable development goals (SDG) (M. Kraus, 2016). Air quality and its impact on occupants' thermal comfort and well-being tended to be often forgotten in the building energy debate. Well insulated, airtight, and naturally ventilated domestic buildings are energy efficient and have low carbon footprint, but they are often vulnerable to an increased risk of dampness and condensation, which may result in poor indoor air quality.

Another aim of this paper is to evaluate occupants' lifestyle response to energy performance, air infiltration rates, the possible risk of CO_2 concentration, and the formation of condensation in residential buildings (A. Hashemi, N. Khatami, 2015).

The paper is part of a PhD research programme the overall aim of which is to investigate how to effectively balance the impact of energy saving, reducing energy cost and carbon emissions and at the same time devise strategies for adequate indoor environment and air quality for occupant's comfort and wellbeing (Howieson et al., 2014).

3. Methodology

A mixed method approach was utilised to assess occupants' perception and satisfaction. These are the qualitative, quantitative, and computational fluid dynamic approaches to explore the occupants' satisfaction and perception of energy usage and the impact of airtightness upon the indoor environment.

To measure human behaviour, that is the measurement of occupants' wellbeing and thermal comfort, an online qualitative questionnaire was administered using google forms. The questionnaire was structured in five different sections including:

1. Occupant demography,
2. Building indoor air quality and sources of indoor pollutants
3. Energy consumption impact on indoor air quality
4. Occupant satisfaction/perception of Indoor Air Quality (IAQ) and Indoor Environmental Quality (IEQ).
5. Occupant perception of / Satisfaction with indoor thermal comfort and ventilation.

The target population included occupants living in 3 dwelling categories: housing association properties, local authority properties, and private properties. There were forty-seven valid responses from the questionnaire.

To assess indoor thermal comfort as well as air quality indicators, a series of quantitative measurements were conducted within the sample dwellings. Measured indicators included carbon dioxide, relative humidity, air temperature, air velocity and other pollutants such as benzene, formaldehyde, PM2.5 and PM10.

An assessment of the dwellings' fabric performance was also conducted to establish levels of energy efficiency and carbon emission. Two sample standard residential buildings in different locations in Edinburgh were used. The houses were constructed in 1980s, and 2020s. The choice of these 2 houses is the first stage of a larger sample of contemporary units used for the PhD research programme. Various building fabric indicators were assessed to establish the energy efficiency and carbon emission rate using the Standard Assessment Procedure software (SAP12).

3.1 EQUIPMENT

The equipment used for indoor measurements are illustrated in figure 2. The Chauvin Arnoux Indoor Air Quality Monitor was used to measure indoor air quality and thermal comfort indicators. This piece of equipment is capable of measuring Temperature, Relative Humidity and Carbon Dioxide. While the Orium (Quaelis 40) indoor air quality monitor is capable of measuring Particulates (PM2.5, PM10, HCHO, Benzene and TVOCs). It measures particulate in real time and all parameter Monitors benefit from built-in data logging. The data was then analysed using Excel spreadsheet. Also, an ATP instrument was used to measure indoor air velocity.

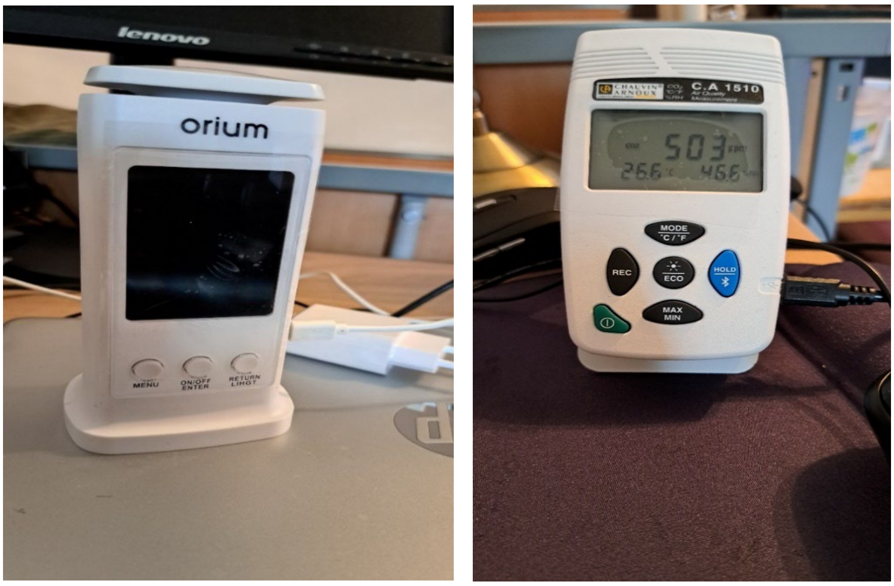

Figure 2. Quaelis 40 monitor & C.A 1510 Monitor

3.2. SAMPLE HOUSES USED IN THE RESEARCH

As explained in the methodology (paragraph 3 above), the 2 houses below form the first phase of a larger sample utilised to assess the fabric performance, carbon emission and indoor air quality. A measured survey was conducted by the author for each house to determine the data required for the energy assessment simulation. Data of the building elements are provided in Table 1.

