EBC

Energy in Buildings and Communities Programme

International Energy Agency, EBC Annex 68

Indoor Air Quality Design and Control in Low-Energy Residential Buildings

Subtask 5: Field measurements and case studies

Appendix to final report: Case studies

October 2020

Subtask 5 co-leaders:

Jelle Laverge (jelle.laverge@ugent.be), Ghent University, Belgium

Fitsum Tariku (fitsum_tariku@bcit.ca), British Columbia Institute of Technology, Canada

Editors:

Sarah L. Paralovo, Ghent University, Belgium

Contributing Authors:

Alula Assefa, BCIT Building Science Centre of Excellence, Canada
Esfand Burman, UCL Institute for Environmental Design and Engineering, UK
Klaas De Jonge, Ghent University, Belgium
Gaëlle Guyot, Cerema; University of Savoie Mont Blanc, France
Roman Jaques, BRANZ, New Zealand
Manfred Plagmann, BRANZ, New Zealand
Shahrzad Pedram, BCIT Building Science Centre of Excellence, Canada
Gabriel Rojas-Kopeinig, University of Innsbruck, Austria
Maarten Spruyt, VITO, Belgium
Marianne Stranger, VITO, Belgium

Summary

This document is an annex to the final report of EBC Annex 68 Subtask 5. As part of Subtask 5's activities, the energy use and indoor air quality data monitored in recently built high-performance buildings were presented at each annex meeting and, as a common exercise, collected using a common template. Data from 7 (groups of) buildings in 5 countries, namely Austria, Canada, France, New Zealand and United Kingdom, comprise the outcome of the second common exercise of Subtask 5.

In this annex are gathered all 7 data collection sheets, one for each specific experiment. The common template for data collection includes snapshots of the indoor air quality and energy uses of the buildings, as well as the measurement locations, sensors types and monitoring periods for each building. In addition to the common indoor air measurements, temperature, relative humidity and CO_2, formaldehyde, TVOC and particular matter (PM) are measured and reported in the houses, and other gaseous indoor pollutants in the high-rise buildings. Occupants perception is also provided.

Table of content

Subtask 5: Case Studies - 1. CaseStudy_AT_UIBK1
Annex 68 Design and Operational Strategies for High IAQ in Low Energy Buildings

Project Title:	**Lodenareal**		

Contributor	**Name**	Gabriel Rojas	
	Country	Austria	
	Institution	University of Innsbruck	

General	**Building Location**	Innsbruck, Austria	
	Building Type	Multi-Unit Low-rise	Ground + 5 topfloors
	Year of Construction	2009	
	Major Renovation Year (if applicable, for older buildings)		
	Building Floor Area (m²)	26000	354 apartments (apt)
	Reference (URL or Citation: Report, Journal, Conference)	https://doi.org/10.1080/17512549.2015.1040072 https://passivehouse-database.org/index.php?lang=en#d_1225	

The image (from July 2020) shows the use of retrofitted external shading device more than 10 years after construction.

Building Description	**Building envelope**	**Construction type**	**mass wall construction**			
		Window to Wall ratio (%)				
		Above Grade Wall R-value (K.m²/W)	7,7	(U-value: 0,13 W/K.m²)		
		Below Grade Wall R-value (K.m²/W)				
		Roof R-value (K.m²/W)	9,1	(U-value: 0,11 W/K.m²)		
		Slab on grade R-value (K.m²/W)	7,7	(U-value: 0,13 W/K.m²)		
		Window U-value (W/K.m²)	0,72			
		Airtightness (ACH at 50 Pa)	0,18			
	Interior finishing		**Type**			
		Interior paint				
		Flooring	Wood laminat			
		Window cover (fabric, plastic, wood etc.)	plastic			
	Mechanical systems		**Terminal unit**	**Equipment/Source**		
		Heating	underfloor heating	Wood pellets, gas boiler and solar thermal		
		Cooling	no			
		Heat/Energy recovery	Heat Recovery			
		Humidity control	No			
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**	
		Heating season	Mechanical Ventilation	Continious	0.35-0.4 ACH	3-level switch for occupants
		Cooling season	Hybrid	Continious	>0.4 ACH	It is assumed that occup. also use their windows for additional airing and night ventilation
		Shoulder seasons	Mechanical Ventilation	Continious	0.35-0.4 ACH	

Building Performance Monitoring & Measurement Techniques

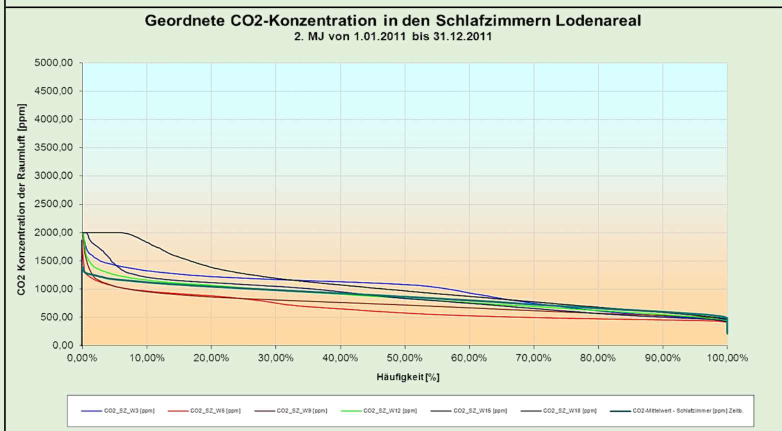
Occupancy	**Typical Occupant Density (person/m2)**	0,05
	Typical Occupant Type (mainly office workers, elders living, family with children)	Social housing

