IEQ7570/3

Forced Air Ventilation Systems

Final

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About This Report

Title

Forced Air Ventilation Systems

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Abstract

Forced air or supply only ventilation systems have increased in popularity over the last 10 years and are now a frequently encountered system in new and renovated houses. It is estimated that 150,000 (almost 10%) households have a system. However, there has been little verification of how these systems operate under New Zealand conditions.

This project monitored 10 houses in Wellington and Christchurch with forced air ventilation systems, monitoring temperatures and humidities, fan properties and (in eight cases) the airtightness of the house. The houses, with existing systems were selected from participants in Beacon's HomeSmart Renovation Project, without reference to the system brand or age. This allows the study to be related more generally to how these systems operate.

This report discusses the methodology used to monitor the systems, the results of the monitoring and operation of forced air ventilation systems. Data from two houses in this study found that the time of operation of these forced air ventilation systems was important. At times, operation during the day would increase the moisture levels within the house while night time operation would tend to reduce moisture levels, but also reduce house temperatures. Forced air ventilation system controllers could be more effective if they are better able to distinguish when favourable times to operate are.

Reference

Pollard A and McNeil S June 2010. Forced Air Ventilation Systems. Report IEQ7570/3 for Beacon Pathway Limited.

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1 Executive Summary

Forced air or supply only ventilation systems have increased in popularity considerably over the last 10 years and are commonly encountered in new and renovated houses. These systems take fresh air from the roofspace and introduce it into the house. This transfers moisture and heat from the roofspace. Forced air ventilation systems have been promoted as assisting with moisture-related problems such as reducing the incidence of condensation on windows. Despite their popularity, there has been little verification of how these systems perform in New Zealand. It is important to establish if these systems are providing a solution to our cold and damp houses and this project makes a start in addressing this.

Ten houses with forced air ventilations systems in Wellington and Christchurch were selected for examination. Eight of these houses were subject to airtightness (‘blower door’) testing, which confirmed that these generally older houses tended to have a high level of base ventilation. Any moisture issues in these houses may relate to a lack of thermal insulation, insufficient levels of heating, particular user behaviours, or uncontrolled moisture sources, rather than from a too airtight construction.

To complete this research project a monitoring system needed to be designed and developed. The research design was to use 10 houses to provide data on the temperature and relative humidity in the following key areas:

- Outside the house
- In the roofspace
- In the ductwork of the ventilation of the system
- In the Delivery Space (the space within the house into which the ventilation system discharges – usually a hallway)
- In the perceived coldest room of the house (frequently a south-facing bedroom), i.e. the ‘Cold Room’.

To explore the dampness within the house, the wall surface temperature and relative humidity in the Cold Room was also measured. The operation of the ventilation system was recorded by measuring the electrical energy use of the ventilation fan and the airflow rate through the ventilation system.

Although the monitoring system and data collection was successful at the piloting stage, when adopted for longer term, remote data collection technical challenges were experienced. This meant in some case study homes the data collection was not complete and limited the amount of analysis possible. Four houses provided sufficient data to allow a detailed examination of the temperatures and relative humidity as it related to the ventilation system.

While three of the houses recorded high relative humidities, particularly in the Cold Room and on the wall surface in the Cold Room, one household which used heaters regularly in the Delivery Space had relative humidity levels that were low and frequently drier than the recommended range of 40-70%.

Data from two houses in this study found that the operation of the forced air ventilation system during the day was found at times to increase moisture levels within the house. The roofspace temperatures increased during the day due to solar radiation incidence on the roof. The transfer of air from the roofspace during the day will increase the temperature inside. At night the operation of the forced air ventilation system decreased moisture levels, but at the same time cooled the house down.

The effectiveness of a forced air ventilation system depends on the conditions in the roofspace and Delivery Space. The controllers for the forced air ventilation systems currently respond only to temperature measurements in these areas. An ideal control system for forced air delivery from the roofspace clearly needs to take account of the temperature and humidity in both spaces. With this data, the system will be able to determine when operation will reduce the relative humidity in the building. There is clearly an opportunity to develop forced air ventilation system controllers that consider all of these aspects of building performance. It may be that the controller is set to a particular function, such as managing relative humidity (and therefore condensation risk), moisture removal, harvesting heat or increasing ventilation for a short time to remove odours (‘burnt toast’ setting).

2 Introduction

Beacon's vision is to "Create homes and neighbourhoods that work well into the future and don't cost the Earth". To reach this vision Beacon are guided by two goals:

- 90% of New Zealand homes will be sustainable to a high standard by 2012; and
- Every new subdivision and any redeveloped subdivision or neighbourhood from 2008 onwards is to be developed with reference to a nationally recognised sustainability framework.

The research is managed under six streams: Energy, Water, Indoor Environment Quality (IEQ), Systems, Neighbourhoods, Homes (retrofit and new). The IEQ strategy has one research target: to provide a robust definition for the IEQ component of Beacon's HSS® and decrease the number of homes failing to meet that performance. Reflecting Beacon's whole-of-house approach, IEQ targets need to be achieved without compromising energy efficiency targets.

The current HSS® benchmarks (2008) for IEQ (Easton, 2009) are given in Table 1.

Table 1: HSS® (2008) IEQ targets

Temperature	Living room evening in winter >18°C Bedroom overnight in winter >16°C
Relative humidity	Living room evening in winter 40-70% Bedroom overnight in winter 40-70% Surface relative humidity <80% year round
Checklist	Mechanical extractor ventilation of kitchen, bathroom and laundry Means to passively vent dwelling No unflued gas heaters No indoor clothes drying

Forced air or supply only ventilation systems have increased in popularity considerably over the last 10 years in New Zealand and are a frequently encountered system in new and renovated houses. The 2000 BRANZ house condition survey (Clark et al 2000) reported that 1.3% of houses (around 11,000) had a forced air ventilation while the 2005 survey found this had increased to 6% or about 70,000 systems (Clark et al, 2005). McChesney (2009) estimates that in 2008/2009 almost 10% of houses, or around 150,000 systems, had a forced air ventilation system.

There has been little verification of how these systems operate in New Zealand conditions. Given this large investment in residential ventilation, it is important to establish that these systems are providing a solution to our cold and damp houses, and if they are being used appropriately and only installed when they will be of benefit.

This research has been undertaken to examine the operating characteristics of forced air ventilation systems in New Zealand. The actual measured performance of these systems has not previously been determined. The research methodology and results from 10 homes are presented in this report, along with key findings that provide an insight into how these systems operate. This report reviews how the systems are being controlled, and how they are contributing to achieving the HSS®, both with regard to IEQ and Energy.

3 Managing Indoor Environmental Quality (IEQ)

IEQ takes into consideration impacts of the indoor environment on human health and performance. Good IEQ practice seeks to provide an environment which is:

- Healthy and free from pollutants
- Thermally comfortable
- Acoustically comfortable.

While there are a range in indoor pollutants encountered in New Zealand (Phipps, 2007), the most common is water vapour or moisture (Clark, 2005). The level of moisture in the air is referred to as the 'humidity'.

Water vapour in the air can condense out onto building surfaces causing condensation on non-porous surfaces (such as windows) and dampness on porous surfaces (such as walls). Extended periods of dampness on walls can promote the growth of mould and fungi (Sedlbauer, 2002) which can be a health risk to the occupants. Window condensation is more of a nuisance than a health risk and may require windows to be wiped down to prevent water accumulating and damaging the window sills.

The five factors that impact on the level of moisture within a home are the:

- Management of moisture sources
- Performance of the thermal envelope (R-values of the roof, walls, floor and windows)
- Ventilation rate
- Level of heating
- Use of dehumidifiers.

If a home has a moisture problem then the first step should always be to determine whether there is a moisture source that should be controlled. There are many sources of moisture within a home including the occupants themselves, moisture from showers and cooking, drying clothes inside, using unvented clothes dryers, or from a damp subfloor. Managing moisture sources may include actions such as not drying clothes inside, ensuring that lids are on pots while cooking, that the clothes dryer is vented outside, and that damp ground under the house is covered with plastic sheeting.

The level of insulation within a home is important. The lower the R-value of a component the 'colder' its surface will be. If the moist air hits a surface that is cold the moisture from the air will condense on that surface.

Heating within the house will also increase the temperature of the components (walls, windows) within the house, but a higher air temperature will also allow more moisture to remain in the air and not condense onto surfaces.

Dehumidifiers remove moisture from the air using mechanical energy and may be used in combination with heaters.

Ventilation is a measure of the fresh air delivered by ventilation systems present, the occupants opening windows and natural air leakage through the building envelope. Increasing the ventilation rate will lower the humidity level in a home where humidity of fresh air is lower than that inside that home (subject to all potential moisture sources).

In examining ventilation, it is useful to consider the separate contributing factors such as: the uncontrolled flow of air through the building envelope with all the windows and doors closed (the infiltration); passive ventilation from open windows, doors, louvres or other airflow mechanisms; and mechanical ventilation from extractor fans in bathrooms, rangehoods in kichens, as well as any supply or extract systems present (BRANZ, 2007).

Localised extract ventilation in areas with high humidity, such as extractor fans in bathrooms and rangehoods in kitchens, can remove moisture in those areas with a high level of moisture that would otherwise migrate throughout the house.

The relationship between heating, ventilation and insulation level (R-value) is shown in Figure 1. In this case the curves are for walls and single-glazed windows. This shows that with more heating, less ventilation is required to avoid condensation, but as ventilation increases the amount of heating can be reduced. However both ventilation and heating are needed, particularly to offset poor thermal envelope performance (i.e. uninsulated ceilings, walls and single-glazing which all have low R-values). The upper curve representing the requirements to prevent condensation on a wall is for an uninsulated wall.

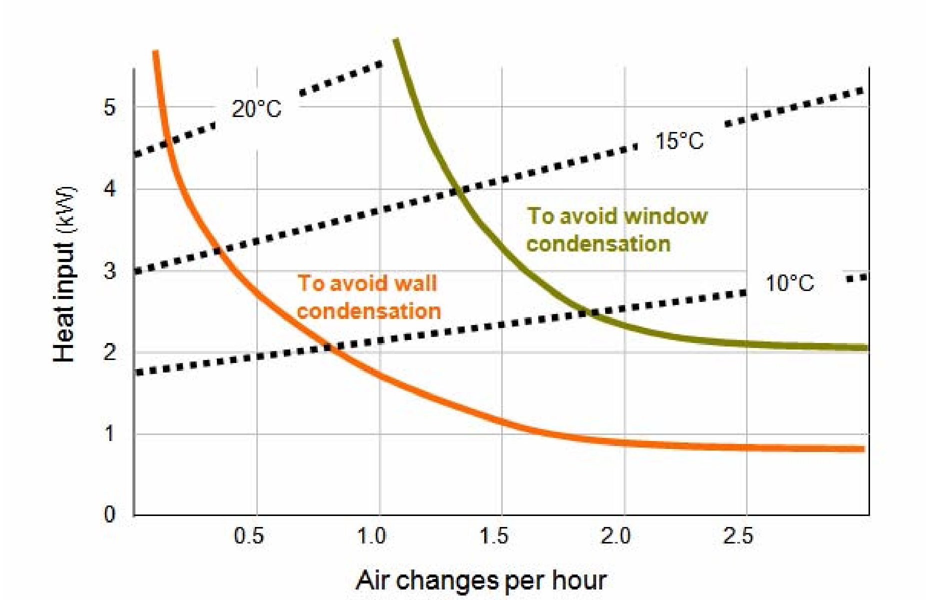

Figure 1: Typical ventilation, heating and insulation solutions to avoid condensation (Source: BRANZ)

It is traditional in New Zealand to ventilate our houses passively by opening windows. This allows wind and buoyancy pressures to drive the airflow that is needed to dispose of moisture and other contaminants in indoor air.

Wind pressures are the main driver of passive ventilation in the New Zealand climate. The actual pressures applied to a building vary around the building and depend on the shape of the house, wind direction and the local terrain. Typically the side of the house that faces the wind will have a positive pressure where outside air will be 'drawn into' the house, and the other sides of the house will have negative pressure where the stale air will be 'sucked out' of the house (Figure 2).

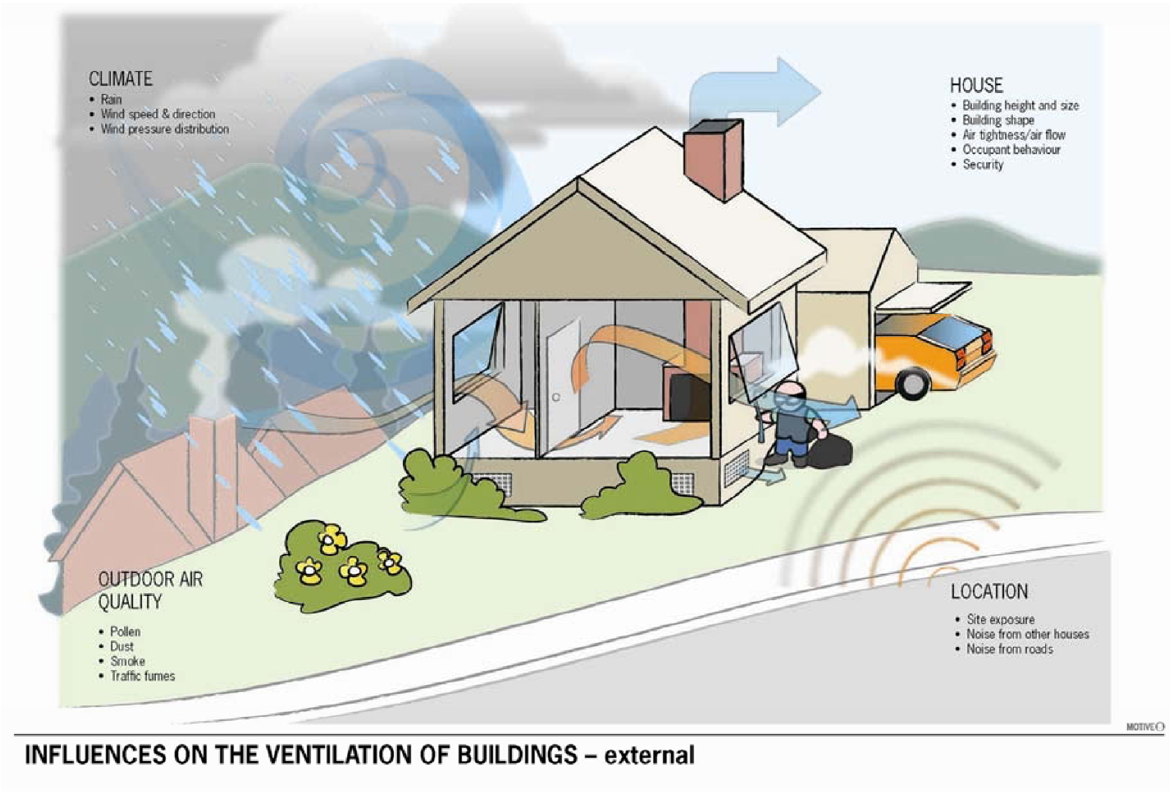

Figure 2: Passive ventilation and influences on ventilation (Source: Winstone Wallboards)

3.1 Infiltration and airtightness

The infiltration rate is the minimum ventilation rate within a home that occurs when any ventilation systems present are turned off, and doors and windows are closed. The level of infiltration for a house is a measure of its airtightness. An airtight house is one which has a low level of infiltration. A house which has a high level of infiltration may be described as leaky or draughty, having a poor level of airtightness.

A blower door test is a common method to ascertain a building's level of airtightness, but this can only be done once the building is completed. It is difficult to quantify the airtightness of a building at the planning stages because variable construction practices and workmanship can have a large impact on the level of airtightness achieved.

A general categorisation of building airtightness (airtight, average, leaky and draughty) can be made based on the age, size and overall complexity of the building (see Table 2). Traditionally New Zealand buildings have not had a high level of airtightness. Changing construction practices have generally increased the airtightness of buildings, lowering the infiltration rate. One reason for this is the increased use of sheet materials with fewer joints than traditional materials. For example, since the 1960s particle board flooring largely replaced the use of tongue and groove flooring.

Table 2: Airtightness categorisation and base level infiltration rates from building descriptions

Building description	Airtightness category	Base level infiltration [ac/h]
Post-1960 houses with a simple rectangular single-storey floor plan of less than 120 m^2 and airtight joinery (windows with airtight seals)	Airtight	0.3 ac/h
Post-1960 houses of larger simple designs with airtight joinery (buildings may be two storeys)	Average	0.5 ac/h
Post-1960 houses of more complex building shapes and unsealed windows	Leaky	0.7 ac/h
All pre-1960 houses with strip flooring and unsealed timber windows	Draughty	0.9 ac/h

As homes have become more airtight, methods to increase ventilation such as installing 'trickle vents' fixed into the window framing or adding louvres have become more popular. These options rely on occupants to actively manage the system by opening the vents or windows. It is entirely possible that lifestyle changes and security concerns will continue to discourage window opening which, in turn, limits the prospect of adequate control of moisture and other contaminants in New Zealand homes.

