Evaluation of the Impact of Retrofitting a Mid-terrace 1950's House in Dublin on Indoor Air Quality

2010/11

Aereco S.A.

9 allée du clos des charmes ▪ Collégien ▪ 77615 Marne La Vallée cedex 3 ▪ FRANCE ▪ tel. + 33 (0)1 60 06 44 65 ▪ fax. + 33 (0)1 64 80 47 26 ▪ www.aereco.com
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Introduction

Whilst regulations focus on new built properties, the majority of the housing stock consists of dwellings which have been built with no particular care about ventilation, Indoor Air Quality (IAQ) or energy efficiency.

The Irish government has recently launched a consultation in order to give guidelines on how to retrofit one million homes by 2020, with an aim to improve their energy efficiency. One of the main targets is to make these homes more airtight, through increased insulation, reduction of air leakage, double glazing to name the most common measures.

All too often, the impact of such measures on the fabric of the dwelling or on the health of the occupants is not taken into account or is underestimated. Ventilation is commonly seen as one of many possible features but not essential.

This study aims at evaluating the current situation in a typical Dublin house built in the 1950's and the impact of standard and deep retrofit measures in terms of IAQ. Several ventilation upgrades will be considered. Ventilation heat loss will also be assessed.

We have sought advice from leading architect firms in order to confirm our hypotheses. We would like to thank Jay Stuart, RIBA, Managing Director at D&W EcoCo and Joseph Little, BArch, from Joseph Little Architects and Building Life Consultancy for their help and guidance.

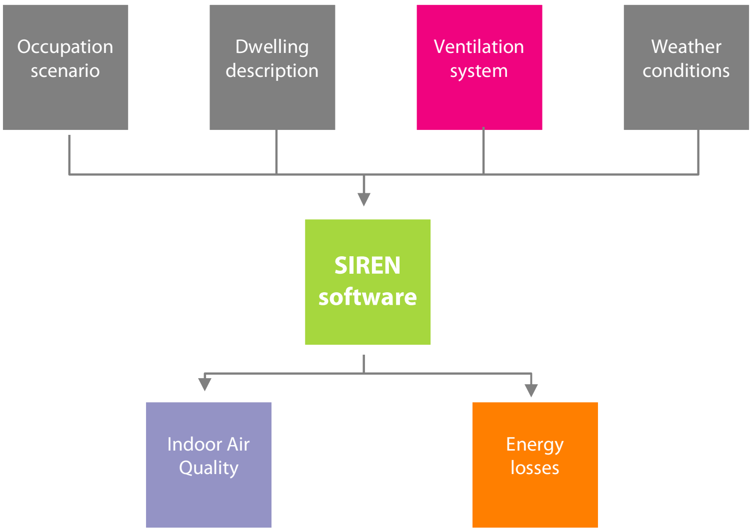
Implementation

The assessment study is based on simulations with the SIREN software (version 9). This software was developed by the CSTB[1] for the instruction of French Technical Approvals. It offers an assessment of the energy efficiency and indoor air quality (IAQ) provided by innovative ventilation systems. This dynamic simulation tool offers a calculation method to characterise the aeraulic behaviour of a described ventilation system as well as the exposure of the occupants to various pollutants.

The input data are:

- weather conditions (outdoor temperature and relative humidity, wind speed and direction)
- dwelling configuration
- amounts of water vapour generated by human metabolism and activity
- amounts of CO_2 generated by human metabolism
- room occupancy
- dwelling permeability
- ventilation components and their characteristics and airflows

As described on the graph below, the software computes the indoor air quality (CO_2, relative humidity and VOC amounts), and the energy loss due to ventilation (thermal loss). Several other parameters are computed – see below.



Graph1 - SIREN input data and outputs

[1] CSTB = Centre Scientifique et Technique du Bâtiment. French body for the delivery of Technical Approvals and member of EOTA (European Organisation for Technical Approvals).

The outputs are:

- Time-accumulated CO_2 exposure. SIREN characterises CO_2 exposure as follow: CO_2 concentrations over 2,000 ppm are tracked over time and aggregated. They are expressed in parts per million, per hour (ppm.h). The simulation is run over the heating season and the exposure threshold is set at 500,000 ppm.h of CO_2.

- Hourly ppm of VOCs in each room

- Room dependent airflow rates

- Histogram of indoor relative humidity values

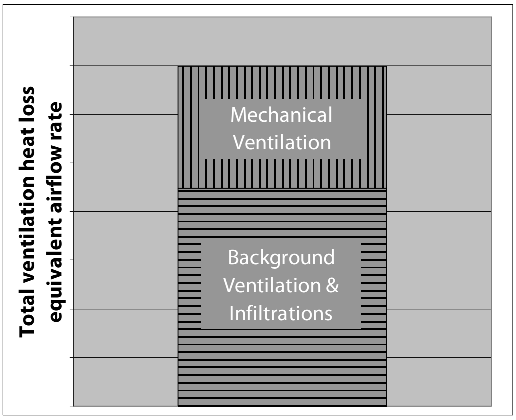
- Number of hours with condensation on windows (single-glazed and double-glazed)

- Air flow rates:

  In order to characterise the energy impact of various ventilation options, SIREN computes equivalent constant airflow rates. It does so for background ventilation and infiltrations on one side and for mechanical extraction on the other. This way, systems with constant airflows can be compared with intermittent or variable systems (such as ventilation relying on cross ventilation and infiltrations, or such as Demand Controlled systems).

  It also calculates a ventilation heat loss equivalent airflow rate. In the case of ventilation with heat recovery, the heat loss recovered is "deducted" from the actual ventilation heat loss. For instance, the actual volume extracted by a heat recovery unit can be 75 m^3/h, but as part of it is recovered, the heat loss equivalent airflow rate can be only 17 m^3/h. This way, systems with heat recovery can be compared with systems without it.

  In this study, we will consider the total ventilation heat loss equivalent airflow rate, consisting of one part coming from background ventilation and infiltrations, and another from air extracted by mechanical means[2].



Graph 2 - Composition of Total Ventilation Heat Losses

[2] These values take the local weather data into account: the air extracted by ventilation is naturally renewed by incoming cold air, and the energy required to heat it depends on the outside-inside temperature difference. Both equivalent airflow rates are calculated over the heating season. The airflow rates and temperature differences are computed every 3 minutes.

Dynamic input and output of data are defined with a 30 minutes or 1 hour step, whereas the calculation is run with a 3-minute step.

The simulation is run over the heating season only, since the model aims at evaluating the ventilation related thermal loss.

The model takes into account numerous parameters such as exposure of the dwelling (influence of wind pressures), air leakages, infiltration, location of the ventilation components, activity of the occupants, water vapour adsorption and desorption phenomena[3], etc. to best mimic the real airflow behaviour.

Nowadays the software is designed to assess mechanical ventilation systems on a dwelling, but it is planned that other modules will deal with natural and hybrid ventilation in multi-family houses. More than ten years of use by the scientists, researchers and industrials have improved the possibilities and the reliability of the tool. User licences can be bought from the CSTB, which is the owner of the calculation algorithm.
For more information, please contact the CSTB (Centre Scientifique et Technique du Bâtiment) – France (http://international.cstb.fr/)

The SIREN predictive model has been validated through a large scale experiment in Paris and Lyon called "Performance de la ventilation et du bâti" in 2008-2009. The partner organisations involved include a ventilation association (AIR.H), consultants (Allie'Air, PBC), builders (Bouygues construction, GFC contruction), registered social landlords (Paris Habitat, CIRMAD Grand SUD and OPAC du Rhône), Demand Controlled ventilation equipment manufacturers (Aereco, Anjos), distributors (Aldes, Atlantic) and various official bodies (CETE, CETIAT, COSTIC). The project has been funded by the French equivalent to SEAI, ADEME. This monitoring study, which related to a total of 29 occupied dwellings in two building sites, confirmed the simulation results using SIREN (with a highly satisfactory discrepancy ratio).

[3] Adsorption, not to be confused with absorption, is the adhesion of atoms, ions, bio molecules or molecules of gas, liquid, or dissolved solids to a surface. Desorption is a phenomenon whereby a substance is released from or through a surface. The process is the opposite of sorption (that is, either adsorption or absorption).

Working hypotheses and constraints

See Appendix A for more details about the input data.

- **Weather data**: Dublin, common design year format, with heating season from 1st October to 21st May. Due to limitations in SIREN, it was not possible to go to 31st May. We consider outside temperature, relative humidity, wind speed and direction every hour.

- **House positioning**: in order to limit the impact of a given house position, the exposure of the house is changed every week, over 4 cardinal directions[4]. The exposure described for each ventilation component (incl. permeability) determines the contribution of infiltrations and cross-ventilation.

- **Dwelling description:** mid-terrace house built in 1950's in Ballyfermot, Dublin, described in the AVASH study[5] under n° 29. The surface, volume and H_2O adsorption capacity[6] of each room are described. We have switched location of living room and dining room because of their respective size. The total surface of the house is 69.1 m^2 and its volume is 171 m^3. See Appendix A1 for more details.

Graph 3 - Layout of house n° 29

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[4] Mid-terrace houses are very sensitive to exposure. French technical approvals are run with 2 different exposures but we used 4 in order to have more homogeneous ventilation across rooms.
[5] The AVASH (Advanced Ventilation Approaches for Social Housing) project was funded by the EU IEE programme to investigate the most appropriate ventilation and insulation upgrade strategy, from the point of view of energy efficiency and health, for existing social housing in Denmark, Ireland and the UK. More information at www.brighton.ac.uk/avash/
[6] Adsorption, not to be confused with absorption, is the adhesion of atoms, ions, bio molecules or molecules of gas, liquid, or dissolved solids to a surface. Values extracted from the set of data selected and approved by the CSTB for the instruction of French Technical Approvals.

- **Number of occupants**: based on the number of bedrooms in the dwelling, it has been decided to consider a couple with two children. The parents occupy bedroom 1 while the children occupy bedrooms 2 and 3.

- **Water vapour generation**: cooking, showers, clothes washing and drying were included[7]. All parameters depend on the number of occupants. Only the mother has lunch at home during the week.

- **Activity scenarios**: room occupancy and activity is described for each occupant, in 30 minute intervals. See Appendix A3 for details. Human metabolic water vapour and CO_2 generation are modelled for awake and asleep periods[5].

- **Permeability**: the actual air tightness of the house described in the AVASH study was 7.8 AC/H at 50 Pa (n_{50}) before retrofit measures. This was found to be quite a good (i.e. low) value for such an old house and was due to the wet plastered masonry walls. It was decided to consider four cases:
  - **Case A: n_{50} at 10 AC/H** before retrofit measures, corresponding to TGD L(2007) or the AVASH house without wet plastered masonry walls. In this case the walls may have had a plasterboard-on-dab wall finish;
  - **Case B: n_{50} at 7.8 AC/H**, corresponding to the AVASH house with wet plastered masonry walls before retrofit measures or Case A after standard retrofit measures;
  - **Case C: n_{50} at 5 AC/H**, which is a key figure in new TGD F (2009). This can also be Case A with deep retrofit measures and Case B with standard retrofit measures;
  - **Case D: n_{50} at 3 AC/H**, which corresponds to Best Practice. This can also be Case B with deep retrofit measures.

  The global volume of air renewal has been distributed relatively to each room's volume (Appendix A2).

- **Ventilation components**: i.e. active ventilation components. Air inlets are assumed to be built into the wall. For each room the ventilation component exposure and airflow rate are described in details in Appendix A4 to A10. We ran simulations to assess the IAQ and energy performance with up to 6 ventilation options:
  - **Wall Vents**: Wall vents in dry rooms and kitchen consisting in grilles on each side of 100 mm diameter through the wall holes;
  - **Blocked Vents**: Case of wall vents blocked by occupants to avoid draughts. In that case, there is no ventilation other than coming from the permeability of the house. The idea is to simulate a "real-life" case seen all too often. As the occupants feel the cold draughts more than they feel poor IAQ, they block the vents with tape, plastic bags or even socks in the ducts;
  - **Intermittent Fans**: Natural ventilation with intermittent fans in wet rooms as per TGD F 2009. As it was described to us, the AVASH house had no intermittent fans. These are however very common, so we have simulated this case. Wall vents in dry rooms and kitchen as above. Intermittent fans in kitchen (no cooker hood) and bathroom;

[7] Values extracted from the set of data selected and approved by the CSTB for the instruction of French Technical Approvals.

- **MEV**: Constant airflow Mechanical Extract Ventilation with existing wall vents in dry rooms and extraction from wet rooms. In this scenario, it is assumed that windows are not replaced and wall vents are kept in dry rooms to minimise retrofit costs[8]. The existing wall vent is suppressed during retrofit in the kitchen. A central <u>constant airflow</u> fan is installed. Extract rates are defined after England and Wales Part F 2010 recommendations, as there is no guidance in the Irish TGD F;

  DC MEV: Demand-Controlled Mechanical Extract Ventilation. Existing Aereco products are used. All dry rooms are equipped with through the wall acoustic, humidity-controlled air inlets (Aereco's EHT969 kits). They fit in existing 100 mm holes. The existing wall vent is suppressed during retrofit in the kitchen. The bathroom and kitchen are equipped with boostable humidity-controlled extract terminals. In the kitchen, the boost rate can be activated by a switch, to compensate for the lack of cooker hood (Aereco's BXC215). In the bathroom, due to toilets, presence detection provides a boost rate to evacuate odours as needed (Aereco's BXC275). There is a 20 minutes overrun in the boost after the last presence detection in the bathroom. Then, the unit reacts based on the humidity sensor. A central <u>constant pressure</u> fan is installed. Extract rates are defined after England and Wales Part F 2010 recommendations, as there is no guidance in the Irish TGD F;
- **MVHR**: Mechanical extract Ventilation with Heat Recovery with a 90% heat recovery ratio, with no pre-heating. Ventilation rates come from the Irish TGD F 2009. Air is supplied in the dry rooms so that the total supply rate is balanced with the total extraction rate in the wet rooms. The heat recovery ratio is multiplied by an "in-use" factor as in SAP2009 Table 4h, in order to allow for pressure losses from ductwork. Ducts are assumed to be insulated, so the heat recovery ratio is multiplied by 0.85. It therefore falls to 76.5%. If the duct were not insulated, it would be multiplied by 0.70 and would fall to 63%.

In total, 20 cases have been studied:

Permeability / Ventilation options	Case A: n_{50} at 10 AC/H	Case B: n_{50} at 7.8 AC/H	Case C: n_{50} at 5 AC/H	Case D: n_{50} at 3 AC/H
Wall Vents	X	X	X	X
Blocked Vents	X	X	X	X
Intermittent Fans	X	X	X	X
MEV			X	X
DC MEV	X	X	X	X
MVHR			X	X

Graph 4 – Ventilation options studied for each permeability level

The various ventilation approaches have been chosen so as to reflect probable choices of owners. The systems described do not always comply with regulations for new dwellings but are likely in a retrofit environment. For instance, it is assumed that owners will not drill extra holes in bathroom or bedroom 1 to comply with the new TGD F in Case D, when permeability is below 5. Similarly, the MEV scenario assumes that existing background ventilation is kept as it was in dry rooms and cancelled in the kitchen. This study is therefore more about real conditions in Irish houses than about conditions suggested in the Technical Guidance Documents.

[8] This choice means that background ventilation remains rather high due to the wall vents. It has a positive impact on IAQ but a negative effect on ventilation heat losses. In the case of VOCs, a scenario called "MEV UK" is also considered to compare DC MEV with a constant airflow system. In this other scenario, there are no more wall vents and windows are equipped with 2,500 mm² equivalent area trickle vents.

- **VOC control**: we have considered values described in England and Wales AD Part F: an emission rate[9] of Total VOC (TVOC) of 300 µg/h per m^2 and an exposure level to TVOC averaged over 8 hours[10] limited to 300 µg/m^3.

- **Gas combustion products control**: England and Wales AD Part F requires a minimum ventilation rate of 12 l/s in the kitchen to ensure a good control of nitrogen dioxide and carbon monoxide emitted during cooking. This is taken into account in the case of mechanical ventilation systems. For humidity-controlled extract terminal in the kitchen, we have used a unit with a switch to boost extraction and ensure this level of ventilation during cooking activities.

[9] Dimitroulopoulou C, Crump D, Coward S K D, Brown V, Squire R, Mann H, White M, Pierce B and Ross D (2005). *Ventilation, air tightness and indoor air quality in new homes*. Report BR 477. BRE Bookshop.

[10] ECA (1992). European Concerted Action on indoor air and its impact on man: *Guidelines for ventilation requirements in buildings*. Working Group Report No. 11. EUR 14449 EN. Commission of the European Communities, Luxembourg.

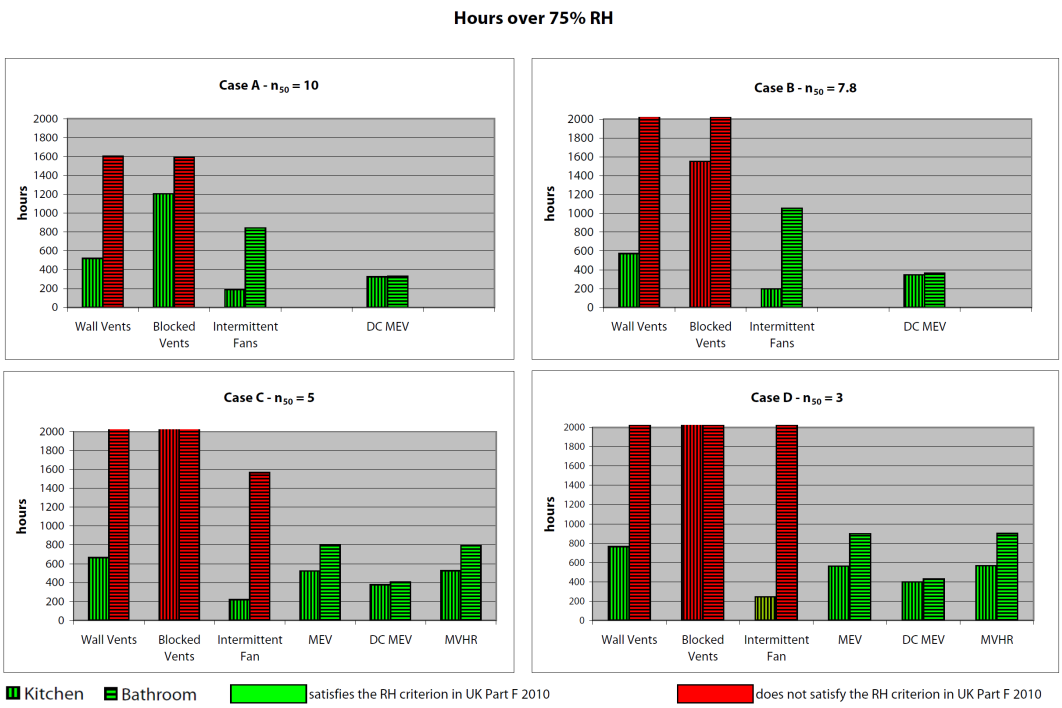
Results

Indoor Air Quality

Relative Humidity and Moisture

SIREN simulations compute the amount of water vapour in the various rooms of the dwelling. The kitchen and bathroom are, of course, the most humid ones. Note that the activity scenarios assume that cloth washing and drying are done in the bathroom.

SIREN directly computes the number of hours with RH higher than 75% for the various rooms and aggregates them over the simulation period, i.e. the heating season. Graph 5 below shows the results.

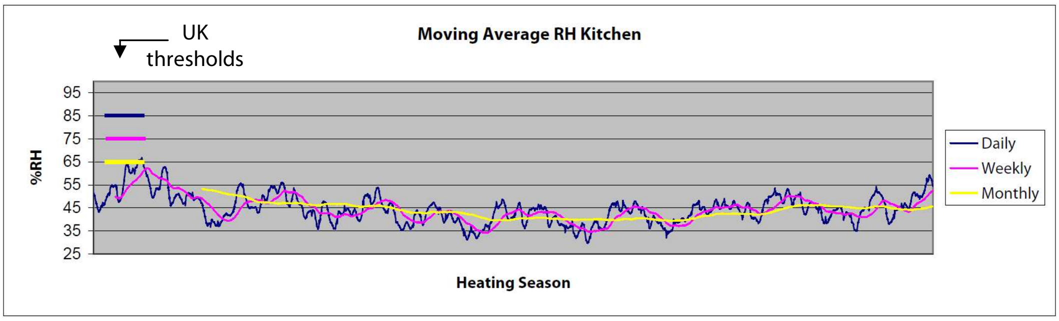


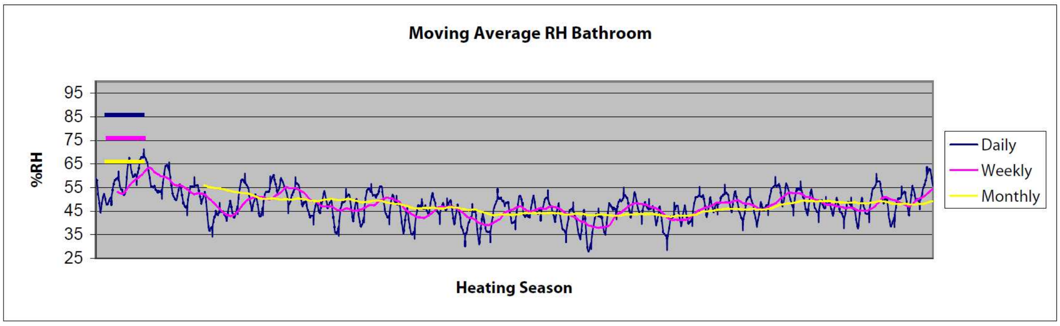
Graph 5 - Number of hours above 75% Relative Humidity over the heating season

Furthermore, hourly rates in each room are also available. From them, moving averages per wet room can be calculated, so as to confirm compliance with England and Wales Part F2010 criteria[11]: average Relative Humidity should not exceed 85% RH any given day, 75% RH any 7 day period and 65% RH any given 30 days period. The detailed graphs of these moving averages are available in Appendix B1 to B20, and one example is given in Graph 6. When the criteria are satisfied, the corresponding bar in Graph 5 is green, and it is red if they are not.