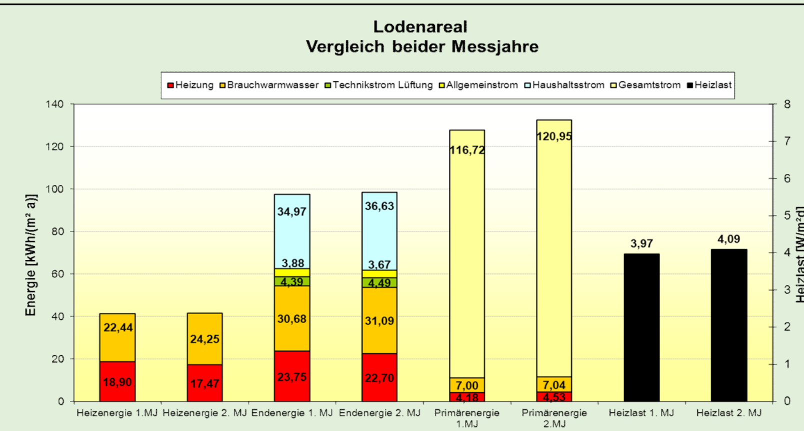
IAQ		Sensors used	Sampling locations	Measurement period	Data type	Minimum valu	25 Percentile	Average	Median	75 Percentile	Maximum	
	Temperature (°C)	E+E Elektronik	18 apt. In living room (6 thereof also in bedroom)	2010, 2011, 2012	Time series	16	23,5	23.5 (in winter only)	24	24,5	27	All year (2011); avg 18 living room; values estimated from graphic.
	Relative Humidity (%)	E+E Elektronik	18 apt. In living room (6 thereof also in bedroom)	2010, 2011, 2012	Time series	20%	30%		35%	45%	60%	All year (2011); avg 18 living room; values estimated from graphic.
	CO_2 (PPM)	E+E Elektronik	18 apt. In living room (6 thereof also in bedroom)	2010, 2011, 2012	Time series	300	700		800	1000	2000	All year (2011); avg 6 bedrooms; values estimated from graphic.
	Formaldehyde (PPM)											
	TVOC (PPM)		6 apt.	Before handover	Snap shot	<20µg/m³					155 µg/m³	
	Particulate matter (µg/m³)				--							
	Other	Ambient T, RH										

Energy	**Temperature control--Thermostat**	Constant	
	Heating set point (°C)	Occupant	
	Cooling set point (°C)	n/a	
	Energy measurement (KWh)	Hourly or less	
	Total Building Energy use--on site (KWh/m²/a)	98	
	Total Thermal Energy use--on site (KWh/m²/a)	41,7	
Occupants' perception of the their unit IAQ		Good	Question refered to ventilation system; see paper or report.
Occupants' view of their unit thermal comfort		Comfortable	Question refered to heating system; see paper or report.

Photos of typical instrumentations for IAQ measurements

Photos of typical instrumentations for Energy measurements





Lesson learned	Problems identified	Adapted solution
	Elevated summer temperatures in some top floor apartments due to not installed external shading (but planned).	External shading devices installed on demand.
	Even with relative low nominal ventilation rates, 30% of occupants perceived indoor air as too dry.	Extended cascade ventilation (no supply air in living room) was tested in some apartments with postive results; the housing company applies extended cascade ventilation in new building projects.
	The use of passive volumenflow control valves (two in a row) to provide 3 level control did not prove to be a very reliable solution.	No adaption was made, the main result is that the "boost/party ventilation mode" is rather ineffective (no substantial change in airflow).

Subtask 5: Case Studies - 2. CaseStudy_CA_Residential)
Annex 68 Design and Operational Strategies for High IAQ in Low Energy Buildings

Project Title:	**Lodenareal**

Contributor	**Name**	Fitsum Tariku
	Country	Canada
	Institution	British Columbia Institute of Technology (BCIT)

General	**Building Location**	Pemberton, British Columbia, Canada	
	Building Type	Multi-Unit Low-rise	Three storey
	Year of Construction	2017	
	Major Renovation Year (if applicable, for older buildings)	New	
	Building Floor Area (m²)	3600	45 Units Appartment
	Reference: URL or Citation: Report, Journal, Conference	https://doi.org/10.1080/17512549.2015.1040072 https://passivehouse-database.org/index.php?lang=en#d_1225	

Building Description	**Building envelope**	**Construction type**	**wood-frame construction**			
		Window to Wall ratio (%)	35			
		Above Grade Wall R-value (K.m²/W)	6,2			
		Below Grade Wall R-value (K.m²/W)	4,2	ICF Wall		
		Roof R-value (K.m²/W)	12,3			
		Slab on grade R-value (K.m²/W)		Underground garage		
		Window U-value (W/K.m²)	0,8			
		Airtightness (ACH at 50 Pa)				
	Interior finishing		**Type**			
		Interior paint	Latex paint			
		Flooring	Vinyl			
		Window cover (fabric, plastic, wood etc.)	plastic			
	Mechanical systems		**Terminal unit**	**Equipment/Source**		
		Heating		Air to Air Heat Pump	Electric baseboard as supplement heating unit	
		Cooling		Air to Air Heat Pump		
		Heat/Energy recovery	Energy Recovery			
		Humidity control	No			
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**	
		Heating season	Mechanical Ventilation	Continious	33 L/s	As per ASHRAE 55
		Cooling season	Mechanical Ventilation	Continious	33 L/S	As per ASHRAE 55
		Shoulder seasons	Mechanical Ventilation	Continious	33 L/s	As per ASHRAE 55

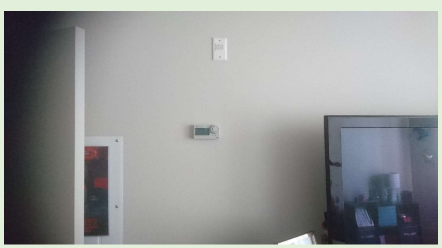
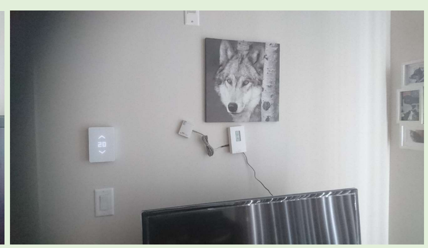
Building Performance Monitoring & Measurement Techniques

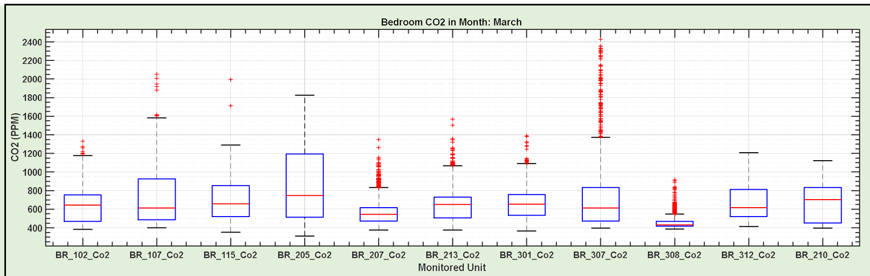
Occupancy	Typical Occupant Density (person/m²)	0,03
	Typical Occupant Type (mainly office workers, elders living, family with children)	Family

