Study Report

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Could damp homes be too cold/underheated?

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Abstract

Many New Zealand homes are cold and damp.

High moisture levels in homes can be due to low indoor temperatures, excessive moisture production or lack of ventilation. This report looks at existing data collected by BRANZ to see what extent low indoor temperatures have in determining high moisture levels. While moisture levels are highly variable between rooms within a home, low indoor temperatures appear to be a large contributor to the high moisture levels observed.

Heating rooms to a minimum level of 18°C reduces the risk of high moisture levels in many homes, suggesting many homes are underheated or too cold.

Keywords

Moisture, dampness, relative humidity, underheating, indoor conditions

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Executive summary

Cold and damp are common problems in New Zealand homes. These problems are connected.

Condensation, dampness and mould will occur on cold surfaces when there are extended periods of high relative humidity (moisture) within a room. When a room cools, the relative humidity of the room air will increase.

This situation suggests a question:

> In homes where there is a high relative humidity level, is this due to too much moisture in the home or is it due to the home not being maintained at a sufficiently high temperature (underheating)?

To consider this, data from a number of varied BRANZ research projects was examined. This data revealed that, for many homes, if they were to be heated to a minimum of 18°C throughout, they would experience far fewer periods of high relative humidity.

This suggests that, for homes with dampness problems, many of them would be due to the home being kept too cold and not sufficiently heated. The observed high relative humidity has a greater dependency on the low temperatures within the home rather than excessive moisture production or too little ventilation.

For this project, high relative humidity is defined as a relative humidity over 70%. A high humidity level will be when the relative humidity is higher than 70% for more than 20% of the time.

The Occupant Behaviour project examined the use of ventilation in a subset of homes from the BRANZ House Condition Survey. Data on the indoor temperature and relative humidities, largely in bedrooms and bathrooms, was collected from 66 homes. Overall, 65% of homes had at least one room in which high humidity levels were present. If these rooms had been heated to a minimum of 18°C, the occurrence of high humidity levels would reduce to 21% of homes.

The other projects focused on heating with measurements mainly coming from heated rooms within the homes. Not including unheated rooms would tend to underestimate the underheating risk for that home.

In the Key Energy Uses project, room conditions were recorded in rooms that had a heat pump for 134 households from around New Zealand. Despite these rooms being heated, 17% of the homes had high humidity levels. If these rooms had been heated to a minimum of 18°C, all but one home would have had a high humidity level.

The other research project involved Wellington City Council's Kōtuku Apartments, which were subject to an upgrade. The humidity levels of the original apartments were high in five of the 11 apartments. However, if a minimum heating level of 18°C had been applied, none of the apartments would have had high humidity levels.

The upgrades to the Kōtuku Apartments included increases to the insulation levels with double glazing to the north side as well as adding insulated plasterboard to the exposed concrete walls. The upgrades were sufficient that none of the post-renovation apartments had high humidity levels, and they did not require a minimum heating level to ensure the humidity levels were not exceeded.

1. Introduction

Many New Zealand homes have high levels of moisture. Evidence for this is frequently indirect, such as that around half of New Zealand homes have some degree of visible mould present (White et al., 2017). Mould will germinate and grow when there are extended periods where surfaces are damp, which in turn is sustained when the room air has high levels of moisture. The World Health Organization's guidelines for indoor air quality for dampness and mould (WHO, 2009) discusses the limits of mould growth extensively. While the dynamic nature of micro-environments needs to be considered, reviews such as Rowan et al. (1999) suggest that mould growth may be limited when surface relative humidities are kept below 75%. For this paper, broader room measurements of relative humidity were taken, and a lower relative humidity limit of 70% is used to provide some margin between the two measurements.

In addition to the risk of mould, high room moisture levels can also result in negative consequences such as providing growth conditions for dust mites, some bacteria and viruses as well as increasing chemical interactions with formaldehydes, sulphur and nitrogen oxides (Arundel et al., 1986, Sterling et al., 1985). These consequences occur at lower relative humidity levels than those levels that cause problems with mould growth. Above a relative humidity of 45–50%, dust mites will begin to grow (WHO, 2009). This paper will focus on mould growth and will use the 70% relative humidity threshold, which may be too high to prevent dust mites and other negative consequences.

There are many different ways of measuring the moisture level of air (see, for example ASHRAE (2013)). Some of these ways are independent of the temperature. For example:

- the humidity ratio gives the grams of water vapour present per kilogram of air
- absolute humidity gives the grams of water vapour present per cubic metre of air.

At a particular temperature, however, there is a maximum (saturation) water vapour pressure. This saturation water vapour pressure increases with increasing temperature. A given humidity ratio (say 5 grams of water vapour per 1 kg of air) at say 15°C will be closer to saturation than air with the same humidity ratio at a higher (say 20°C) temperature. The 15°C air would be at greater risk of condensation than air with the same humidity ratio at 20°C. As this condensation risk is important, many moisture measurements consider the temperature of the air as well.