Overall the ventilation rate of a house needs to not be too low or too high. The ventilation rate should be above the fresh air delivery needed for pollutant control for good IEQ. The ventilation rate within a house should also not be so high that large amounts of heating are required to bring the temperature within the home to within a desirable range.

5.1.1 Airtightness data

BRANZ has collected airtightness data from over 100 residential buildings of various ages and construction details up until the mid-1990s, and a new measurement programme has recently begun to update this data.

Figure 3 shows histograms of the measured airtightness for each of these houses in the existing BRANZ airtightness database grouped by the airtightness category following the building descriptions. There is a range of resultant airtightness values for each of the categories, suggesting that further information is needed about each house to determine its airtightness other than just its building description and airtightness category.

During a blower door test, it is necessary to seal up substantial openings in the building envelope, including ventilation ducts and damaged windows, rangehoods etc. This is so there is consistency between the set of measurements, and also because it is difficult to establish a stable pressure across the envelope with large airflow paths present.

Likewise the base level infiltration rate for the various airtightness categories (airtight, average, leaky or draughty) in Table 2 assumes no large openings in the building envelope.

The contribution of these openings to the infiltration rate in the building can be calculated using the BRANZVent procedures to assess what, if any, additional ventilation is required for moisture control. After adding in the various known infiltration sources (chimneys, flues, windows left open) around the building, corrections are then made for the region that the building is located in, as well as its level of exposure. This accounts for the effect that wind conditions around the building can have on the level of infiltration.

The recent updated version of ALF (ALF3.2) incorporates these ways of adjusting air change rates for different building characteristics. It also provides a ventilation estimate that is used inside the ALF program to calculate space heating energy losses by ventilation.

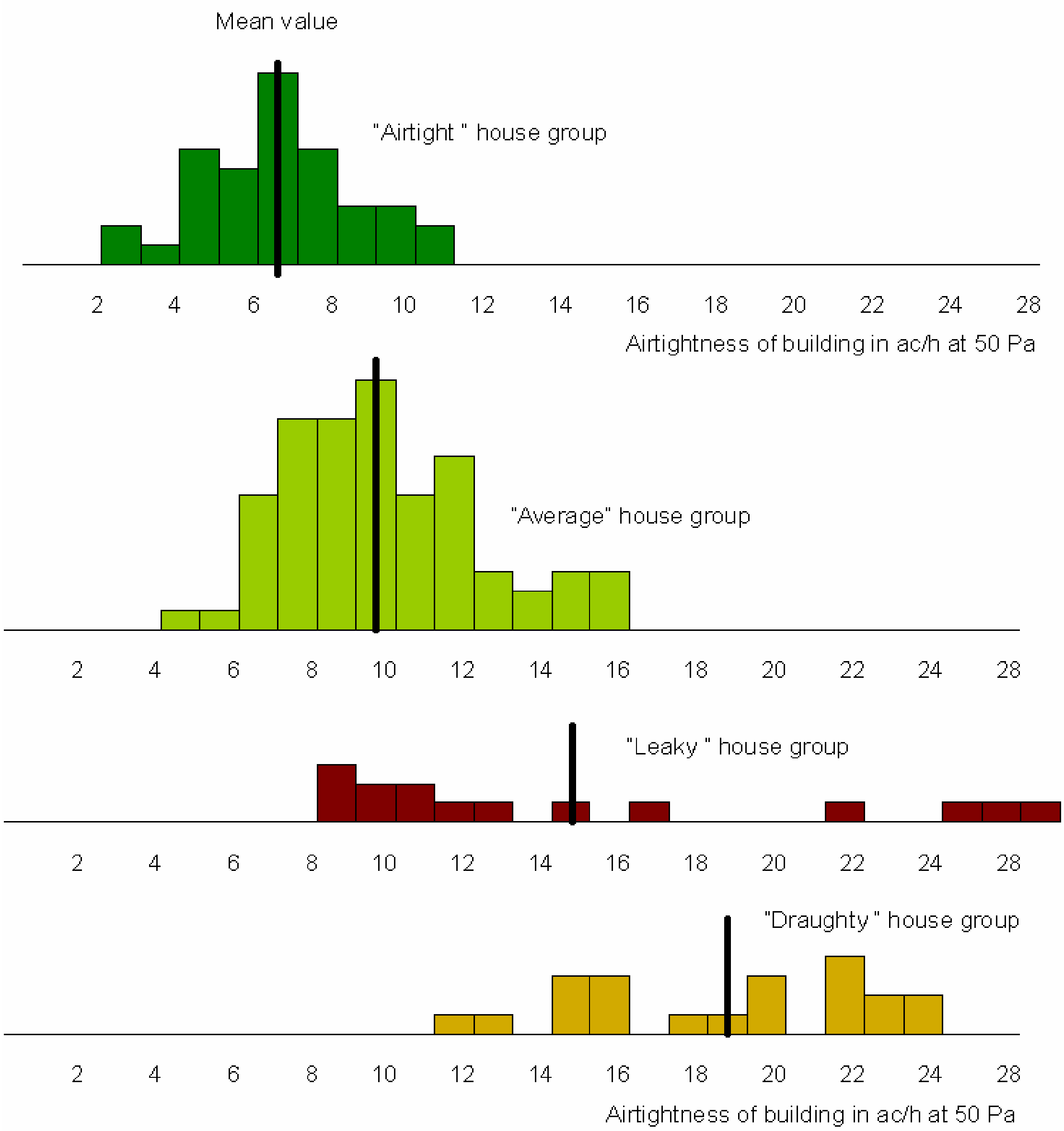

Figure 3: Histograms of New Zealand house airtightness in four type categories [Bassett, 2001]

3.2 Measures of moisture

The moisture content of air can be expressed in a number of different ways. The most familiar is relative humidity, which is defined as the ratio of water vapour pressure in a sample of air-to-water vapour pressure required to saturate that sample at the given temperature (ASHRAE, 1997). The required vapour pressure to achieve saturation depends on the temperature of the air. Air at a higher temperature can support a higher vapour pressure before saturation occurs. A consequence of this is that if air is heated without changing its moisture content then its relative humidity will go down. Conversely, if air is cooled without changing its moisture content then its relative humidity will go up.

Relative humidity can be perceived in broad terms: environments with high relative humidity seem moist, while environments with low relative humidity seem dry. The moistness or dryness of an environment forms part of the acceptability of an environment so that relative humidity is a factor in thermal comfort.

Relative humidity is also a good indication of condensation risk. Air that has a high level of relative humidity may achieve saturation if the air has a small drop in temperature. Surfaces that are colder than the air, such as single-pane glazing, may cause condensation to occur.

There are a number of other measures for the moisture content of air. One measure that is not dependent on the current temperature of the air is the humidity ratio (also known as the moisture content or mixing ratio), which is defined as the ratio of the mass of water vapour in moist air to the mass of dry air (ASHRAE, 1997). In this report the humidity ratio is expressed in kilograms of water vapour per kilogram of dry air [kg/kg]. The humidity ratio for a sample of moist air can be calculated from measurements of the relative humidity and temperature of that sample.

When moisture is added to air, its humidity ratio will increase. An example of this would be the use of an unflued LPG gas heater which releases water vapour into the surrounding air as it operates, therefore raising the humidity ratio.

The relationship between the conditions in the roofspace and the room or area where the air is delivered (Delivery Space) is a critical area in the performance of forced air ventilation systems. It is frequently assumed that the roofspace conditions are drier (have a lower humidity ratio) and warmer than the Delivery Space into which the ventilation system discharges.

3.3 Dampness

Moisture within the home exists in forms other than water vapour within the air. Porous materials (including wall surfaces) and furnishings within the house can hold moisture. This stored moisture in these materials can buffer the effects of changing air humidity levels on the moisture levels of these materials. These moisture levels will be referred to as dampness and are examined by measuring the relative humidity at the surface of the material. Cold surfaces, such as external walls and uninsulated ceilings, are at risk of dampness and consequently of mould, bacterial or fungal growth (see Sedlbauer, 2002).

3.4 Forced air ventilation systems

There are a variety of types of ventilation systems (BRANZ, 2007). These can be categorised by where air is drawn from and where it is delivered to. Extract systems take moist air from within the building and transfer it outside (these systems should not transfer the air to the roofspace as this may cause moisture problems there). Forced air ventilation systems generally take fresh air from the roofspace and mechanically force the air into the home via a diffuser in the ceiling. The moist air within the house is diluted with the increased ventilation and migrates outside through openings in the building envelope.

Although each company's system may have slightly different products, in generic terms a forced air ventilation system has the following components (Figure 4):

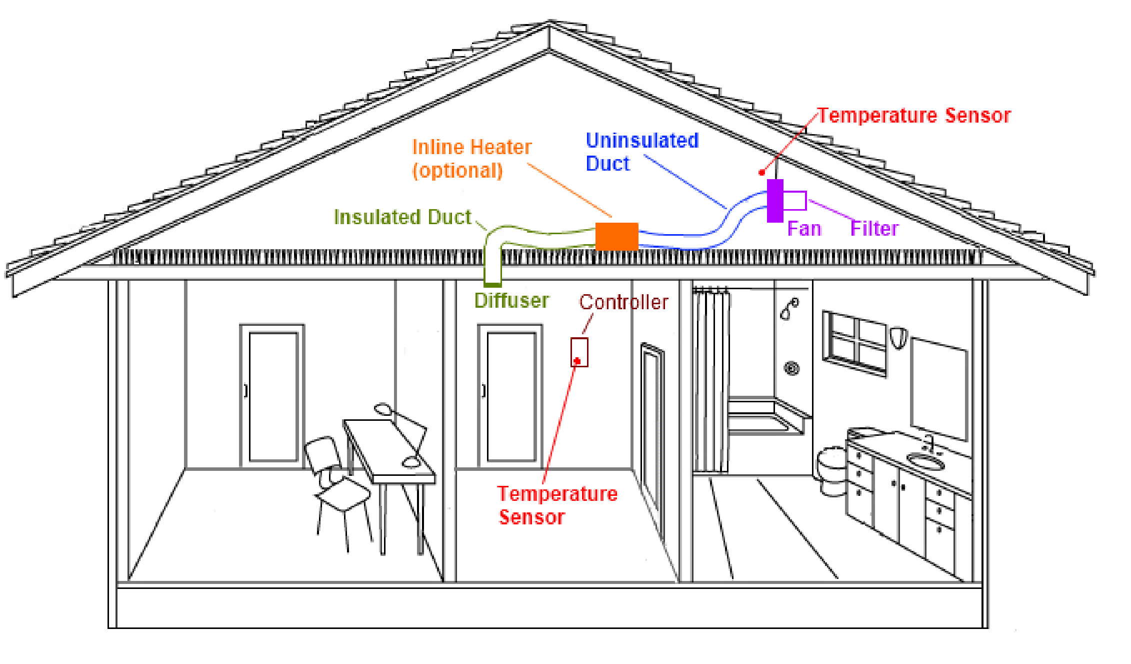

Figure 4: Diagram of a forced air system

- **Air filter:** Attached to the intake side of the unit in the roofspace. Typically this needs to be replaced annually to ensure effective removal of dust, fibres and other contaminants that may be found in the roofspace. However, the frequency of replacement depends on the characteristics of the home and the environment it is in. Failure to replace the air filter may reduce the life expectancy and operational efficiency of the system. Replacement filters can be installed either by the company or the homeowner. The filter does not remove vapour or moisture from the incoming air.
- **Fan unit:** The fan units are generally suspended from the roof structure and can be arranged in an in-line (axial) or transverse (centrifugal) configuration with the duct work. The fan units frequently include speed control so the airflow through the system can be varied via the controller (see below).
- **Roofspace sensor:** A temperature sensor is frequently used to determine conditions inside the roofspace. Sometimes this sensor is integrated into the fan unit.
- **Flexible ducting:** To connect the ceiling diffusers with the fan unit. This ductwork will include intersections if a number of ceiling diffusers are used and may be insulated, especially if in-line heating (see below) is used.
- **In-line heater (optional):** This unit heats the ventilation air prior to release into the rooms and is controlled via the controller.
- **Ceiling diffuser:** Mounted on the ceiling from which the air is pushed into the house. Systems can range from one diffuser in a centralised location (such as a hallway) to systems which include multiple ceiling diffusers throughout the house.
- **Delivery Space sensor:** An additional sensor usually integrated into the controller to estimate the conditions within the house.
- **Controller:** This device allows for the adjustment of the speed of the fan and operation of the in-line heater if one of these is present. These controllers frequently include an adjustable thermostatic control from the temperature sensors in the roofspace and controller. Depending on the model, the thermostats allow the systems to stop when the temperature of the roofspace reaches certain temperatures, either absolute (e.g. a preset temperature) or in relation to the living spaces (e.g. no more than 6°C in temperature difference between the Delivery Space and the roofspace temperatures).

4 Research design

4.1 Sample

The housing sample was drawn from Beacon's Home*Smart* Renovation Project. This project gathered information about households and building characteristics for a number of homes throughout New Zealand, which provided an ideal database to generate a list of households with ventilation systems for this project. It also gives Beacon the opportunity to understand some of the Home*Smart* Renovation Project homes in more detail.

A sample size of 10 was selected to provide a range of models and operating conditions. Rather than measuring all of the systems in one area, it was decided to split the sample between two cities with different climates. Originally Wellington and Dunedin were chosen, but due to the low number of systems in the Home*Smart* Renovation Project houses in Dunedin, Christchurch was substituted.

A tabulation of households participating in the Home*Smart* Renovation Project in Wellington and Christchurch which had ventilation systems was generated in May 2009. The houses for the study were randomly selected from the houses in these areas that have systems. The brand of the systems was not considered as part of the selection process, nor was the age of the system. The sample is therefore a collection of case studies rather than forming a representative group.

It was intended that two of these systems be heat recovery ventilation systems, where exhaust air from the room is used to pre-heat incoming outdoor air. Unfortunately the Home*Smart* Renovation Project did not have any such systems in either their Wellington or Christchurch sample, so these were replaced with standard forced air ventilation systems.

While the list of forced air systems in Christchurch was 11, a number of these systems were not available to be monitored. Further investigation revealed seven of them were heat transfer systems rather than roofspace forced air ventilation systems. One of the households had two systems installed, and the occupants for one household were not available during the visit to Christchurch when the installation of the monitoring equipment was to take place.

As only two Christchurch systems were available from the Home*Smart* Renovation Project database, two additional households were enrolled: one from a referral from one of the households unable to participate; while the other general household was known to have a roofspace ventilation system from personal association.

Six households in Wellington were enrolled from the Home*Smart* Renovation Project list of 12. Of the six households not participating:

- One had a heat transfer system
- One stated that they had switched the ventilation system off and were using heat pumps instead
- One was undertaking extensive building renovations
- Two were unavailable for personal reasons, and
- One had a homemade system, which was not selected as the results from this system would be difficult to generalise to other systems.

The result being that six systems from Wellington and four systems from Christchurch were used for the project and had monitoring equipment installed.

4.2 Monitoring

5.1.2 Airtightness (blower door) tests

Eight houses underwent a blower test using a Retrotec Q5E blower door system. Blower door measurements are a quick method for establishing building airtightness characteristics. They consist of a large fan inserted into a doorway (or other suitable opening), which is then used to depressurise a building under computer control. The Retrotec system used for the blower door tests stepped the indoor/outdoor differential pressure from 60Pa down to 10Pa in 10Pa increments while measuring the airflow through the fan unit.

The results of these tests are used to calculate the building airtightness, typically given as an 'n50' value, the number of air changes per hour that the building undergoes at a pressure differential of 50 Pa between indoors and outdoors.

A 50 Pa differential, however, is well above the average pressure experienced across the envelope over a building's lifetime. This value is therefore typically scaled by a factor of 1/21 to account for the reduced pressure differential in the normal operation of the building.

5.1.3 Environmental conditions

A forced air ventilation system modifies the state of the indoor environment by making use of the conditions (e.g. temperature and humidity) within the roofspace of the building. A complete understanding of the operation of such ventilation systems should include measurements of these environments.

The measurements of the environments included the air temperature and the relative humidity. These measurements are commonly recorded, from which other humidity measures (such as the humidity ratio) can be calculated.

Roofspaces are outside the thermal envelope of the house and can have varied temperature and humidity levels depending on the climate, roof design, materials used and construction. The conditions within roofspaces in New Zealand homes have not been extensively measured and little knowledge of this was available to this project.