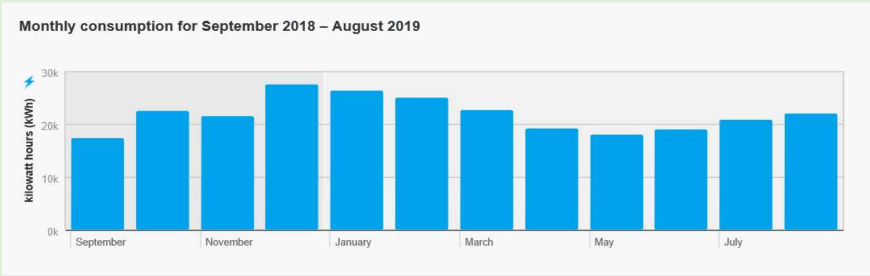
		Sensors used	Sampling locations	Measurement period	Data type	Minimum value	25 Percentile	Average	Median	75 Percentile	Maximum
IAQ	Temperature (°C)	HOBO Carbon Dioxide - Temp - RH Data Logger - MX1102A	11 Units: Living room/Bedroom	March 2019 to August 2019	Time series	17.9/14.3	22.0/21.8	22.9/22.9	22.9/22.9	23.7/23.8	28.8/32.6
	Relative Humidity (%)	HOBO Carbon Dioxide - Temp - RH Data Logger - MX1102A	11 Units: Living room/Bedroom	March 2019 to August 2020	Time series	22.6/19.6	36.6/36.2	42.8/41.9	42.0/41.2	48.8/47.4	67.43/69.8
	CO_2 (PPM)	HOBO Carbon Dioxide - Temp - RH Data Logger - MX1102A	11 Units: Living room/Bedroom	March 2019 to August 2021	Time series	-/300	439/463	542/654	550/592	671/762	1697/2549

Energy	Temperature control--Thermostat	Constant	
	Heating set point (°C)	occucpant	
	Cooling set point (°C)	occucpant	
	Energy measurement (KWh)	Hourly or less	
	Total Building Energy use--on site(KWh/m²/a)	73	Total Energy Measured including DHW and plug Loads
	Total Thermal Energy use--on site (KWh/m²/a)		
Occupants' perception of the their unit IAQ		Good	
Occupants' view of their unit thermal comfort		Comfortable	





	Problems identified	Adapted solution
Lesson learned	In general, the units have good thermal comfort except in the summer hot days when their units experience overheating.	Interior shading (Blinds) are installed to limit solar gain through the windows.
	Constant single speed fan is used for ventilation, heating and cooling, which is found to be not enough for cooling.	Based on the lesson learned with respect to overheating issue, the builder choose an HRV with double speed fan for his new building project, which has a similar design and size as Radius building.
	The existing duct size doesn't allow for increases in airflow.	In his next building project, the builder doubled the air duct.
	Occupants in the NW and SW corner units experience more overheating problem.	To address overheating problem, separate heat pump units are are installed in a couple of the units.

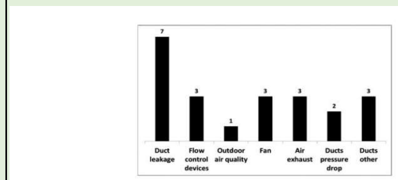
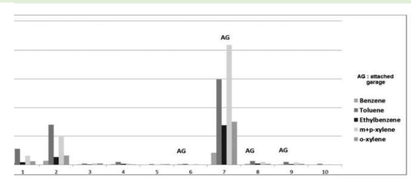
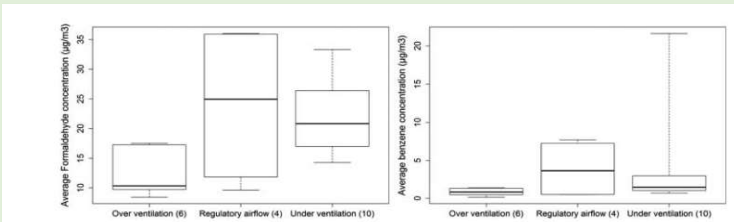
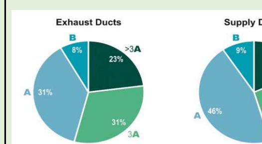
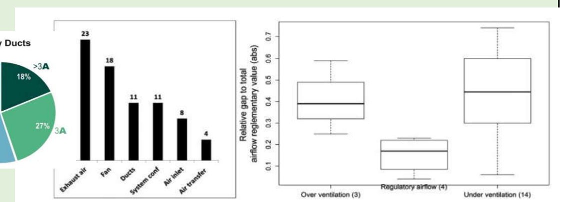
Project Title:	**Total Operational Performance of Low Carbon Buildings ('TOP'): case studies from two**

Contributor	**Name**	Guyot Gaëlle
	Country	France
	Institution	Cerema + University Savoie Mont Blanc

General	**Building Location**	21 in France center region	
	Building Type	Single	
	Year of Construction	2014-2015	
	Major Renovation Year (if applicable, for older buildings)	Not applicable	New-build
	Building Floor Area (m2)	67 to 176	
	Reference: URL or Citation: Report, Journal, Conference	Guyot, G., Melois, A., Bernard, A.-M., Coeudevez, C.-S., Déoux, S., Berlin, S., Parent, E., Huet, A., Berthault, S., Jobert, R., Labaume, D., 2017. Ventilation performance and indoor air pollutants diagnosis in 21 French low energy homes. International Journal of Ventilation 1–9. https://doi.org/10.1080/14733315.2017.1377393	

Building Description	**Building envelope**	**Construction type**	variable			
		Window to Wall ratio (%)	variable, total energy consumption under 50 kWhep/year/m²			
		Above Grade Wall R-value (K.m²/W)	variable, total energy consumption under 50 kWhep/year/m²			
		Below Grade Wall R-value (K.m²/W)	variable, total energy consumption under 50 kWhep/year/m²			
		Roof R-value (K.m²/W)	variable, total energy consumption under 50 kWhep/year/m²			
		Slab on grade R-value (K.m²/W)	variable, total energy consumption under 50 kWhep/year/m²			
		Window U-value (W/K.m²)	variable, total energy consumption under 50 kWhep/year/m²			
		Airtightness (ACH at 50 Pa)	less than 2,3 vol/h		qa4Pa<0,6 m³/h/m²	
	Interior finishing					
		Interior paint	variable			
		Flooring	variable			
		Window cover (fabric, plastic, wood etc.)	variable			
	Mechanical systems		**Terminal unit**	**Equipment/Source**		
		Heating			variable	
		Cooling	without			
		Heat/Energy recovery			only 7 with balanced ventilation	
		Humidity control	Yes		only 14 with DCV systems	
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**	
		Heating season				7 houses with heat recovery balanced ventilation + 14 houses with humidity DCV
		Cooling season	---			winter campaign
		Shoulder seasons				winter campaign