Langloan House is an End Terrace house. It was built less than ten years ago. The envelope is brick walls with an average thermal transmittance of 0.21 W/m²K. The Roof Average thermal transmittance is 0.14 W/m²K, and the Floor Average thermal transmittance 0.17 W. The house is situated close to a 40 mile per hour main road and centrally heated. The fuels used are gas and electricity with solar hot water panels. It is 3-bedroom house with 3 adults and three children and one infant, total of seven occupants.

Kilkliston House was built over 30 years ago with brick walls and internally insulated to reduce heat losses. It was built to prevent draught and unwanted air leakages. The floor is suspended wooden floor, and the windows are double glazed. The fuels used are gas and electricity, with central heating. The occupants living in this three-bed house are a total of eight: three Adults, three children above 10 years and two infants. This semi-detached house external walls are made of brick finished in rough cast render.

Figure 3. Langloan House (left) and Kilkliston House (right) Edinburgh (Source: Authors)

TABLE 1. Building Elements Data Source:Authors Survey

	Langloan House (A)	**Kilkliston House (B)**
Element	**Description**	**Description**
Walls	Type of wall: cavity / timber frame average of thermal transmittance of 0.21 W/m^2K	Cavity walls, filled cavity
Roof	Pitched / flat Average thermal transmittance 0.14 W/m^2K	Pitched, 200 mm loft insulation
Floor	Average thermal transmittance 0.17 W/m^2K	Suspended, no insulation (assumed)
Windows	High performance double glazing	Fully double glazed
Main heating	Boiler and radiators, mains gas	Boiler and radiators, mains gas
Main heating control	Programmer, room thermostat and TRVs	Programmer, room thermostat and TRVs
Secondary heating	None	None
Hot water	From the main system	From main heating system
Air tightness	Air permeability of 6.0 m^3 /h. (Assumed)	Air tightness Air permeability 6.0 $m^3/h.m^2$ (assumed)

3.3 ENERGY PERFORMANCE ANALYSIS (SAP12)

The targets to tackle the impact of climate change in view of reducing carbon and greenhouse gas emission in buildings vary across the world. National targets in the European Union (EU) including UK align with the commitments under the Paris agreement toward achieving carbon neutrality by 2050 at the latest. While the Passivhaus (PH) was developed in Germany for homes with low rise domestic buildings, this standard has been applied to houses in a range of other countries including non-domestic buildings. In Scotland, Passivhaus targets are being assimilated in the national targets and expected to be integrated in the technical standards. The following baseline benchmarks are used in this paper for analysis purposes (Straube 2009).

- CO_2 emissions: 0 -15 Kg/m2/y
- EPC band: A or A+
- SAP value: 92 – 100
- Typical regulated energy consumption: 4622 kwh/y.

The Standard Assessment Procedure (SAP12) was used to calculate the energy performance of the sample dwellings as illustrated in table 2. House A annual energy consumption is 5775.66 kwh/year, with a total annual CO2 emission of 1596.5 (13.47 Kg/m2/y). While the total annual energy consumption in House B is 5388.65 kwh/year and annual total CO_2 emission is 3023.2 Kg/year (60.17 Kg/m2/y). The annual energy consumption of both houses is close but above the typical 100 m2 house consumption in UK of 4622 KWh per annum. This may be due to the number of occupants, occupants' ages, and pattern of use. House A CO_2 emissions is within the benchmark (0 – 15 kg/m2/y) whereas that of house B is 4 times above the benchmark maximum. The explanation resides in 2 main factors, house A is less than 10 years old with better standard of fabric as well as PV panels supply energy for hot water, hence total energy consumption higher but CO_2 is much lower than House B. This confirms that the environmental impact is dependent on renewable energy sources regardless of total energy consumption. With EPC ratings of B and E (potential D), both houses remain well below the A band target for potential upgrades to meet future carbon neutrality targets.

TABLE 1. Energy Performance from SAP12 for both houses

Performance values		
SAP Performance	House A, Langloan	House B, Kilkliston
Total delivered energy KWh/year	5775.66	5388.65
Total CO_2 Kg/year	1596.5	3023.2
SAP Value	85.45	54.42
SAP Band	B	E
CO_2 Emission Kg/m^2/year	13.47	60.17
(EI Value) Kg/m^2/year	87.41	58.89
EI Rating (Kg/m^2/year)	87	59
Potential Performance values		
EI Band	B	D
Target Emission Rate (TER)	15.24	63.81
Dwelling Emission Rate (DER)	15.36	65.04
Annual Space heating fuel KWh/year	3374.78	3552.74
Water heating fuel KWh/year	1898	1012.13

4 Data collection and analysis

4.1 DATA COLLECTION

The baseline of the measured data according to the World Health Organisation and US Environmental Protection Agency (EPA), are indoor CO2 should not exceed the limit of 1000 ppm, the temperature (dry bulb) range should be 23 - 26 C during summer and 20 - 23 during winter. The PM2.5 should be within the range 10 - 50µg/m3 for an average of 24 hours (WHO, 2021). Also, to reduce the possibility of transmission through air, the World Health Organisation recommends a natural ventilation rate of at least 60 Litre per second and per person and at least six air changes per hour (WHO, 2020a; WHO, 2020b). Relative humidity indoors should range between 30 – 70% for human thermal comfort.