[11] This criterion is used in absence of requirements in the current ventilation guidance in Ireland.

3ACH - DC MEV





Graph 6 – Example of follow-up of Relative Humidity over the heating season and compliance with UK Part F

The main findings from the graphs above are the following:

- **Wall Vents**: systems relying on cross ventilation only (wall vents in dry rooms and kitchen) cannot extract humidity in the bathroom, even with low air tightness.

- **Blocked Vents**: even though the criteria are not fully satisfied in Case A with blocked vents (n_{50} = 10), the results are good in the kitchen and close to requirements in the bathroom.

  But as soon as air tightness increases, the results go far beyond limits in both wet rooms. In the bathroom, the number of hours above 75% RH goes to 2,024 for n_{50} = 7.8, 3,024 for n_{50} = 5 and 4,719 for n_{50} = 3. This last figure represents more than 196 days out of 233, or 84% of the time.

  When RH is at 75%, the dew point is around 17°C. With so many days above that value, condensation is very likely to appear on all thermal bridges left or created after the retrofit, when the heating system is delivering an air temperature of 19 to 20°C, but could appear on all non-absorbent surfaces if design temperatures are 17°C or lower (such as in households experiencing fuel poverty).

  This confirms the need to change habits in more airtight building by offering ventilation solutions which take the comfort of the occupants into account and avoid draughts.

- **Intermittent fans**: systems are efficient at extracting moisture from wet rooms when the air infiltration rate is as low as $n_{50} = 7.8$. When it goes down to 5 AC/H, the bathroom fan cannot cope and the study shows several daily averages are above 75% RH. In Case D where $n_{50} = 3$, the criteria would be met thanks to the addition of background ventilation in the bathroom but it is very unlikely that owners would create extra holes in the fabric after spending money on making their house more airtight. Based on the latter view the number of hours above 75% RH would therefore be very high, at 2,392 hours over the heating season, or 100 days out of 233. The remarks on the dew point above apply in that case as well.

  This simulation assumes that fans are used every time the wet rooms are used. It means 2 hours per day in the kitchen and 2 ½ hours for the bathroom. Because of the noise they are generating and also because of the energy cost which people sometimes associate with that noise, we know that the fans are frequently used less than they should be. We believe this is even true when fans are triggered by a light switch, because light is not always necessary when there is a window in the bathroom, which is the case here. Therefore, in reality, this approach, which depends on occupant behaviour, is unpredictable at best and not a reliable safeguard of occupants' health. When the fans are not running, the system is comparable to wall vents only.

- **MEV**: this system can cope with moisture, because even though its extraction rates are lower than the intermittent fans, it is constantly running and does not depend on occupants' behaviour.

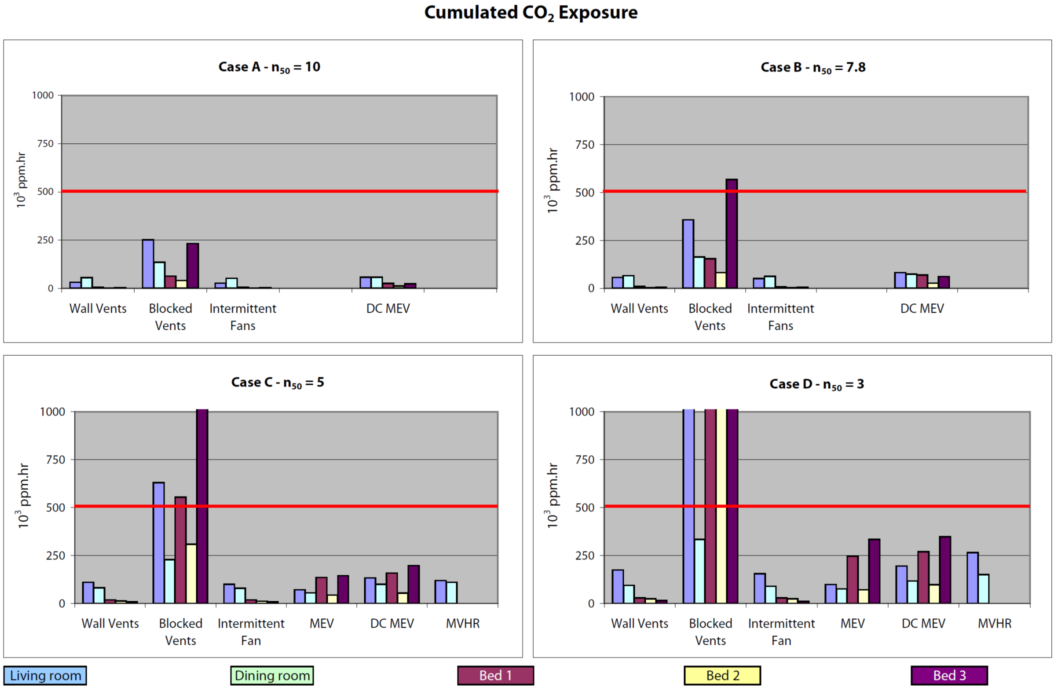
- **DC MEV**: this system gives excellent results, better than any other system and in all tightness conditions. This is particularly true in the bathroom, where the extraction rates are adapted continuously based on RH levels. Because extraction rates go beyond minimum rates (61 or 70 m^3/h instead of 29 m^3/h in the bathroom for instance), moisture is evacuated more swiftly and the average RH level is lower. This minimises the risks linked with excessive moisture for the health of the occupants as well as for the lasting quality of the property.

- **MVHR**: the system gives results comparable to MEV, as the extraction rates are the same.

CO_2 exposure

During the assessment of the systems, SIREN characterises CO_2 exposure as follow: CO_2 concentrations over 2,000 ppm are aggregated over the heating season, and they are expressed in ppm.h. The recommended exposure threshold for that period[12] is 500,000 ppm.h of CO_2.

The results are summarised in Graph 7 below.



Graph 7 - Cumulated CO_2 exposure over the heating season

These results demonstrate again the danger of having no ventilation in the case of blocked vents in more airtight houses. Dangerous levels are reached in Bedroom 3 (the smallest of the three) even with n_{50} = 7.8; Bedroom 1 and Living Room are also concerned with n_{50} = 5 and Bedroom 2 as well for n_{50} = 3.

All other ventilation approaches are satisfactory on this criterion.

It is interesting to note that DC MEV gives comparable results to MEV even though background ventilation surface and extraction rates are lower. Even in very airtight dwellings, the air inlets open more where the pollution is highest (e.g. living room and dining room during the day, bedrooms at night), so fresh air is introduced where it is most needed to replace stale air.

[12] CSTB recommendation

VOC amounts

At the outset it is important to acknowledge that Volatile Organic Compounds are not easy to assess[13].

First of all, there are various definitions among the experts:

- US EPA's Office of Radiation and Indoor Air: "compounds that vaporize (become a gas) at room temperature"
- Health Canada: "organic compound that have boiling points roughly in the range of 50 - 250 ºC"
- EU (various directives): "any organic compound with a boiling point less than 250 ºC"

Secondly, the identification and measurement of individual VOCs are expensive and time-consuming, and invariably the total is underestimated because the VOCs present at very low concentrations are difficult to identify or measure.

In summary, there are different sampling/analytical methods to measure different compounds. It is still very much a research topic.

It can also be mentioned that they are more relevant in commercial environments than in dwelling.

Their emission rates decrease over time, so it is a moving target. There is not even a clear agreement on the levels to be achieved to maintain a good IAQ. We have considered the limit mentioned in England and Wales Part F 2010 of 300 µg/m^3 on an 8-hour average. This level comes from a study[8] which gives the following table:

Table 12. Proposed guidelines for acceptable TVOC concentrations in indoor air

Author	*Concentration ($\mu g\ m^{-3}$)*	*Comment*
National Health & Medical Research Council (Australia) (Dingle and Murray, 1993)	500	No single compound should contribute > 50%
Mølhave, L ECA (1992)	< 200 200 – 3,000 3000 – 25,000 > 25,000	Comfort range Multifactorial exposure Discomfort Toxic
Seifert, B ECA (1992)	300	Target guideline value. No individual compound should exceed 10% of target value
Finnish Society of Indoor Air Quality and Climate (1995)	< 200 < 300 < 600	Target values of indoor climate; best air quality; 90% of occupants satisfied Intermediate air quality-room may have slight odour Minimum requirement
Japanese Ministry of Health, Labour and Welfare (2000)	< 400	Advisable TVOC value for indoor air quality for residential air

Table 8 - Proposed guidelines for acceptable Total VOC (TVOC) concentrations in indoor air in BRE study

[13] Based on the presentation "*Comparison of Sampling & Analytical Methods for Total Volatile Organic Compounds (TVOC) in Green Buildings*" by Alyson Fortune - Air Quality Scientist - Columbia Analytical Services - Florida Brownfields Conference - November 1, 2009

The level finally used in Part F comes from a European Collaborative Action study from 1992. But one line above in that table (see Table 8 above), another study from the same organisation the same year considering levels of 200 to 3,000 µg/m^3 to be acceptable. This shows how difficult it is to evaluate the outputs of the study.

For all these reasons, we will not go too deep into the analysis of the results of VOCs levels.

SIREN version 9 can output the hourly concentration of Total VOCs (TVOC) in each room of the dwelling. The amounts are expressed in ppm related to an arbitrary emission rate of 1 l/h per m^2. The data were calculated assuming a TVOC emission rate of 300 µg/h per m^2 - as referred to in England and Wales Part F, and ppm were translated into µg/m^3. An 8-hour average was calculated for TVOC amounts in each dry room along the heating season.

The latter criterion is very much linked to the amount of air supplied in the dry rooms. As DC MEV tends to reduce airflows as much as possible, the amount of TVOC is therefore greater than other systems with higher cross ventilation or high fixed airflow rates. It is important to evaluate the performance of DC MEV with a comparable benchmark. We have used the UK constant airflow MEV reference, which calls for only 2,500 mm^2 of background ventilation in dry rooms. Even though this approach does not solve the question of whether the emission rate and the IAQ threshold are right or wrong, it shows the IAQ performance of DC MEV compared to the MEV UK reference.

Graph 9 on the next page compares the average and standard deviation of TVOC amounts (averaged over 8 hours) for each room in the dwelling when an occupant is present, in the different ventilation approaches of Case D, which is the worst case scenario. MEV UK has been added as well. Detailed data is available in Appendix B21.

The results depend mainly on the emission rate, which has been arbitrarily[14] fixed to a constant 300 µg/h per m^2. As we have seen above, the threshold of 300 µg/m^3 is also arguable. The main result from the study is the confirmation that no ventilation (e.g. where vents are blocked) leads to very high levels of TVOC in all dry rooms. There is a significant number of hours above 800 µg/m^3. The peak is 2243 µg/m^3.

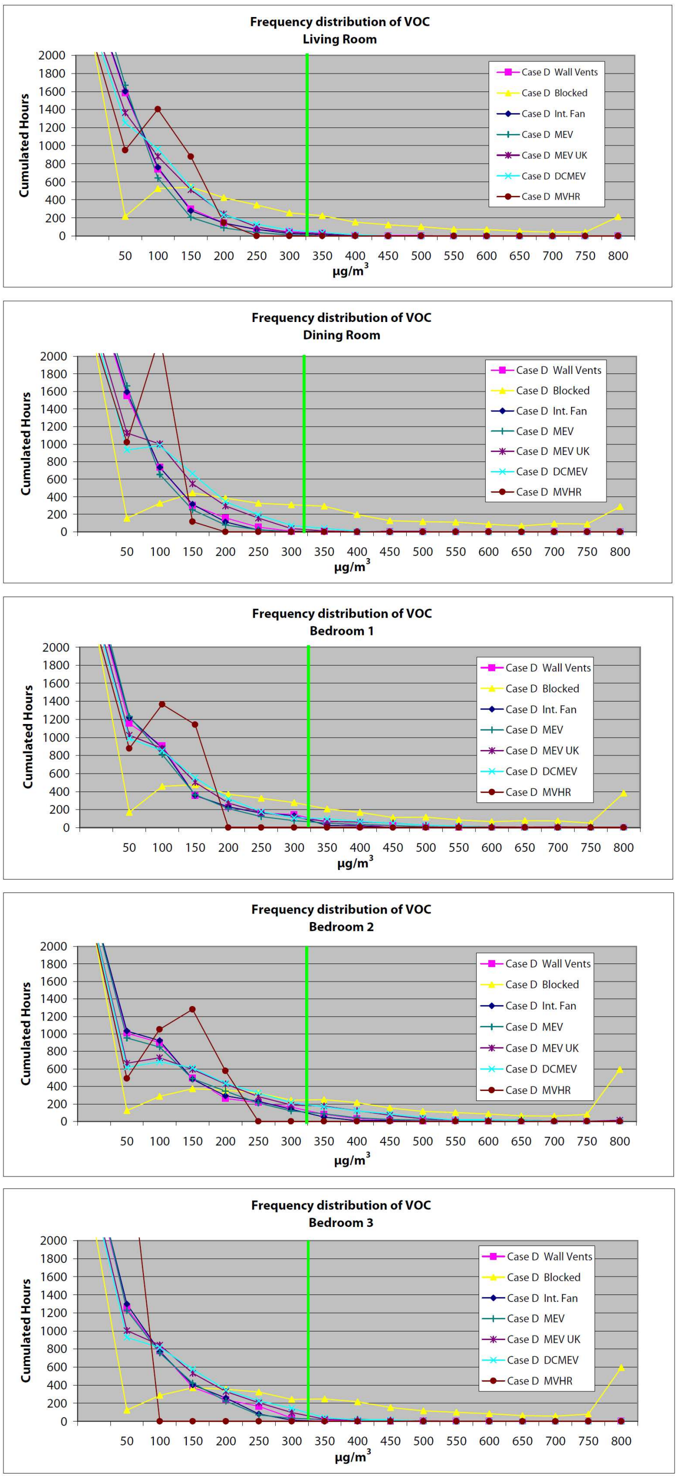
Another way of looking at VOCs is to look at the exposure of each person instead of looking at the situation in each room when someone is in the house.

Graph 10 shows the results for DC MEV compared to MEV UK for each occupant. The results are comparable. Even though DCV results are higher, it is not significant in comparison with the above reservations. Detailed data is available in Appendix B22.

Note that the hourly amounts of TVOCs are extremely variable and depend primarily on the emission rate. As discussed in "*Humidity Controlled Exhaust Ventilation in Moderate Climate*" VIP paper published by AIVC in June 2009, since VOC sources are so variable and time dependant, relying on high ventilation rates to extract them is not energy-efficient. VOCs should rather be tightly controlled at the source. Purge ventilation can be used in case of exceptional peak concentrations (painting, new carpet …).

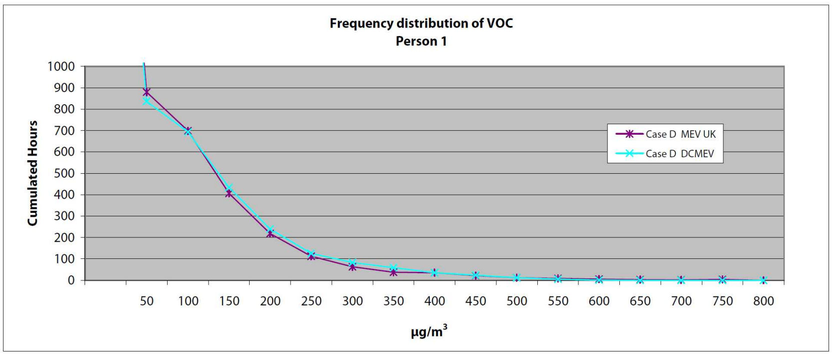
[14] The emission rate comes also comes from England and Wales Part F 2010. It is based on the study mentioned in footnote 8 but the study itself does not mention it. It seems to have been deducted as the emission rate which it compatible with the concentration limit chosen and the minimum recommended airflow rate (0.3 l/s/m^2).

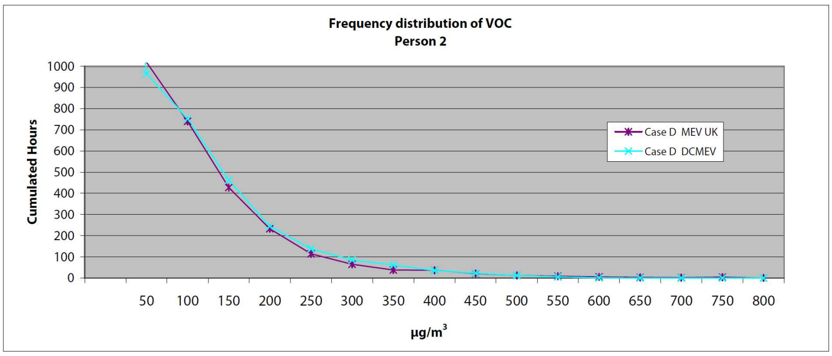
AVERAGE OVER 8 HOURS DURING PRESENCE - ROOM BY ROOM

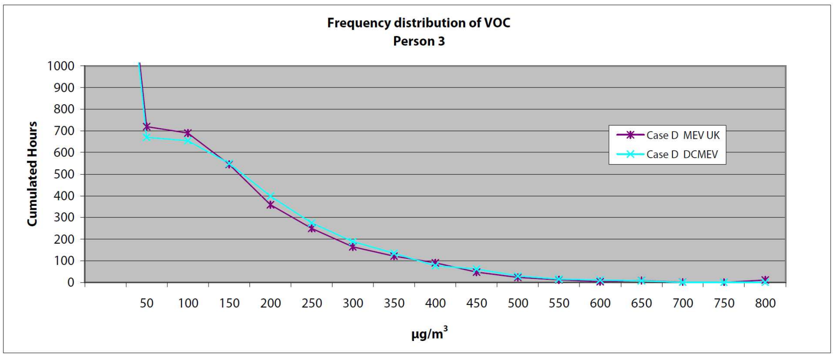


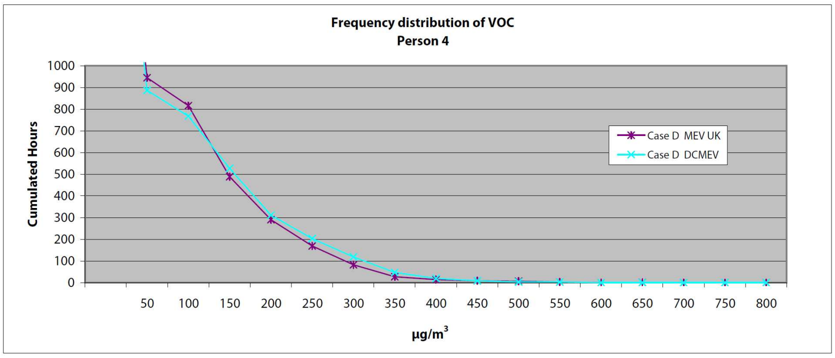
Graph 9 - Frequency distribution of TVOCs averaged over 8 hours in dry rooms in case of presence of an occupant in Case D

AVERAGE OVER 8 HOURS DURING PRESENCE - FOLLOW-UP PER PERSON









Graph 10 - Frequency distribution of exposure of occupants to TVOCs averaged over 8 hours in Case D

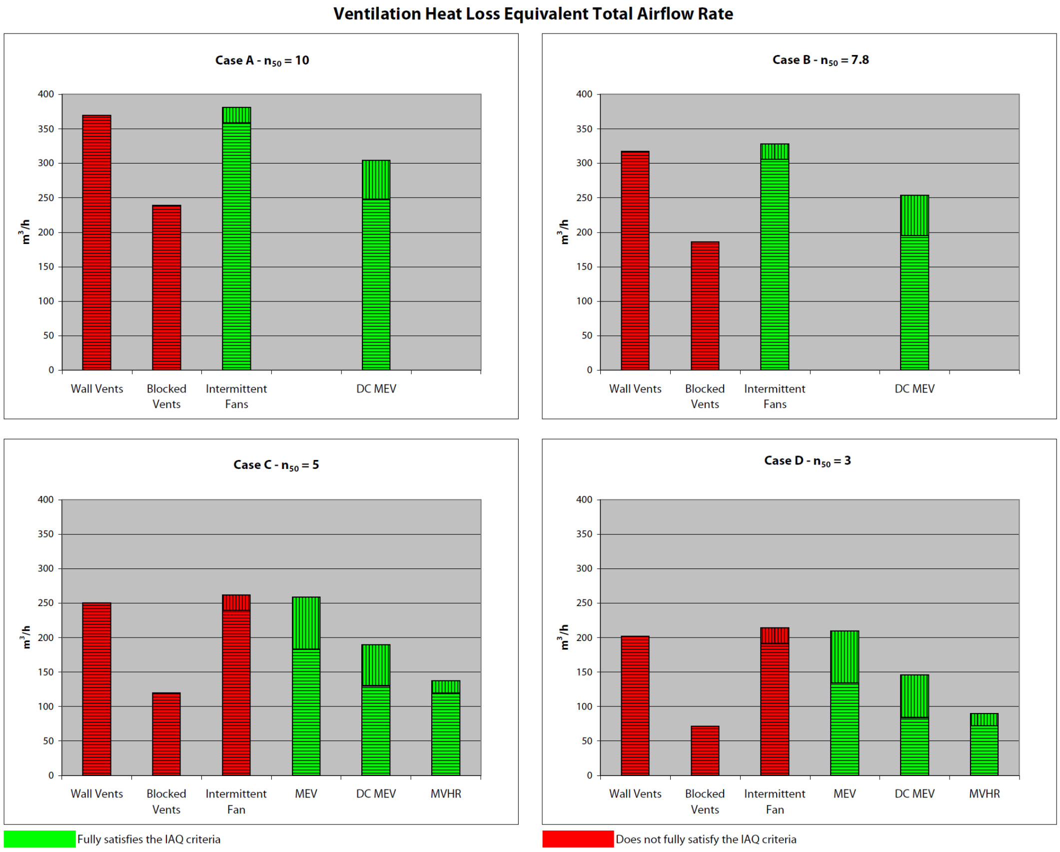
Airflow rates and Energy savings

We have seen before which ventilation options fulfil the IAQ criteria. It is also important to look at how efficiently they do so.