The Delivery Space is the immediate room or area within the house that contains a ceiling diffuser. Table 3 gives the type of area this Delivery Space was for each of the monitored houses. It can be seen that the Delivery Space was frequently a hallway.

As part of the monitoring, an assessment was made as to which room would be the coldest room of the house and as such would be at the highest risk for high moisture levels (i.e. the worst case scenario). Table 3 also identifies what type of room this Cold Room was. This room was frequently on the south side of the building, receiving little direct solar gains and often outfitted as a bedroom. Four of the bedrooms had additional items stored in them suggesting that they were used as guest bedrooms and not regularly occupied. House F had a change of use during the project changing from a study to a child's bedroom in the summer.

Table 3: The room type of the Delivery Space and the Cold Room

House	Delivery Space	Cold Room
A	Living Room	Guest Bedroom
B	Hallway	Storage Room
C	Living Room	Main Bedroom
D	Hallway	Third Bedroom
E	Dining Room	Guest Bedroom
F	Hallway	Study / Bedroom
G	Hallway	Main Bedroom
H	Hallway	Third Bedroom
I	Main Bedroom	Guest Bedroom
J	Living Room	Guest Bedroom

Outside conditions are also of interest as they influence the roofspace conditions. While an external humidity sensor may provide some interesting data, the equipment budget was restricted so external measurements were limited to the outdoor temperature.

5.1.4 Surface conditions

As was discussed in Section 3.3 the surface humidity of cold walls and ceilings are important in a house to understand the dampness and to quantify the risk of mould, bacterial or fungal growth.

For greatest dampness risk within the house, the surface humidity and temperature were measured on the external wall in the Cold Room within the house. This measurement was made about 400 mm above the floor (see Figure 5) away from the studs in the wall. The thermal resistance of the wall is lower away from the stud if there is no insulation in the wall. Two of the houses (House E and House I) did have wall insulation in the Cold Room, but for the sake of consistency the measurement of the surface humidity for these two houses was also made away from the wall stud.

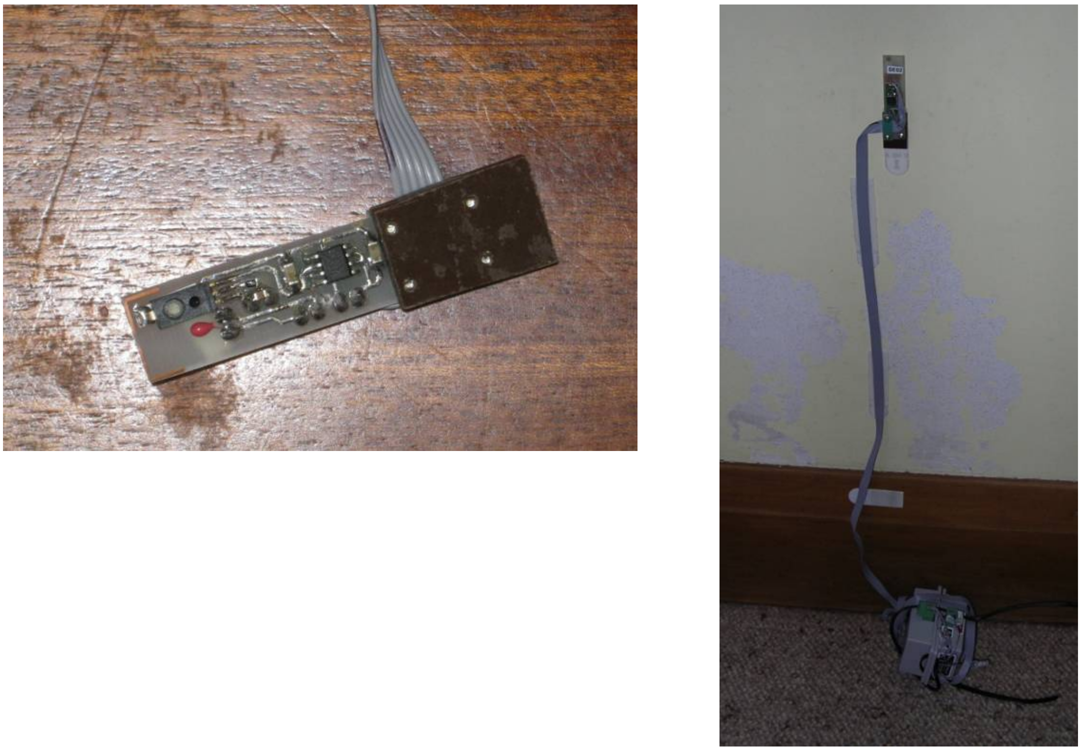

Figure 5: Surface temperature and humidity probe developed for this project

5.1.5 Other measures

Other parameters to measure the operation of the forced air ventilation system include the airflow through the system. This was measured by a pressure-averaging tube consisting of a 1.5 m straight section of PVC pipe immediately after the fan unit. This pipe had two sampling tubes at right angles to one another, which measured the average pressure across the pipe cross-section, which in turn could be converted to an airflow rate (Ma, 1967).

The electrical energy of the fan was also recorded by placing a pulsed output Watt-hour meter on the fan motor. The pulse outputs of this meter were totalised by the data collection system. The meter also displayed an independent total of the energy consumption which was read at the time the monitoring equipment was removed from the house.

5.1.6 Data collection

As the measurements were undertaken in regularly occupied houses, and because a number of measurements were required from many different locations throughout each house, a wireless data collection system similar to that used in the Rotorua NOW Home® (Pollard and Jaques, 2009) was chosen as the most appropriate method option. Rather than using a dedicated computer on-site to collect the radio data from each sensor, an alternate system was used. This system used a small (105 × 85 × 35 mm) data manager to receive the radio data from each sensor within each house, which then periodically transferred this data to a server computer at a specified internet address. A schematic of the measurement system is shown in Figure 6 .

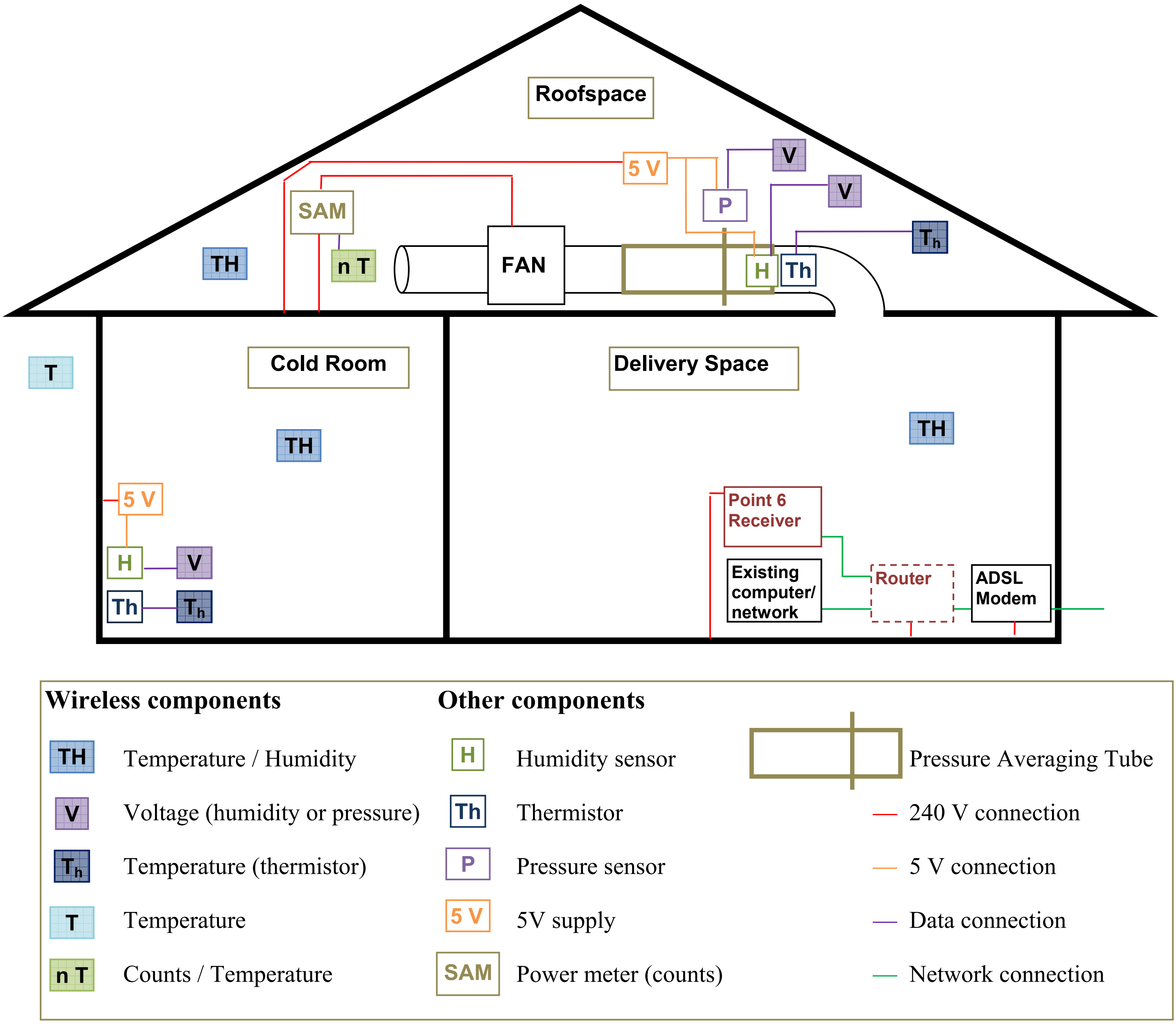

Figure 6: Experimental arrangement for each house

5.1.7 Monitoring experience

The approach as described above for both collecting the data and using monitoring sensors was new and developed during a pilot phase with two houses. At the completion of the pilot phase the monitoring had been successful so was adopted for use for the main project houses with an offsite data collection process. However further technical challenges in relation to the data gathering were experienced, as is often the case with monitoring research projects when it is not possible to have regular contact with the houses. This meant in some case study homes the data collection was not complete and therefore limited the amount of analysis possible. There were three broad areas that lead to the incomplete datasets, as follows:

1. *Remote transfer of data*: All of the sites monitored had an existing broadband internet connection, so these were used to integrate the data manager into the householders' existing computer network to share their internet connection to transfer data back to the server computer.
    - The householders' network was often a single computer attached to a single ADSL or cable modem, and frequently switches or routers were installed to allow the additional internet traffic to be managed.
    - Difficulties were encountered configuring the data collection unit to work within some of the computer networks and with some of the internet providers who restricted the use of internet services (forwarding for particular ports) necessary for communication with the data manager.
    - Many of the households did not have static (fixed) IP addresses for their internet connections, making communication with the data manager dependent on the data manager establishing a communication link to the server computer.
2. *Data collection programme*: The monitored data was stored in a transactional database on the server computer by a configuration and data collection programme called Pointware. Extracting simple data from PointWare became surprisingly unwieldy once more than a month of data had been collected. To extract the complete set of monitored information, the structure of the underlying database was examined and queries were written to extract the data directly. This involved a one-off process once all the data had been collected.
3. *Airflow monitoring*: It was confirmed that pressure from the pressure-averaging tubes was being recorded in the data collection system at the time of the installations. However it was not until the analysis stage, once data collection had stopped, that it was discovered that the airflow information could not be determined from this data. This may have been picked up if analysis was carried part-way through the data collection stage. This was due to a mismatch between the pressure transducer and the data collection system, which resulted in only small fluctuations of pressure being recorded. This was not revealed during pilot and earlier stages of the project due to the test equipment better matching the pressure transducer. If future research in this area is carried out, special attention would be needed to ensure the data collection equipment matched the pressure transducer.

Ultimately only four sites provided time series data sufficient for detailed analysis.

4.3 Data from Home*Smart* Renovation Project

As eight of the 10 ventilation households were participating within a wider Home*Smart* Renovation Project, additional information on these householders was collected via the Home*Smart* Renovation Project.

Information on the condition of the dwellings for this project came from the in-home assessment used in the Home*Smart* Renovation Project. This in-home assessment process involved a building assessor from one of the community partner organisations making a physical assessment of the dwelling. This assessment included an examination of the building envelope, the hot water system, household energy and water use, space heating and water heating as well as identifying issues affecting the IEQ. Results relevant to this project are summarised in Section 6.1 of this report. For the two houses not participating in the Home*Smart* Renovation Project, equivalent assessment information was collected by BRANZ.

The evaluation process for the Home*Smart* Renovation Project included a number of surveys gathering the occupants' experiences about which renovation options to pursue. Some monitoring of the environment was also carried out in a subset of houses within the Home*Smart* Renovation Project. Details of these results can be found in the Beacon report on the Home*Smart* Renovation Project (Saville-Smith et al, 2010).

4.4 Data availability

The data available for the different aspects of this project are summarised in Table 4.

Table 4: Summary of data availability

House	Location	HomeSmart Renovation Project	HSR Project Data Collection	Blower door Test	Temperature and Humidity Data	Roofspace and Delivery Space Data
B	Christchurch	✓	×	✓	✓	×
C	Christchurch	✓	✓	✓	✓	×
D	Christchurch	×	×	✓	✓	✓
E	Christchurch	×	×	✓	×	×
F	Wellington	✓	✓	✓	×	×
G	Wellington	✓	×	✓	×	×
H	Wellington	✓	✓	✓	✓	✓
I	Wellington	✓	×	×	×	×
J	Wellington	✓	×	×	×	×
A	Wellington	✓	✓	✓	×	×

5 Description of ventilation systems

The characteristics of forced air ventilation systems were discussed in Section 3.4 and were seen as being fairly consistent, so the sample was constructed (see Section 4.1) without consideration of brand. Within the total sample of 10 systems, there were five brands of forced air ventilation systems. Only one brand had more than one system in the sample.

Table 5: Characteristics of the forced air ventilation systems

House	Location	Fan Type	Recent (<5 yrs) System?	Number of Outlets	Fixed Wired	In-line Heater	Ductwork Insulated
B	Christchurch	Axial	Yes	1	No	No	No
C	Christchurch	Centrifugal	Yes	4	No	No	Yes
D	Christchurch	Axial	Yes	2	No	No	No
E	Christchurch	Axial	No	2	No	No	No
F	Wellington	Axial	Yes	2	No	No	No
G	Wellington	Centrifugal	No	1	Yes	No	No
H	Wellington	Axial	No	1	No	No	No
I	Wellington	Axial	Yes	4	Yes	Yes	Yes
J	Wellington	Axial	Yes	1	No	Yes	Yes
A	Wellington	Axial	No	2	Yes	Yes, but not used	No

5.2 Roofspace ventilation

Most of the roofspaces were well enclosed. Two of the houses (B and E) had tiled roofs and a degree of leaf debris on the ceiling insulation, suggesting a highly ventilated roofspace. House B also included a passive roofspace vent as shown in Figure 7.

Figure 7: Roofspace vent in House B

5.3 Fan units

Except for one case, the fan units were suspended by a bungy cord or strapping to purlins or rafters. This allowed the fan unit to be placed mid-way within the roofspace (see Figure 8 for example). Suspending the fan unit using the cord also suppressed any vibration or noise from the fan unit being transferred into the building.

Figure 8: Fan unit suspended from purlin (House B)

The exception to this was the system in House G which is shown in Figure 9. In this case the unit was placed on two supporting lengths of timber which, in turn, was screw-fixed to the framing with rubber spacings between the timber support and the roof framing.

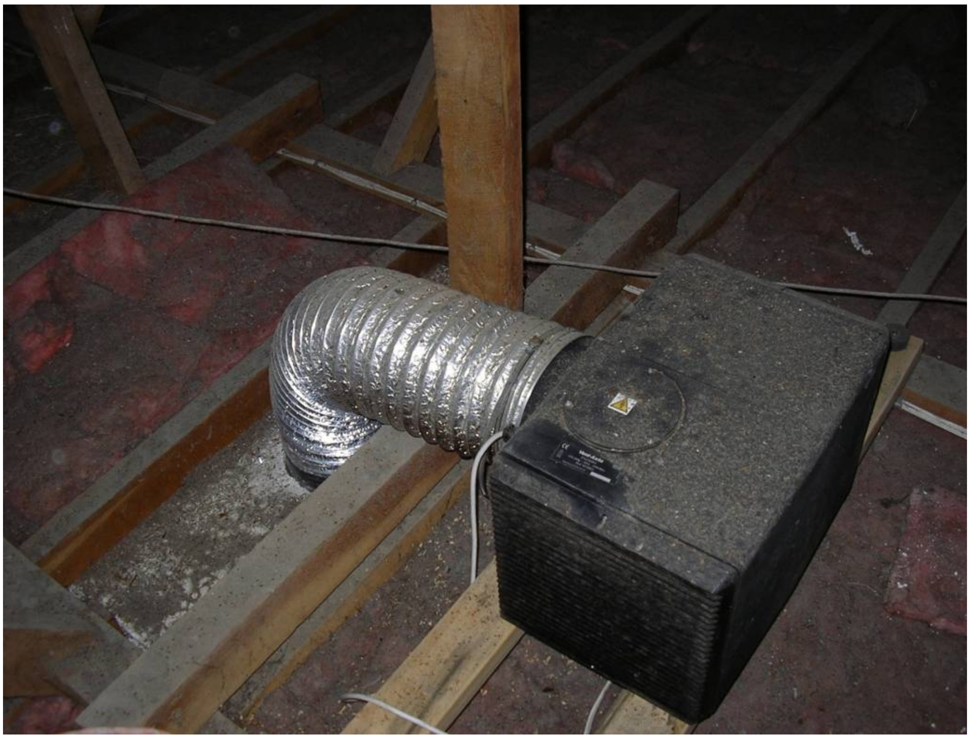

Figure 9: Fan unit in House G

Air filters were installed external to the fan unit system, except for the House G system. The House C system shown in Figure 10 had two air filters. Many of the filters exhibited signs of blackening. The length of time since the last filter replacement was not picked up in the study.