One such measurement is relative humidity, which is the ratio of the water vapour pressure to the maximum water vapour pressure (at saturation) for that particular temperature. Air that has, say a 50% relative humidity at 20°C, when cooled naturally (the humidity ratio or moisture content of the air will stay the same) will increase in relative humidity and be at greater risk of condensation. (In this case, if the 50% RH 20°C air is reduced to 16°C, the relative humidity will increase to 64%.) The reverse of this is when the room air is heated up. It will reduce in relative humidity and therefore be at a lower risk of condensation.

There is little information on what indoor temperatures are like in New Zealand homes. Between 1999 and 2004, as part of the BRANZ Household Energy End-use Project (HEEP), around 400 randomly selected households throughout New Zealand were instrumented to record their energy use and indoor temperatures (Isaacs et al., 2010). It was found that many of these homes were cold (Isaacs et al., 2010) and were frequently at temperatures that may pose health risks to the occupants (Raw et al., 2001).

This poses the central question for this report:

> In homes where there is a high relative humidity level, is this due to too much moisture in the home or is it due to the home not being maintained at a sufficiently high temperature (underheated)?

To answer this question, an investigative approach was used with existing datasets. These existing datasets were collected for other purposes so do not provide an ideal match. However, this avoids the expense of a complicated data collection process to answer the question more definitely.

It is important to remember that individual homes may have quite different physical and social factors that impact on the relative humidity found within their home. These different factors may require different management approaches in order to bring the relative humidity for a specific home into an appropriate range.

2. Existing temperature and humidity data

2.1 Temperature studies

An early study on indoor temperatures in New Zealand was the 1971–72 Survey of Household Electricity Consumption (New Zealand Department of Statistics, 1973). This study included temperature measurement in a subsample of 295 households (New Zealand Department of Statistics, 1976). The indoor temperatures were measured in a number of rooms within each of the households using electrolytic cells (Trethowen, 1977). These cells provided an average temperature over a 2-month measurement period. One of these periods was August–September 1971, and the other was February–March 1972.

Table 1 gives the winter (August–September) temperatures from this survey. It shows that the average temperatures in New Zealand homes in the early 1970s were cold. Only the kitchen and lounge temperatures from the northern North Island (Auckland, Hamilton and Central Waikato) had average temperatures approaching the recommended minimum 18°C (WHO, 1985).

Table 1. Mean temperature levels, August–September 1971.

Region	Sample size	Kitchen [°C]	Lounge [°C]	Bedroom [°C]
Northern North Island	98	17.8	17.7	16.1
Southern North Island	64	16.4	16.6	15.1
Christchurch	69	15.3	15.2	13.8
Southern South Island	64	15.0	13.6	12.6

Source: (New Zealand Department of Statistics, 1976).

The 1971–72 survey did not find a difference in the mean indoor temperatures between those houses that had roof insulation and those that did not have roof insulation. This is in part due to the fact that the low amount of heating used and the presence or not of insulation has only a small impact on the 2-monthly mean of the indoor temperature.

The 1971–72 study also reported that the resultant indoor temperatures for a particular room type tended to be at a similar offset from the external temperature in the four locations studied (northern North Island, southern North Island, Christchurch and southern South Island).

The next large-scale survey of indoor temperatures was undertaken as part of the BRANZ Household Energy End-use Project (HEEP). The temperature information collected for this project was from around 400 randomly selected households throughout New Zealand between 1999 and 2004 (Isaacs et al., 2010).

The comparison of temperatures between the 1971–72 Survey and HEEP was presented in the HEEP final report (Isaacs et al., 2010) and is reproduced here in Table 2. This shows that there has not been wide-scale increases in winter indoor temperatures (presented just for the living rooms) between the two studies. The mean HEEP temperatures from the four regions is similar, with the warmer regions slightly cooler and the colder regions slightly warmer.

Table 2. Comparison of HEEP and 1971–72 temperatures using 1971–72 regions.

Aug–Sep temperatures [°C]	Northern North Island		Southern North Island		Christchurch		Southern South Island	
	HEEP 2001–2004	1971	HEEP 1999, 2002–2004	1971	HEEP 2002	1971	HEEP 2003	1971
Living room mean temperature	16.5	17.7	16.1	16.6	16.1	15.2	14.7	13.6
Living room 95% confidence interval	16.2–16.8	-	15.0–16.5	-	15.4–16.7	-	13.7–15.8	-
External mean temperature	11.9	12.0	9.3	11.0	10.3	9.3	7.3	8.6
Mean temperature difference (living room and external)	4.6	5.7	6.9	5.6	5.7	5.9	7.4	5.0
Sample size (n)	112	98	74	64	34	69	30	64

Source: (Isaacs et al., 2010; New Zealand Department of Statistics, 1976).