SIREN calculates various airflows: average cross ventilation and average intended ventilation, but also the average equivalent cross ventilation and the average equivalent intended ventilation. The equivalent airflows correspond to a constant airflow which would give the same ventilation heat losses. The best example is with MVHR: in Case D, the average cross ventilation is 73.06 m^3/h and average intended ventilation is 75.34 m^3/h, so a total of 148.4 m^3/h. This is what is actually extracted on average from the dwelling. Because part of the heat loss is recovered, the average ventilation heat loss equivalent total airflow rate is only 89.86 m^3/h.

The average airflow is useful to compare constant systems (MEV) with intermittent systems (Intermittent Fans) and modulating systems (DC MEV), whereas the equivalent airflow is useful to compare those systems with ventilation with heat recovery (MVHR).

Graph 11 below gives the summary of the results. Only systems in green should be considered, as they comply with IAQ criteria.



Graph 11 - Comparison of Equivalent airflow rates for various systems in the four cases

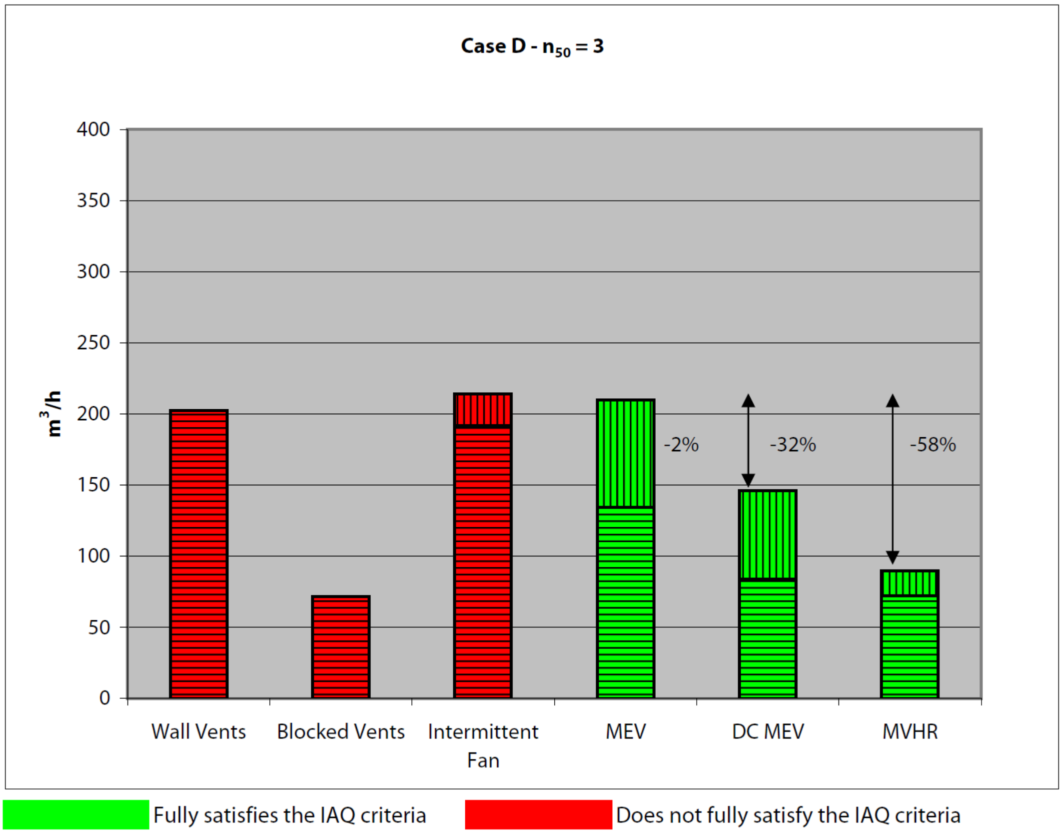
The graph shows the range of energy savings according to the approach chosen.

In **Cases A and B**, DC MEV can save 20 to 23% of the ventilation heat loss compared to intermittent fans.

In **Case C**, the savings vary between 1 and 47% depending on the system chosen, with DC MEV at 28% and MVHR at 47%.

But it must be noted that the Intermittent Fans option does not comply. It means that it should not be chosen as a ventilation solution for this air tightness. However other approaches with continuous extraction do comply, and in the worst case scenario generate equivalent heat losses. Adding humidity sensitive air inlets in existing holes in the wall and using demand-controlled extract grilles and a constant pressure fan instead of air valves and a constant airflow fan saves 28% of the ventilation heat loss. To reach the level of 47% with heat recovery, additional work is compulsory: all supply vents must be blocked, and a supply and extract duct network must be created, which is not always convenient.

Graph 12 focuses on Case D.



Graph 12 - Comparison of Equivalent airflow rates for various systems in Case D

In **Case D**, the situation is similar but the savings are even greater as cross ventilation is reduced evenly by around 50m^3/h for all systems. In terms of percentages, the more economical systems benefit from this.

DC MEV can save 32% of ventilation heat losses, to be compared to 58% for the 90% MVHR system.

On top of the extra installation costs involved in the choice of MVHR, other parameters should also be taken into account such as purchasing cost, running cost (in particular in the case of the two fans of MVHR) or maintenance cost.

The graphs above give a good description of the impact of the various systems on ventilation heat losses. However, they do not take the primary energy use of those systems into account. DC MEV needs one fan only and its power consumption reduces as the airflow rates diminish. This should be remembered when comparing it to MVHR, which needs two fans running constantly.

Summary

Case	Criteria / Ventilation options	Indoor Air Quality: Excessive Relative Humidity	Indoor Air Quality: Excessive CO_2	Indoor Air Quality: Good IAQ	Total Ventilation Heat Losses (From more to less)	Comments
Case A – n_{50} = 10 AC/H	Wall Vents	Bathroom	-			Bad IAQ
	Blocked Vents	Bathroom	-			Bad IAQ
	Intermittent Fans	-	-	☑		Very high heat loss
	DC MEV	-	-	☑		High heat loss
Case B – n_{50} = 7.8 AC/H	Wall Vents	Bathroom	-			Bad IAQ
	Blocked Vents	Kitchen/Bathroom	Bedroom 3			Very bad IAQ
	Intermittent Fans	-	-	☑		High heat loss
	DC MEV	-	-	☑		Reduced heat loss
Case C – n_{50} = 5 AC/H	Wall Vents	Bathroom	-			Bad IAQ
	Blocked Vents	Kitchen/Bathroom	LR/B1/B3			Very bad IAQ
	Intermittent Fans	Bathroom	-			Bad IAQ
	MEV	-	-	☑		High heat loss
	DC MEV	-	-	☑		Reduced heat loss
	MVHR	-	-	☑		Low heat loss
Case D – n_{50} = 3 AC/H	Wall Vents	Bathroom	-			Bad IAQ
	Blocked Vents	Kitchen/Bathroom	LR/B1/B2/B3			Very bad IAQ
	Intermittent Fans	Bathroom	-			Bad IAQ
	MEV	-	-	☑		Reduced heat loss
	DC MEV	-	-	☑		Low heat loss
	MVHR	-	-	☑		Very low heat loss

Table 13 – Summary of the findings of the study

Relying on draughts (i.e. high air infiltration rates) to satisfy IAQ needs in airtight houses can prove hazardous. This is exactly what happens however with Wall Vents and to some extent with Intermittent Fans, which are often tampered with. Both are heavily depending on background ventilation and occupants' behaviour. Only ten out of twenty ventilation options comply with IAQ criteria.

The habit of blocking vents is a reality and it should be considered. The study confirms that it puts people's health and properties at risk after the implementation of retrofit measures which make dwellings more air tight. Even if the least significant case considered here (Case A), IAQ very quickly reaches dangerous[15] levels, regarding both moisture and VOCs concentrations.

In the case of Intermittent Fans, when vents are not blocked, chances that retrofit measures include more background ventilation than before are limited and without them, a satisfactory level of IAQ cannot be reached, in particular in the bathroom.

This is why continuous mechanical ventilation systems[16] should be preferred in order to secure a good Indoor Air Quality.

In wet room, where Relative Humidity is the most relevant pollution indicator, DC MEV gives the best results as it continuously adapts to the actual level of moisture and extracts it faster than other systems.

In dry rooms, where CO_2 exposure is the best indicator of IAQ, all continuous mechanical ventilation systems give satisfactory results.

As for VOCs, even though many parameters remain unclear, the study shows that the reduced average extraction rate of Demand Controlled Ventilation systems does not increase the exposure level compared to the reference level.

Finally, the study shows that compliance with IAQ criteria can be achieved with various energy efficiency levels. If we consider the Intermittent Fans described in this study as the base case (the simplest case which complies with IAQ requirements), the savings in ventilation heat loss equivalent total airflow rate are the following:

	Average Ventilation Heat Loss Equivalent Total[17] Airflow Rate (m^3/h)			
Ventilation options	$n_{50} = 5$	Savings	$n_{50} = 3$	Savings
Intermittent Fans	261.8	-	214.0	-
MEV	258.3	1%	209.6	2%
DC MEV	189.7	28%	145.9	32%
MVHR	137.7	47%	89.9	58%

Table 14 – Savings in ventilation heat loss of the various mechanical ventilation options

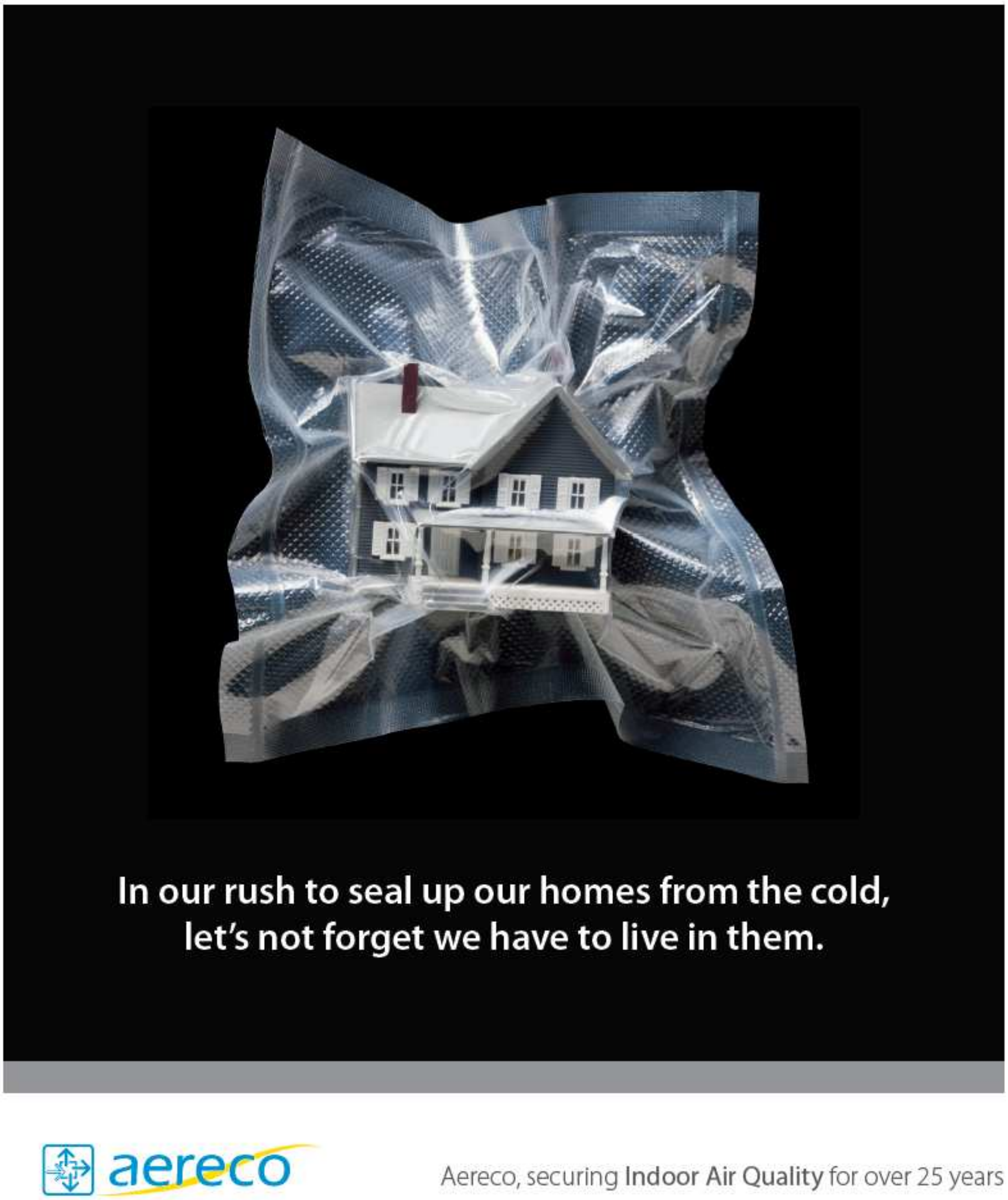
This evaluation does not take into account the power consumptions of the various systems. It does not consider either capital costs, installation costs or the maintenance costs. Yet, given its advantages in all these aspects as well as its unique adaptability to all occupancy levels and scenarios, Demand Controlled MEV appears as a genuine alternative to MVHR when considering both IAQ and energy efficiency.

[15] These levels can be dangerous for the health of the occupants, causing headaches or asthma, favouring dust mites, and for the fabric of the dwelling, with the apparition of mould for instance.
[16] There are other continuous ventilation systems, such as Passive Stack Ventilation and Hybrid Ventilation, which combines PSV and low pressure MEV. Both an include humidity sensors to reduce draughts and improve energy efficiency. Yet, they are more complicated to simulate as they fully depends on natural forces.
[17] Includes background ventilation, infiltrations and mechanical ventilation. Refer to Page 4 for more details.

Even though this study focuses on one particular case, it has the advantage of comparing systems in identical conditions, whereas monitoring studies always depend on the particulars of the environment. Other cases (less occupancy, different dwelling) could be assessed in comparable conditions.

The study shows that a good, robust, certifiable ventilation system is critical as houses become more airtight, but high airflows do not necessarily mean good IAQ and good IAQ does not necessarily mean high airflows. The ventilation systems with intermittent fans and constant airflow MEV presented here have the same ventilation heat losses but only the second group ensures a good IAQ. DC MEV goes further because, instead of recovering the heat, it extracts less air in the first place, which results in energy savings as well.

At the current time there is no recognition of these savings in DEAP. We hope this study will be seen as an important contribution to showing the real value of various ventilation options, and the benefits of Demand Controlled Ventilation in both new build and retrofit.



For more information please contact Aereco
pierre.lopez@aereco.com

Appendix A: Input data

- **Dwelling description**:

The hall and stairs space have been combined into one single room despite the fact that they are located on two different levels, with no impact on the model. The dining and living room have been kept separated but we have switched their respective location in order to have the living room bigger than the dining room.

Room	Room no.	Area (m^2)	Volume (m^3)	Seq H_2O[18] (m^2)
Hall incl. stairs (GF+FF)	1	14.3	35.3	10
Living Room	2	11.1	27.5	25
Dining Room	3	7.8	19.4	25
Bedroom 1	4	10.0	24.8	15
Bedroom 2	5	10.7	26.4	15
Bedroom 3	6	4.4	10.9	15
Kitchen	7	6.1	15.2	-
Bathroom + WC	8	4.7	11.6	-
	Total	69.1	171.1	105

Table A1: Area, volume and water absorption equivalent surface for each room

- **Dwelling permeability**:

It is based on various n_{50} air tightness, before and after retrofitting. Permeability is spread over rooms based on volume. Permeability is described as a vent in the wall and is exposed to wind pressure. This is why the exposure of the wall is important.

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Permeability airflow rate n_{50} = 10 AC/H (l/s)	Permeability airflow rate n_{50} = 7.8 AC/H (l/s)	Permeability airflow rate n_{50} = 5 AC/H (l/s)	Permeability airflow rate n_{50} = 3 AC/H (l/s)
Hall incl. stairs (GF+FF)	1	0	33.6	26.2	16.8	10.1
Living Room	2	4	26.1	20.4	13.1	7.8
Dining Room	2	0	18.5	14.4	9.2	5.5
Bedroom 1	3	4	23.6	18.4	11.8	7.1
Bedroom 2	4	0	25.1	19.6	12.5	7.5
Bedroom 3	5	0	10.3	8.0	5.2	3.1
Kitchen	6	4	14.4	11.2	7.2	4.3
Bathroom + WC	7	4	11.0	8.6	5.5	3.3
		Total	162.5	126.8	81.3	48.8

Table A2: Exposure and permeability-related ventilation rates for each room

[18] Extracted from the set of data selected and approved by CSTB for the instruction of French Technical Approvals.

- **Occupation scenarios[19]:**

For each person, a data file specifies the person's presence in the various rooms: 1 = present, 0.1 to 0.9 = presence shared between several rooms. The file also defines if the occupant is awake or asleep (asleep = 2) which corresponds to different levels of water and CO_2 generation – see corresponding section below.

The scenario is split between week days and week end. The week end starts Fridays at 6pm and stops Sundays at 6pm. The weekly scenario is repeated over the heating season.

			Pers1 (Mother having lunch at home)					Pers2 (Father working full time)					Pers3 & Pers4 (Kids at school)				
	From	To	Living	Dining	Bed1	Kitchen	Bath_WC	Living	Dining	Bed1	Kitchen	Bath_WC	Living	Dining	Bed2 / Bed3	Kitchen	Bath_WC
Week	00:00	06:00			2					2					2		
	06:00	06:30				1						1			2		
	06:30	07:00					1				1				2		
	07:00	07:30				0.5	0.5									0.5	0.5
	07:30	08:00				0.5	0.5									0.5	0.5
	08:00	12:00															
	12:00	12:30		0.5		0.5											
	12:30	13:00		0.5		0.5											
	13:00	17:30															
	17:30	18:00															
	18:00	18:30				1									1		
	18:30	19:00				1		1							1		
	19:00	19:30		1					1					1			
	19:30	20:00		1					1					1			
	20:00	20:30	1					1					1/0.7				-/0.3
	20:30	21:00	1					1					0.7/1				0.3/-
	21:00	21:30	1					1							2		
	21:30	22:00	0.7				0.3	1							2		
	22:00	22:30	1					0.7				0.3			2		
	22:30	23:00			2					2					2		
	23:00	23:30			2					2					2		
	23:30	00:00			2					2					2		
Week-end	00:00	08:00			2					2					2		
	08:00	08:30				1						1			2		
	08:30	09:00					1				1				2		
	09:00	09:30						1								0.5	0.5
	09:30	10:00						1								0.5	0.5
	10:00	10:30															
	10:30	11:00															
	11:00	11:30						0.5							0.5		
	11:30	12:00						0.5							0.5		
	12:00	12:30		0.5		0.5			1					1			
	12:30	13:00		0.5		0.5			1					1			
	13:00	13:30	1					1					1				
	13:30	14:00	1					1					1				
	14:00	14:30	1					1					0.5		0.5		
	14:30	15:00	1					1					0.5		0.5		
	15:00	15:30															
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	17:00	17:30						0.5							0.5		
	17:30	18:00						0.5							0.5		
	18:00	18:30				1		1					0.5		0.5		
	18:30	19:00				1		1					1				
	19:00	19:30		1					1					1			
	19:30	20:00		1					1					1			
	20:00	20:30	1					1					1/0.7				-/0.3
	20:30	21:00	1					1					0.7/1				0.3/-
	21:00	21:30	1					1							1		
	21:30	22:00	1					1							1		
	22:00	22:30	0.7				0.3	1							1		
	22:30	23:00	1					0.7				0.3			1		
	23:00	23:30	1					1							2		
	23:30	00:00	1					1							2		

Table A3: Room occupancy scenario for each person. Absence periods in grey.

- **Metabolic Water vapour and CO_2 generation[20]** :

A person awake generates 16 l/h of CO_2 and 40 g/h of water vapour. A person asleep generates 10 l/h of CO_2 and 40 g/h of water vapour.

[19] Adapted from the set of data selected and approved by CSTB for the instruction of French Technical Approvals.
[20] Values extracted from the set of data selected and approved by CSTB for the instruction of French Technical Approvals.

- **Water vapour generation[21]:**
Water vapour is generated when the person is in the corresponding room, see the 'Occupation scenarios' section.

Kitchen:	Breakfast preparation	50 g per occupant over half hour
	Lunch preparation	150 g per occupant over one hour
	Diner preparation	300 g per occupant over one hour

Bathroom: 300 g per occupant over half hour (1 shower per occupant and per day).
Clothes washing and drying is assumed to take place in the bathroom.
One wash cycle per week and per person, distributed over the week.
200 g per wash cycle, over 2 hours.
1,000 g for drying after each washing cycle, spread over 20 hours.