Figure 10: Air filters for the system in House C

5.4 Other components

The systems in House A and House E had additional components that were suspended. The House A system (shown in Figure 11) had the in-line heater suspended while the system in House E (shown in Figure 12) had the ductwork suspended. There is no clear reason why they have chosen to install the ductwork this way. This was an older installation and this may reflect old practice. The remaining system's components were unrestrained and lying on top of the insulation. The pressure-averaging tubes (PAT) used for this study were placed after the fan unit and were supported by the ceiling joists (an example is shown in Figure 13).

Two systems (Houses I and J) included in-line heating systems, and while these were appropriately supported by strapping to hold their weight by roof framing, they had not been fully restrained. These two systems had the ductwork insulated and this is discussed later. Given these devices are supplied with electricity, large movement of these units in an earthquake may present a hazard.

Figure 11: Suspended in-line heater (section of metal ductwork) for the House A system

Figure 12: Suspended ductwork in House E

Figure 13: Pressure-averaging tube placed after the fan unit (note the clean air filter)

5.5 Electricial

The electrical supply to both the fan unit and any in-line heaters should be able to be switched off from within the roofspace. For the majority of monitored systems this was possible as the units were not hardwired and could be disconnected from within the roofspace. This would provide anyone undertaking maintenance on the unit, such as replacing an air filter, certainty that electricity to the fan was disconnected. The monitoring equipment included a plug-in electricity meter in series with the fan unit (and the in-line heater if one was present). Where the units were hardwired, an electrical outlet was added to allow an electricity meter to be installed.

5.6 Ducts

The standard means used for these systems to attach the fan units to the ductwork was to use PVC tape or duct tape and generally a secure connection was made. Work by Walker and Sherman (2004) has identified concerns about the durability of some fixing methods, in particular duct tape. The House G system provided only a mechanical fixing using a hose clamp as shown in Figure 14. This arrangement provided a poor seal around the duct and the duct could be disconnected and reconnected without adjustment to the screw.

Figure 14: Poor connection on the House G system

All of the systems featured 200 mm diameter flexible ducting. This ducting featured a stiff metal or plastic coil with plastic or metal walls. Intersections were either mounted plastic or sheet metal. An example of an intersection is shown in Figure 15.

Figure 15: Example of a plastic intersection within the ductwork

The roofspaces were all outside of the thermal envelope as the insulation for the house was placed at the ceiling level as expected.

Three of the systems featured an in-line heater, although one of these was not used. As the air in the roofspace is frequently colder than the Delivery Space, pre-heating the air before it enters the room can reduce possible discomfort from cold draughts. Having both the heater and the ductwork outside of the thermal envelope means that there is potential for heat loss for this arrangement. Locating a heater within the thermal envelope reduces the amount of heat loss and would be the preferred option from an energy efficiency point of view.

The two systems that used in-line heaters, as well as one additional unheated system, had insulated ductwork. This typically comprise protective plastic sleeving containing a 40 mm thick layer of polyester insulation over the flexible duct. This arrangement would have a thermal resistance (R-value) of approximately 0.6 m^2 °C/W (similar to an uninsulated timber-framed wall). This level of thermal resistance is low in comparison to the insulation level of other insulated building elements such as ceilings, floors and walls. For those systems that pre-heat the delivered air, losses will be reduced by limiting the length of ductwork present in the roofspace.

In addition to the forced air ventilation systems, other measures to control moisture and ventilation were present in many of the houses. In particular, many houses had bathroom extractor fans and these systems were ducted outside. House B also featured an insulated heat transfer system to take air from the living room, which was heated by a solid fuel burner, and deliver it to the bedroom.

6 Results

6.1 Summary of Home*Smart* Renovation Project results

The Home*Smart* Renovation Project houses were of varying condition. Unlike other monitored renovations projects, these householders were strongly interested in improving the energy efficiency and thermal comfort of their home (Saville-Smith et al, 2010). Table 6 gives the age and insulation level and heating systems in the 10 houses.

The level of roof insulation was varied. All of the houses had pitched roofs with a ceiling cavity and some level of ceiling insulation, although two houses had an area of skillion roof as well. The majority of the buildings were constructed before ceiling insulation was mandatory and the insulation present is likely to have been retrofitted at an earlier date.

Knowledge about the level of insulation in the floor and walls was sometimes restricted by lack of access. All of the houses featured suspended timber floors. For those houses which had underfloors that could be seen, four were uninsulated and three had foil insulation. The other two houses had floors that were insulated with glasswool blanket insulation, one fully throughout the house and the other under the kitchen and dining room.

Wall insulation was hard to assess as the presence of insulation and its thickness could not be established without detailed investigation. For this project, a good level of insulation was assumed for the house built after insulation requirements came into force (House I). The only other houses for which some knowledge about wall insulation was available were Houses E and B which had renovations made to them. House E had been reclad and had all the exterior walls insulated, while House B had exterior wall insulation added as part of a bathroom renovation. It is expected that most of the other houses had little or no exterior wall insulation.

The last column of Table 6 provides a listing of the commonly used heater types in the houses. Flued gas heaters are popular amongst the sample as a primary heating method, while portable electric heaters are widespread as a secondary heating system. Three households had portable unflued LPG gas heaters; although one of these reported that they no longer used this heater since they had two heat pumps installed. Unflued gas heaters have many undesirable characteristics (Cowan et al, 2010), e.g. from a moisture management point of view they release water vapour into the room as they operate.

Table 6: Age, insulation and space heating details from the HomeSmart Renovation Project audit (Houses D and E separately inspected)

House	Age	Insulation			Window Details	Space Heating
		Roof	Floor†	Wall†		
A	1900s	Good	–	–	Timber single-glazed, some double-glazed, some uncovered	Enclosed wood burner, underfloor heating, electric portable
B	1930s	Poor	None	One room*	Timber single-glazed,	Pellet fire, electric portable
C	1950s	Fair	None	–	Timber single-glazed, 50% of windows have pelmets	Pellet fire, electric portable
D	1950s	Good	Good, (Blanket)	–	Timber single-glazed	Heat pump, enclosed wood burner electric fixed & portable
E	1960	Poor	Partial**	Good	Aluminium single-glazed some double glazed	Heat pump, electric portable
F	1930s	Fair	Fair (Foil)	–	Timber single-glazed, Aluminium single-glazed	Flued gas heater, electric portable
G	1950s	Poor	None	–	Timber single-glazed, all windows have pelmets	Flued gas heater, unflued gas heater
H	1950s	Good	Fair (Foil)	–	Timber single-glazed, some uncovered	Flued gas heater, unflued gas heater electric portable
I	1990s	Fair	Fair (Foil)	Good	Aluminium single-glazed skylight double-glazed	Flued gas heater, electric portable
J	1970s	Fair	None	–	Aluminium single and double-glazed	Two heat pumps, electric portable unflued gas heater‡

† Refers to items for which it was not possible to assess the level of insulation due to a lack of access.

‡ The unflued gas heater for House J was reported as it was not used after the heat pumps were installed.

* The bathroom wall was insulated as part of renovations.

** Renovations to kitchen and dining room included installing floor insulation in those areas.

As part of the HomeSmart Renovation Project in-home assessments, the checklist items for the HSS® IEQ (Table 1) were examined. Table 7 provides the results for the 10 houses, with a green tick showing a desirable outcome from a moisture management point of view, while a red cross is an undesirable outcome likely to increase the moisture loadings within the house. Half of the houses had appropriate moisture extraction from all of sources (bathrooms, kitchen and from the clothes dryer in the laundry). Many of the kitchens did not have extraction systems.

The checklist item that the house can be passively vented was not developed as a specific question in the in-home assessment. All the houses were regarded as being able to be passively vented by having windows left open.

Three houses had portable unflued gas heaters, although one was not used once two heat pumps had been purchased. As discussed previously, these types of heaters are undesirable from a moisture management point of view.

The checklist item with the lowest compliance was whether they dried clothes inside. Only three of the 10 households reported that they did not dry clothes inside.

Following all of the checklist items will reduce the moisture sources within a house, however the importance of each checklist item is different for each household. For example, the moisture risk potential of a bathroom depends not only on the presence of an extractor fan, amongst other reasons, whether the occupants open windows, close doors to the rest of the house, how many showers were taken, the duration of showers, as well as the temperature of water used.

Only one house (House C) had favourable outcomes for each of the checklist items while House G had more than half of the checklist items having unfavourable results.

Table 7: HSS® IEQ checklist items

(a green tick is a good outcome, a red cross an undesirable one)

House	Bathroom Extractor	Kitchen Extractor	Dryer Vented†	Can Be Passively Vented	No Unflued Gas Heater	No Drying Clothes Inside
A	✓	✓	✓	✓	✓	×
B	✓	×	–	✓	✓	✓
C	✓	✓	–	✓	✓	✓
D	✓	✓	–	✓	✓	×
E	✓	✓	–	✓	✓	×
F	×	✓	✓	✓	✓	✓
G	✓	×	×	✓	×	×
H	✓	✓	✓	✓	×	×
I	×	×	✓	✓	✓	×
J	✓	×	✓	✓	×‡	×

† Those households without dryers are shown as a dash.
‡ The unflued gas heater was reported as it was not used after two heat pumps were installed.

The HomeSmart Renovation Project in-home assessment also identified other factors that may impact upon the moisture levels within the house and these are shown in Table 8. An orange tick for the first two left-hand columns indicates measures that tend to reduce the moisture levels within the house, while a blue cross in the right-hand column indicates measures that tend to increase the moisture levels within the house.

Dehumidifiers remove moisture from the air but use energy in the process. Only House F used a dehumidifier and this usage was limited to the winter season.

Ground vapour barriers commonly comprise a polyethylene sheet placed on the ground under the house. The sheeting is taped together and around piles to prevent ground moisture from moving into the subspace. House D was identified as having a ground vapour barrier, while House E had a ground vapour barrier under the kitchen and dining room renovations.

The condition of the roofspace, gutters, subspace, windows and doors was also assessed. Two houses had increased moisture in the roofspace due to broken roof tiles and roof leaks. The front door in House F allowed some water to get in under the door. A more concerning leak occurred in House C when the built-in guttering overflowed causing water leakage into the house.

Table 8: Other actions affecting moisture levels within the houses

House	Use a Dehumidifier	Ground Vapour Barrier	Free of Leaks into House or Roofspace
A	×	×	✓
B	×	×	× Broken roof tiles
C	×	×	× Built-in gutter
D	×	✓	✓
E	×	✓ Partial	✓
F	✓ In winter	×	× Under door
G	×	×	× Some roof leaks
H	×	×	✓
I	×	×	✓
J	×	×	✓

Table 9 give details of occupant-reported mould or mildew within the house and condensation on the bedroom windows on winter mornings. Two houses reported mildew inside the house. For one of these (House C) they also reported that window condensation always occurred. Two other houses indicated that they had window condensation problems sometimes or often.

Table 9: Occupant-reported mildew and window condensation within the houses

House	Mildew Inside House	Winter Morning Condensation on Bedroom Windows
A	×	Seldom or never
B	×	Seldom or never
C	✓	Always
D	×	Seldom or never
E	×	Seldom or never
F	×	Sometimes
G	×	Often
H	✓	Seldom or never
I	×	Seldom or never
J	×	Seldom (one window)

Part of the data collection in the Home*Smart* Renovation Project was to collect temperature information from the living rooms and bedrooms in a subset of houses. Four of the ventilation houses were included in this measurement sub-sample and Table 10 provides the winter season (May to September) living room evening temperature and the average winter season bedroom overnight temperature from these houses. The green shading shows that only the living room temperatures in House A were achieving the HSS® levels.

Table 10: Average winter season (May to September) temperatures for comparison with the HSS®

House	Living Room Evening Temp [°C]	Bedroom Overnight Temp [°C]
A	21.2	13.8
C	16.5	13.0
F	17.1	13.8
H	16.6	15.1

6.2 Airtightness and ventilation rates

Table 11 and Figure 16 shows the approximate infiltration rates from blower door measurements of the houses. Table 11 also gives the age, size and the complexity measures for the eight houses subject to blower door tests. Complexity is defined as the sum of all the joint lengths of the building enclosure divided by the building's volume. Figure 17 shows a plot of the approximate infiltration rate and the building complexity. This plot has the expected general trend of increasing air infiltration as the complexity of the house increases – more complex houses are less airtight.

A key point to note here is that a blower door is an indirect measurement of the average infiltration rate experienced by a building, and this measure can be improved further by the application of a BRANZVent calculation. BRANZVent provides a series of corrections based on the location of the building within New Zealand as well as the site exposure and specific features (such as the presence of chimneys or passive vents). The corrected value provides an improved value for the infiltration rate of the house.

Table 11: Results of the blower door tests for eight houses

House	Age	Floor Area [m^2]	n_{50} [ach @ 50Pa]	Complexity (vol/joint length)	Infiltration (approx) [ach]
A	1900s	97	14.32	0.24	0.68
B	1930s	121	14.40	0.21	0.69
C	1950s	102	20.24	0.36	0.96
D	1950s	92	24.39	0.30	1.16
E	1960s	164	12.07	0.18	0.57
F	1930s	113	13.99	0.25	0.67
G	1950s	125	18.77	0.23	0.89
H	1950s	107	18.02	0.30	0.86

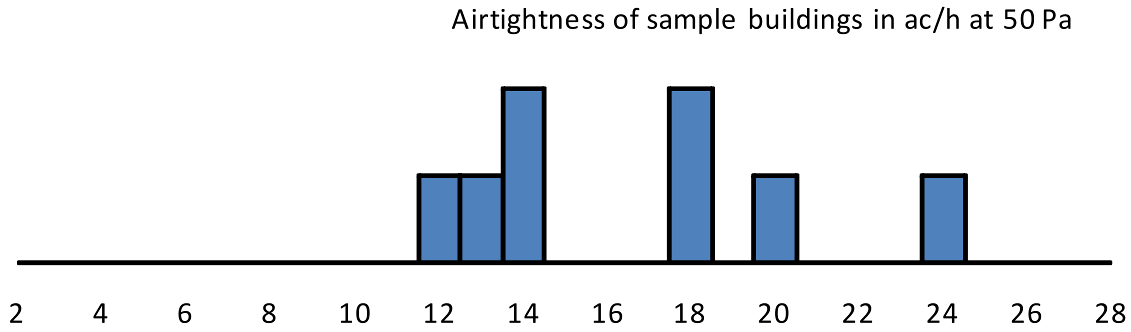

Figure 16: Histogram of the airtightness measurements for the houses given in Table 3

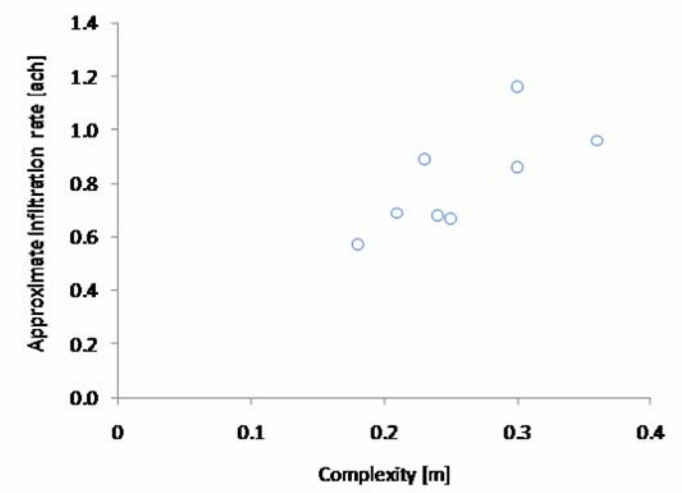

Figure 17: Approximate infiltration rate along with the complexity of the house design

6.2.2 BRANZVent calculations, approximate infiltration rates

Below is a summary of the infiltration rates in the buildings tested compared with the BRANZVent corrected values, and as you can see the general trend is an increase in ventilation rate compared with the uncorrected values. There was one house (House E) that had a decrease in the corrected ventilation rates which may be as a result of re-lining walls, the fitting of new joinery, as well as the region and exposure conditions that the building is in. As can be seen from the table, over half the houses are operating at around one air change per hour.