Building Performance Monitoring & Measurement Techniques	**Occupancy**	**Typical Occupant Density (person/m²)**											
		Typical Occupant Type (mainly office workers, elders living, family with children)			family with and without children								
	IAQ		**Sensors used**	**Sampling locations**	**Measurement period**	**Data type**	**Minimum value**	**25 Percentile**	**Average**	**Median**	**75 Percentile**	**Maximum**	
		Temperature (°C)	Thermometer	1 bedroom & Living Room	7 days heating season	Time series							15min intervals
		Relative Humidity (%)	Capacitive RH	1 bedroom & Living Room	7 days heating season	Time series							15min intervals
		CO_2 (PPM)	NDIR	1 bedroom & Living Room	7 days heating season	Time series							15min intervals
		Formaldehyde (ug/m³)	Radiello passive (diffusive) samplers by reaction with 2-4 DNPH and liquid chromatography and UV detection	1 bedroom & Living Room	7 days heating season	Snap shot				17,4			ug/m³
		Other aldehydes (acetaldehyde, hexaldehyde, benzaldehyde, butyraldehyde, valeraldehyde, propionaldehyde, acroleine)	Radiello passive (diffusive) samplers by reaction with 2-4 DNPH and liquid chromatography and UV detection	1 bedroom & Living Room	7 days heating season	Snap shot							PPB - 15min intervals
		Particulate matter (µg/m³) - PM2.5	Active air sampling on a fi lter with a pump	1 bedroom & Living Room	7 days heating season	Snap shot							15min intervals
		NO_2 (ppb)	Passam AG passive diffusive sampler and spectrophotometry	1 bedroom & Living Room + outdoor	7 days heating season	Snap shot							15min intervals
		Radon	Passive sampling with Alpha track detection	1 bedroom & Living Room	2 months heating season	Snap shot							
		Ozone (ug/m³)	Palmes diffusion tube	1 bedroom & Living Room	7 days heating season	Snap shot							
		Benzene (ug/m³)	Radiello passive (diffusive) samplers by thermal adsorption+ Gas chromatography and mass spectrometry	1 bedroom & Living Room	7 days heating season	Snap shot							
		Toluene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
		Trichloroethylene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
		Tetrachloroethylene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
		Styrene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
		Naphthalene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
		d-limonene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
		alpha-pinene (ug/m³)		1 bedroom & Living Room	7 days heating season	Snap shot							
	Energy	**Temperature control--Thermostat**	Programable										
		Heating set point (°C)	21										
		Cooling set point (°C)	Not applicable										
		Energy measurement (KWh)	Monthly										
		Total Building Energy use--on site(KWh/m²/a)	37.7 kWh/m²/annum electricity, 141.9 kWh/m²/annum fossil fuel (natural gas)										
		Total Thermal Energy use--on site (KWh/m²/a)	141,9	Note: community heating system is not as efficient as design assumptions. The heating demand of the dwelling during the measurement period was 70.9 kWh/m²/annum.									
	Occupants' perception of the their unit IAQ		Good										
	Occupants' view of their unit thermal comfort		Comfortable										

	  	 Figure 3. Main causes of non-compliance on airflows.  ɔncentrations in living rooms of the 10 houses, regarding the presence of an attached garage.
	 Figure 4. Average concentration distributions, according to the compliance category for: (a) formaldehyde and (b) benzene.	  Figure 1. Non-compliances on inspected ventilation systems. (a) Number by type and (b) measured total airflows: relative gap to regulatory values according to the compliance category.
Lesson learned	**Problems identified**	**Adapted solution**
	No house is found to comply fully with the ventilation regulation. 81% of the houses don't reach the minimum required total airflows (standard running mode), including 82% under-ventilation rates and 18% over-ventilation rates.	In the project, we developed tools leading to better practices at every stage of the construction. Many dysfunctions could be avoided through the implementation of quality management tools. With such tools, one could pretty easily, not costly, but efficiently, control ventilation system at each stage of the building construction: from design to installation, even including maintenance and final use.
	Around 50% of the ducts, including exhaust- and supply duct, have an airleakage class greater than or equal to 3 times the class A	
	Links between ventilation level and VOCs and aldehyde concentrations (Figure 4): The three over ventilated houses have lower concentrations while in the 2 regulatory houses and in the 5 under ventilated houses results are diverse. This observation is balanced by the fact that IAQ is connected to ventilation quality, but also to building materials, decorations and furnishings, to occupant behaviours, to outdoor environment	Impact of the sources are concerned in the tools we developed for our quality managment approach.
	In one case, the large outdoor pollution fills in the filters (no prefilter, F7 alone) and reduces the airflow to zero after 2 months.	
	Cases show that even if the global air flow is correct, bad doors undercut.s can explain high CO_2 concentrations especially in main bedroom.	
	The presence of an attached garage with access to the house can explain a part of high BTEX concentrations, but it is not a general explanation	
	A very critical case is underlined with high CO concentration in the presence of ventilation- and wood stove-dysfunctions	

Project Title:	**Indoor air quality of four higher performance homes - pilot study**

Contributor	**Name**	Roman Jaques, Manfred Plagmann
	Country	New Zealand
	Institution	BRANZ Ltd

General	**Building Location**	Christchurch, New Zealand	
	Building Type	Single	two storey
	Year of Construction	2016	
	Major Renovation Year (if applicable, for older buildings)		
	Building Floor Area (m²)	169	excl. Garage
	Reference: URL or Citation: Report, Journal, Conference	BRANZ Study Report 'Indoor air quality of four higher spec'd New Zealand homes – Pilot study' (2019)	
	Confidential - so no pictures available.		

Building Description	**Building envelope**	**Construction type**	**wood-frame construction**	actually SIPs	
		Window to Wall ratio (%)	32% (approx.)		
		Above Grade Wall R-value (K.m2/W)	4,3	estimated	
		Below Grade Wall R-value (K.m2/W)		no below grade	
		Roof R-value (K.m2/W)	5,7	estimated	
		Slab on grade R-value (K.m2/W)	1,8	estimated	
		Window U-value (W/K.m2)	2,1		
		Airtightness (ACH at 50 Pa)	3,3	measured	
	Interior finishing		**Type**		
		Interior paint	Acrylic		
		Flooring	comcrete	and timber upper level	
		Window cover (fabric, plastic, wood etc.)	fabric		
	Mechanical systems		**Terminal unit**	**Equipment/Source**	
		Heating		Underfloor hydronic	
		Cooling		None	
		Heat/Energy recovery	Heat Recovery	EcoMaster - Moisture Master (central)	
		Humidity control	No		
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**
		Heating season	Mechanical Ventilation	Continious	unspecified
		Cooling season	Mechanical Ventilation	Continious	unspecified
		Shoulder seasons	Mechanical Ventilation	Continious	unspecified