- **Ventilation components**
  - **Wall Vents**: We have considered 100 mm holes through the walls, with grilles on each side. The grilles let 75 m^3/h through individually, but combined the air flow is reduced to 53 m^3/h (or 14.7 l/s) at 10 Pa. The grilles are positioned in all dry rooms and in the kitchen, 2.3 m high compared to the floor.

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Airflow rate (l/s)
Hall incl. stairs (GF+FF)	1	0	-
Living Room	2	4	14.7
Dining Room	3	0	14.7
Bedroom 1	4	4	14.7
Bedroom 2	5	0	14.7
Bedroom 3	6	0	14.7
Kitchen	7	4	14.7
Bathroom + WC	8	4	-

Table A4: Wall Vents - Exposure and ventilation rates @ 10 Pa for each room

  - **Blocked Vents**: In that case, the vents are blocked by the occupants and there is no ventilation other than coming from the permeability of the house. The idea is to simulate a "real-life" case seen all too often. As the occupants feel the cold draughts more than they feel poor IAQ, they block the vents with tape, plastic bags or even socks in the ducts.

  - **Intermittent Fans:** Natural ventilation with intermittent fans. As it was described to us, the AVASH house had no intermittent fans. These are however very common, so we have simulated this case. Intermittent fans in kitchen (no cooker hood) and bathroom. The fans are equipped with anti-backdraught shutters and are running during cooking and bathroom time. Extraction rates as per TGD F 2009. Background ventilation as in the case of Wall Vents. The 6 vents are compatible with TGD F 2009 based on 69 m^2 and a permeability down to 5 $m^3/h/m^2$. Two more vents would be necessary below that level, but they are unlikely to be added. We have therefore considered the same amount of vents in Case D.

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[21] Values extracted from the set of data selected and approved by CSTB for the instruction of French Technical Approvals. Note that these data generally consist in greater vapour generation than mentioned in England and Wales AD Part F for whole-house ventilation (Appendix A), which gives emission rates unrelated to the number of occupants: 1000 g over one hour for kitchens, and 650 g over two hours for bathrooms.

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Airflow rate (l/s)
Hall incl. stairs (GF+FF)	1	0	-
Living Room	2	4	14.7
Dining Room	3	0	14.7
Bedroom 1	4	4	14.7
Bedroom 2	5	0	14.7
Bedroom 3	6	0	14.7
Kitchen (background / fan)	7	4	14.7 / 60
Bathroom + WC (background / fan)	8	4	- / 15

Table A5: Intermittent fans –
Exposure and ventilation rates for each room

- **MEV**: Constant airflow Mechanical Extract Ventilation. In this scenario, it is assumed that wall vents are kept in dry rooms (corresponding to 53 m^3/h or 14.7 l/s at 10 Pa). The existing wall vent is suppressed during retrofit in kitchen. A central extract unit is installed. Extract rates are defined after England and Wales Part F 2010 recommendations.

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Airflow rate (l/s)
Hall incl. stairs (GF+FF)	1	0	-
Living Room	2	4	14.7
Dining Room	3	0	14.7
Bedroom 1	4	4	14.7
Bedroom 2	5	0	14.7
Bedroom 3	6	0	14.7
Kitchen	7	N/A	13.0
Bathroom + WC	8	N/A	8.0

Table A6: MEV- Exposure and intended ventilation rates for each room

- **MEV UK**: Constant airflow Mechanical Extract Ventilation with window inlets. We use this scenario only to evaluate VOC levels. It is assumed that windows are changed and equipped with background ventilation in the form of 2,500 mm^2 inlets in dry rooms (corresponding to 25 m^3/h or 6.9 l/s at 10 Pa). Existing wall vents are suppressed during retrofit in dry rooms and kitchen. A central constant airflow extraction fan is installed. Supply and extract rates are defined after England and Wales Part F 2010 recommendations.

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Airflow rate (l/s)
Hall incl. stairs (GF+FF)	1	0	-
Living Room	2	4	6.9
Dining Room	3	0	6.9
Bedroom 1	4	4	6.9
Bedroom 2	5	0	6.9
Bedroom 3	6	0	6.9
Kitchen	7	N/A	13.0
Bathroom + WC	8	N/A	8.0

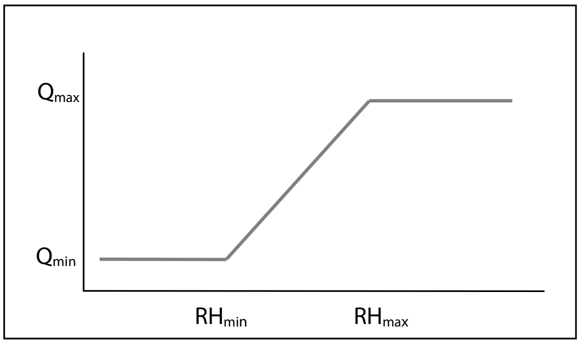
Table A7: MEV UK - Exposure and intended ventilation rates for each room

- **DC MEV**: Demand-controlled Mechanical Extract Ventilation. Existing Aereco products have been used.

  All dry rooms are equipped with through the wall acoustic, humidity-controlled air inlets (Aereco's EHT969 kits). They fit in existing 100 mm holes. The bathroom and kitchen are equipped with boostable humidity-controlled extract terminals. In the kitchen, the boost rate can be activated by a switch, to compensate for the lack of cooker hood (Aereco's BXC215). In the bathroom, due to toilets, presence detection provides a boost rate to evacuate odours as needed (Aereco's BXC275). There is a 20 minutes overrun in the boost after the last presence detection in the bathroom. Then, the unit reacts based on the humidity sensor. A central constant pressure extraction fan is installed. Extract rates are defined after England and Wales Part F 2010 recommendations.

Mise en forme : Puces et numéros

For the needs of the simulations, humidity-controlled components are described by the airflow rate (Q) as a function of indoor relative humidity (RH). A typical curve is shown below. The boundaries of Q and RH variable ranges (Q_{min} – Q_{max}, RH_{min} – RH_{max}) are enough to describe the component to the software. The boost rate corresponds to Q_{max}.



Graph A8: Typical behaviour of a humidity-controlled ventilation terminal

Demand-Controlled MEV is described as follows:

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Flow parameters (Q range in l/s – %RH range)	Reference pressure difference
Hall incl. stairs (GF+FF)	1	0	-	-
Living Room	2	4	1.4 - 11.1 - 35 - 65	10
Dining Room	3	0	1.4 - 11.1 - 35 - 65	10
Bedroom 1	4	4	1.4 - 11.1 - 35 - 65	10
Bedroom 2	5	0	1.4 - 11.1 - 35 - 65	10
Bedroom 3	6	0	1.4 - 11.1 - 35 - 65	10
Kitchen	7	N/A	3.3 – 19.4 - 30 - 75 Boost during cooking: 19.4	100
Bathroom + WC	8	N/A	3.3 – 19.4 - 30 – 75 Boost during presence: 19.4	100

TableA 9: DC MEV - Exposure and ventilation characteristics for each room

- **MVHR:** Mechanical Ventilation with Heat Recovery. We have simulated a 90% heat recovery system, with no pre-heating. Ventilation rates come from the Irish TGD F 2009, at 21 l/s based on 4-person occupancy. Air is supplied in the dry rooms so that the total supply rate is balanced with the total extraction rate in the wet rooms. The heat recovery ration is multiplied by an "in-use" factor as in SAP2009 Table 4h, in order to allow for pressure losses from ductwork. Ducts are assumed to be insulated, so the heat recovery ratio is multiplied by 0.85. It therefore falls to 76.5%. If the duct were not insulated, it would be multiplied by 0.70 and would fall to 63%.

Room description	Room no.	Exposure N=0 E=2 S=4 W=6	Airflow rate (l/s)	Reference pressure difference
Hall incl. stairs (GF+FF)	1	0	-	100
Living Room	2	N/A	4.2	100
Dining Room	3	N/A	4.2	100
Bedroom 1	4	N/A	4.2	100
Bedroom 2	5	N/A	4.2	100
Bedroom 3	6	N/A	4.2	100
Kitchen	7	N/A	13	100
Bathroom + WC	8	N/A	8	100

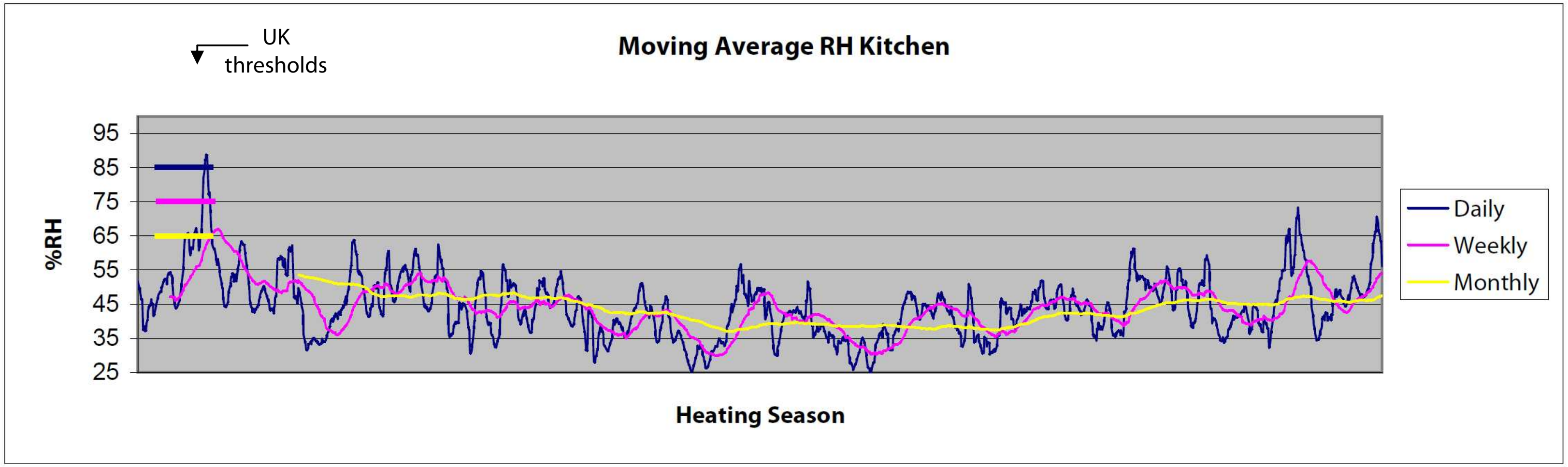
Table A10: MVHR - Exposure and ventilation characteristics for each room

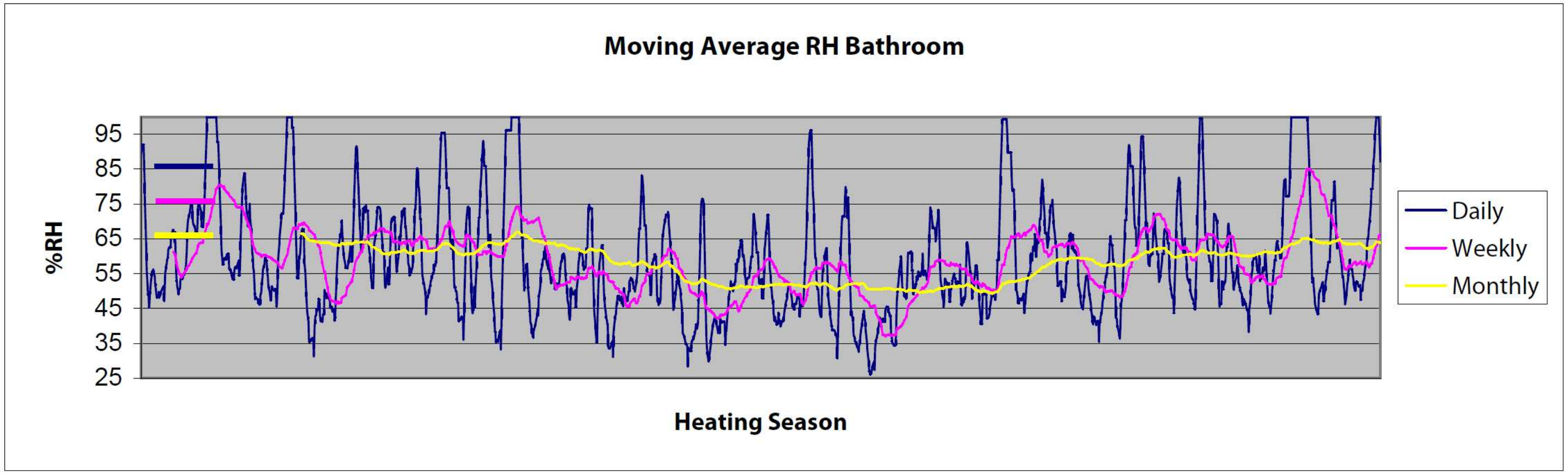
Appendix B – Detailed Results

The following pages shows detailed results of the evolution of Relative Humidity over the heating season in all cases, as well as the detailed results of TVOCs frequency distributions in Case D.