Table 12: Inferred infiltration rate from blower door test and infiltration rate after BRANZVent corrections have been applied

House	Infiltration Rate [ach]	
	From Blower Door Raw Results [ach]	After BRANZVent Corrections [ach]
G	0.89	1.27
D	1.16	1.24
C	0.96	1.10
H	0.86	1.08
F	0.67	1.03
A	0.68	0.88
B	0.69	0.75
E	0.57	0.52

All but one house had an infiltration rate greater than 0.75 air changes per hour. It is therefore questionable whether there is any benefit in adding a supplemental ventilation system as most of these buildings are already over-ventilated. It is possible that any moisture issues they are exhibiting are related to a lack of thermal performance, space heating (as indicated by the measured indoor temperatures), or a previously undiscovered moisture source (i.e. very wet subfloor, leaking roof or similar).

6.3 HSS® temperature and humidity benchmarks

Four of the houses (Houses B, C, D and H) produced extended data on the temperatures and humidities within each house for detailed analysis. The Home*Smart* Renovation Project also undertook evaluation monitoring in a sample of the houses participating in that project. Four of the houses examined for this project (Houses A, C, F and H) were included in this monitoring.

While the data collection for this project was focussed on the effectiveness of the ventilation system, some approximations to Beacon's HSS High Standard of Sustainability® (HSS®) (Easton, 2009) for IEQ could also be made.

6.3.1 HSS®

The current HSS® benchmarks (2008) give the following (Table 13) measurable targets for IEQ:

Table 13: Measurable HSS® (2008) IEQ targets

Temperature	Living room evening in winter >18°C Bedroom overnight in winter >16°C
Relative humidity	Living room evening in winter 40-70% Bedroom overnight in winter 40-70% Surface relative humidity <80% year round

The rooms specified for the HSS® are those that are thought to be regularly occupied – the living room in the evening and the bedroom overnight. The rooms monitored for this project were not necessarily regularly occupied spaces within the building. The Delivery Space was the area in which the ventilation system had an outlet, and as reported in Table 3 was frequently a hallway. The Cold Room was typically a bedroom on the south side of the house and was generally close to the Delivery Space.

The Delivery Spaces (Table 3) in three out of the four cases examined (Houses B, C, D and H) are not occupied zones, so only an approximate comparison to the HSS® targets can be made. So that a range of comparisons can be made, the proportion of the time the evening (5pm-11pm) and overnight (11pm-7am) temperatures were over 16°C and over 18°C was examined. For this analysis winter is June, July and August and summer is December, January and February.

As Table 3 shows the Cold Rooms are commonly bedrooms, so the HSS® target of having overnight (11pm-7am) winter temperatures warmer than 16°C may be an appropriate comparison. To allow a similar comparison to the Delivery Space, the proportion of the time the overnight temperatures were greater than 18°C was also examined, as was the proportion of the time the evening temperatures were over 16°C and over 18°C, and this information is shown in Table 14.

Table 14: Proportion of time the Cold Room temperature is within HSS®

House	Evening		Overnight	
	Over 16°C	Over 18°C	Over 16°C	Over 18°C
B	0.4%	0%	0%	0%
C	14.3%	0.6%	4.1%	0%
D	80.5%	22.2%	81.3%	27.3 %
H	67.6%	9.7%	–	–

The unoccupied Cold Room in House B is cold. The overnight temperatures over winter are never over 16°C and the evening temperature is over 16°C for less than 1% of the time.

The winter-time overnight temperatures in the occupied Cold Room in House C are also cold, only exceeding 16°C for just over 4% of the time. The evening temperatures more often exceed 16°C, although the proportion is still low at less than 15% of the time.

The overnight winter temperatures in the Cold Room in House D are over 16°C over 80% of the time, although the proportion of the time the temperature is over 18°C is just over one-quarter of the time. The evening temperatures are similar but with slightly less time over both thresholds.

The sensor measuring the conditions in House H did not record consistently overnight, so only the winter evening temperatures were available. While the Cold Room temperatures were over 16°C for over two-thirds of the time, the Cold Room evening temperatures were over 18°C just less than 10% of the time, indicating that the temperatures above 16°C were infrequent.

Table 15 gives the proportion of the time over winter when the Delivery Space temperature is above 16°C and above 18°C during the evening and overnight periods. The Delivery Space temperatures show similar patterns to the Cold Room temperatures.

Table 15: Proportion of time the Delivery Space temperature is within HSS®

House	Evening		Overnight	
	Over 16°C	Over 18°C	Over 16°C	Over 18°C
B	8.7 %	0%	0.5%	0%
C	–	–	–	–
D	94.6%	84.2%	88.7%	83.5%
H	70.8%	7.2%	–	–

The Delivery Space temperatures in House B are warmer than the Cold Room temperatures, but still fail to exceed 16°C for more than 90% of the time in winter evenings.

The sensor measuring the Delivery Space conditions in House C did not reliably communicate data so no suitable information was available.

The Delivery Space in House D was a hallway that was the heated (with an electric panel heater) and consequently the temperatures in House D were warm. The temperatures during the winter evening and overnight periods were in excess of 16°C for over 85% of the time and over 18°C for over 80% of the time, tapering off less steeply than the Cold Room. This indicated that the temperatures were warmer in the Delivery Space than in the Cold Room.

In House H, over 70% of the time the winter evening temperatures were warmer than 16°C, while only just over 7% of the time did the winter evening temperatures exceed 18°C, indicating only occasional heating beyond 16°C.

The relative humidity winter benchmark of the HSS® is to maintain a 40-70% relative humidity. Table 16 shows the proportion of time the relative humidity is outside of this range in the Delivery Space and the Cold Room in the evening and overnight periods. Blue shading indicates that when the relative humidity is outside this range it is over the 70% threshold. Yellow shading indicates that the out-of-range relative humidity is less than 40%, while the green shading indicates that the out-of-range relative humidity includes values both over 70% and less than 40%.

While the Delivery Space is slightly more damp than ideal in House B, the evening and overnight relative humidities in the Cold Room are higher than the 70% more than 90% of the time.

Table 16: Proportion of time the Delivery Space and Cold Room relative humidity levels are outside target levels

House	Proportion of time outside 40-70% relative humidity over winter			
	Delivery Space Evening	Delivery Space Overnight	Cold Room Evening	Cold Room Overnight
B	5.0 %	5.6 %	93.5 %	96.0 %
C	–	–	41.7 %	60.6 %
D	51.5 %	73.6 %	24.8 %	3.7 %
H	9.3 %	–	1.6 %	–

For House C, data is not available on the relative humidity in the Delivery Space in winter, and the Cold Room relative humidity is greater than 70% for over 40% of the time in the evenings and over 60% of the time overnight.

House D is unique in that low relative humidities are a problem. In the Delivery Space over half of the time in the evenings and almost three-quarters of the time overnight the relative humidity is below 40%. The Cold Room has higher relative humidity, but still close to one-quarter of the time in the evenings the relative humidity is less than 40%. The low relative humidity is thought to accrue from the higher standard of heating maintained in this house.

The evening relative humidity in the Delivery Space in House H is over 70% for just under 10% of the time. Interestingly, the Cold Room in the winter evenings in House H has lower relative humidity, exceeding 70% relative humidity for less than 2% of the time. A possible reason for this could be due to this room being warmer than other Cold Rooms from increased occupancy or possible heating.

The other relative humidity benchmark of the HSS® is that the surface relative humidity remains below 80% year round. Figure 18 gives histograms of the combined winter and summer relative humidities of the surface temperature of the wall in the Cold Room for each of the four houses. Table 17 gives the proportion of the time the summer, winter and combined periods exceed the 80% target. Except for House D, the surface relative humidity is of concern for over 40% of the time for the combined period and over 80% of the time during winter.

Table 17: Proportion of time the wall surface relative humidity in the Cold Room is above 80% during winter, summer and the combined summer and winter periods

House			
	Summer & Winter	**Winter**	**Summer**
B	73.8%	89.2%	40.4%
C	71.4%	98.2%	40.6%
D	12.8%	11.0%	15.4%
H	43.6%	83.7%	25.7%

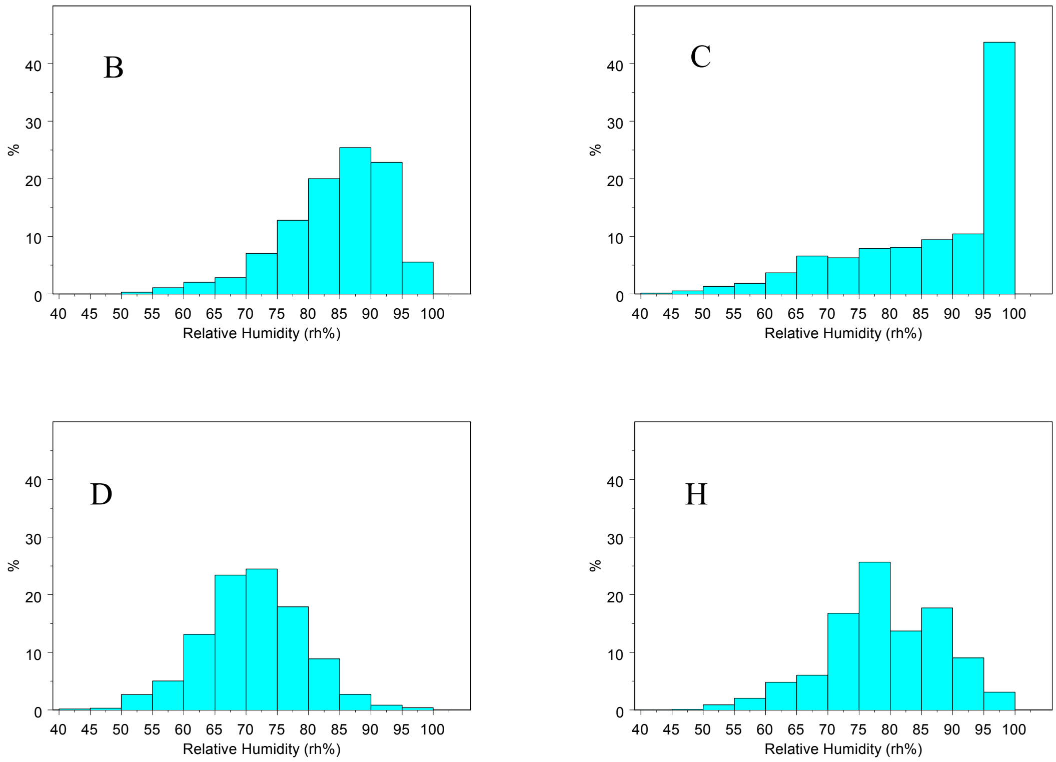

Figure 18: Histograms of the combined summer and winter wall surface relative humidities in the Cold Room

6.4 Temperature and humidity conditions

Figure 19 provides a graph of the seasonal average temperatures for different locations in each of the four houses examined. The temperatures are arranged by categories with the lines connecting the points to allow the separate houses to be more easily distinguished. The categories are arranged in order from the outside temperature on the left, to the wall surface temperature in the Cold Room within the house on the right. The summer temperatures are plotted with hollow points and dotted lines, whereas the winter temperatures are shown with solid points and solid lines. The same colour is used for each house.

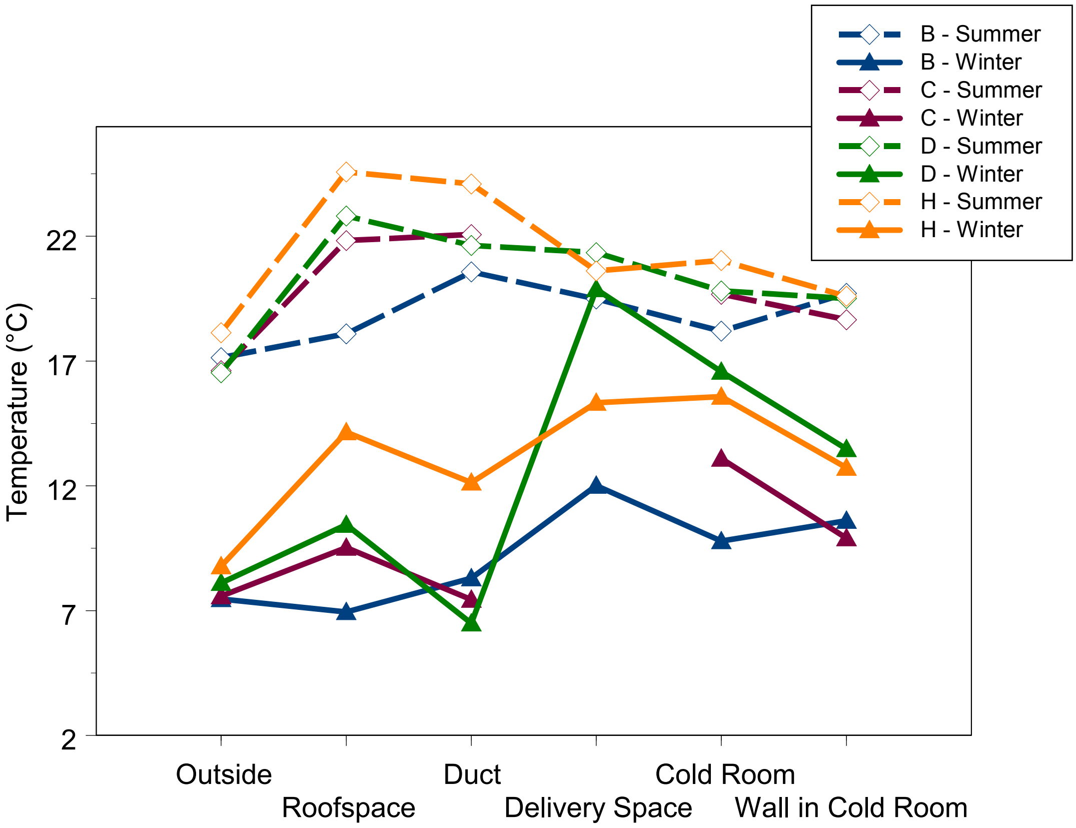

Figure 19: Summer and winter temperatures at various locations within each house

It is easy to see the separation between the summer-time and winter-time temperatures. The summer-time temperatures for each category are much warmer that the corresponding temperature during winter. The separation between houses is also clear, with the coolest summer temperatures being warmer than the warmest winter temperatures, with the exception of the warm Delivery Space temperatures in House D.

During winter the air being delivered into the house is colder than the air that is already there. In the summer the opposite is happening with warmer air being delivered into the house.

The variation in outside temperatures between the four systems during winter is small with a range in average winter temperatures of 1.3°C. The range in summer temperatures is a similar 1.6°C. However the summer temperatures are around 9°C warmer than the winter temperatures, with an average summer-time temperature of 17.1°C.

The range of roofspace temperatures is much larger in winter (7.7 °C) and in summer (6.5 °C) than was the case for the outside temperatures. This reflects the varying ability of the roofspaces to capture and hold heat from solar radiation incidence onto the roof.

House B shows little change between the average roofspace temperatures and the outside temperatures, while House H shows a winter roofspace gain of 5.9°C and a summer roofspace gain of 6.5°C. The other two houses show similar intermediate gain.

The duct temperatures show similar temperatures to the roofspace temperatures, although there are some anomalies (particularly in the winter temperatures).

The Delivery Space into which the duct discharges is on average warmer in the winter and cooler in the summer than the temperature outside, in the roofspace and in the duct. The most striking example of this is the winter temperatures in House D where the Delivery Space is a heated hallway with an average winter temperature of 19.9°C, whereas the air in the duct and presumably close to what is being delivered to the hallway has an average winter temperature of 6.5°C. The range in the winter temperatures in the Delivery Space (7.9°C) is much larger than the range in summer temperatures (1.8°C). A ventilation system that runs continuously would be likely to cool the Delivery Space down in winter and heat it in summer.

The Cold Room is at a similar temperature in House H, or slightly cooler than the Delivery Space temperatures. The differences between the summer and winter temperatures is narrower than say for the roofspace temperatures, perhaps indicating the lower importance of solar gains to the temperatures in the Cold Room.