TABLE 3. Langloan House and Kilkliston House,Average CO2, Temperature Relative Humidity and air velocity

Average, Minimum and Maximum values of the measured parameters					
House Measured	Descriptives	CO2 (PPM)	TEMP (ºC)	RH (%)	Air Velocity (m/s)
House A, Langloan	Mean	689	24	35	0.9
	Minimum	417	22	31	0.08
	Maximum	2290	25	41	0.34
House B, Kilkliston	Mean	618	23	38	0.06
	Minimum	452	20	30	0.02
	Maximum	971	25	50	0.1

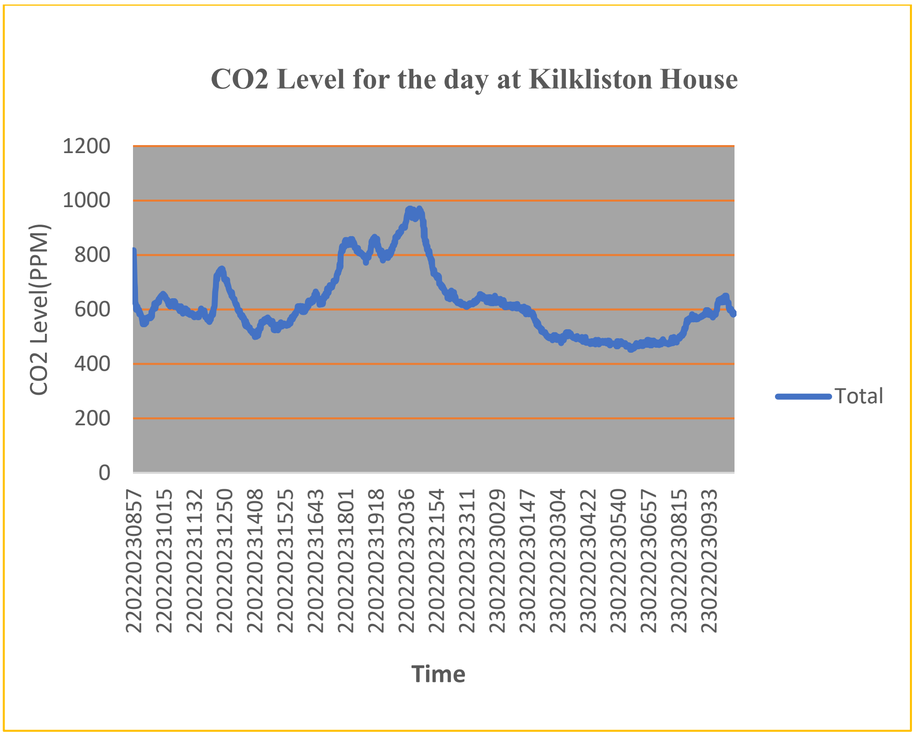

Figure 4. CO_2 level for the day at Kilkliston House

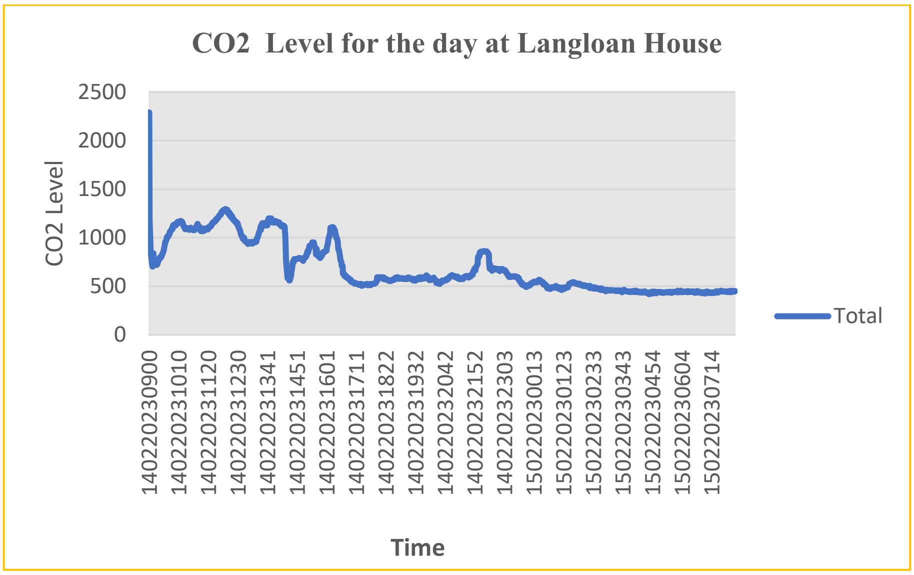

Figure 5. CO_2 level for the day at Langloan House

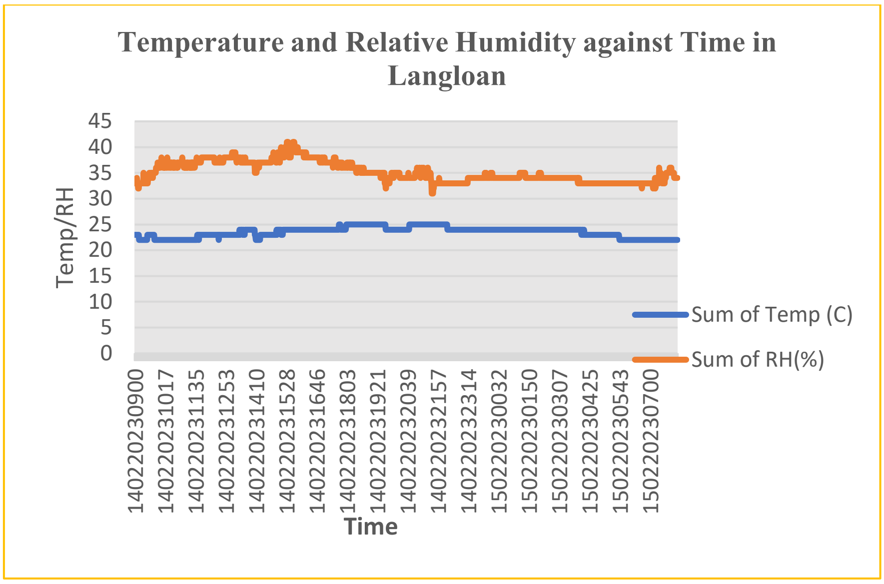

Figure 6. Temperature and Relative humidity against Time in Langloan house

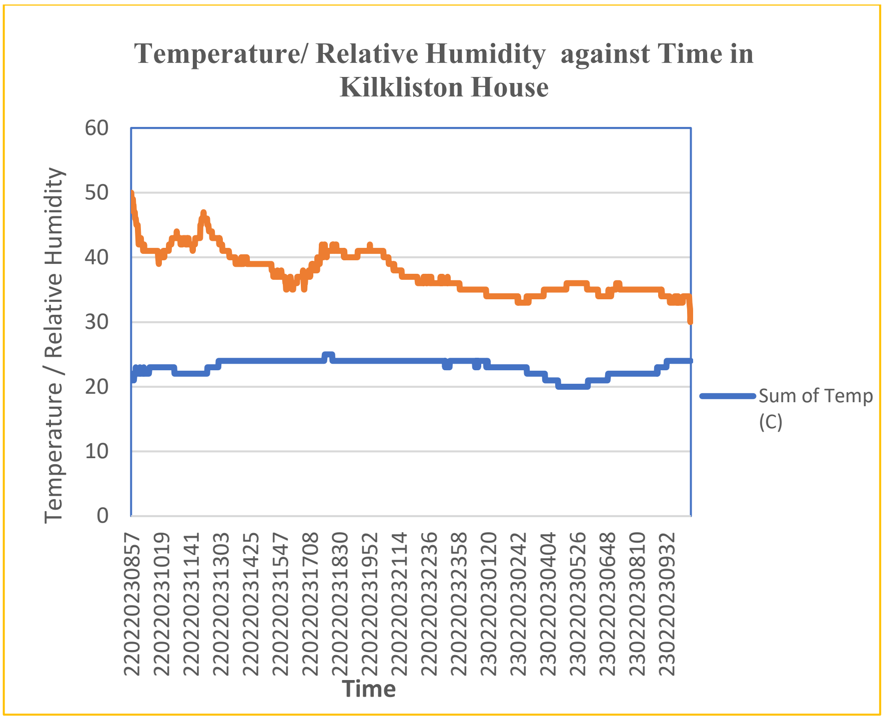

Figure 7. Temperature and Relative humidity against time at Kilkliston house

4.2 DATA ANALYSIS

With reference to figure 6 and 7, it is shown from table 3, that the minimum and maximum temperature in Langloan House is 22 and 25 degrees, while in the Kilkliston house the minimum and maximum temperature is 20 and 25 degrees, this range of temperature is within the acceptable WHO threshold. Also, the relative humidity in the Langloan house range from 31 to 41, while in the Kilkliston house the relative humidity ranges from 30 to 50%. Hence, the relative humidity is within the WHO acceptable threshold. However, the relative humidity of the Langloan house fall below 40 to 60% threshold of WHO acceptable guideline,

Table 3 illustrates the average data collected for the indoor air quality parameters for House A and House B. From the graph in House A, the CO_2 at a point rose twofold above the stipulated standard to over 2000 PPM (Figure 5), although this was not uniform for 24 hrs. The mean carbon dioxide levels recorded are less than 1000ppm. The mean recordings for both houses are within the recommended standard by the World Health Organisation (WHO Std). As such it is suitable for occupant's comfort and wellbeing. Relative humidity and temperature recorded for both houses are still within the recommended threshold. Mean air velocity, an indicator of natural ventilation, is 0.9 m/s for house A which is within an acceptable range for winter conditions under UK CIBSE standards. In house B, however, the mean air velocity of 0.06 m/s is well below the benchmark of 1 m/s. This may result in increased air pollution. Apart from the lower level of natural ventilation in house B, all other values of indoor air quality are within the standard benchmarks.