Appendix B1

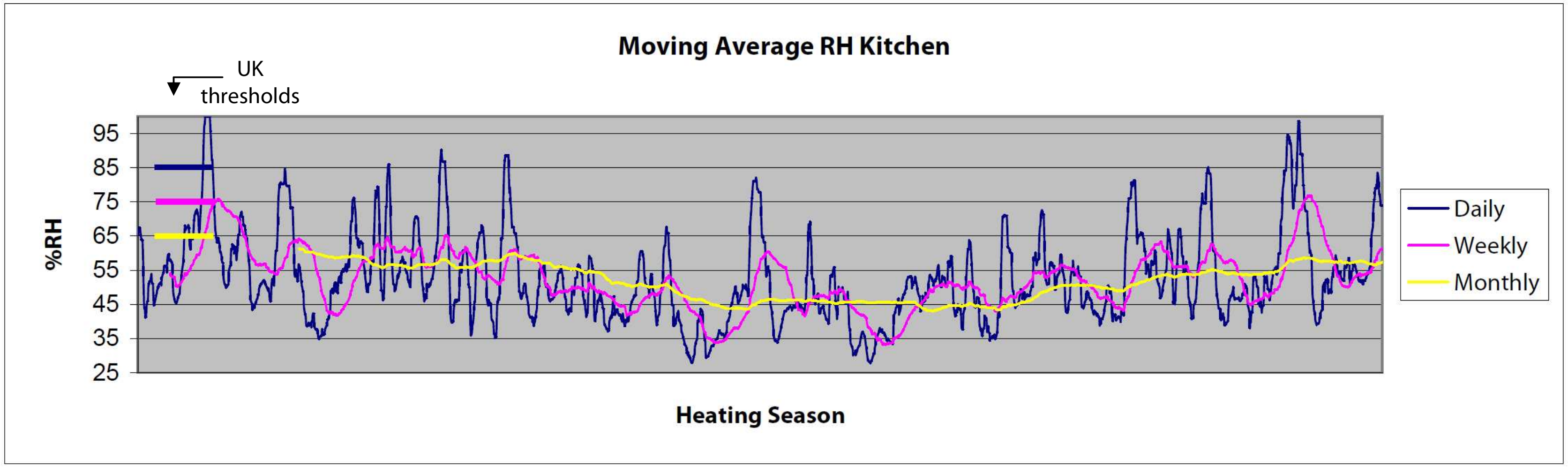
10ACH - Wall Vents

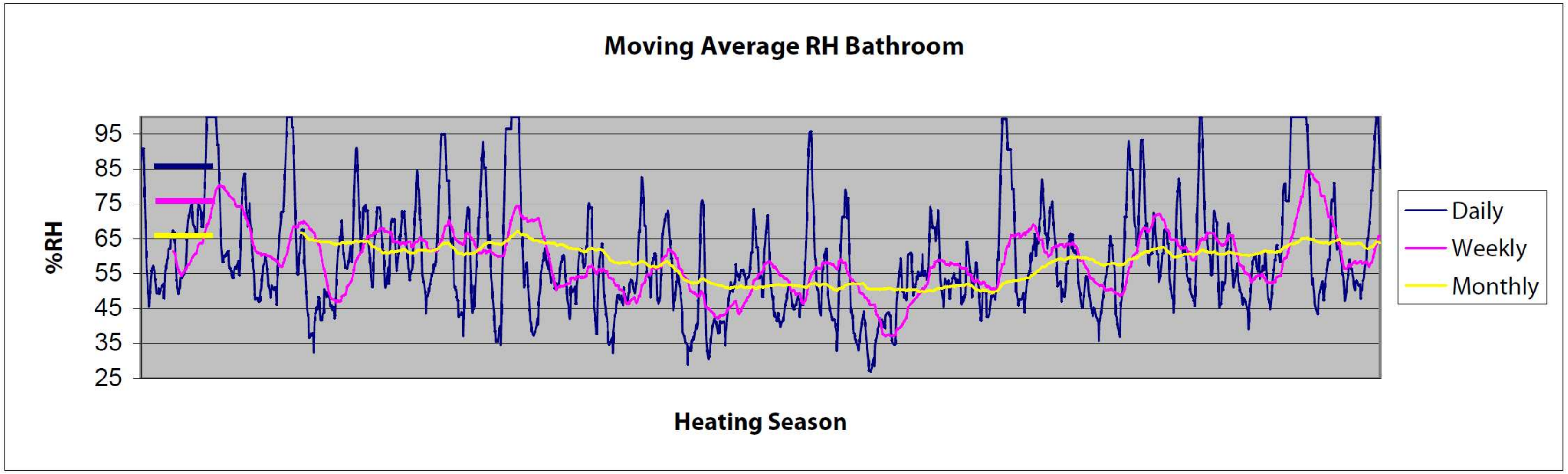




Appendix B2

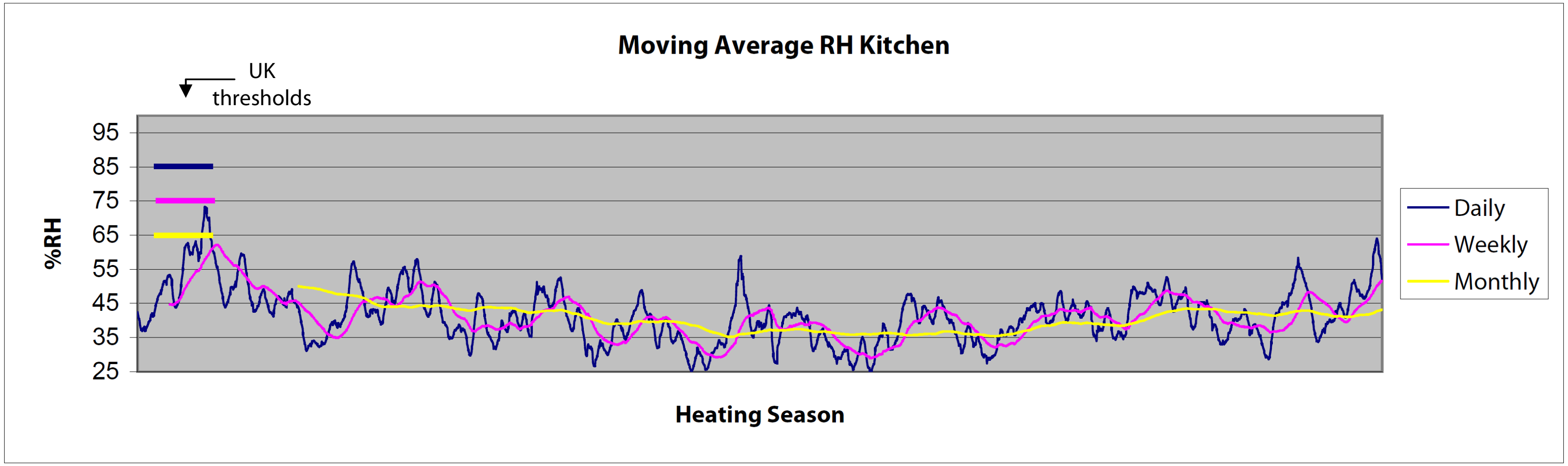
10ACH - Blocked Vents

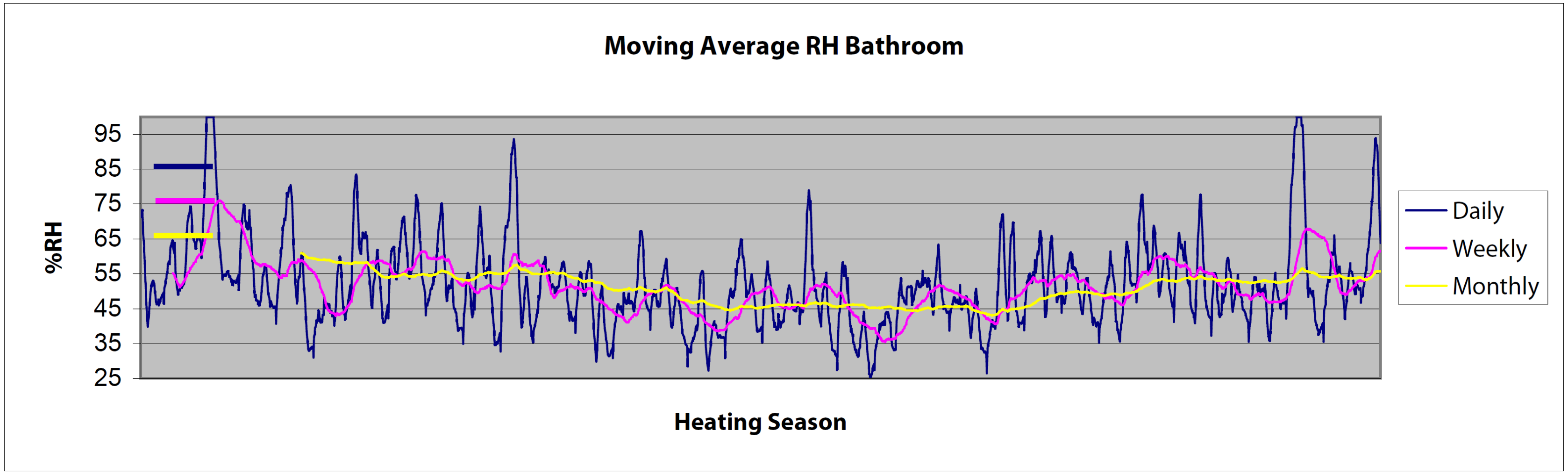




Appendix B3

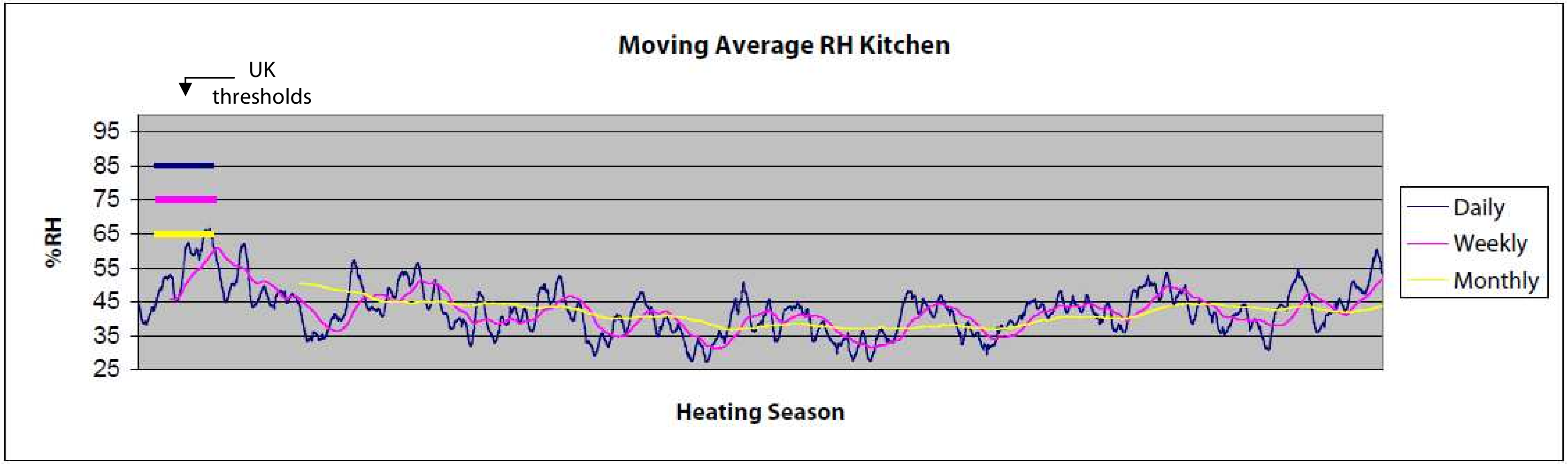
10ACH - Intermittent Fans

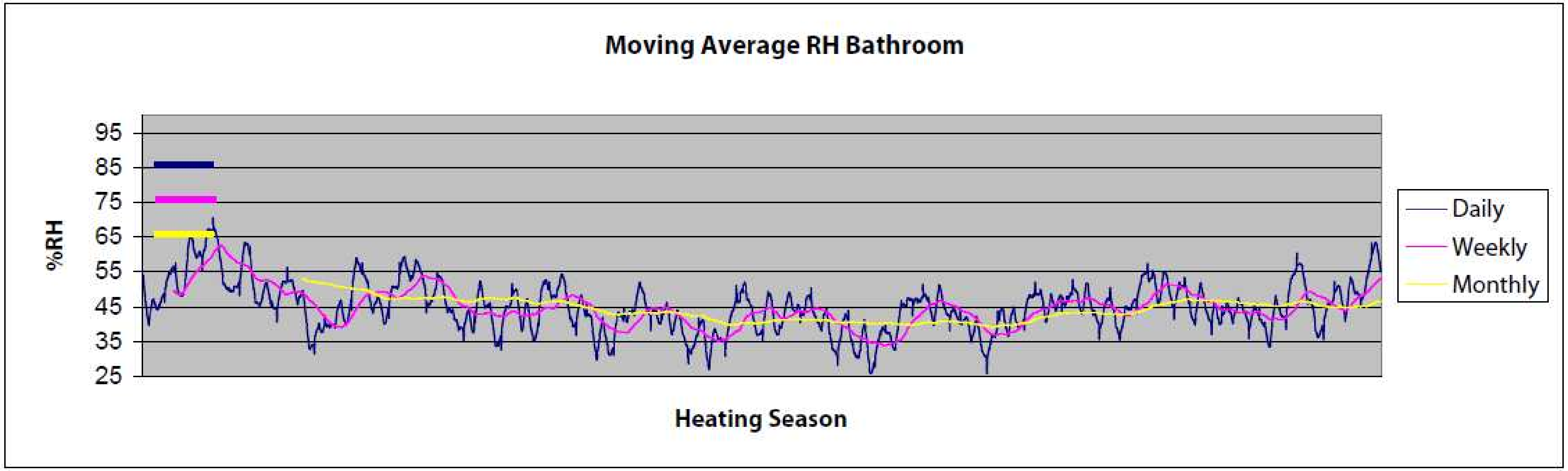




Appendix B4

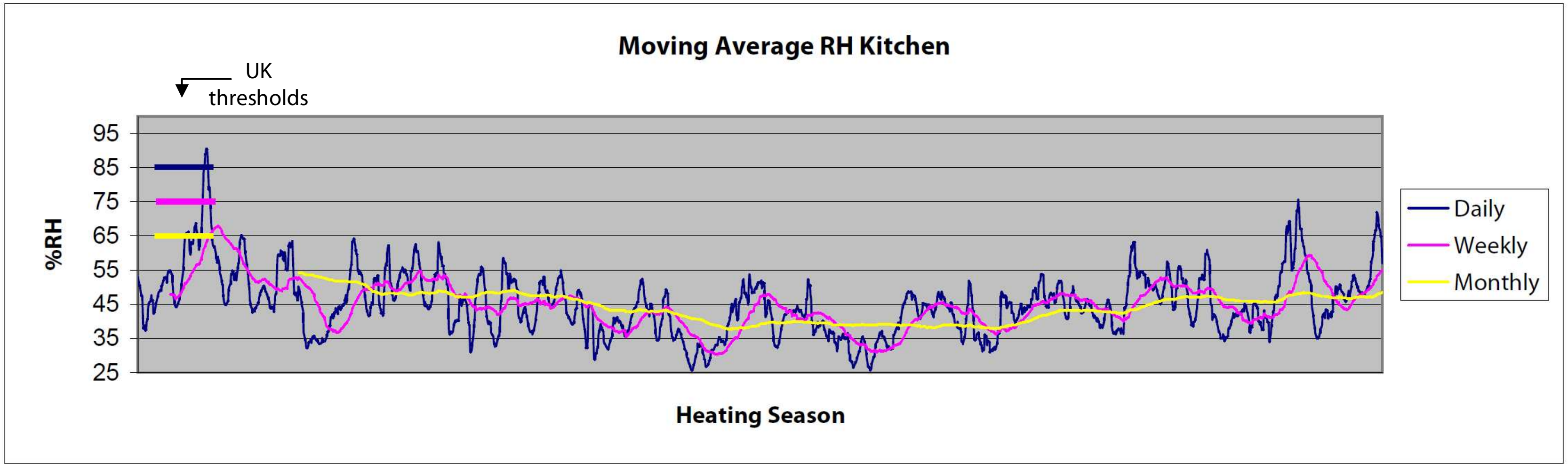
10ACH - DC MEV

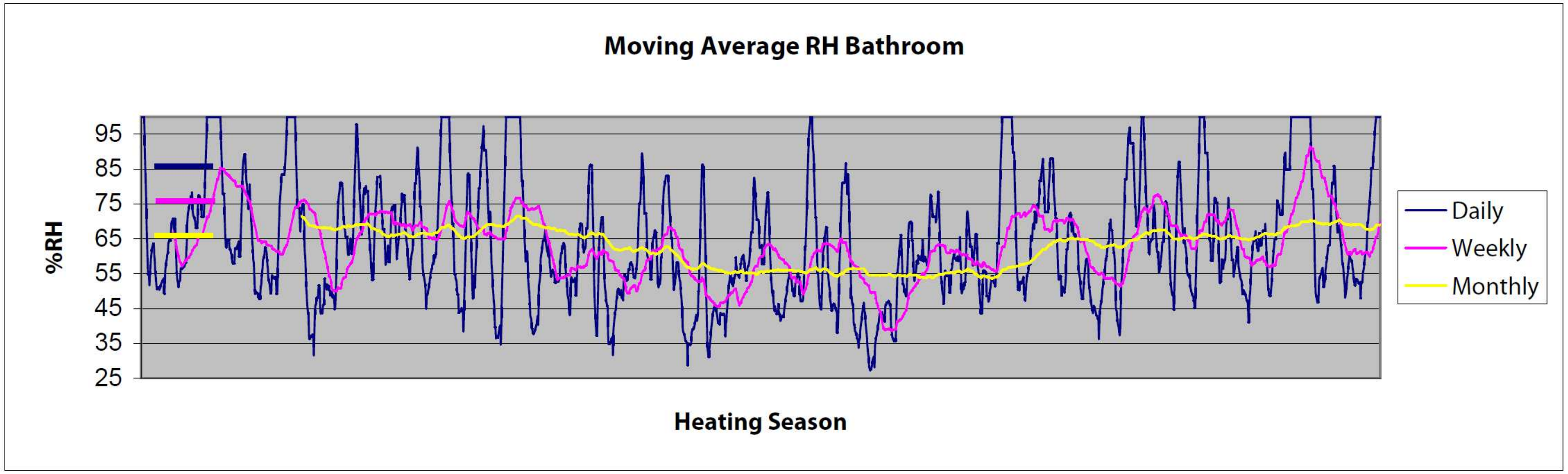




Appendix B5

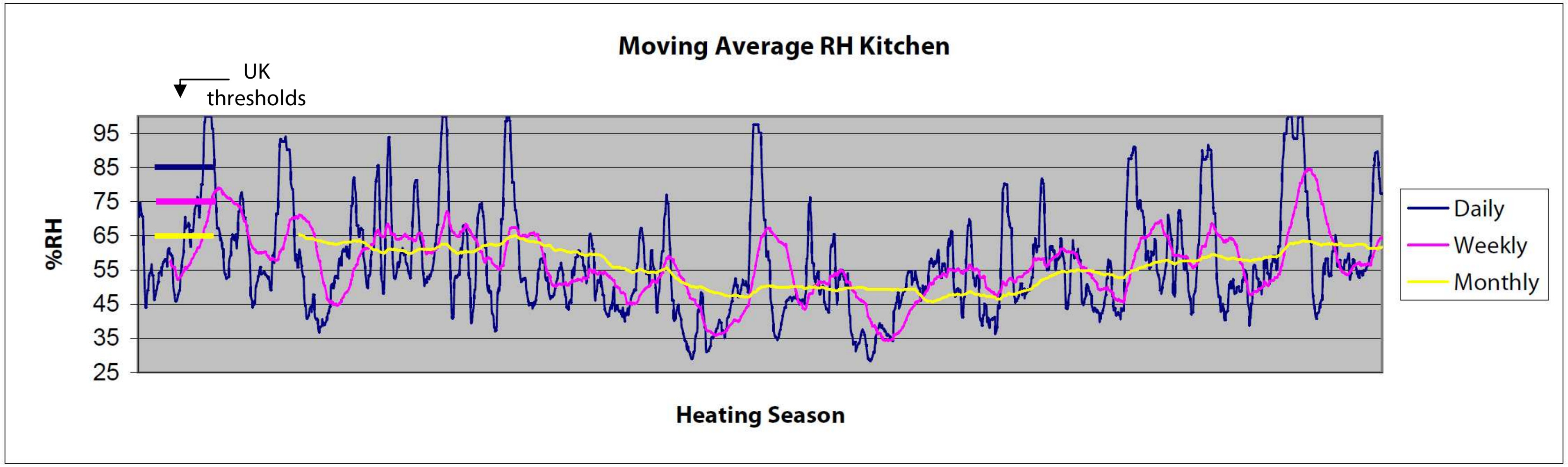
7.8ACH - Wall Vents

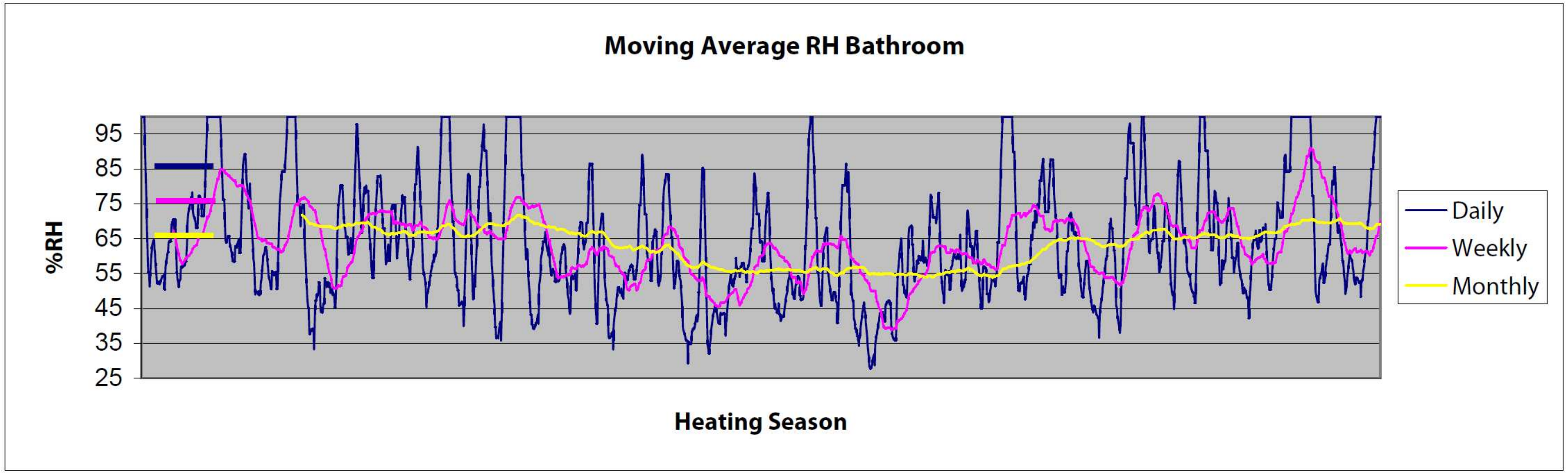




Appendix B6

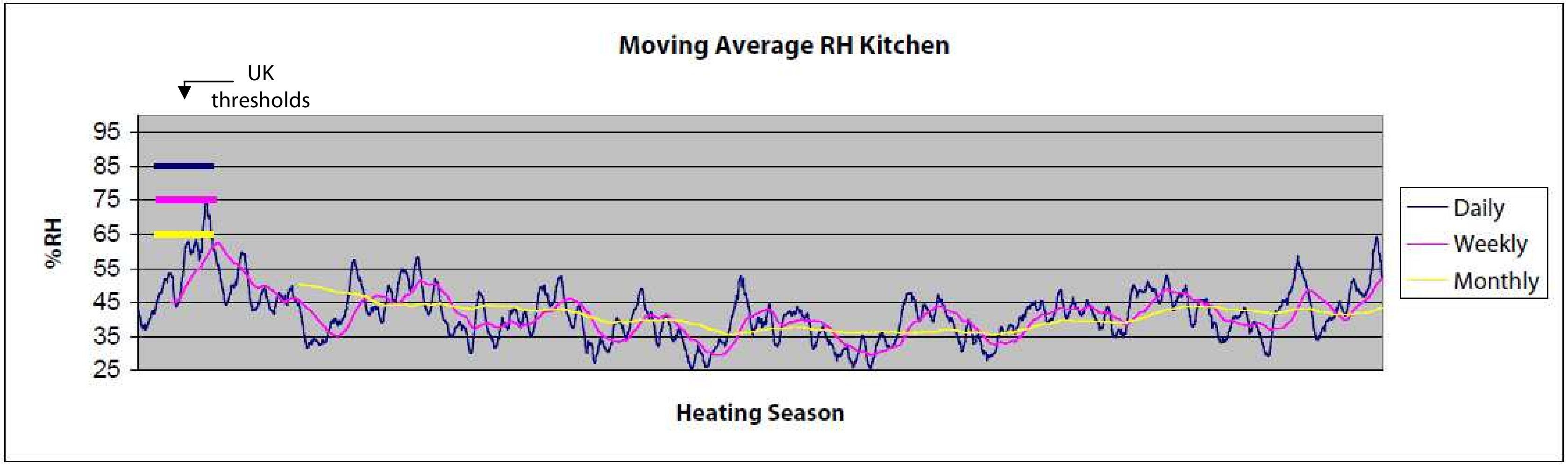
7.8ACH - Blocked Vents

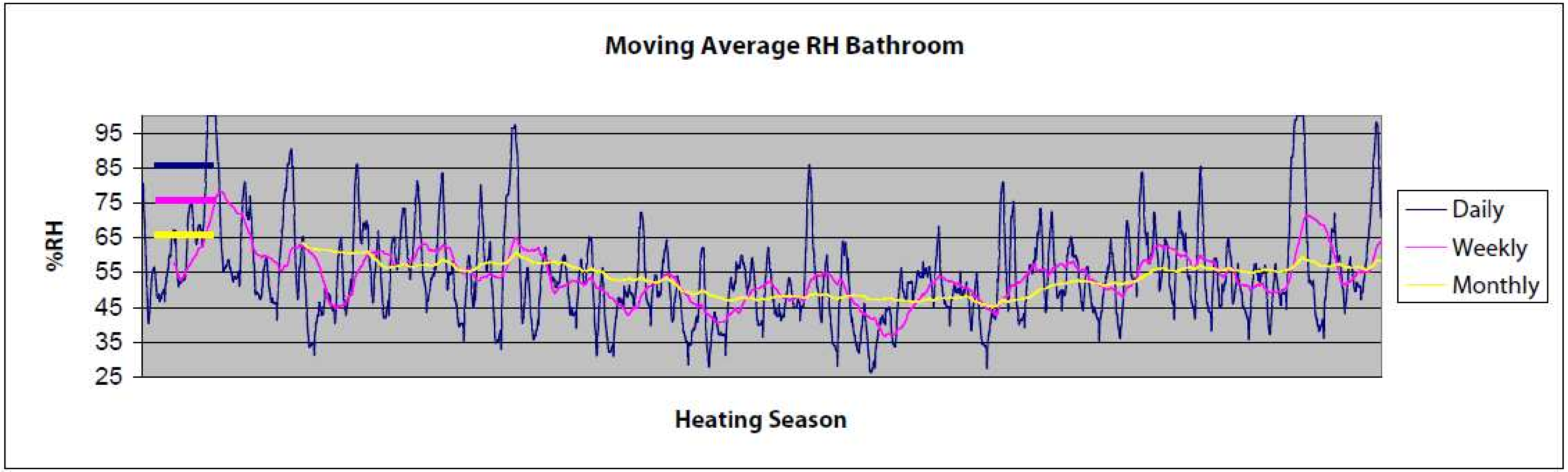




Appendix B7

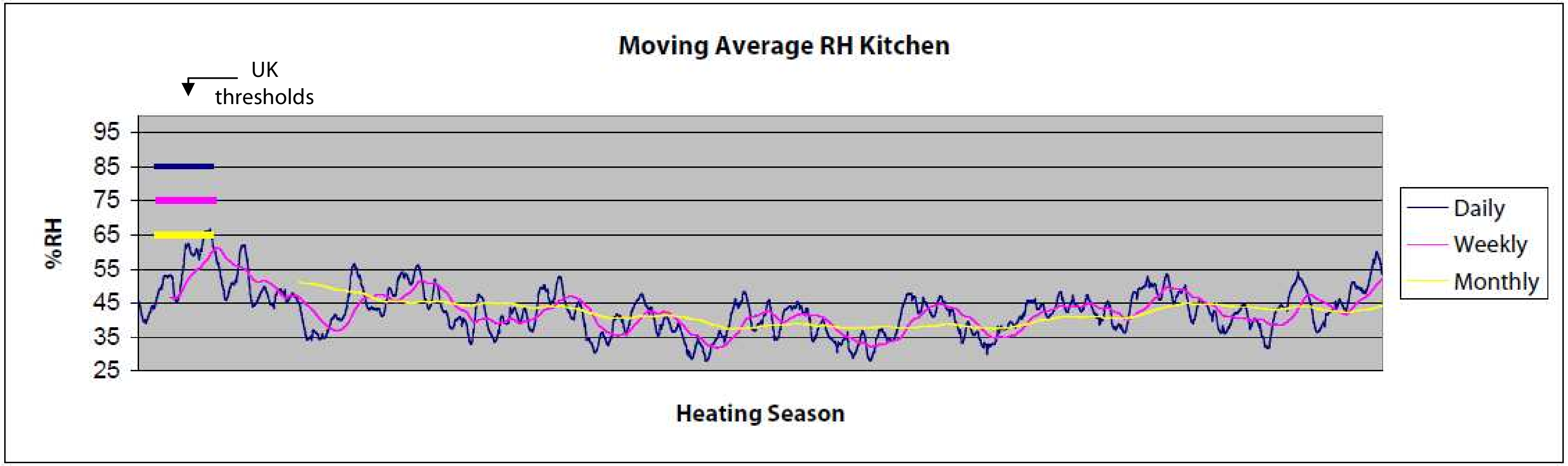
7.8ACH - Intermittent Fans

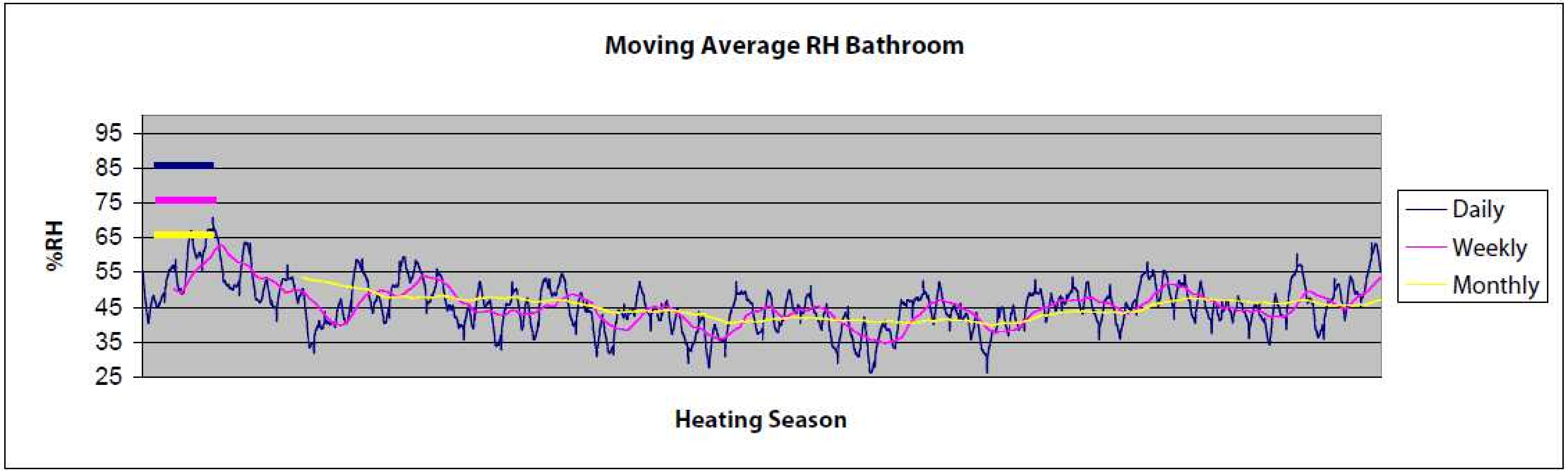




Appendix B8

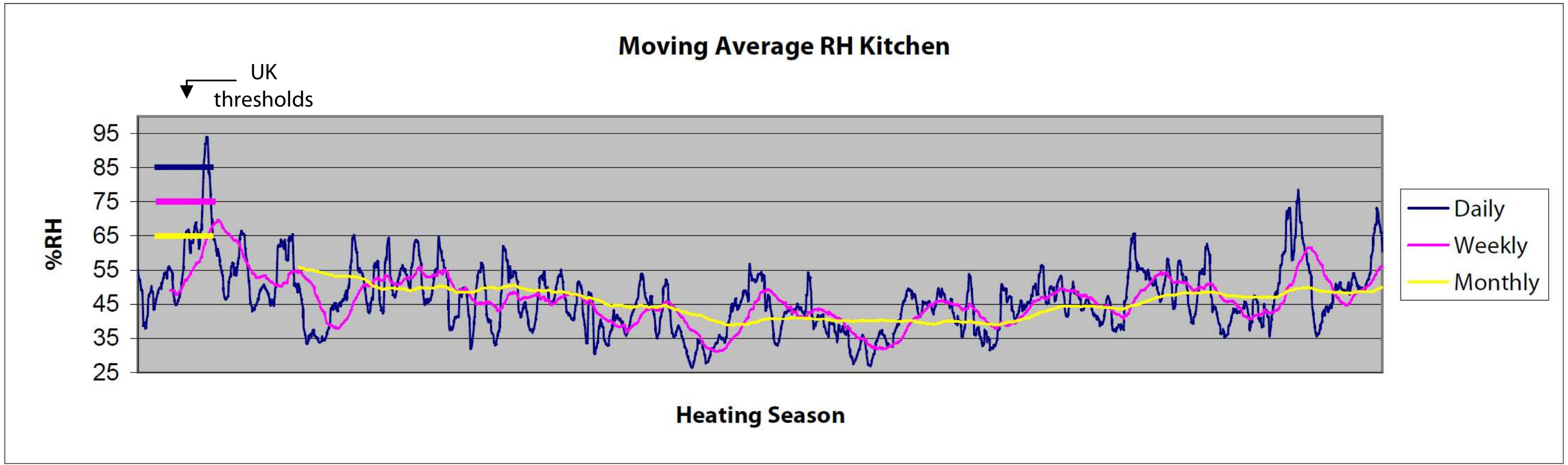
7.8ACH - DC MEV

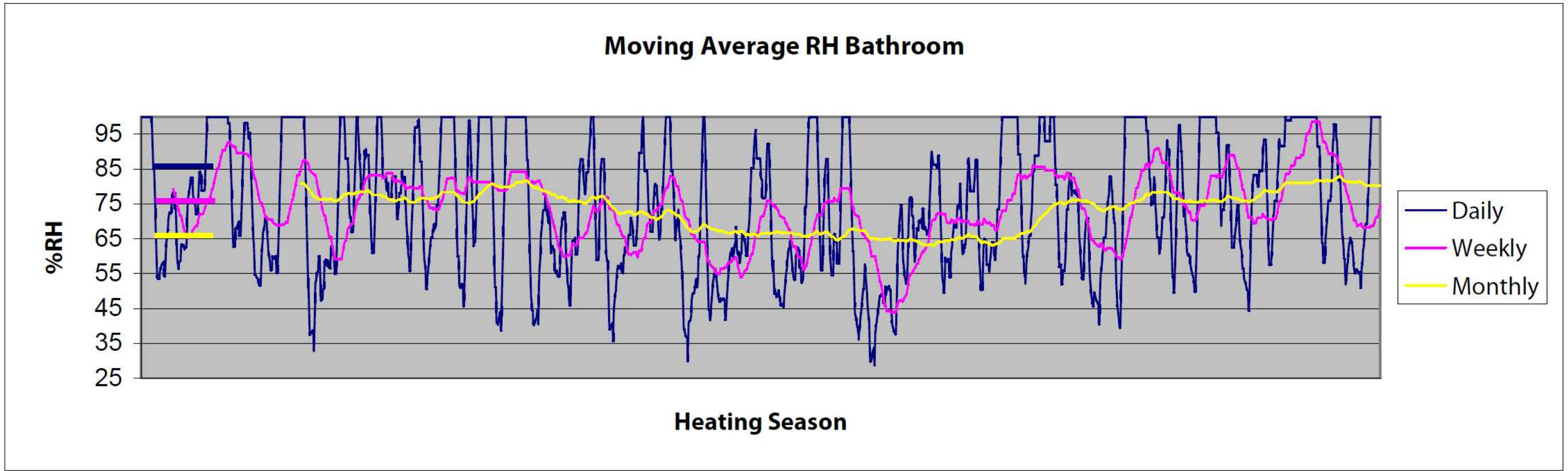




Appendix B9

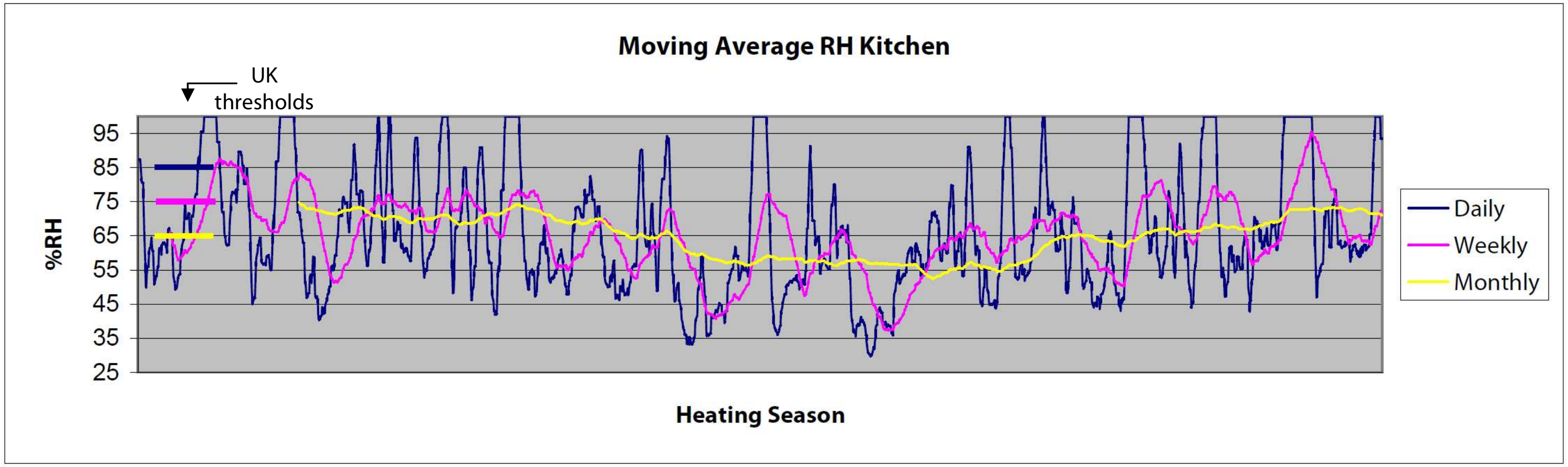
5ACH - Wall Vents

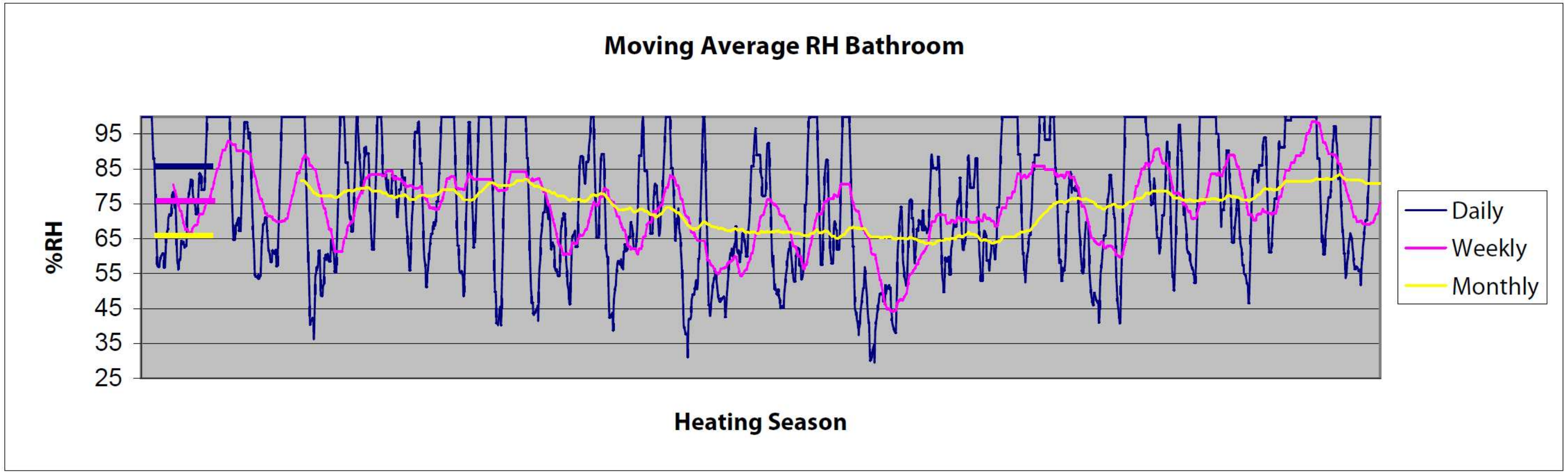




Appendix B10

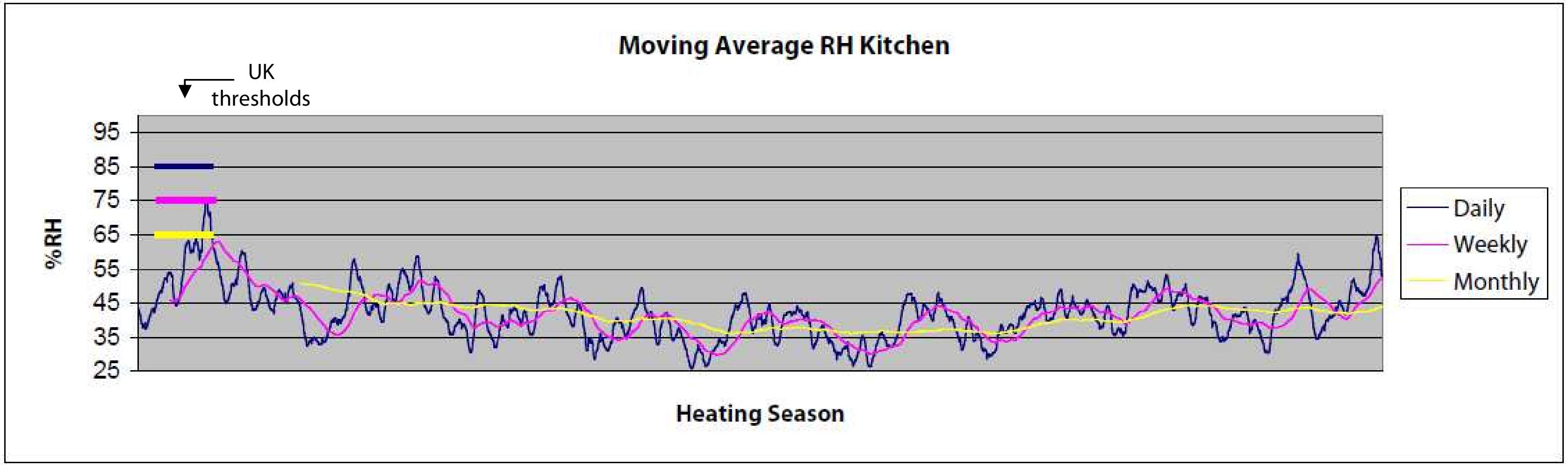
5ACH - Blocked Vents

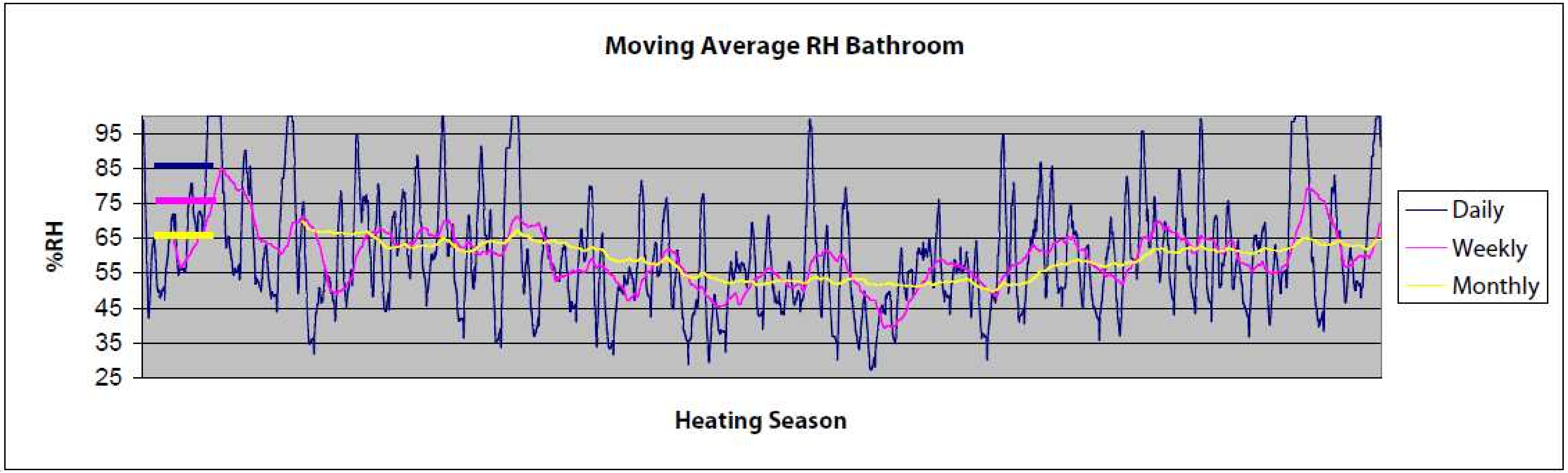




Appendix B11

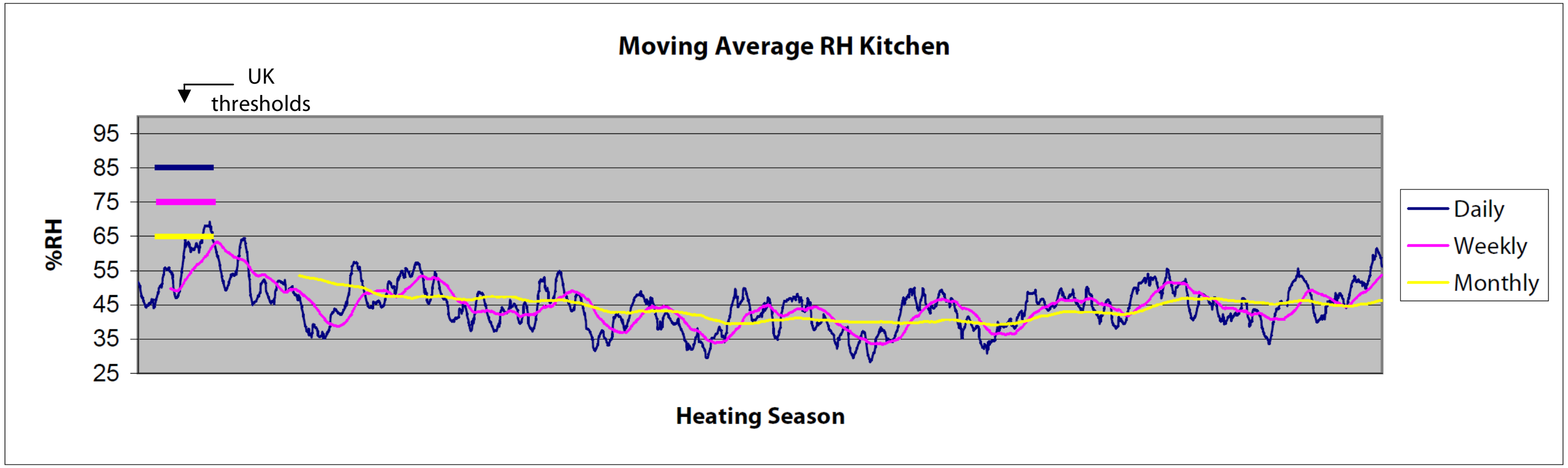
5ACH - Intermittent Fans

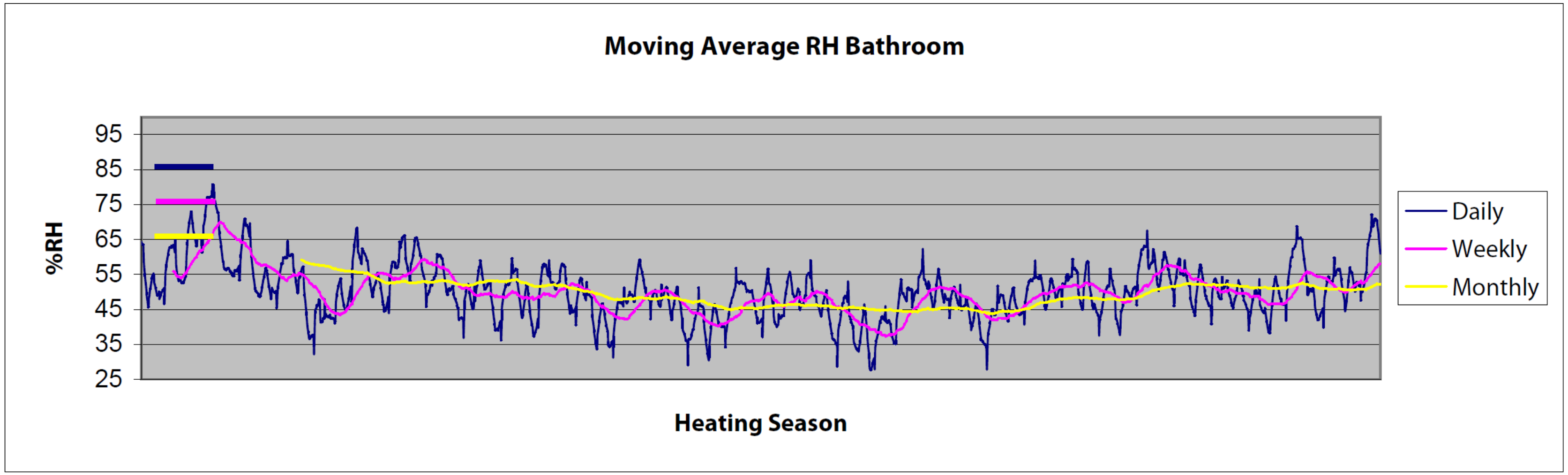




Appendix B12

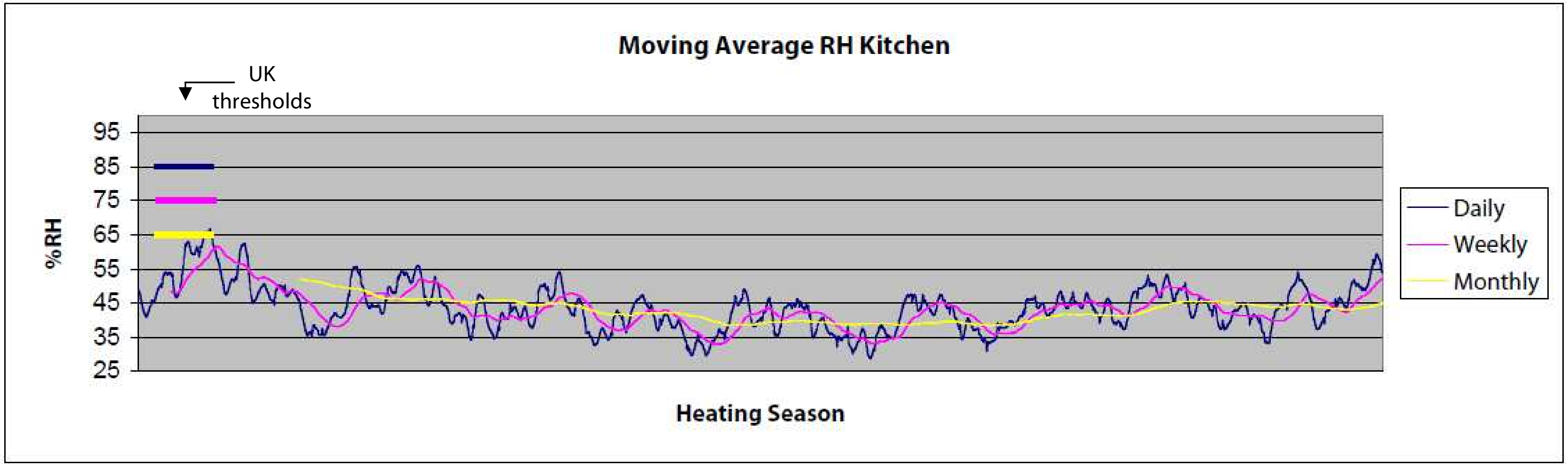
5ACH - MEV

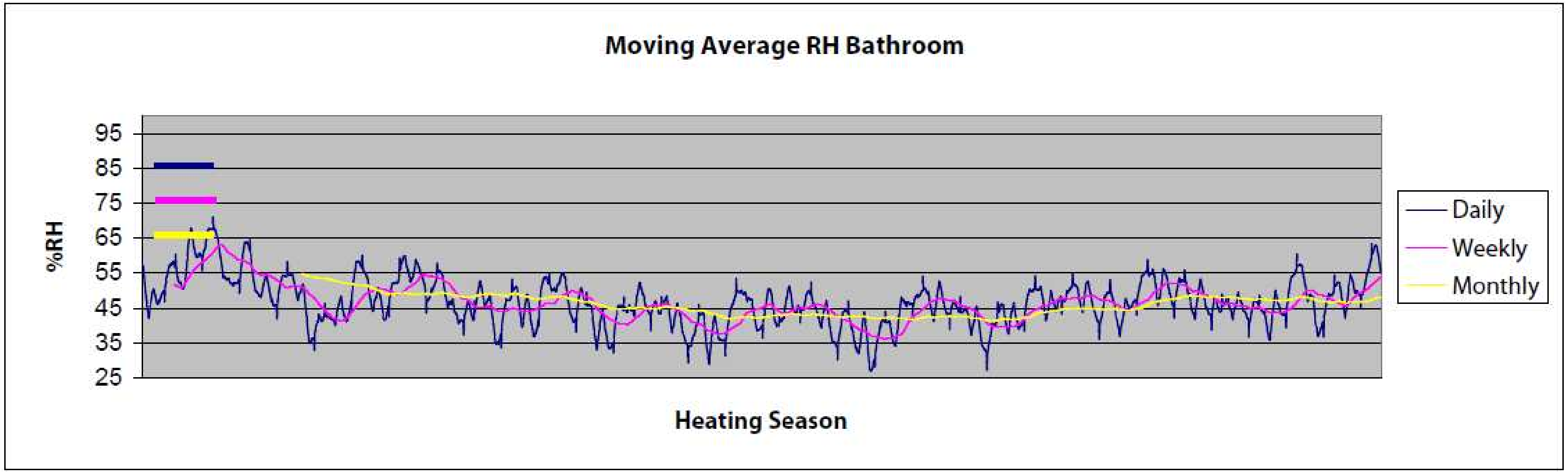




Appendix B13

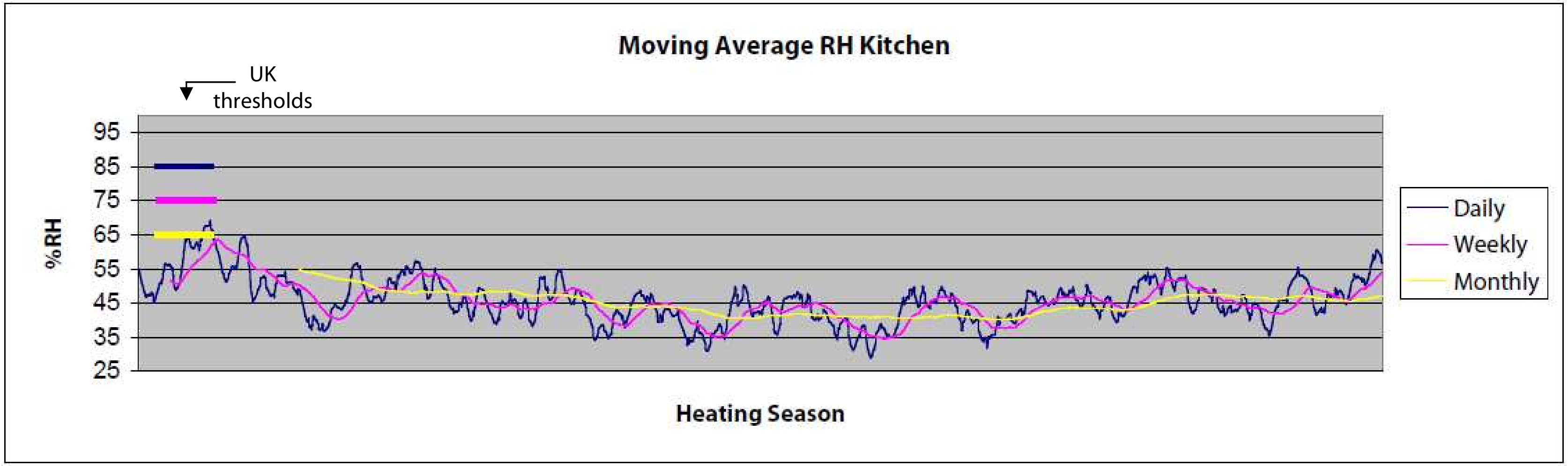
5ACH - DC MEV