Figure 20 shows the seasonal average relative humidities for the four houses with a 40-70% relative humidity range shown in grey. The seasonal differences between summer and winter are less obvious than was the case for the temperatures. While the winter relative humidity levels are generally higher than the summer humidity levels, there are summer-time conditions in some houses that are more humid than the winter-time conditions in other houses.

Even within the same house there are changes in whether the winter-time or summer-time humidity levels are higher. For example in House D, while the roofspace humidity levels are much higher in winter than in summer, the high degree of winter-time heating in the Delivery Space for House H results in lower relative humidity levels in the Delivery Space in winter than in summer.

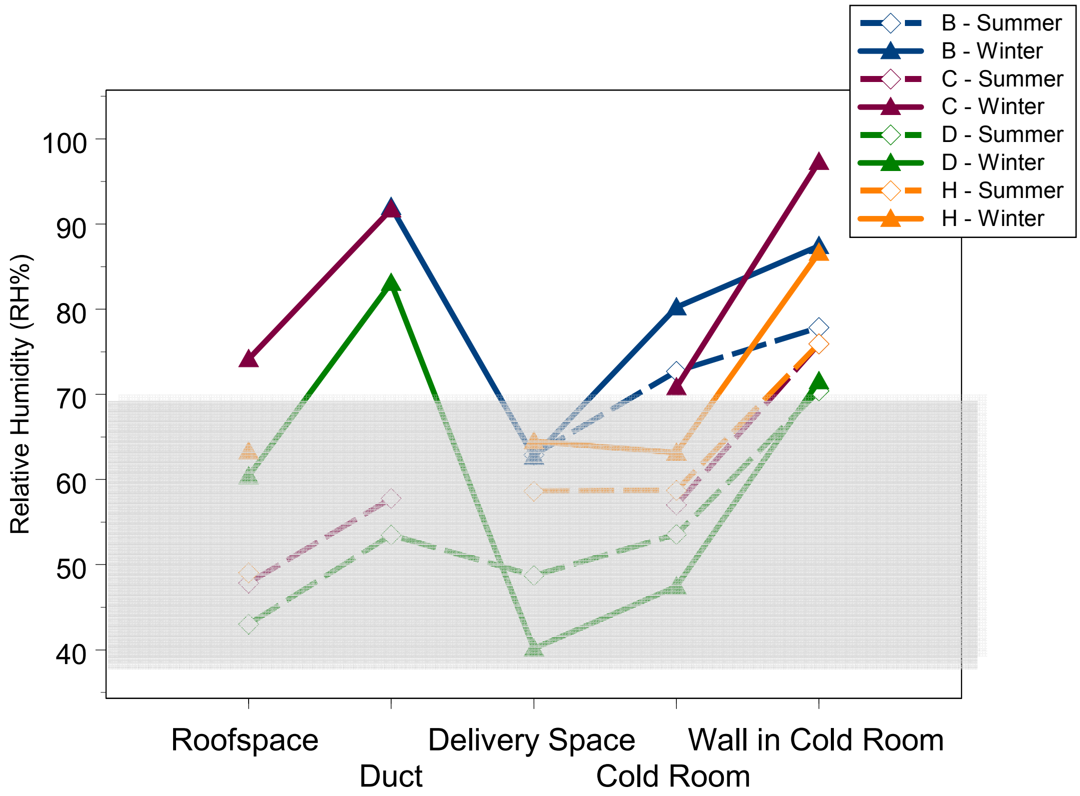

Figure 20: Summer and winter relative humidities at various locations within each house

The 24 hour average roofspace relative humidity levels in winter are moderately high, ranging from 60-74%. During summer the average relative humidity levels are lower, ranging from 43-49%.

It was difficult to measure the relative humidity in the duct, especially during winter. The high relative humidities of the roofspaces meant than many times the duct humidity sensors were saturated, indicating 100% relative humidity and interfering with the sensor's ability to respond to changing relative humidity levels.

The average summer-time relative humidity levels in the Delivery Space are at a higher level and have a wider range (49% to 63%) when compared with the average roofspace summer-time relative humidity levels. This is due to differences in temperature and the presence of other moistures sources in the building.

The average winter Delivery Space relative humidities are around 63% for House B and House H, similar to the average winter roofspace relative humidity levels. However House D has a low average winter Delivery Space relative humidity level of 40%, much reduced from the average winter roofspace relative humidity level of 60%. This reduction is presumably from the extensive winter use of a wall panel heater in the Delivery Space which was the hallway.

The relative humidity levels in the Cold Rooms were generally higher than in the Delivery Space. This general trend was in alignment with cooler temperatures in the Cold Room as shown in Figure 19. The Delivery Space and Cold Room in House H seem to be the exception to this trend, with similar relative humidity and temperatures between the two spaces.

The relative humidity levels seen in House B are high, particularly in the Cold Room. The average winter relative humidity level was 63% in the Delivery Space and 80% in the unoccupied Cold Room.

The average wall surface relative humidity levels in the Cold Room were all much higher than the air relative humidity levels in the Cold Room, even in the case of House B where the room air temperature was higher than the wall temperature. The average winter wall relative humidity levels of the Cold Room walls were between 5% and 19% higher than the relative humidity levels of the Cold Room air, while the winter-time relative humidity levels were between 7% and 26% points higher on the wall than the air.

All of the average wall surface relative humidities had winter and summer averages above 70% and many were above the humidity at which moulds would be expected to establish. The winter-time Cold Room wall relative humidity levels had averages above 85% for all cases except for House D.

6.4.1 Humidity ratios

The moisture transport from the roofspace to the Delivery Space is only part of the IEQ picture. The ultimate outcome for the air within the house is that temperature and relative humidity are within healthy and comfortable ranges. Difficulties in determining the airflow through the ventilation systems in this project have limited the analysis for this project and further work is required to consider the combined effects of the moisture and heat transfer between the roofspace and the Delivery Space. This section will consider the moisture levels in the roofspace and Delivery Space.

In the previous section it was seen that the average winter-time roofspace relative humidity levels in House D were 60%, while the Delivery Space into which the ventilation system discharged had an average winter relative humidity level of 40%. While this appears undesirable, the absolute moisture content of air in the Delivery Space (expressed as a humidity ratio) may still be higher than in the roofspace. In this case air from the roofspace will reduce the moisture content of air in the Delivery Space and help control moisture.

House D and House H had information on both the temperatures and relative humidities in the roofspace and the Delivery Space that allowed for the humidity ratios to be calculated for both spaces. For House B there were data limitations with the temperature humidity data from the roofspace, while House C had data limitations for the Delivery Space conditions.

Figure 21 shows a time-of-day average of the winter conditions in the roofspace and Delivery Space in House D. The roofspace humidity ratio is shown as a solid red curve and is measured according to scale on the right-hand side of the graph measuring the kilograms of water per kilogram of dry air. The Delivery Space humidity ratio is shown as the solid orange curve, also according to the scale on the right. The remaining measurements use the scale on the left and include the roofspace relative humidity (shown as a dashed dark blue line), the Delivery Space relative humidity (shown as a dashed red line), and the Delivery Space temperature (shown as a dashed light blue line). Figure 21 also shows the average use of the ventilation system fan as a brown line.

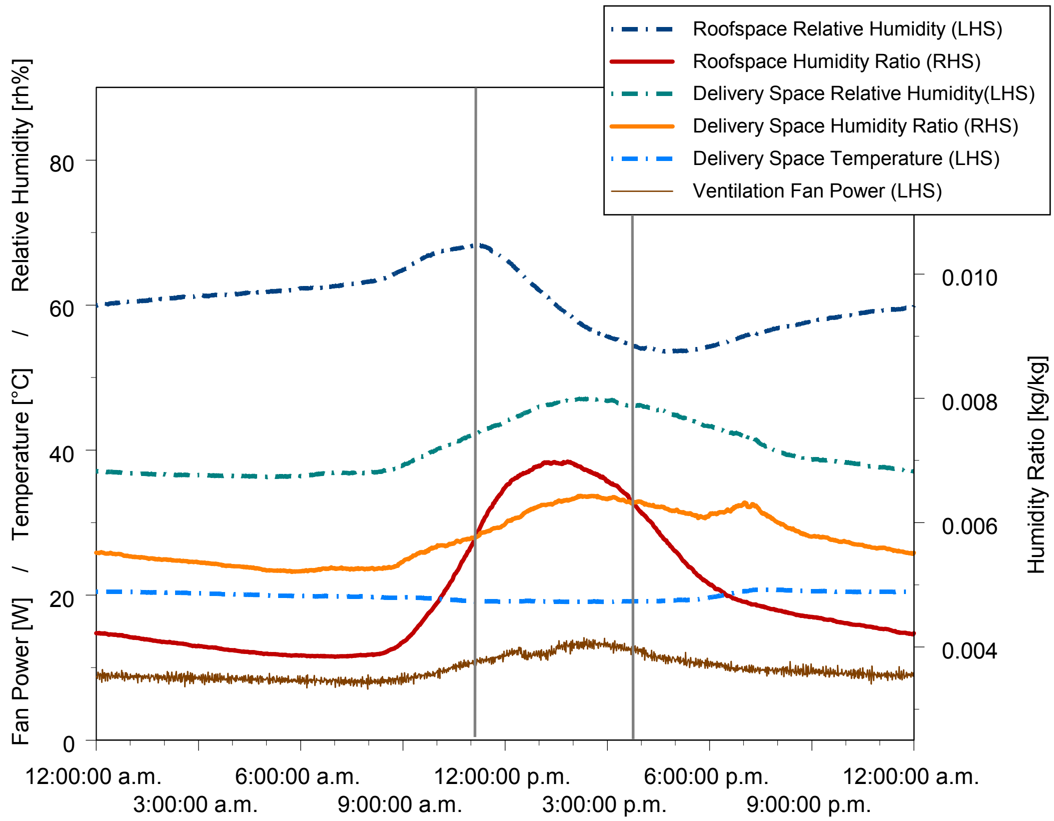

Figure 21: Winter conditions in the roofspace and Delivery Space and fan use for House D

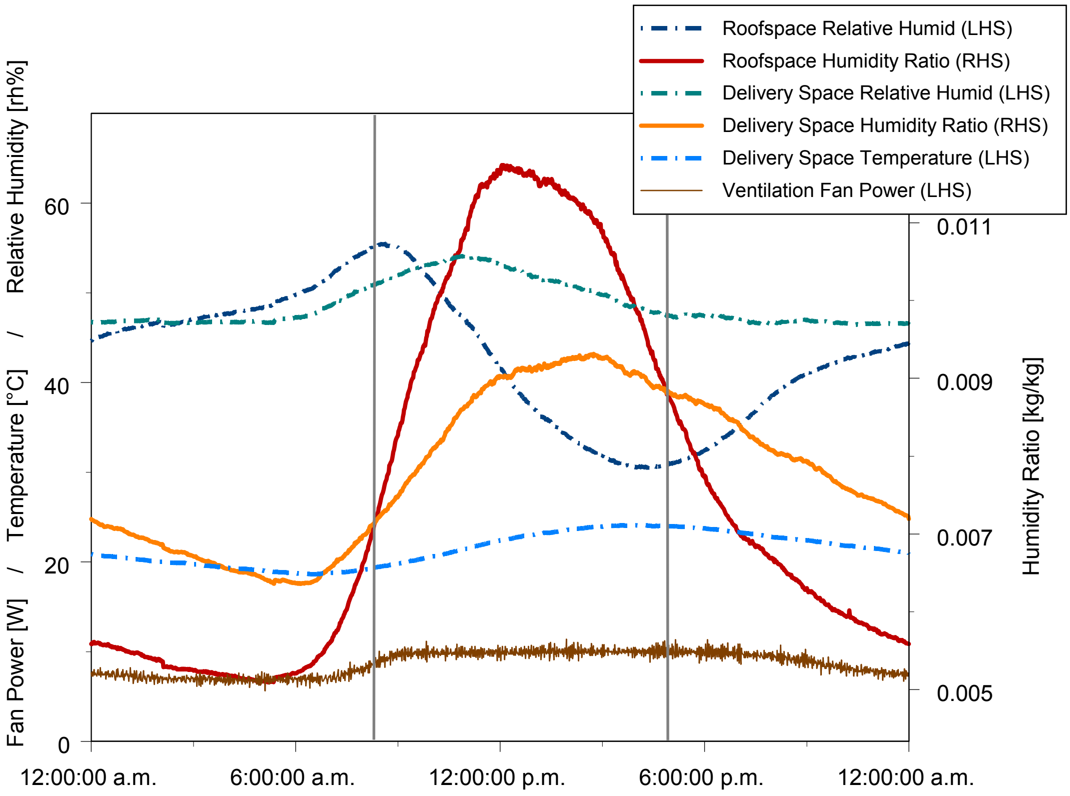

Figure 22: Summer conditions in the roofspace and Delivery Space and fan use in House D

The roofspace humidity ratio (shown as the red line in Figure 21) follows the expected shape of an outdoor air humidity ratio. An outdoor air humidity ratio peaks during the middle of the day (around 1:30pm) as solar radiation drives evaporation processes. The Delivery Space humidity ratio (orange line) in Figure 21 shows a smaller range of values and peaks after the roofspace humidity ratio curve at around 2:30pm. A blip is also seen in the Delivery Space humidity ratio at around 7pm, presumably due to moisture-generating activities such as cooking or the use of showers.

Typically the Delivery Space humidity ratio is greater than the roofspace humidity ratio. In these situations it makes sense, from a moisture control point of view, to displace moist Delivery Space air with less moist roofspace air. However the roofspace humidity ratio peaks during the day raising the moisture content of the roofspace air to levels higher than the Delivery Space humidity ratio. During these periods, operating the ventilation system will transfer moisture from the roofspace to the Delivery Space. However, there is also a transfer of heat (if the roofspace is warmer than the Delivery Space) from the roofspace to the Delivery Space, and this extra heat would impact on the relative humidity of the room air.

The time when the two humidity ratio curves swap over is shown by vertical grey lines. For winter in House D the time between 11am and 4pm has roofspace moisture levels higher than the moisture levels in the Delivery Space, so operation of the ventilation system during these times could be undesirable from a moisture point of view. This is not to say that the ventilation system should not be operated during these times, as ventilation may be required for pollutant control and there may be some thermal advantage if the roofspace temperatures are high in comparison to the Delivery Space temperatures.

The fan operation in Figure 21 shows an increased use during the day when moisture conditions are not favourable. How the fan is controlled is important. If the fan operation is controlled by temperature sensors in the roofspace and Delivery Space, then the fan may be operating because the roofspace is warm and the Delivery Space is cold, rather than because the roofspace is drier than the Delivery Space.

Figure 22 plots the same information as Figure 21 for the summer-time in House H. During summer, the roofspace humidity ratios peak at a higher level and higher levels of the humidity ratio are also seen for the Delivery Space. Overall, the period of higher roofspace moisture has extended from between 11am and 4pm in winter to between 8am and 5pm in summer. The fan operation still sees an increase in operation during this period of higher roofspace moisture.

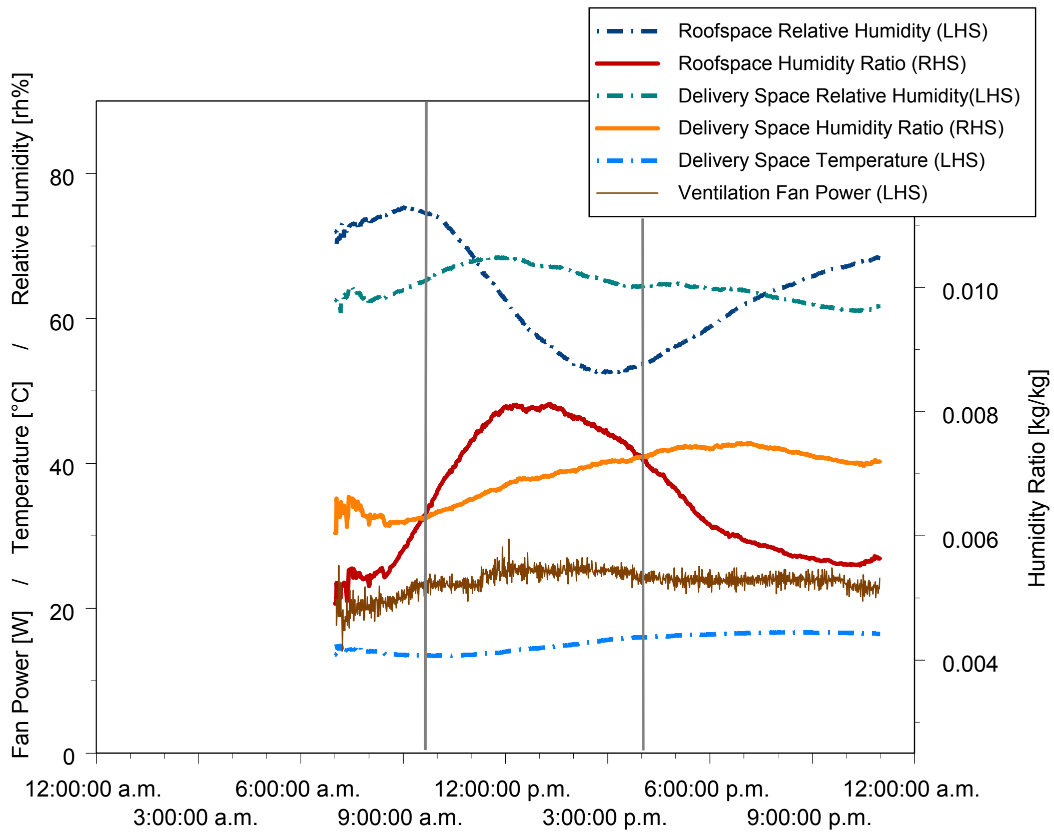

Figure 23: Winter conditions in the roofspace and Delivery Space and fan use for House H

Overnight measurements were not available.