Building Performance Monitoring & Measurement Techniques

Occupancy	Typical Occupant Density (person/m2)	115
	Typical Occupant Type (mainly office workers, elders living, family with children)	2 adults only

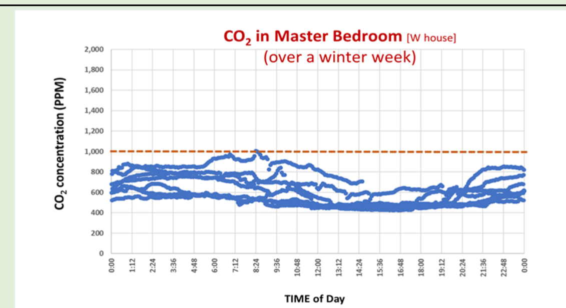
IAQ	Sensors used	Sampling locations	Measurement period	Data type	Minimum value	25 Percentile	Average	Median	75 Percentile	Maximum	
Temperature (°C)	Digital (Onset Hobo U10)	Lounge (open to kitchen)	1 week in Winter/Summer	Snap shot	18.2 / 20.0		20.5 / 23.0			23.5 / 30.0	
Relative Humidity (%)	Digital (U10)	Lounge	1 week in Winter/Summer	--							didn't record
CO2 (PPM)	Dual Beam Absorption Infrared	Master bedroom	1 week in Winter/Summer	Snap shot	530 / 403		817 / 468			1277 / 611	
Formaldehyde (PPM)	Photoelectric Absorptiometric (Passive diffusion)	Lounge	1 week in Winter/Summer	Snap shot							< 10 PPB = undetectable limit
TVOC (PPM)	NA	NA		--							didn't measure
Particulate matter (μg/m³)	Optical, non-Finite Element Method (in parallel)	Lounge	1 week in Winter/Summer	Snap shot	0.1 / 0		3.8 / 3.1			93.8 / 178	2.5 micros only
CO (PPM)	3 Electrode Electrochemical cell	Lounge	1 week in Winter/Summer	Snap shot	0 / 0		0.5 / 0			8 / 0	

Energy		
Temperature control--Thermostat	---	didn't record
Heating set point (°C)		Note that NZers don't have continuous heating, as in other countries, generally
Cooling set point (°C)		Note that NZers don't have continuous cooling, as in other countries, generally
Energy measurement (KWh)	--	not recorded during period
Total Building Energy use--on site (KWh/m²/a)		not used for monitoring period
Total Thermal Energy use--on site (KWh/m²/a)		not used for monitoring period

Occupants' perception of the their unit IAQ	Good
Occupants' view of their unit thermal comfort	Comfortable

MASTER BEDROOM

House Reference:	P		J		W		A	
Statistics	Sum	Win	Sum	Win	Sum	Win	Sum	Win
average CO2	741	881	572	1127	444	604	NA	NA
minimum	438	438	408	400	404	424	NA	NA
maximum	1232	1711	1164	4523	562	1,007	NA	NA
% of time above 1000ppm	8%	32%	0%	41%	0%	0%	NA	NA
% of time above 1500ppm	0%	0%	0%	28%	0%	0%	NA	NA
median CO2	758	835	534	741	438	573	NA	NA



	Problems identified	Adapted solution
Lesson learned	Whole house mechanical ventilation is very new to NZ, and nowhere is this more evident in the placement and treatment of ducting.	A national training for propoer ducting installation practices is needed for NZ.
	Useful placement of HRV controls is essential for user utility, which was not the case for this install.	This issue will fade as HRV systems all shift to smartphone controls and feedback.

Project Title:	**Indoor air quality of four higher performance homes - pilot study**					
Contributor	**Name**	Roman Jaques, Manfred Plagmann				
	Country	New Zealand				
	Institution	BRANZ Ltd				
General	**Building Location**	Christchurch, New Zealand				
	Building Type	Single	Single storey house			
	Year of Construction	2017				
	Major Renovation Year (if applicable, for older buildings)					
	Building Floor Area (m²)	140				
	Reference: URL or Citation: Report, Journal, Conference	BRANZ Study Report 'Indoor air quality of four higher spec'd New Zealand homes – Pilot study' (2019)				
	Confidential - so cannot include pictures/plans of houses					
Building Description	**Building envelope**	**Construction type**	**wood-frame construction**			
		Window to Wall ratio (%)	32% (approx.)			
		Above Grade Wall R-value (K.m²/W)	6,1	Estimated (140mm framing)		
		Below Grade Wall R-value (K.m²/W)		no below grade		
		Roof R-value (K.m²/W)	7,8	Estimated		
		Slab on grade R-value (K.m²/W)	4,5	Estimated		
		Window U-value (W/K.m²)	1,25			
		Airtightness (ACH at 50 Pa)	1,77	measured		
	Interior finishing		**Type**			
		Interior paint	Acrylic			
		Flooring	concrete - with hydronic heat			
		Window cover (fabric, plastic, wood etc.)	fabric			
	Mechanical systems		**Terminal unit**	**Equipment/Source**		
		Heating		Underfloor hydronic		
		Cooling			No cooling source	
		Heat/Energy recovery	Heat Recovery	Titan - whole house		
		Humidity control	No			
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**	
		Heating season	Mechanical Ventilation	Continious	unspecified	
		Cooling season	Mechanical Ventilation	Continious	unspecified	
		Shoulder seasons	Mechanical Ventilation	Continious	unspecified	

Building Performance Monitoring & Measurement Techniques			
Occupancy	Typical Occupant Density (person/m²)	47	
	Typical Occupant Type (mainly office workers, elders living, family with children)	3 adults only	

IAQ		Sensors used	Sampling locations	Measurement period	Data type	Minimum value	25 Percentile	Average	Median	75 Percentile	Maximum	
	Temperature (°C)	Digital (Onset Hobo U10)	Lounge (open to kitchen)	1 week in Winter/Summer	Snap shot	17.7 / 20.9		21.6 / 23.0			26.2 / 25.9	
	Relative Humidity (%)	Digital (U10)	Lounge	1 week in Winter/Summer	--							didn't record
	CO2 (PPM)	Dual Beam Absorption Infrared	Master bedroom	1 week in Winter/Summer	Snap shot	424 / 404		604 / 444			1007 / 562	
	Formaldehyde (PPM)	Photoelectric Absorptiometric (Passive diffusion)	Lounge	1 week in Winter/Summer	Snap shot	0 / 0		0 / 0			0 / 0	< 10 PPB = undetectable limit
	TVOC (PPM)	NA	NA		--							didn't measure
	Particulate matter (μg/m³)	Optical, non-Finite Element Method (in parallel)	Lounge	1 week in Winter/Summer	Snap shot	0 / 0		12.5 / 4.4			390 / 21	2.5 micros only
	Carbon Monoxide (PPM)	3 Electrode Electrochemical cell	Lounge	1 week in Winter/Summer	Snap shot	0 / 0		0 / 0			0 / 0	