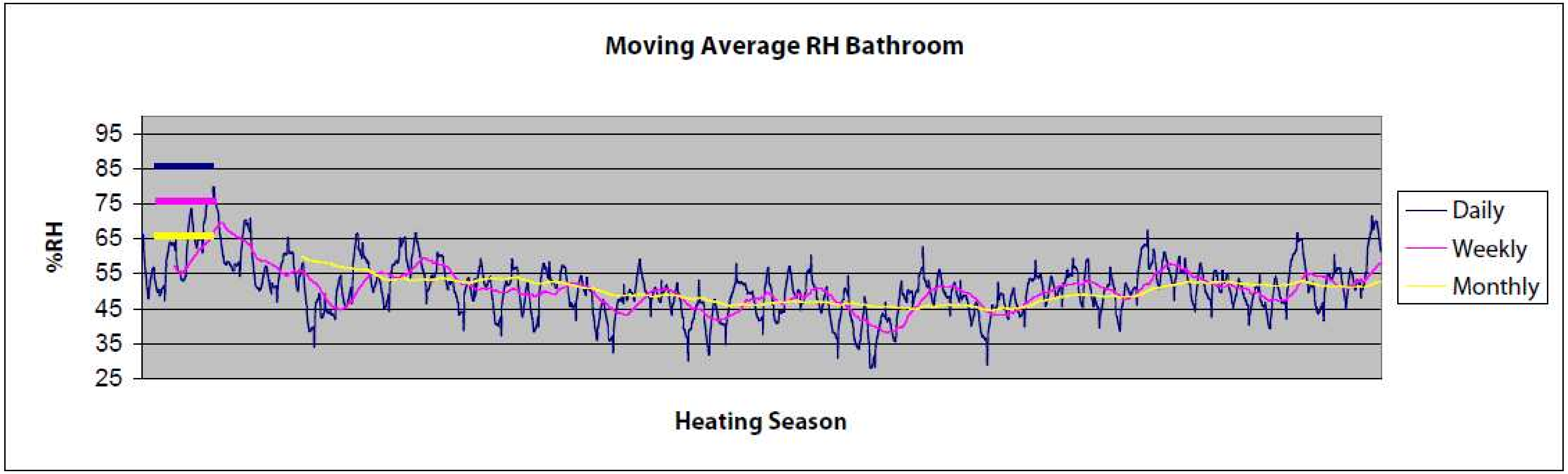




Appendix B14

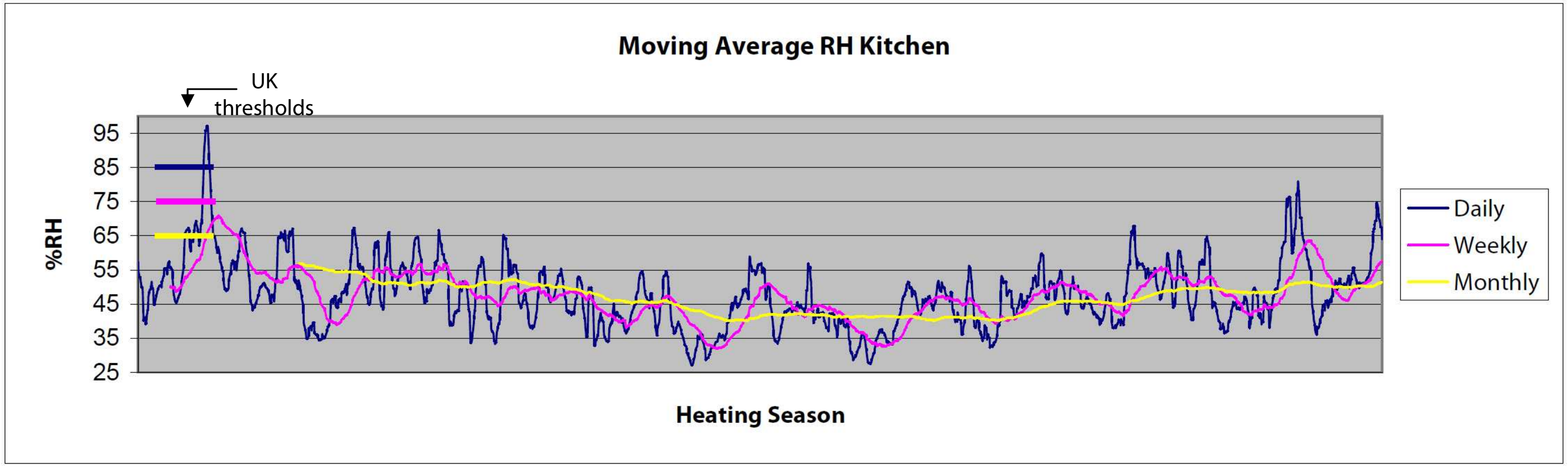
5ACH - MVHR

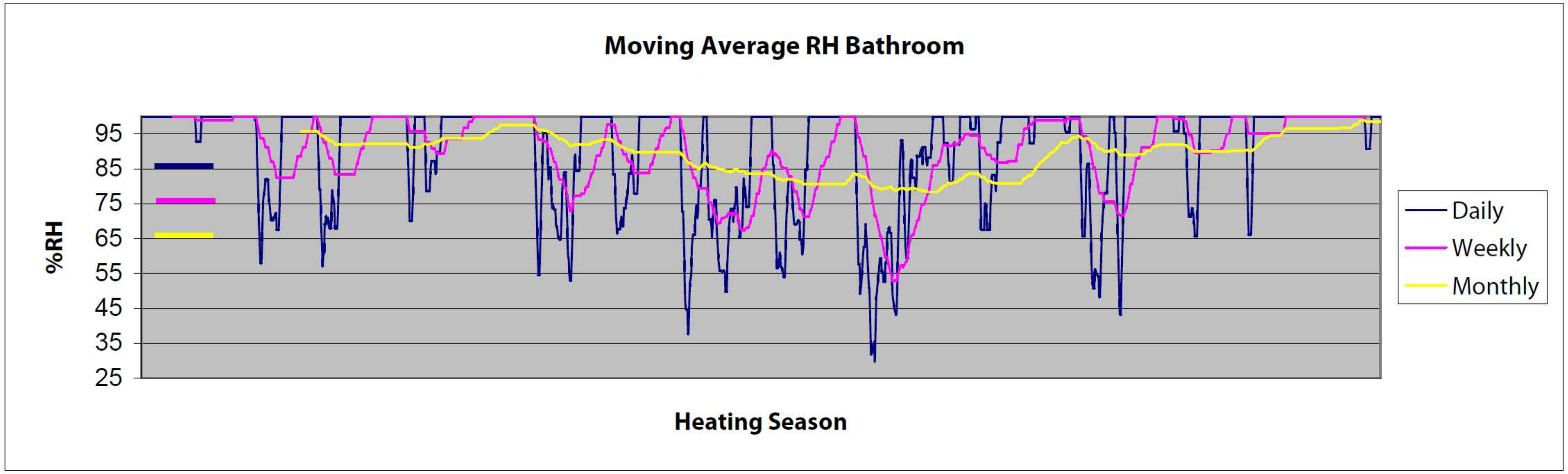




Appendix B15

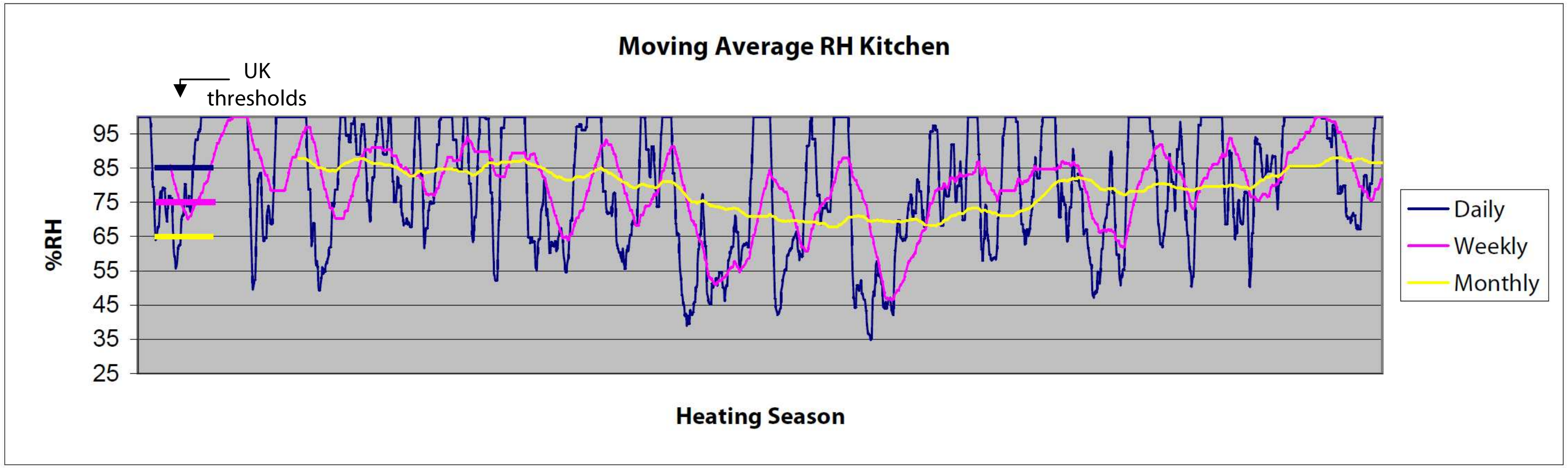
3ACH - Wall Vents

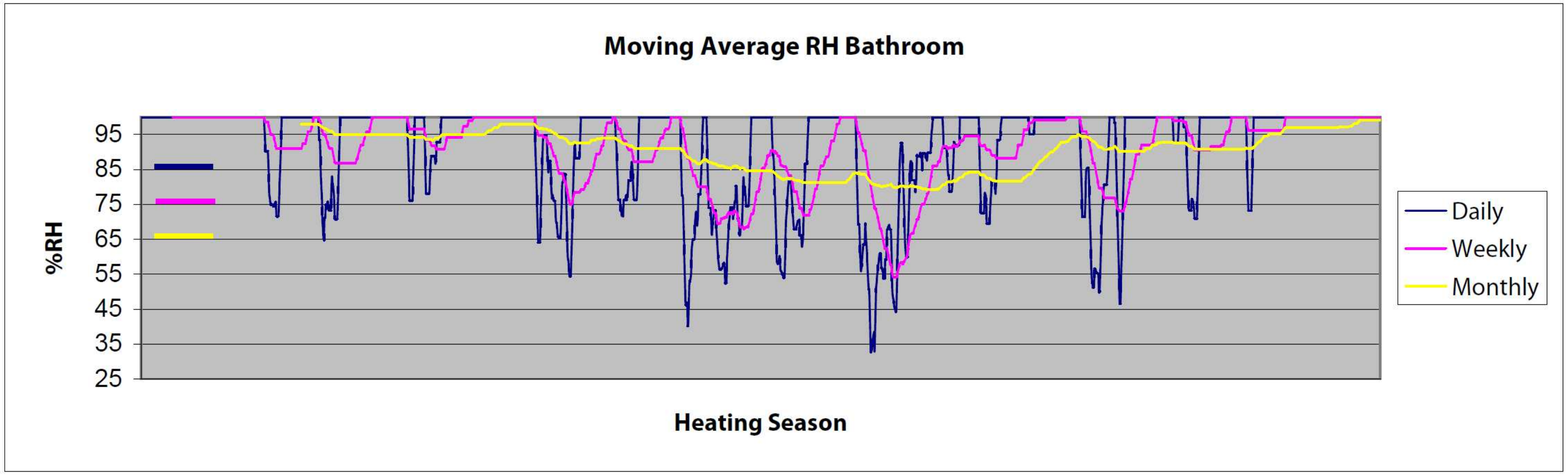




Appendix B16

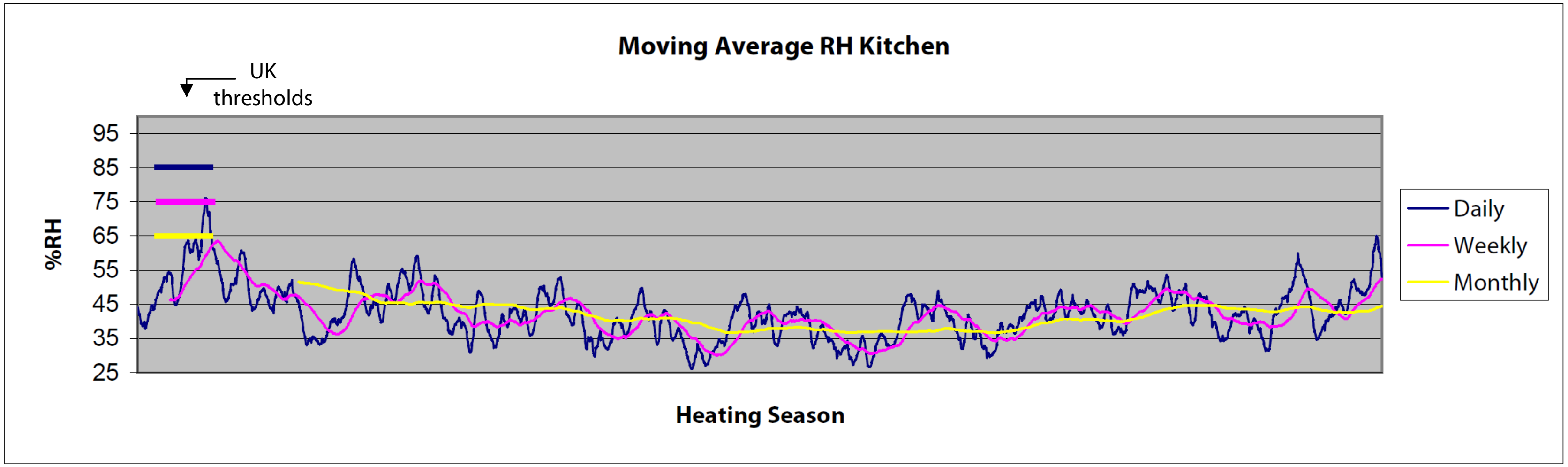
3ACH - Blocked Vents

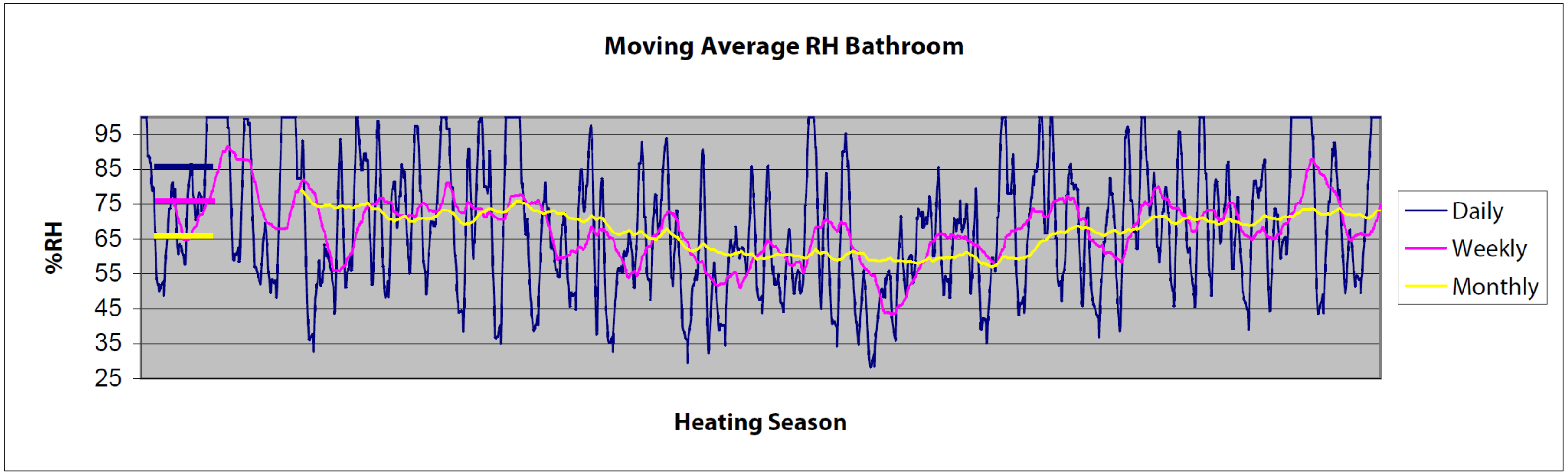




Appendix B17

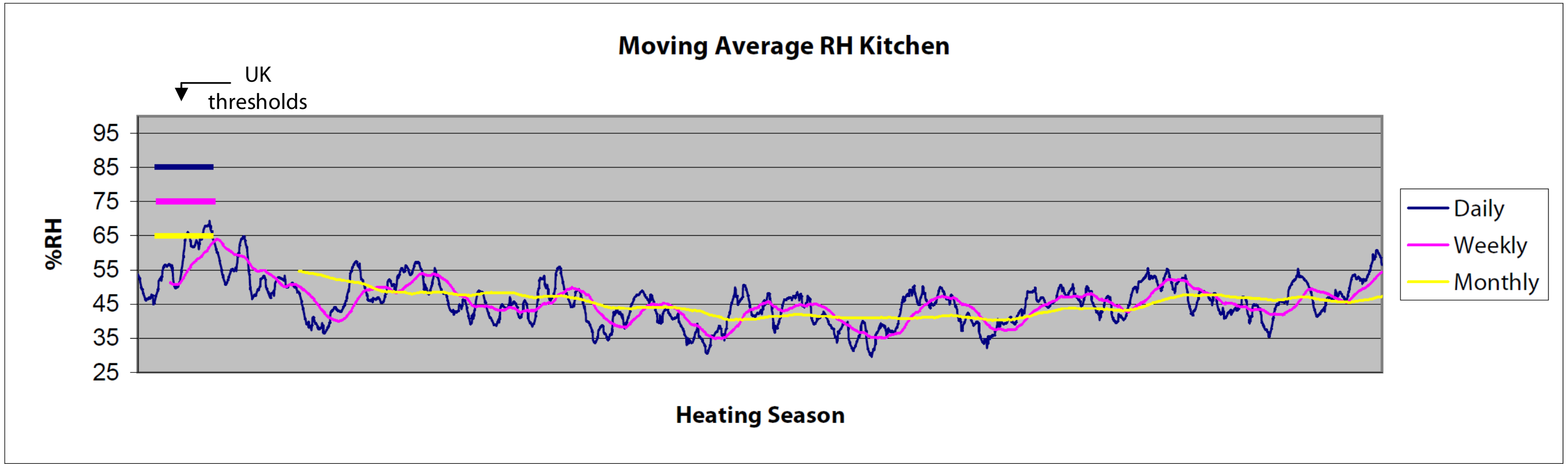
3ACH - Intermittent Fans

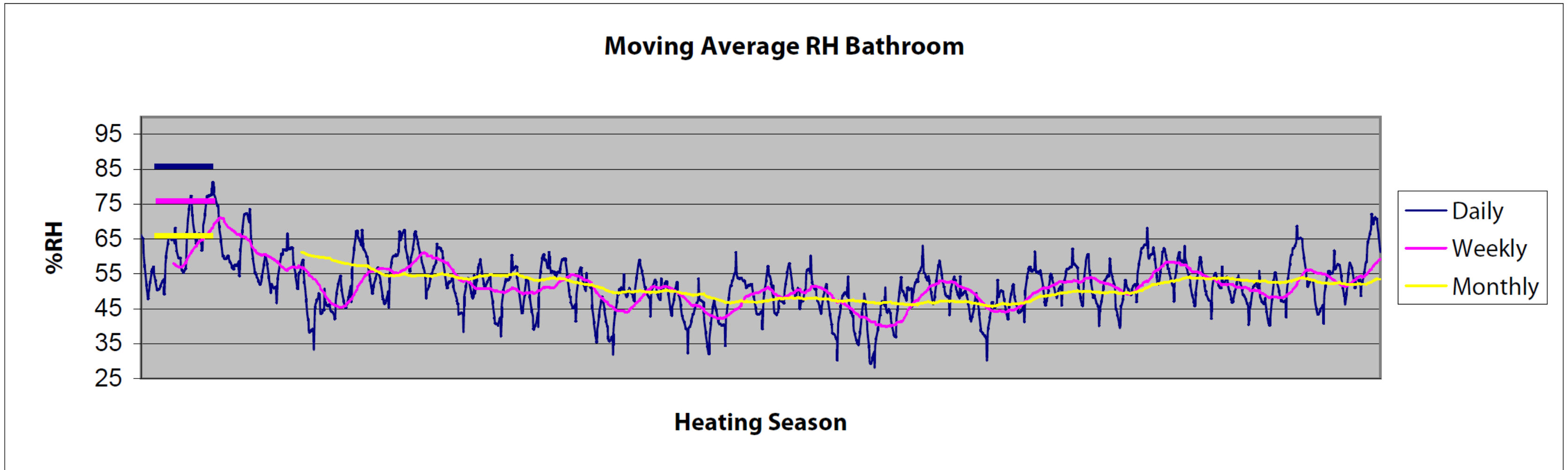




Appendix B18

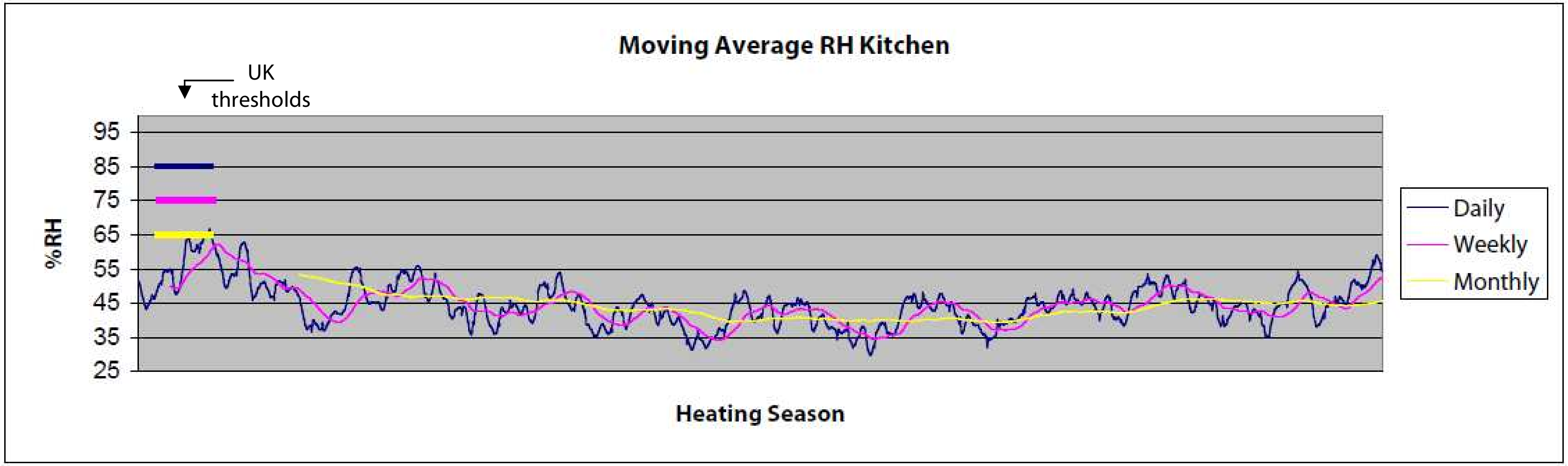
3ACH - MEV

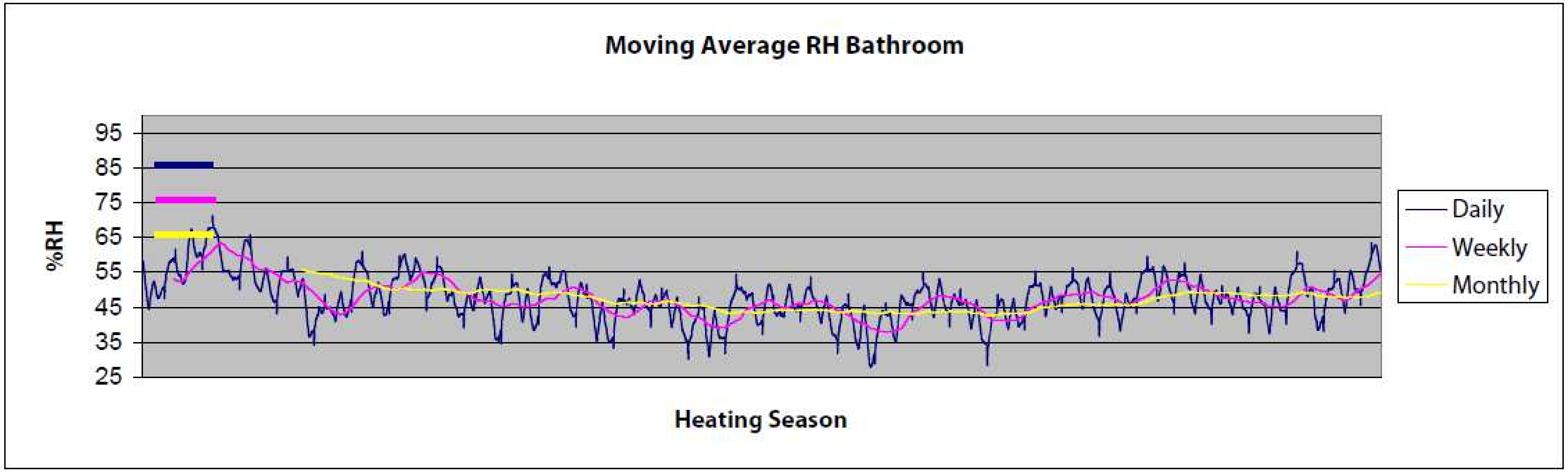




Appendix B19

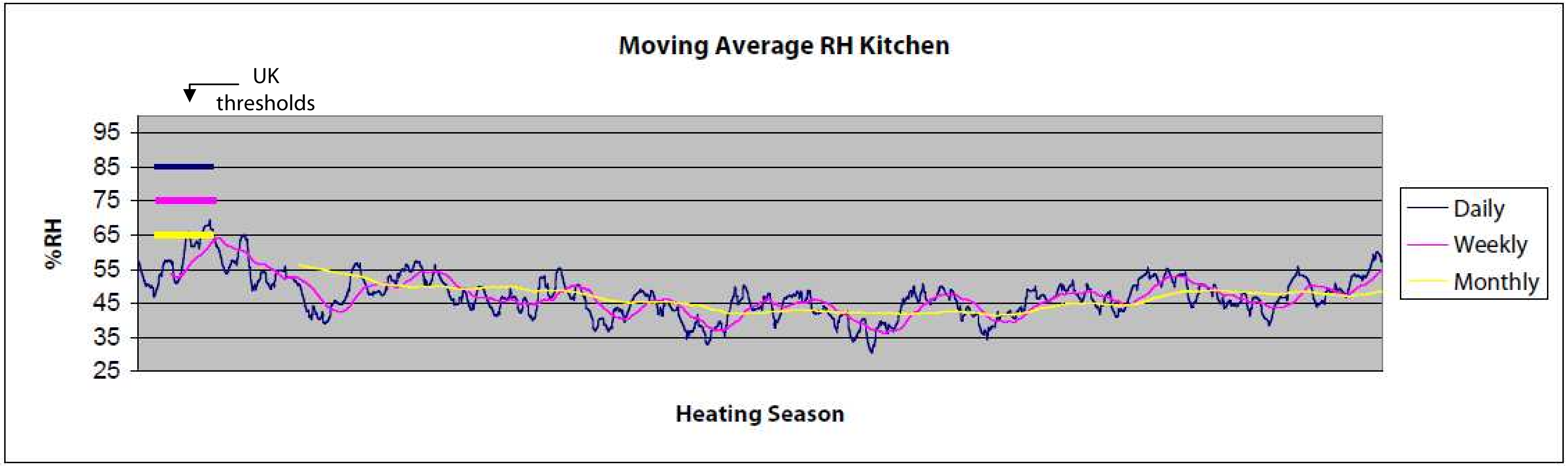
3ACH - DC MEV

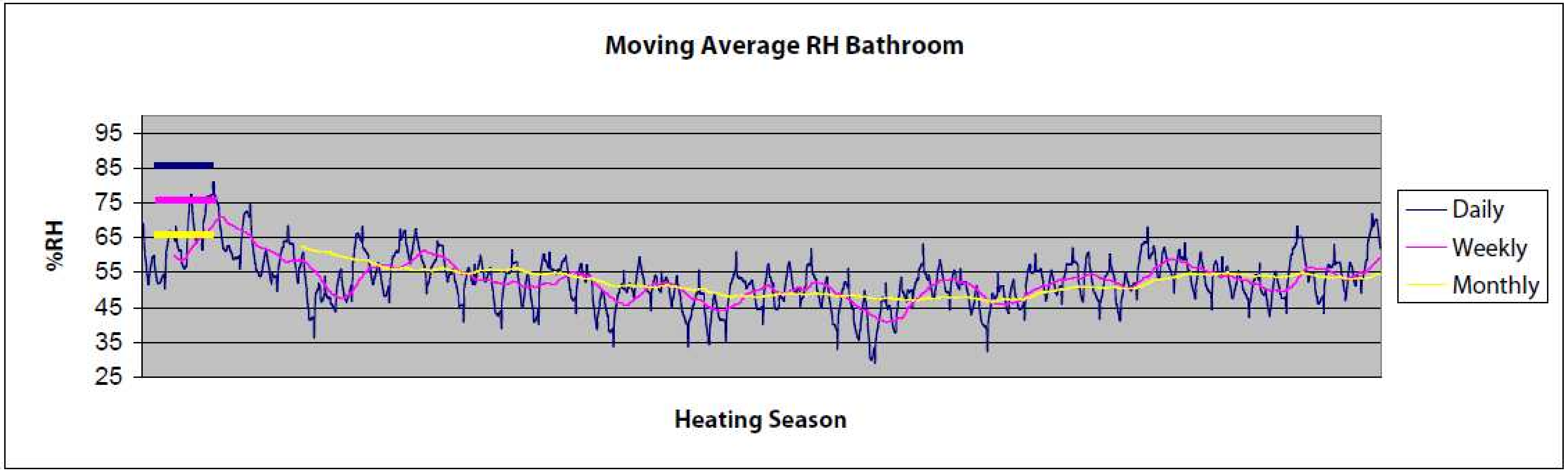




Appendix B20

3ACH - MVHR





Appendix B21

AVERAGE OVER 8 HOURS DURING PRESENCE - ROOM BY ROOM

Living

Intervals	Case D Wall Vents	Case D Blocked	Case D Int. Fan	Case D MEV	Case D MEV UK	Case D DCMEV	Case D MVHR
	2655	2184	2684	2929	2408	2345	2203
50	1584	216	1602	1669	1364	1254	949
100	738	525	760	640	882	963	1405
150	302	540	281	205	513	540	879
200	146	425	142	89	243	233	149
250	68	343	74	39	99	133	0
300	50	255	26	10	38	64	0
350	29	223	15	3	26	40	0
400	9	152	1	1	9	13	0
450	2	125	0	0	0	0	0
500	2	102	0	0	2	0	0
550	0	73	0	0	1	0	0
600	0	70	0	0	0	0	0
650	0	53	0	0	0	0	0
700	0	43	0	0	0	0	0
750	0	43	0	0	0	0	0
800	0	213	0	0	0	0	0

UK thresholds

Dining

	Case D Wall Vents	Case D Blocked	Case D Int. Fan	Case D MEV	Case D MEV UK	Case D DCMEV	Case D MVHR