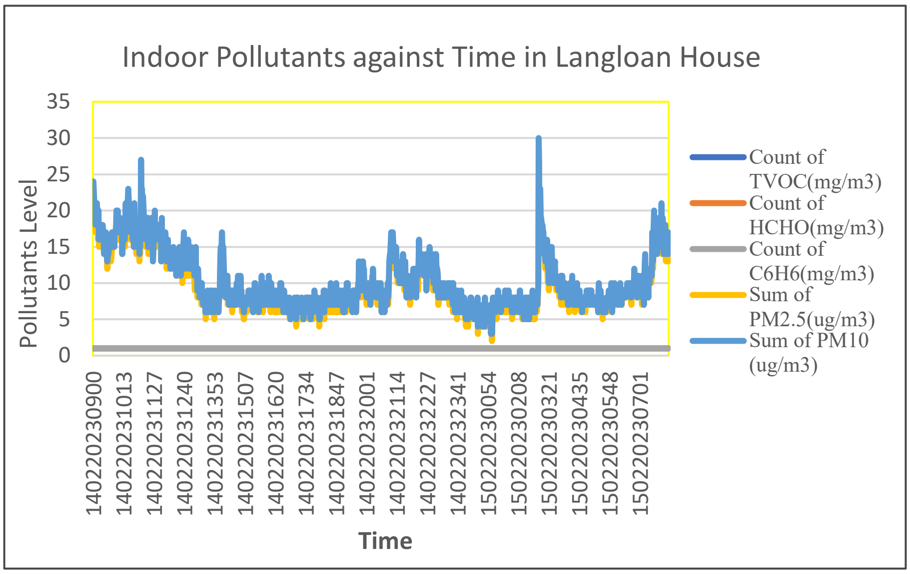

Figure 8. Indoor pollutants against the Time at Langloan House

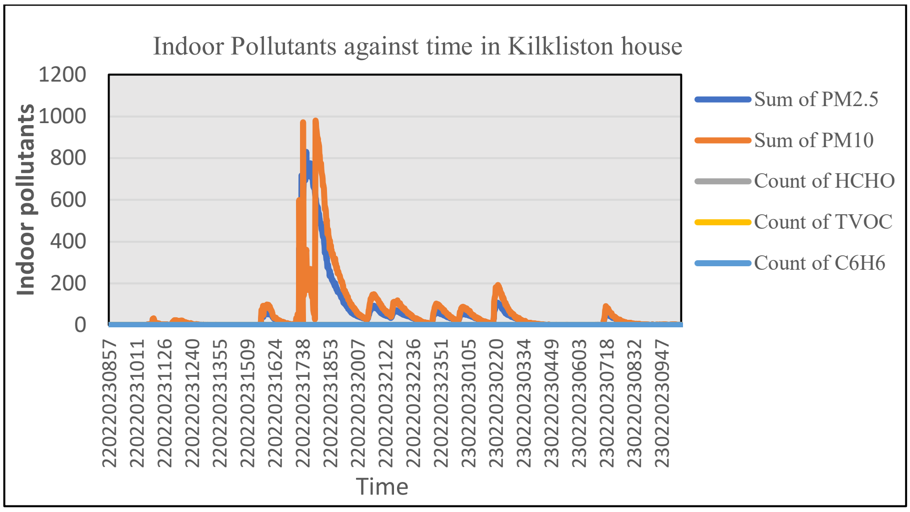

Figure 9. Indoor pollutants against Time at Kilkliston House

TABLE 4. Indoor Pollutants at Langloan and Kilkliston Houses
(*WHO 2006 and 2021 Guidelines)

	Formaldehyde HCHO (mg/m3)	TVOC (mg/m3)	Benzene C6H6 (mg/m3)	Particulate matter PM2.5 (ug/m3)		Particulate matter PM10 (ug/m3)	
Benchmark*	0.1mg/m3	Under 0.25 mg/m3.	N/A 2.6-5.8 mg/m3	Annual	5	Annual	15
				24 hrs	15	24 hrs	45
House A Langloan	Min-Max 0.01 – 5.67	Min-Max 0.31 – 2.67	Min-Max 0.07 – 0.56	Min-Max 2 - 27		Min-Max 3 - 30	
House B Kilkliston	Min-Max 0.00 – 0.10	Min-Max 0.31 -0.75	Min-Max 0.07 – 0.15	Min-Max 0 - 830		Min-Max 0 - 980	

4.3 ANALYSIS OF INDOOR POLLUTANT

Table 4 shows the level of indoor pollutants in both houses, also graphically depicted in figure 8 and figure 9. The range of formaldehyde pollutant level in Langloan house is from 0.01–5.67, well above the recommended benchmark, while the level in the Kilkliston house ranges from 0.00 to 0.10 and below the recommended value by WHO. The range of TVOC level in both houses is above the WHO recommendation. In contrast the measured levels of benzene pollutant in houses A and B are well below recommended benchmark.

Measured data shows that Pm2.5 pollutant in House A ranges from 2 to 27, slightly above the world health organisation guidelines (WHO, 2021) while in House B the level ranges from 0 to 830. This is extremely above the WHO guideline maximum level of 15 ug/m3, although this was for a very short period as illustrated in figure 9.

The level of PM10 pollutants in House A ranges from 3 to 30, this is within the acceptable guideline or benchmark of the WHO, however, the level of PM10 of House B ranges from 0 to 980, this is extremely far above the acceptable WHO benchmark or guidelines.