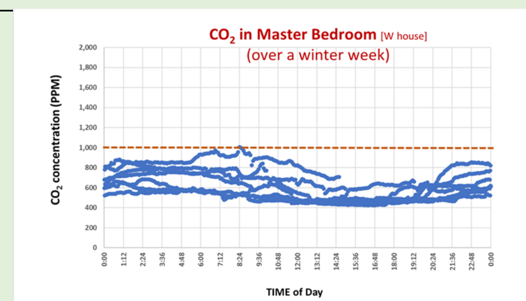
Energy			
	Temperature control--Thermostat	Programable	didn't record
	Heating set point (°C)	unknown	have continuous heating,
	Cooling set point (°C)	unknown	have continuous cooling,
	Energy measurement (KWh)	---	period
	Total Building Energy use--on site (KWh/m²/a)		not used for monitoring period
	Total Thermal Energy use--on site (KWh/m²/a)		not used for monitoring period
Occupants' perception of the their unit IAQ		Good	
Occupants' view of their unit thermal comfort		Comfortable	





MASTER BEDROOM

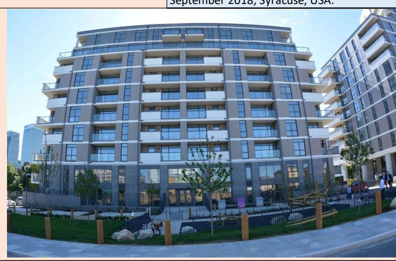
House Reference:	P		J		W		A	
Statistics	Sum	Win	Sum	Win	Sum	Win	Sum	Win
average CO2	741	881	572	1127	444	604	NA	NA
minimum	438	438	408	400	404	424	NA	NA
maximum	1232	1711	1164	4523	562	1,007	NA	NA
% of time above 1000ppm	8%	32%	0%	41%	0%	0%	NA	NA
% of time above 1500ppm	0%	0%	0%	28%	0%	0%	NA	NA
median CO2	758	835	534	741	438	573	NA	NA



Lesson learned	Problems identified	Adapted solution
	House is alongside an arterial road, so its particulate count is higher than expected.	Not an easy problem to solve.
	The more detailed the entry interviews can be, in terms of capturing user behaviour to interpret the results, the better.	User behaviour, especially around the control of the HRV and opening of windows, is especially important.

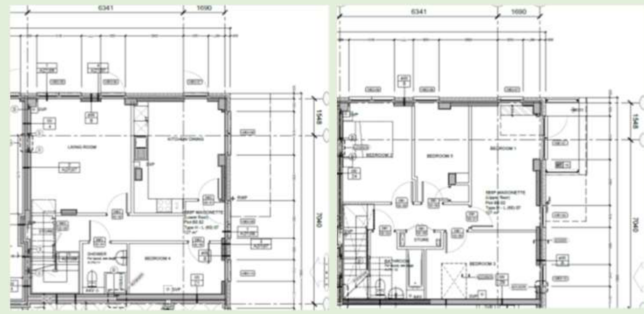
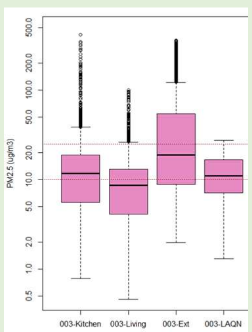
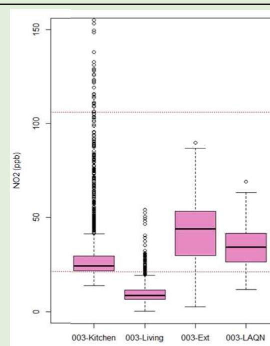
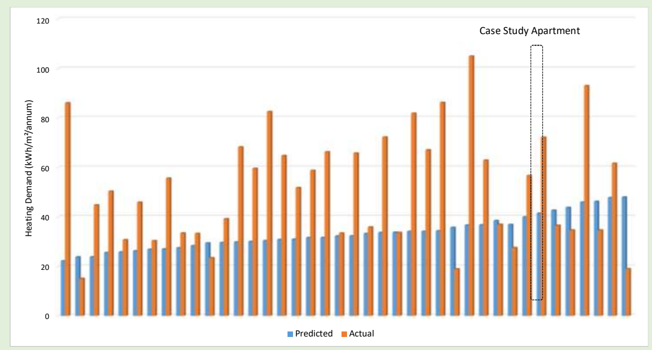
Project Title:	**Total Operational Performance of Low Carbon Buildings ('TOP'): case studies from two apartment blocks in East London, UK**

Contributor	**Name**	Esfand Burman, Samuel Stamp
	Country	United Kingdom
	Institution	UCL Institute for Environmental Design and Engineering

General	**Building Location**	East London (UK)	
	Building Type	Multi-Unit High-rise	The case study is an apartment on the ground floor of this block.
	Year of Construction	2014	
	Major Renovation Year (if applicable, for older buildings)	Not applicable	New-build
	Building Floor Area (m²)	127	
	Reference: URL or Citation: Report, Journal, Conference	Burman, E., Shrubsole, C., Stamp, S., Mumovic, D., Davies, M., 2018. Design and operational strategies for good Indoor Air Quality in low-energy dwellings: performance evaluation of two apartment blocks in East London, UK, the 7th International Building Physics Conference (IBPC 2018), 23-26 September 2018, Syracuse, USA.	
			