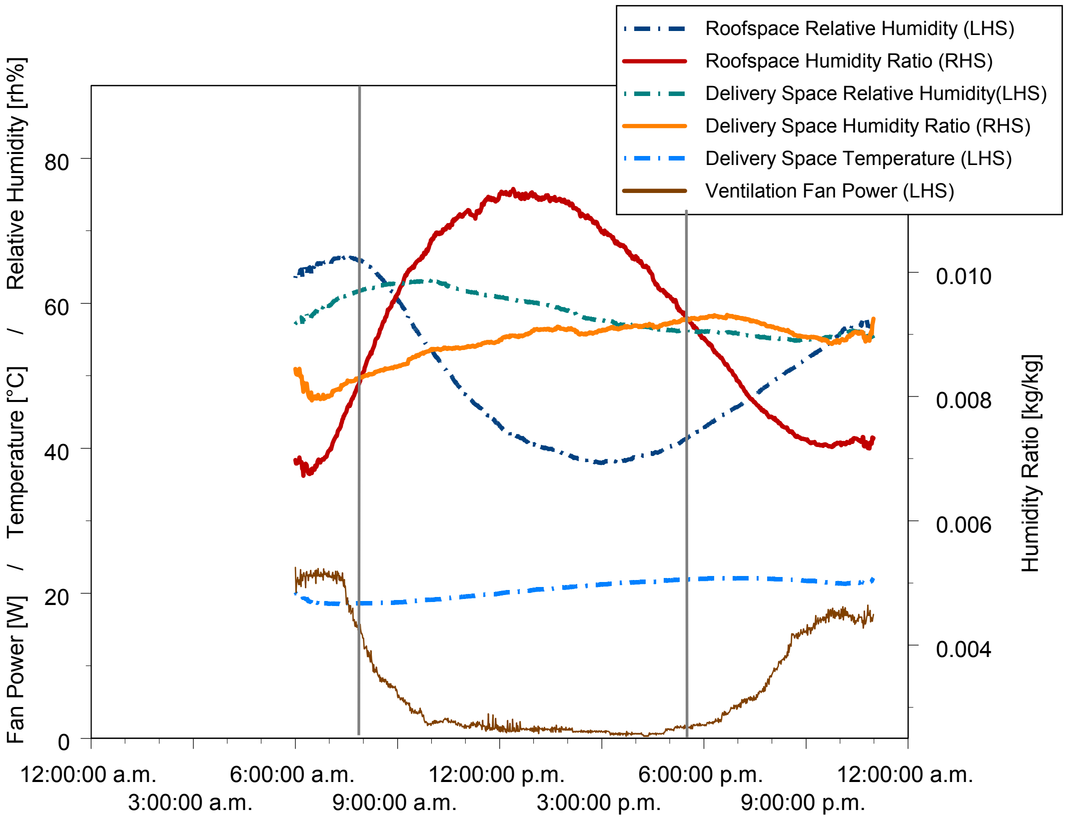

Figure 24: Summer conditions in the roofspace and Delivery Space and fan use in House H

Overnight measurements were not available.

The humidity ratios for the roofspace and Delivery Space air for House H are given for winter in Figure 23 and for summer in Figure 24. The winter profile for House H is similar to that for House D, i.e. the roofspace humidity ratio peaks at around 12:30pm while the peak Delivery Space humidity ratio continues to rise for an extended period peaking at around 7pm. The roofspace humidity ratio is greater than the Delivery Space humidity level between 10am and 3pm.

The summer humidity ratio profiles shown in Figure 24 again show larger peaking roofspace humidity ratios at around 1pm, with the Delivery Space humidity ratio peaking around 6:30pm. The time the average summer roofspace humidity ratio exceeds the Delivery Space humidity ratio is between 8am and 5:30pm.

The summer-time fan operation shows the fan operating regularly in the morning and then the average fan use tapers off between 7:30am and 10am, having little usage during the day before increasing usage between 5:30pm and 9pm before regular use after that. It was seen in the seasonal temperatures in Figure 19 that the temperatures in the roofspace are much higher in House H than outside due to the good capture of heat from solar radiation. The summer-time control of the ventilation system in House H presumably prevents operation of the ventilation fan when the Delivery Space is sufficiently warm and warmer air from the roofspace would be undesirable. It so happens that this control is also beneficial in reducing the transport of air from the roofspace that had more moisture content than the air in the Delivery Space during the day.

6.5 Fan energy of ventilation system

Most of the ventilation systems operated year round. Figure 25 shows the detailed time series graph of the fan power over the monitoring period from winter on the left-hand side of the graphs to summer on the right-hand side. Only House B appeared to be off during summer with the fan unit being turned off from the end of November.

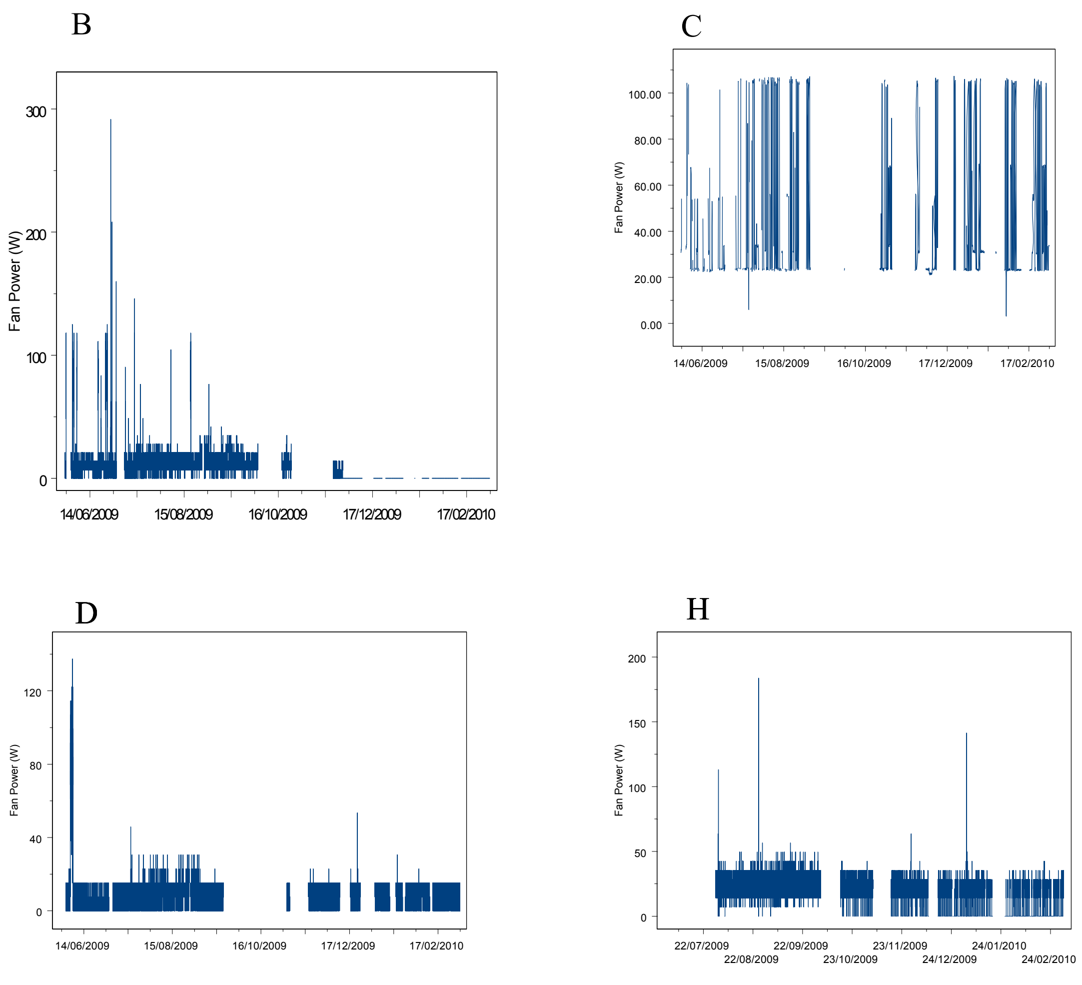

Figure 25: Fan power for the systems examined (gaps are missing values)

A totalised energy use for the fans could be collected from the electricity meter attached to the fan at the time the system was removed. The annual energy use estimates of the systems that had been removed at the time of writing are shown in Table 18. There is a large degree of variation between the systems. For the newer axial fan units in Houses B, D and F, the resulting fan energy use is low. Houses E and H had the older axial fan units which had a higher electrical energy demand. The centrifugal fan in House C had a large power demand and resulted in high annual energy use. At 400 kWh per year the ventilation system in this house would be a sizeable component of the electricity usage, being 5% of an average household's electricity requirements (Isaacs et al, 2006).

Table 18: Estimated annual fan energy use for a number of houses

House	Fan Energy Use [kWh/year]
B	63
C	400
D	75
E	250
F	53
H	150

Potentially more important than the fan energy is the impact on heating requirements from the use of the ventilation system. The time when the winter-time humidity ratio in the roofspace is lower than the Delivery Space is in the evenings and overnight when the temperature in the roofspace is cold.

7 Discussion

7.1 Moisture management

The data from the HomeSmart Renovation Project in-home assessments showed the moisture management for the houses that already had forced air ventilation systems was varied. Only one out of the 10 houses was compliant with all of the HSS® IEQ checklist items management options. Seven households dried their clothes inside, while half (five) of the houses did not have extractor fans in both the bathrooms and kitchen. Two households operated unflued gas heaters, while one of the six clothes dryers used in these houses was not vented to the outside.

Insulation levels in the houses were varied and only two houses had some form of ground vapour barrier. Water leaks were identified within a number of houses.

Effective moisture management requires effectively addressing all these areas to ensure that the moisture loading that has to be managed with mechanical ventilation or dehumidification is kept to a minimum.

7.2 Airtightness

The houses used in the project were sourced from the Home*Smart* Renovation Project and as such tended to be older houses. Of the eight systems which had blower door tests undertaken on them, five had an infiltration rate of greater than one air change per hour. These buildings have a high level of base ventilation, and the need for supplemental mechanical ventilation should be questioned as moisture issues may be arising from poor moisture management practices, lack of thermal insulation, insufficient levels of heating or particular user behaviours.

7.3 Forced air ventilation systems

Forced air ventilation systems are promoted as a means of reducing moisture problems (such as window condensation within houses) by increasing the level of ventilation. Some systems are also marketed as providing energy benefits from transferring heat from the roofspace into the rooms of the house.

The ventilation systems measure temperatures in the roofspace and the Delivery Space (such as a hallway) within the house, and operate the system when the roofspace is warm enough, providing that the Delivery Space is not too hot.

For the two systems for which roofspace and Delivery Space conditions could be determined, in winter the operation of the ventilation systems is regular. The fan time of day profiles (Figure 21 and Figure 23) are flat with a rise during the middle of the day. This rise is due to warming of the air in the roofspace during the day.

Calculation of the humidity ratio of the roofspace air and the air in the Delivery Space within these houses shows that in winter during the day the moisture content of the roofspace can exceed the moisture content of the Delivery Space. The increased operation of the ventilation system during the day can therefore increase the moisture content of the air in the Delivery Space during the day. The impact of this on the relative humidity in the Delivery Space will also depend on the heating taking place within the Delivery Space and the heat transferred from the roofspace by the ventilation system.

The operation of the ventilation system at night takes drier air from the roofspace and is therefore effective at reducing the level of moisture in the Delivery Space air. However the roofspace temperatures are cold during this time so temperatures in the Delivery Space may fall.

An ideal control system for forced air delivery from the roofspace clearly needs to take account of the temperature and humidity in both spaces. With this data the system will be able to determine when operation will reduce the relative humidity in the building. There are other considerations though, such as does the building need ventilation to remove other contaminants? Is heat from the roofspace more valuable than moisture removal (because moisture is already under control)? There is clearly an opportunity to develop forced air ventilation system controllers that consider all of these aspects of building performance. It may be that the controller is set to a particular function such as managing relative humidity (and therefore condensation risk), moisture removal, harvesting heat or increasing ventilation for a short time to remove odours (‘burnt toast’ setting).

The operation of a forced air ventilation system during the day will increase moisture levels within the house, but this may be compensated for by solar heat captured from the roofspace. The operation of a forced air ventilation system at night will decrease moisture levels, but will cool the house down as well.

Dampness and condensation and mould growth on walls and windows will also depend on the temperature of surfaces, so that insulation is also an important part of the overall tactics for controlling indoor moisture. Another contributor to warm indoor conditions (and to indoor moisture control) is the overall passive solar design of the building. This includes access to solar gains and effective thermal storage to moderate temperature swings within the building.

Where a house is particularly airtight and is left closed up, the natural ventilation rates may not be sufficient to control pollutants. In this case the ventilation systems may be beneficial in providing for an increased level of ventilation. It is important, however, to remember that another important part of controlling indoor moisture (certainly the most important part) is source control. Measures that eliminate moisture sources are ultimately more effective than ventilation. As Pettenkofer says:

> *“If there is a pile of manure in a space do not try to remove the odour by ventilation. Remove the pile of manure.”*

7.4 Operating systems to reduce moisture

The control systems in the forced air ventilation systems examined were controlled by temperature and not by the humidity ratio or moisture content of the air. These sensors do not provide the necessary information to the system to reliably reduce the moisture levels in the house. Designing more effective ventilation control functions is a task for the future but this project has demonstrated that there are important opportunities here, especially if ventilation for moisture control can somehow be better integrated with opportunities for moisture source control and the heating energy performance of the building.

The timing of processes becomes important to the effective operation of the systems. The timing of the peak Delivery Space moisture content varied between the two systems. House D had a peak Delivery Space humidity ratio in the early afternoon, an hour or so after the roofspace humidity ratio had peaked. House H had a peak in its Delivery Space humidity ratio at around 6:30pm, two to three hours after the roofspace humidity ratio levels had dropped below that of the Delivery Space and when ventilation may be of benefit.

The two systems for which temperature and humidity information was available (for both the roofspace and the Delivery Space) may have benefitted from more restrictive operation of the ventilation system such as operating at a higher level in the evening period. At this time the roofspace humidity ratio is lower than the level in the Delivery Space, the roofspace temperatures may not have dropped far, and occupant-controlled heating may be applied.

8 Conclusions

The houses examined in this project tended to be older houses with high levels of base ventilation and it is unclear whether they require additional ventilation. In these cases it seems likely that any moisture issues are related to a lack of thermal insulation, insufficient levels of heating, particular user behaviours or uncontrolled moisture sources. The use of additional mechanical ventilation may only be beneficial when a house is particularly airtight or where large moisture sources are present.

The temperatures, relative humidities and fan operation of the forced air ventilation systems were measured, and in four houses were analysed in detail. Three systems had various issues with high relative humidities, particularly in the Cold Room and on the wall surface in that room. While one household used heaters regularly in the Delivery Space and relative humidity levels were low and frequently drier than the recommended range of 40-70%.

The operation of a forced air ventilation system depends on the conditions in the roofspace and Delivery Space within a house. The control systems respond to measurements of roofspace and Delivery Space temperatures and, as such, may not operate at appropriate times for moisture control. There are opportunities to improve the control function of these systems so that they deliver better performance.

Examining two systems in detail as case studies showed that during the day the roofspace humidity ratio is often higher than the Delivery Space humidity ratio, and operation of the ventilation system during such times will therefore increase the humidity ratio of the Delivery Space air. At night the humidity ratio of the roofspace air was often lower than the Delivery Space air. However the roofspace temperatures at night are cold and use of the ventilation system then will reduce the Delivery Space temperatures.