	2766	2172	2801	2905	2397	2337	2217
50	1552	155	1593	1663	1125	934	1021
100	735	327	735	653	1001	983	2231
150	305	441	315	253	547	665	116
200	160	385	113	79	295	344	0
250	55	325	22	25	158	195	0
300	7	310	2	2	39	72	0
350	5	292	4	5	11	41	0
400	0	199	0	0	4	8	0
450	0	127	0	0	3	1	0
500	0	116	0	0	4	1	0
550	0	110	0	0	1	4	0
600	0	87	0	0	0	0	0
650	0	68	0	0	0	0	0
700	0	94	0	0	0	0	0
750	0	90	0	0	0	0	0
800	0	287	0	0	0	0	0

UK thresholds

Bed1	Case D Wall Vents	Case D Blocked	Case D Int. Fan	Case D MEV	Case D MEV UK	Case D DCMEV	Case D MVHR
	2532	2180	2559	2653	2381	2328	2201
50	1155	169	1218	1230	1026	987	876
100	908	457	881	811	878	853	1366
150	353	475	357	365	502	552	1142
200	226	369	230	211	271	320	0
250	160	325	160	122	170	176	0
300	146	277	133	76	112	108	0
350	57	206	25	49	70	99	0
400	17	170	22	35	61	68	0
450	24	110	0	23	51	47	0
500	7	115	0	8	23	26	0
550	0	84	0	2	15	16	0
600	0	66	0	0	8	5	0
650	0	76	0	0	6	0	0
700	0	73	0	0	7	0	0
750	0	49	0	0	4	0	0
800	0	384	0	0	0	0	0

Bed2	Case D Wall Vents	Case D Blocked	Case D Int. Fan	Case D MEV	Case D MEV UK	Case D DCMEV	Case D MVHR
	2404	2170	2422	2403	2255	2236	2183
50	1007	123	1034	954	664	618	490
100	902	287	925	850	727	680	1053
150	493	372	481	488	594	612	1280
200	261	356	291	345	428	436	579
250	214	324	228	210	284	325	0
300	163	243	139	120	187	216	0
350	83	247	49	88	175	166	0
400	30	216	8	40	122	119	0
450	16	153	7	21	70	88	0
500	4	115	1	14	30	43	0
550	8	101	0	15	17	17	0
600	0	84	0	12	5	17	0
650	0	62	0	13	11	12	0
700	0	59	0	3	2	0	0
750	0	78	0	4	1	0	0