Building Description	**Building envelope**	**Construction type**	**mass wall construction**			
		Window to Wall ratio (%)	18%			8,333333333
		Above Grade Wall R-value (K.m²/W)		Ground U value: 0.12 W/m² °K		
		Below Grade Wall R-value (K.m²/W)				
		Roof R-value (K.m²/W)	Not applicable (ground floor and first floor aprtment)			
		Slab on grade R-value (K.m²/W)				
		Window U-value (W/K.m²)	0,85	Double-glazed windows + secondary glazing with a large air gap due to acoustic considerations		
		Airtightness (ACH at 50 Pa)		Pressure test result: 3.8 m³/hr./m² @50 Pa		
	Interior finishing		**Type**			
		Interior paint	Crown Vinyl Silk (White) in Kitchen, bathroom and other wet areas, Crown Matt (White) in other areas			
		Flooring	Carpet (except tiles used in kitchen)			
		Window cover (fabric, plastic, wood etc.)	PVC framed double-glazed window			
	Mechanical systems		**Terminal unit**	**Equipment/Source**		
		Heating	Wet radiators	Community heating system	Community heating system is based on natural gas-fired boilers with provision for integration of a CHP system in future.	
		Cooling	None			
		Heat/Energy recovery	None			
		Humidity control	No			
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**	
		Heating season	Hybrid	DCV (Humidity Controlled Ventilation)	Minimum 29 l/s mechanical ventilation, natural ventilation through windows	
		Cooling season	Hybrid	DCV (Humidity Controlled Ventilation)	Minimum 29 l/s mechanical ventilation, natural ventilation through windows	
		Shoulder seasons	Hybrid	DCV (Humidity Controlled Ventilation)	Minimum 29 l/s mechanical ventilation, natural ventilation through windows	

Building Performance Monitoring & Measurement Techniques	**Occupancy**	**Typical Occupant Density (person/m2)**			0,06								
		Typical Occupant Type (mainly office workers, elders living, family with children)			Family with children and grand parents								
	IAQ		**Sensors used**	**Sampling locations**	**Measurement period**	**Data type**	**Minimum value**	**25 Percentile**	**Average**	**Median**	**75 Percentile**	**Maximum**	
		Temperature (°C)	Thermistor	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	17,4	21,6	23,6	23,8	25,4	30,5	15min intervals
		Relative Humidity (%)	Capacitive RH	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	27,2	37,2	43,8	45	49,5	74,2	15min intervals
		CO_2 (PPM)	NDIR	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	450	540	907	747	1103	3491	15min intervals
		Formaldehyde (µg/m³)	UMEX100 BADGES BY HIGH PRESSURE LIQUID CHROMATOGRAPHY	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	11,8	13,1	19,7	17,5	25,9	31,4	ug/m3
		TVOC (PPB)	Alphasense PID	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	0	33	63,7	56,7	76,7	1036,7	PPB - 15min intervals
		Particulate matter (µg/m³) - PM2.5	Alphasense OPC-N2	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	0,26	1,8	6,23	3	6,9	228	15min intervals
		Particulate matter (µg/m³) - PM10	Alphasense OPC-N2	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	0	5	12	8,6	13,9	244,5	15min intervals
		NO_2 (ppb)	Alphasense A43EF (Electrochemical)	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Time series	0	5	10,2	7,2	10,7	254	15min intervals
		NO_2 (ppb)	Palmes diffusion tube	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	8,3	12,4	15,2	13,8	19,6	21,9	
		Ozone (µg/m³)	Palmes diffusion tube	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	3,6	3,6	6,4	4,7	7,8	13,3	
		Benzene (µg/m³)	ION CHROMATOGRAPHY	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,6	0,8	1,3	1,5	1,6	2,1	
		Toluene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,9	1,3	1,9	2,1	2,4	2,6	
		Trichloroethylene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	0,3	0,3	0,3	0,3	0,3	
		Tetrachloroethylene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,4	1,1	1,2	1,3	1,5	1,8	
		Styrene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	0,7	1,1	0,8	1,5	2,1	
		Naphthalene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	0,3	0,6	0,6	0,9	1,3	
		d-limonene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	5,6	7,2	43,2	39,2	76,8	89,6	
		alpha-pinene (µg/m³)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	4,1	4,2	9,2	7,3	10,6	21,5	
	Energy	**Temperature control--Thermostat**	Programable										
		Heating set point (°C)	21										
		Cooling set point (°C)	Not applicable										
		Energy measurement (KWh)	Monthly										
		Total Building Energy use--on site (KWh/m²/a)	37.7 kWh/m²/annum electricity, 141.9 kWh/m²/annum fossil fuel (natural gas)										
		Total Thermal Energy use--on site (KWh/m²/a)	141,9	Note: community heating system is not as efficient as design assumptions. The heating demand of the dwelling during the measurement period was 70.9 kWh/m²/annum.									
	Occupants' perception of the their unit IAQ		Good										
	Occupants' view of their unit thermal comfort		Comfortable										

	  	
	 	
Lesson learned	**Problems identified**	**Adapted solution**
	Energy efficiency issues at the Energy Centre (community heating scheme)	Under investigation as the second phase of the development is constructed
	Information about MVHR filter replacement not provided to building users	Information about type and function of filters, recommended replacement frequency, and method of replacement was provided to building users in a workshop following the research project.
	Basic G3 filter in the installed MVHR systems	Opportunities to improve filtration in commercially available MVHR systems (e.g. F type filters, activated carbon filters, etc.)
	Formaldehyde concentration levels much higher than the most stringent ELV (9 μg/m³)	Better source control + enhanced ventilation (for future projects)

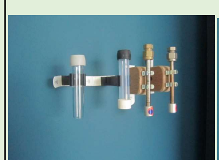
Project Title:	**Total Operational Performance of Low Carbon Buildings ('TOP'): case studies from two apartment blocks in East London, UK**

Contributor	**Name**	Esfand Burman, Samuel Stamp
	Country	United Kingdom
	Institution	UCL Institute for Environmental Design and Engineering

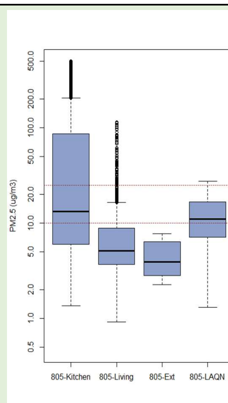
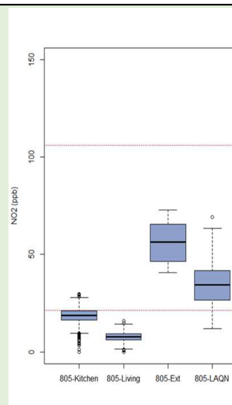
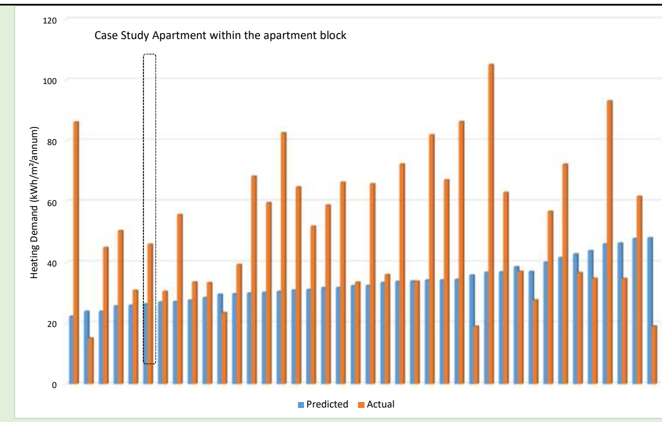
General	**Building Location**	East London (UK)	
	Building Type	Multi-Unit High-rise	The case study is an apartment on the 8th floor of this block.
	Year of Construction	2014	
	Major Renovation Year (if applicable, for older buildings)	Not applicable	New-build
	Building Floor Area (m²)	100	
	Reference: URL or Citation: Report, Journal, Conference	Burman, E., Shrubsole, C., Stamp, S., Mumovic, D., Davies, M., 2018. Design and operational strategies for good Indoor Air Quality in low-energy dwellings: performance evaluation of two apartment blocks in East London, UK, the 7th International Building Physics Conference (IBPC 2018), 23-26 September 2018, Syracuse, USA.	