Comparing houses A and B the levels of PM2.5 and PM10 in House A are relatively low and within the WHO benchmarks as these could be attributed partly to the fact that the building is less than 10 years old and partly to occupants' pattern of use. While in House B, the levels of PM2.5 and PM10 are extremely higher than the WHO benchmark even though for a very short period over a 24-hour period (between 17.38 and 20.07). One explanation for the spike in PM10 and PM2.5 in house B may be partially explained by the timing which coincides with dinner time and associated cooking and other household activities.

5. Questionnaires results

For the purposes of this paper, data analysis will be focused on indoor air quality, sources of indoor pollutants and occupants' perception of /satisfaction with indoor thermal comfort and ventilation. However, the questions centred on the building IAQ and indoor pollutant sources. The responses to the questions related to the building indoor air quality and sources of indoor pollutants are illustrated in Table 4 below. A copy of the questionnaire is available in Appendix 1.

TABLE 4. Percentage of Building indoor air quality and sources of indoor pollutants

	Pollen Sources	Animal dander	Dust	Allergic to mould	Air freshener
Strongly Agree	36.96%	45.65%	60.87%	63.04%	52.17%
Somewhat agree	24.00%	24.00%	14.67%	14.67%	14.67%
Strongly Disagree	7.02%	1.75%	1.75%	3.51%	5.26%
Somewhat Disagree	3.75%	1.87%	3.75%	3.75%	7.49%
Neither agree nor disagree	9.69%	7.75%	7.75%	3.88%	7.75%

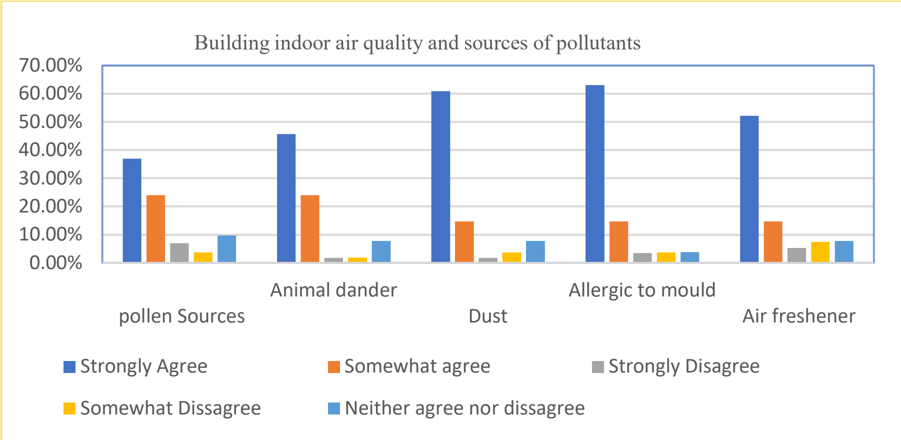

Figure 10. Building indoor air quality and sources of indoor pollutants

Occupants' perception/satisfaction with indoor thermal comfort and ventilation are shown in the Table 5 below. The responses were based on how satisfied or dissatisfied by the indoor thermal conditions, heating and cooling, air movement (high/low), indoor humidity (dry or wet) and overall airtightness perception.

TABLE 5. Percentage of Occupants perception of indoor air quality and Ventilation

	Uneven temper ature	Hot/cold surfaces	Heatin g/ cooling	Air movem ent too high	Air movemen t too low	Dry humidity	Wet humidi ty	Overall airtight ness
Dissatisfied	21.74%	23.91%	18.37 %	21.74%	34.78%	15.22%	32.61 %	13.04 %
Neither satisfied nor Dissatisfied	10.98%	8.64%	17.98 %	12.20%	21.05%	14.12%	16.88 %	3.49%
Satisfied	30.14%	29.73%	21.92 %	25.00%	21.67%	24.66%	23.44 %	30.12 %
Very Dissatisfied	5.88%	7.69%	1.75%	5.56%	0.00%	3.64%	6.12%	6.90%
Very Satisfied	4.17%	4.17%	12.50 %	9.80%	2.13%	13.21%	0.00%	14.81 %

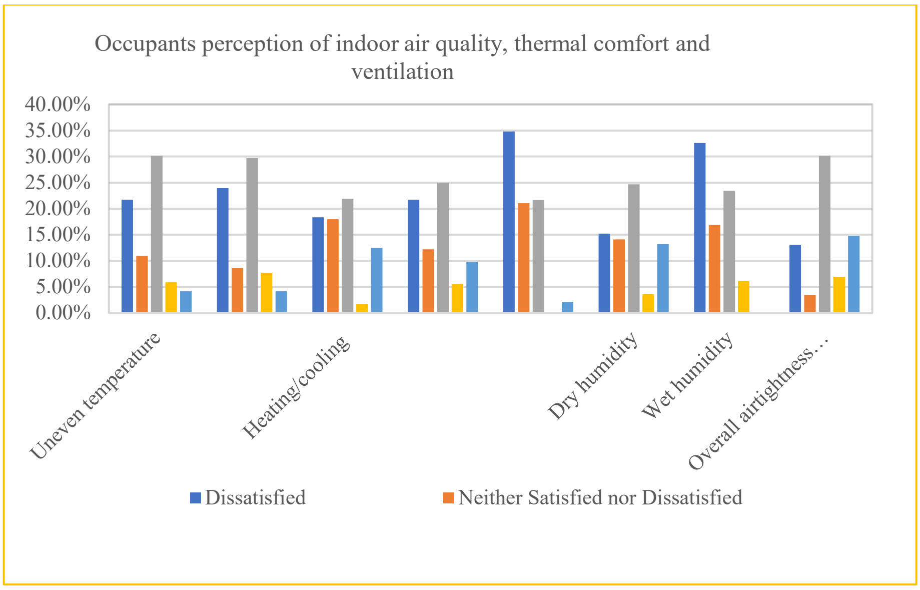

Figure 11. Occupants Perception of indoor air quality, thermal comfort, and ventilation