800	0	595	0	5	13	0	0

Bed3	Case D Wall Vents	Case D Blocked	Case D Int. Fan	Case D MEV	Case D MEV UK	Case D DCMEV	Case D MVHR
	2717	2170	2758	2802	2519	2471	2337
50	1246	123	1297	1228	1005	927	3248
100	781	287	772	755	843	818	0
150	377	372	403	422	531	578	0
200	239	356	259	225	329	349	0
250	167	324	81	70	206	226	0
300	36	243	14	34	98	146	0
350	16	247	1	22	24	39	0
400	6	215	0	23	11	16	0
450	0	153	0	4	11	15	0
500	0	116	0	0	6	0	0
550	0	100	0	0	2	0	0
600	0	85	0	0	0	0	0
650	0	62	0	0	0	0	0
700	0	58	0	0	0	0	0
750	0	79	0	0	0	0	0
800	0	595	0	0	0	0	0

Appendix B22

AVERAGE OVER 8 HOURS DURING PRESENCE

FOLLOW-UP PER PERSON

Person 1

Intervals	Case D MEV UK	Case D DCMEV
	3073	3033
50	879	836
100	699	693
150	406	434
200	219	240
250	113	126
300	64	84
350	38	59
400	36	36
450	22	25
500	12	12
550	9	6
600	6	1
650	3	0
700	2	0
750	4	0
800	0	0

UK thresholds

Person 2

Intervals	Case D MEV UK	Case D DCMEV
	2832	2775
50	1019	965
100	740	752
150	428	462
200	233	245
250	115	138
300	65	86
350	38	62
400	37	36
450	21	24
500	12	12
550	9	6
600	6	1
650	3	0
700	2	0
750	4	0
800	0	0

Intervals	Person 3 Case D MEV UK	Case D DCMEV
	2496	2468
50	720	670
100	690	654
150	545	550
200	359	398
250	250	275
300	165	189
350	121	135
400	90	77
450	48	62
500	23	30
550	12	16
600	3	11
650	9	8
700	1	0
750	0	0
800	11	0

UK thresholds

Intervals	Person 4 Case D MEV UK	Case D DCMEV
	2669	2624
50	945	887
100	816	768
150	488	527
200	290	311
250	169	204
300	83	119
350	28	47
400	14	20
450	9	9
500	7	3
550	3	3
600	0	0
650	1	0
700	0	0
750	0	0
800	0	0