Building Description	**Building envelope**	**Construction type**	**mass wall construction**			
		Window to Wall ratio (%)	30%			
		Above Grade Wall R-value (K.m2/W)		Wall U value: 0.18-0.19 W/m²°K		5,555555556
		Below Grade Wall R-value (K.m2/W)	Not applicable	Not applicable		
		Roof R-value (K.m2/W)	not applicable (8th floor flat)			
		Slab on grade R-value (K.m2/W)	not applicable (8th floor flat)			
		Window U-value (W/K.m2)	0,92	Double-glazed windows + secondary glazing with a large air gap due to acoustic considerations		
		Airtightness (ACH at 50 Pa)		Pressure test result: 2.2 m³/hr./m² @50 Pa		
	Interior finishing		**Type**			
		Interior paint	Crown Vinyl Silk (White) in Kitchen, bathroom and other wet areas, Crown Matt in other areas			
		Flooring	Carpet (except tiles used in kitchen)			
		Window cover (fabric, plastic, wood etc.)	PVC framed double-glazed window			
	Mechanical systems		**Terminal unit**	**Equipment/Source**		
		Heating	Wet radiators	Community heating system	Community heating system is based on natural gas-fired boilers with provision for integration of a CHP system in future.	
		Cooling	None			
		Heat/Energy recovery	None			
		Humidity control	No			
	Ventilation		**Ventilation type**	**Ventilation strategy**	**Design Ventilation rates**	
		Heating season	Hybrid	DCV (Humidity Controlled V	Minimum 21 l/s mechanical ventilation, natural ventilation through windows	
		Cooling season	Hybrid	DCV (Humidity Controlled V	Minimum 21 l/s mechanical ventilation, natural ventilation through windows	
		Shoulder seasons	Hybrid	DCV (Humidity Controlled V	Minimum 21 l/s mechanical ventilation, natural ventilation through windows	

			Sensors used	Sampling locations	Measurement period	Data type	Minimum valu	25 Percenti	Average	Median	75 Percenti	Maximum	
Building Performance Monitoring & Measurement Techniques	**Occupancy**	**Typical Occupant Density (person/m^2)**			0,05								
		Typical Occupant Type (mainly office workers, elders living, family with children)			Family with children								
	IAQ	**Temperature (°C)**	Thermistor	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	17,3	20,2	21,6	21,4	22,8	28,9	15min intervals
		Relative Humidity (%)	Capacitive RH	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	26	36	42	42	46	72	15min intervals
		CO_2 (PPM)	NDIR	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	447	502	708	641	918	1733	15min intervals
		Formaldehyde (ug/m^3)	UMEX100 BADGES BY HIGH PRESSURE LIQUID CHROMATOGRAPHY	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	1,2	1,2	7,5	3,2	11,2	18,8	ug/m3
		TVOC (PPB)	Alphasense PID	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	0	20	54	36,7	76,8	326,7	PPB - 15min intervals
		Particulate matter (µg/m^3) - PM2.5	Alphasense OPC-N2	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	0,7	2,4	19	3,5	6,8	311,5	15min intervals
		Particulate matter (µg/m^3) - PM10	Alphasense OPC-N2	Kitchen & Living Room	7 days heating season, 7 days non-heating season	Time series	0,8	6,4	25,2	9,9	18,3	298,0	15min intervals
		NO_2 (ppb)	Alphasense A43EF (Electrochemical)	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Time series	0,0	2,4	5,2	4,7	7,2	29,5	15min intervals
		NO_2 (ppb)	Palmes diffusion tube	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	13,1	16,9	20,3	20,7	25,8	26,0	
		Ozone (µg/m^3)	Palmes diffusion tube	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	3,8	3,8	10,7	7,0	21,5	28,8	
		Benzene (µg/m^3)	ION CHROMATOGRAPHY	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,6	0,6	1,0	0,9	1,6	1,7	
		Toluene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	1,3	1,4	2,2	1,8	2,1	4,9	
		Trichloroethylene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	0,3	0,3	0,3	0,3	0,3	
		Tetrachloroethylene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,4	0,4	0,4	0,4	0,4	0,4	
		Styrene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	0,5	1,4	1,0	1,4	4,2	
		Naphthalene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	0,3	0,8	0,7	1,2	1,9	
		d-limonene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	0,3	1,0	32,8	15,0	53,0	88,2	
		alpha-pinene (µg/m^3)	Passive (Tenax) – ISO16017	Kitchen, Living Room & Bedroom	7 days heating season, 7 days non-heating season	Snap shot	3,8	4,0	8,6	7,6	10,9	15,8	
	Energy	**Temperature control--Thermostat**	Programable										
		Heating set point (°C)	21										
		Cooling set point (°C)	not applicable										
		Energy measurement (KWh)	Monthly										
		Total Building Energy use--on site(KWh/m^2/a)	37 kWh/m^2/annum electricity, 101 kWh/m^2/annum fossil fuel (natural gas)										
		Total Thermal Energy use--on site (KWh/m^2/a)	101 kWh/m^2/annum	Note: community heating system is not as efficient as design assumptions. The heating demand of the dwelling during the measurement period was 50.6 kWh/m^2/annum.									
	Occupants' perception of the their unit IAQ		Good										
	Occupants' view of their unit thermal comfort		Comfortable										





	 	
Lesson learned	**Problems identified**	**Adapted solution**
	Energy efficiency issues at the Energy Centre (community heating scheme)	Under investigation as the second phase of the development is constructed
	Information about MVHR filter replacement not provided to building users	Information about type and function of filters, recommended replacement frequency, and method of replacement was provided to building users in a workshop following the research project.
	Basic G3 filter in the installed MVHR systems	Opportunities to improve filtration in commercially available MVHR systems (e.g. F type filters, activated carbon filters, etc.)