5.1 DISCUSSION OF QUESTIONNAIRE RESULTS

The analysis in this section discusses the questionnaire's response with respect to sources of indoor air pollution in domestic buildings as illustrated in Table 4 and Figure 11 above. Regarding the effect of pollen and plants and their impact on indoor air pollution, the responses indicate that about 36.96% strongly agree that they contribute to the indoor air pollution while about 3.75% somewhat disagree. Furthermore, 45.65% strongly agree on the effect of animal dander contributing to the indoor environment pollution. 60.87% responded strongly agree that formation of dust in the building contribute to the indoor pollution. On the other hand, 63.04%, strongly agree that condensation and dampness lead to allergies related to mould and about 52.17% strongly agree on the impact of air fresheners on indoor air pollution. Responses related to uneven temperature distribution in the different houses show (Figure 11), only 30.14 + 4.17% were satisfied or very satisfied which leaves about 65% either dissatisfied or unsure. In response to heating/cooling, a crude indication of thermal comfort, 21.92% responded satisfied. However nearly a third felt unsatisfied and another third unsure. This seems to indicate that at least two thirds of respondents are not fully happy with their thermal conditions. In response to air movement being too high 25% are satisfied. Also, when air movement is too low, responses show that 34.78% are dissatisfied and 21.67% response satisfied. These results are variable, and it is difficult to draw any clear results. As for dry humidity conditions 24.66% are satisfied, while on the wet humidity conditions 32.61% are dissatisfied. The response on the overall airtightness, shows that 30.12% are satisfied with the overall airtightness.

Meanwhile, from the measurements conducted from the two houses, the average parameters measured (Table 3 above) include CO_2, temperature, relative humidity, air velocity and indoor air pollutants such as TVOC, HCHO, C6H6, PM2.5 and PM10. The average CO_2 for House A, Langloan is 689ppm, while the maximum value is 2290ppm and the average CO_2 for House B, Kilkliston is 618ppm and the maximum value is 971ppm. The average temperature for house A is 24 °C, average relative humidity is 35% and average air velocity 0.9 m/s. Meanwhile the average temperature for House B is 23 °C, average relative humidity is 38 % and average air velocity 0.06 m/s.

6.0 Conclusions

In conclusion this paper has attempted to address the impact of airtightness and low ventilation on the indoor air quality in domestic buildings. Data presented in this paper and hence related findings only represent partially the outcomes of the full PhD research which is still ongoing.

The assessment of the fabric of the two dwellings seems to indicate that recently built housing stock overall fabric thermal performance is good (EPC band B) compared to houses build 30 years ago (EPC band E). Despite such an improvement, the fabric performance of recent and currently built housing in Scotland remains short of band A target. This will make any retrofitting upgrades more onerous and costly if climate change targets are to be met.

Indoor air pollution measurements indicate that most parameters are within the WHO standards as measured over a 24-hour period and provide healthy conditions. The sample is too small to draw any reliable general conclusions and future analysis of the full set of data is needed. In contrast, the initial and partial findings from the questionnaire seem to paint a mixed picture. No conclusive opinions were made by respondents with regards to Min-Max values of the areas covered. The highest positive or negative response percentage was around 60% which leaves at least 40% with an opposite or unsure opinion.

The two main factors investigated in this paper, namely airtightness and ventilation, remain inconclusive from the questionnaire responses. However, when contrasted with the fabric and key indoor parameters data, both factors seem adequate for the limited sample size.

Further investigation will be carried out with a larger sample size to assess in further detail the impact of ventilation and air tightness in indoor environment given the fact that new build as well as retrofit are expected to be more airtight and even better insulated to try to meet carbon neutrality targets.

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Appendix 1: Questionnaire on Occupant Satisfaction with / perception of indoor air quality of Domestic Buildings.

The Scott Sutherland School of Architecture and Built Environment
Robert Gordon University
The Sir Ian Wood Building, Riverside East
Garthdee Road, ABERDEEN AB10 7GJ UK

Dear Sir/Madam
Please kindly give your candid answer to the questions below. The questionnaire is designed to collect information from occupants living in domestic buildings with regards to the air quality to the indoor environment and examine the impact of ventilation to the indoor environment.
The aim of this study is to examine the impact of ventilation system to occupants and its influence on the Indoor Environmental Quality (IEQ), to generate a substantial data set that will aid in the improvement of future interventions.
This is part of my PhD research programme at Robert Gordon University titled, **Evaluation of the impact of ventilation in domestic building for Occupant Comfort.**
I assure you that information provided will be treated in strict confidence, with total anonymity and in full accordance with university ethical procedures available at
(https://campusmoodle.rgu.ac.uk/pluginfile.procedures
Thanks for your cooperation.
Yours Sincerely
Chukwuweike Abel Okom, PhD Student
c.okom@rgu.ac.uk