There may be conflicting objectives in the use of forced air ventilation systems, such as maximising moisture extraction, making use of solar heat gains and controlling the Delivery Space humidity ratio levels. The ventilation control system has a role in managing these objectives and further work is required to understand these needs better.

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10 Appendix A: Temperature and relative humidity by month and time of day for each house

10.1 Temperature by time of day in House B

Table 19: Average 24 hour temperature for winter and summer months for selected locations

Month	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	6.7	6.0	7.0	11.6	9.3	10.1
July	6.0	5.3	6.4	10.7	8.3	8.8
August	9.5	9.3	11.2	13.5	11.6	12.7
December	16.0	16.7	19.3	18.6	17.2	18.6
January	17.9	19.3	21.6	19.9	18.7	20.2
February	17.6	18.5	21.0	20.0	18.7	20.3

Table 20: Average morning temperature for winter and summer months for selected locations

Month	Morning Temperature					
	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	4.5	3.5	4.0	10.6	8.7	9.0
July	3.7	2.7	3.3	9.4	7.4	7.5
August	7.0	6.1	7.9	12.3	10.3	11.1
December	14.8	14.5	18.2	17.8	16.0	17.5
January	16.4	15.9	19.6	19.0	17.5	19.0
February	15.4	14.2	18.2	19.0	17.6	19.1

Table 21: Average day temperature for winter and summer months for selected locations

Month	Daytime Temperature					
	Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	7.7	7.4	8.9	11.7	9.3	10.1
July	7.2	7.3	9.0	11.2	8.5	9.1
August	11.3	12.3	14.4	14.0	11.7	13.0
December	18.3	21.7	23.0	18.4	17.3	19.0
January	20.5	24.9	25.6	19.8	18.8	20.6
February	20.0	23.8	24.7	20.0	18.7	20.7

Table 22: Average evening temperature for winter and summer months for selected locations

Month	Evening Temperature					
	Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	7.6	6.6	7.7	12.5	9.8	10.7
July	6.7	5.7	6.8	11.1	8.9	9.6
August	10.2	9.8	11.5	14.3	12.5	13.6
December	16.6	17.0	19.6	19.4	18.1	19.4
January	18.1	19.0	21.4	20.6	19.4	20.8
February	18.2	18.9	21.2	20.7	19.5	21.1

Table 23: Average night temperature for winter and summer months for selected locations

Month	Night Temperature					
	Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	5.6	4.7	5.3	11.3	9.1	9.8
July	4.7	3.6	4.5	10.2	7.9	8.4
August	7.9	6.9	8.4	12.7	11.1	12.1
December	13.4	12.0	15.7	18.3	16.7	17.8
January	15.5	14.6	18.1	19.7	18.3	19.6
February	15.1	13.7	17.6	19.7	18.2	19.7

10.2 Relative humidity by time of day in House B

Table 24: Average 24 hour relative humidity for winter and summer months for selected locations

Month	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	na	94.6	63.5	81.3	88.6
July	na	94.0	63.7	82.4	90.7
August	na	87.8	61.1	77.4	83.5
December	na	na	60.8	71.1	78.5
January	na	na	63.5	72.9	81.7
February	na	na	64.2	74.0	77.1

Table 25: Average morning relative humidity for selected months and locations

Month	Morning Relative Humidity				
	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	na	95.0	63.8	81.6	89.9
July	na	94.6	64.5	83.3	92.4
August	na	92.7	62.3	79.1	87.0
December	na	na	62.2	73.9	82.4
January	na	na	64.9	75.9	85.3
February	na	na	66.0	77.2	81.9

Table 26: Average day relative humidity for selected months and locations

Month	Daytime Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	na	94.0	64.1	81.5	88.6
July	na	92.5	64.1	83.0	91.4
August	na	81.3	61.4	78.0	83.3
December	na	na	60.8	70.0	75.7
January	na	na	64.1	72.8	80.5
February	na	na	63.9	73.2	74.4

Table 27: Average evening relative humidity for selected months and locations

Month	Evening Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	na	94.7	63.2	80.9	88.0
July	na	94.7	63.2	81.3	88.9
August	na	88.4	60.3	75.9	81.6
December	na	na	60.1	69.8	77.3
January	na	na	62.6	71.1	79.7
February	na	na	63.4	72.4	75.2

Table 28: Average night relative humidity for selected months and locations

Month	Night Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	na	95.0	63.1	81.3	88.9
July	na	94.9	63.4	82.4	90.9
August	na	92.7	61.0	77.4	84.1
December	na	na	61.0	72.3	81.5
January	na	na	63.3	73.7	83.7
February	na	na	64.6	75.2	80.0

10.3 Temperature by time of day in House C

Table 29: Average 24 hour temperature for winter and summer months for selected locations

Month	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	6.6	8.5	5.9	na	12.6	9.3
July	6.5	8.1	5.6	na	12.0	8.4
August	9.3	11.5	10.2	na	14.4	11.6
December	14.3	19.5	19.5	na	18.2	16.9
January	17.1	22.5	22.7	na	20.1	19.1
February	17.7	22.7	23.1	na	20.2	19.4

Table 30: Average morning temperature for winter and summer months for selected locations

Month	Morning Temperatures					
	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	3.6	5.1	1.1	na	11.6	7.2
July	3.9	4.1	-0.3	na	10.8	6.1
August	6.1	6.6	4.0	na	13.0	9.4
December	14.3	17.4	18.9	na	16.6	14.9
January	16.3	19.0	21.5	na	18.1	16.7
February	16.3	17.3	19.4	na	18.3	17.0

Table 31: Average day temperature for winter and summer months for selected locations

Month	Daytime Temperatures					
	Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	8.5	10.7	9.7	na	12.2	9.3
July	8.4	11.2	10.8	na	11.5	8.7
August	11.9	15.1	15.8	na	14.2	11.6
December	17.0	27.1	27.9	na	18.6	17.5
January	21.0	32.0	32.3	na	20.8	19.9
February	21.1	31.0	31.6	na	20.3	19.7

Table 32: Average evening temperature for winter and summer months for selected locations

Month	Evening Temperatures					
	Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	7.2	9.5	6.6	na	13.3	10.4
July	6.8	8.4	5.1	na	12.8	9.5
August	9.3	11.7	9.8	na	15.3	12.8
December	14.0	19.5	19.0	na	19.2	18.3
January	16.7	21.8	21.7	na	21.2	20.6
February	17.4	22.5	22.5	na	21.5	21.0

Table 33: Average night temperature for winter and summer months for selected locations

Month	Night Temperatures					
	Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	4.8	6.4	2.9	na	12.7	9.0
July	4.9	5.6	1.7	na	12.1	8.0
August	6.9	8.1	5.3	na	14.4	11.2
December	12.0	13.1	12.4	na	17.4	15.6
January	13.7	14.7	14.7	na	19.0	17.7
February	14.6	15.3	15.2	na	19.6	18.4

10.4 Relative humidity time of day in House C

Table 34: Average 24 hour relative humidity for winter and summer months for selected locations

Month	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	76.0	94.8	na	71.4	97.9
July	76.0	93.7	na	71.4	97.6
August	71.2	87.7	na	70.0	96.6
December	49.9	61.4	na	58.6	78.8
January	43.3	52.2	na	51.5	69.0
February	50.0	59.8	na	60.3	79.5

Table 35: Average morning relative humidity for selected months and locations

Month	Morning Relative Humidity				
	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	79.2	99.0	na	70.6	99.5
July	79.9	98.9	na	69.5	98.5
August	77.9	96.7	na	68.6	98.0
December	58.0	66.7	na	61.9	84.3
January	53.4	59.4	na	55.5	75.4
February	63.3	71.3	na	61.7	83.6

Table 36: Average day relative humidity for selected months and locations

Month	Daytime Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	75.3	90.5	na	72.4	97.5
July	74.1	87.1	na	73.2	96.6
August	67.7	78.9	na	72.2	97.3
December	41.5	47.5	na	61.9	82.3
January	33.8	36.7	na	54.0	71.3
February	41.9	45.1	na	64.6	84.1

Table 37: Average evening relative humidity for selected months and locations

Month	Evening Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	73.1	94.2	na	69.0	95.9
July	73.0	94.3	na	69.8	96.6
August	68.8	87.8	na	68.1	93.7
December	46.1	58.6	na	55.7	73.3
January	40.3	51.3	na	48.5	63.8
February	45.8	57.4	na	57.5	74.3

Table 38: Average night relative humidity for selected months and locations

Month	Night Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	78.4	98.6	na	72.5	99.3
July	79.2	99.1	na	70.8	99.2
August	75.8	96.3	na	69.3	98.0
December	58.5	74.7	na	57.2	78.7
January	52.4	66.3	na	50.5	69.1
February	58.9	74.8	na	57.4	77.6

10.5 Temperature by time of day in House D

Table 39: Average 24 hour temperature for winter and summer months for selected locations

Month	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	7.2	9.3	5.0	19.8	16.4	13.0
July	6.9	9.4	5.0	21.0	17.3	13.5
August	10.1	12.5	9.4	18.9	16.0	14.0
December	15.1	21.2	19.9	19.7	18.1	17.8
January	16.6	23.0	22.0	21.5	20.0	19.8
February	17.4	23.6	22.4	22.3	20.7	20.4

Table 40: Average morning temperature for winter and summer months for selected locations

Month	Morning Temperatures					
	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	5.6	6.5	0.4	20.0	16.5	12.1
July	5.2	6.2	-0.2	21.6	17.7	12.6
August	7.7	8.2	2.8	18.7	15.7	12.8
December	12.1	13.1	10.0	17.3	16.2	16.1
January	16.7	24.8	22.9	23.0	21.4	21.1
February	18.5	26.4	24.4	24.1	22.5	22.0

Table 41: Average day temperature for winter and summer months for selected locations

Month	Daytime Temperatures Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	6.6	8.3	4.3	19.6	16.1	12.4
July	6.4	8.4	4.5	20.9	17.1	13.2
August	9.8	11.4	9.1	18.3	15.6	13.4
December	15.7	21.9	22.1	18.8	17.3	16.9
January	15.2	18.8	17.0	21.1	19.8	19.0
February	15.9	18.5	16.5	21.8	20.5	20.1

Table 42: Average evening temperature for winter and summer months for selected locations

Month	Evening Temperatures Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	9.1	13.0	10.3	19.5	16.5	14.2
July	8.9	13.8	11.2	20.0	17.0	14.5
August	12.5	17.7	16.4	19.0	16.5	15.4
December	17.0	28.7	27.3	21.8	19.7	19.8
January	15.5	18.2	17.7	19.6	18.4	18.2
February	15.5	17.1	16.4	20.0	18.6	18.5

Table 43: Average night temperature for winter and summer months for selected locations

Month	Night Temperatures Outside [°C]	Roofspace [°C]	Duct [°C]	Delivery Space [°C]	Cold Room [°C]	Wall in Cold Room [°C]
June	6.9	8.3	2.8	20.2	16.6	12.8
July	6.4	7.9	2.0	21.9	17.6	13.2
August	9.1	10.7	6.2	19.4	16.2	13.8
December	13.7	16.9	14.6	19.5	18.1	17.7
January	18.8	30.3	29.9	22.8	21.1	21.3
February	20.0	32.9	32.3	24.1	22.1	21.6

10.6 Relative humidity by time of day in House D

Table 44: Average 24 hour relative humidity for winter and summer months for selected locations

Month	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	63.7	88.1	40.5	48.1	73.4
July	60.8	85.0	36.3	43.7	69.6
August	56.8	76.5	43.5	50.4	71.7
December	42.0	53.0	47.0	51.7	68.3
January	43.4	53.8	49.1	53.8	70.3
February	43.4	53.6	49.5	54.6	71.9

Table 45: Average morning relative humidity for selected months and locations

Month	Morning Relative Humidity				
	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	64.1	92.9	36.8	43.9	70.2
July	61.9	90.5	32.6	39.5	67.5
August	59.1	83.9	39.6	46.8	69.7
December	47.4	65.1	46.0	50.2	68.7
January	37.2	49.5	47.9	53.6	69.9
February	36.1	47.6	48.3	53.8	71.2

Table 46: Average day relative humidity for selected months and locations

Month	Daytime Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	67.2	91.4	39.9	47.2	73.0
July	65.1	88.8	35.7	42.8	68.7
August	61.9	80.5	43.9	49.7	71.0
December	47.1	54.7	49.9	53.2	70.1
January	45.5	60.5	47.3	52.5	70.8
February	44.7	60.0	47.5	52.8	69.8

Table 47: Average evening relative humidity for selected months and locations

Month	Evening Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	60.5	80.8	45.0	52.1	75.5
July	56.0	75.5	41.6	48.0	71.3
August	50.3	65.3	48.2	53.8	73.0
December	32.5	39.8	46.1	51.1	65.4
January	50.7	63.1	49.1	53.2	70.0
February	52.2	65.4	49.4	53.8	70.6

Table 48: Average night relative humidity for selected months and locations

Month	Night Relative Humidity				
	Roofspace [%rh]	Duct [%rh]	Delivery Space [%rh]	Cold Room [%rh]	Wall in Cold Room [%rh]
June	62.6	89.3	38.6	47.0	72.9
July	59.9	87.0	33.7	42.4	69.7
August	56.0	79.0	40.6	49.5	71.8
December	42.7	58.1	45.2	50.9	68.7
January	37.6	41.7	51.1	55.5	70.0
February	37.4	39.9	51.9	57.2	75.0

10.7 Temperature by time of day in House H

Table 49: Average 24 hour temperature for winter and summer months for selected locations

Month	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	na	na	na	na	na	na
July	na	13.1	10.5	17.1	17.1	13.9
August	8.4	14.2	12.2	15.3	15.5	12.7
December	16.8	22.9	22.5	19.3	19.7	18.3
January	17.9	25.0	24.4	20.4	21.0	19.5
February	19.4	25.7	25.2	21.8	22.2	20.8

Table 50: Average morning temperature for winter and summer months for selected locations

Month	Morning Temperatures					
	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	na	na	na	na	na	na
July	na	11.2	8.8	15.9	15.0	12.0
August	7.9	8.4	5.4	13.8	13.1	11.2
December	15.6	17.8	18.9	17.4	17.7	16.3
January	15.9	17.8	19.0	18.3	18.6	17.4
February	17.3	18.2	19.6	19.9	19.5	18.6

Table 51: Average day temperature for winter and summer months for selected locations

Month	Daytime Temperatures					
	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	na	na	na	na	na	na
July	na	17.3	15.7	16.3	16.5	13.7
August	8.4	17.1	15.9	14.5	15.0	12.0
December	17.7	27.0	26.8	19.2	19.9	18.3
January	18.7	29.6	29.0	20.1	21.0	19.5
February	20.5	30.8	30.2	21.5	22.4	20.9

Table 52: Average evening temperature for winter and summer months for selected locations

Month	Evening Temperatures					
	Outside	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
June	na	Na	na	na	na	na
July	na	10.2	6.9	17.8	17.9	14.3
August	8.6	12.2	9.5	16.4	16.7	13.9
December	16.1	19.7	18.6	20.4	20.3	19.1
January	17.9	22.2	21.0	21.8	21.9	20.4
February	19.0	22.8	21.7	22.9	23.1	21.6

10.8 Relative humidity by time of day in House H

Table 53: Average 24 hour relative humidity for winter and summer months for selected locations

Month	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	na	na	na	na	na
July	63.9	na	59.5	59.7	83.5
August	63.3	na	64.7	63.3	86.8
December	50.0	na	59.7	59.1	75.8
January	47.3	na	57.4	57.1	74.4
February	49.6	na	58.7	59.6	77.2

Table 54: Average morning relative humidity for selected months and locations

Month	Morning Relative Humidity				
	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	na	na	na	na	na
July	78.2	na	63.0	65.9	90.1
August	73.8	na	63.0	65.1	88.1
December	63.0	na	62.2	61.4	78.8
January	64.7	na	61.9	62.0	78.7
February	66.1	na	61.1	62.6	78.8

Table 55: Average day relative humidity for selected months and locations

Month	Day-time Relative Humidity				
	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	na	na	na	na	na
July	60.5	na	62.7	62.3	85.0
August	60.8	na	66.3	63.5	87.1
December	45.4	na	60.9	58.5	74.8
January	42.3	na	58.6	56.6	73.9
February	44.1	na	60.1	59.2	77.5

Table 56: Average night relative humidity for selected months and locations

Month	Evening Relative Humidity				
	Roofspace	Duct	Delivery Space	Cold Room	Wall in Cold Room
	[%rh]	[%rh]	[%rh]	[%rh]	[%rh]
June	na	na	na	na	na
July	65.0	na	56.9	57.1	82.0
August	63.3	na	63.3	62.1	85.2
December	50.5	na	56.9	59.0	75.7
January	46.4	na	54.3	55.8	73.2
February	49.1	na	56.1	58.5	76.0