Demography of occupants in domestic building
Q1. What is your age?
18 – 40
41 – 60
61 – 70
70 and above
Other…
Title
Description (optional)

Q2. What is your sex?
Male
Female
Other
Q3. When was your house built?
Less than 10 years

11 to 20years
21 -30years,
more than 30years ago
Other…
Q4. Please tick as applicable to your house from the following question.
Has your house been refurbished /upgraded in the last 10 years:
♣ New windows double glazing
♣ New windows triple glazing
♣ New external doors
♣ Loft insulation added
♣ Cavity insulation
♣ New boiler /new heating system
♣ Any mechanical ventilation such as air extraction
Other…

After section 1 Continue to next sections: Section 2 of 3

Indoor Air Quality
Please give your opinion on your level of agreement from the following questions
Q5. The pollen and plants as a source of indoor air pollutant may be allergic to occupant**.**
Strongly Agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly Disagree
Other…

Q6. The animal dander's are source of indoor air pollutant may be allergic to occupants in domestic building**.**
Strongly Agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly Disagree
Other…
Q7. Dust formation sources of indoor air pollutant in the home may be harmful to the occupants.
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree,
Strongly disagree
Other…

Q8. The occupants of domestic building may be allergic to mould formation due to condensation.
Strongly agree
somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree
Other…
Q9. The use of air freshener, insecticide and other related spray chemical are sources of indoor air pollutant in domestic building and may be allergic to occupants.
Strongly agree
somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree
Other…
After section 2
Continue to next section
Section 3 of 3

Consumption of energy

Description (optional)
Q10. Does your income impact on energy usage?
Yes No Other…
Q11. Does the use of tumble dryer and washing machine affect the indoor air quality of your home?*
Yes No Other…
Q12.Does inadequate heating negatively impact occupant comfort and satisfaction?
Yes No Other…
Q13.Poor air circulation and low heating can result in mould formation, which pose a risk to occupant's health.
Yes No Other…
Q14.During summer do you heat your home regularly?
Yes No Other…
Q15. Does your home get damp and cold during winter without adequate heating?
Yes No Other…

Occupant Satisfaction/perception of Indoor Air Quality (IAQ and IEQ

Please check the category below that best describes the frequency of odours in your domestic building.

Q16. Tobacco smoke
Never
Monthly
Weekly
Daily
Always
Other…

Q17. musty, mouldy, damp basement smell
Never
Monthly
Weekly
Daily
Always
Other…

Q18. food smells
Never
Monthly
Weekly
Daily
Always
Other…

Q19. paint and/or construction odours
Never
Monthly
Weekly
Daily
Always
Other…

Q20.fuel or other exhaust odours
Never
Monthly
Weekly
Daily
Always
Other…

Q21. Chemical odours
Never
Monthly
Weekly
Daily
Always
Other…

Q22. How often you experience the sick building syndrome? This mean when you are in the building you feel unwell and when you are out of the building you feel well.
Never
Monthly
Weekly
Daily
Always
Other…
Occupant Satisfaction/perception of Indoor Air Quality (IAQ and IEQ
Please ignore this section if your home has not been retrofitted or refurbished.

In retrofitted domestic building how often, did occupants observe any of the following odours in the building?

Q23. Tobacco smoke
Never
Monthly
Weekly
Daily
Always
Other…

Q24. musty, mouldy, damp basement smell
Never
Monthly
Weekly
Daily
Always
Other…

Q25. food smells
Never
Monthly

Weekly
Daily
Always
Other…

Q26. paint and/or construction odours
Never
Monthly
Weekly
Daily
Always
Other…

Q27.fuel or other exhaust odours
Never
Monthly
Weekly
Daily
Always
Other…

Q28. Chemical odours
Never
Monthly
Weekly
Daily
Always
Other…

Q29. How often you experience the sick building syndrome? This mean when you are in the building you feel unwell and when you are out of the building you feel well.
Never
Monthly
Weekly
Daily
Always
Other…

Occupant perception on Indoor thermal comfort
Please check the category below that best describes how **satisfied or dissatisfied** in the indoor environmental of you domestic building. Please answer based on how **satisfied or dissatisfied** with the indoor environmental quality when ..

Q30. Uneven temperature (some parts always hot while others always cold
very satisfied
satisfied
Neither satisfied nor dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q31. Hot/cold surrounding surfaces (floor, ceiling, walls, or windows)
Very Satisfied
Satisfied
Neither Satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q32. Heating/cooling system does not respond quickly enough to the thermostat
Very Satisfied
Satisfied
Neither Satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q33. Air movement too high
Very Satisfied
Satisfied
Neither Satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q34. Air movement too low
Very Satisfied
Satisfied
Neither Satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q35. Dry humidity
Very Satisfied
Satisfied
Neither Satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q36. Wet humidity
Very Satisfied
Satisfied
Neither satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…

Q37. Overall airtightness including doors and windows
Very Satisfied
Satisfied
Neither Satisfied nor Dissatisfied
Dissatisfied
Very Dissatisfied
Other…