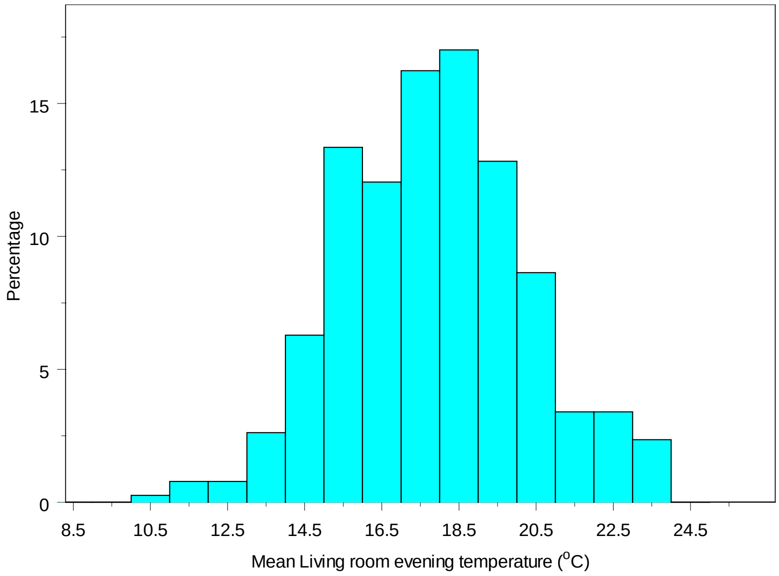
Temperature measurement technology has advanced since the 1971–72 study, with low-cost electronic temperature data loggers being available (Pollard, 2001). Data loggers allowed for the collection of temperature information at short 10 or 15-minute intervals. HEEP included monthly visits to each of the households to retrieve data from the data loggers, which required direct connection of the data logger to a laptop computer. Ideally, this monitoring would continue for a year. However, the need to rotate the data logging equipment between study areas meant the data collection period was typically 11 months.

Analysis of the early HEEP temperature monitoring (Pollard, 2001) revealed that three measurement points were particularly important for each household. The measurement at two heights in the lounge provided some information on how the lounge was heated. Another measurement point in the master bedroom gave an indication as to whether the bedrooms were heated.

The collection of a 10-minute time series of temperatures allows for a much greater analysis of resultant temperatures and the underlying causal factors. HEEP found that less than 5% of households heated their homes continuously over winter. However heating the living room in the weekday evenings was popular, with around 89% of households reporting heating at this time.

Figure 1 provides a histogram from HEEP (Isaacs et al., 2010) of the evening (5pm–11pm) living room temperatures over winter (defined as the months June, July and August).

This histogram shows that, despite this time being the most popular for heating, many houses are too cold. Around 25% of the households had a mean winter evening temperature below 16°C.



Source: (Isaacs et al., 2010).

Figure 1. Distribution of winter evening living room temperatures.

As mostly likely to be heated, the living room is less likely than the other rooms in the home to suffer from high relative humidity. Table 3 shows the mean temperatures between the living room and the main bedroom from HEEP showing the cooler temperatures in the bedrooms.

Table 3. Mean temperatures: living room, bedroom and ambient.

Room	Mean temperatures [°C]			
	Morning	Day	Evening	Night
Living room	13.5	15.8	17.8	14.8
Bedroom	12.6	14.2	15.0	13.6
Ambient	7.8	12.0	9.4	7.6

Source: (Isaacs et al., 2010).

At the time HEEP was being designed, the cost of data loggers that included humidity measurement was much higher than data loggers that solely measured temperature. As HEEP was primarily concerned with heating energy, the decision was made to only collect temperature information so that a sufficient number of households could be monitored. Since then, the cost of data collection technologies has significantly reduced, and now it would be unusual not to measure the indoor humidity when the indoor temperatures are being recorded.

2.2 Temperature and humidity studies

A number of projects have been undertaken by BRANZ since HEEP was concluded that have included measurements of indoor humidity as part of their data collection. Care must be taken when considering these datasets as they were constructed for other reasons and may not accurately represent the humidity throughout the house.

A subsample of the current BRANZ House Condition Survey (White et al., 2017) has included measurements of window and door openings undertaken within the home as part of a study of occupant behaviour regarding use of ventilation. Included within these measurements were indoor temperature and humidity in a number of rooms within each house. Overall, 66 homes with measurements in 222 rooms were collected over the winter period. This Occupant Behaviour subset was subject to few selection criteria and is used to provide a good representation of the indoor conditions within New Zealand homes.

A recently completely project involved the renovations to Wellington City Council's Kōtuku Apartments (Buckett & Jaques, 2016; Jaques et al., 2017). These apartments are part of Wellington City Council's social housing programme. They included approximately 100 similar single apartments (combined living, bedroom space, adjoining kitchen and bathroom) spread over four blocks, each of four levels.

These apartments were built in the 1960s with large amounts of uninsulated concrete and low levels of insulation. The renovations, finished in 2016, saw improved insulation, new glazing and some apartments reconfigured to 1 or 2-bedroom apartments.

The indoor temperatures and relative humidities were measured in 11 apartments before the renovations and nine apartments after the renovations. These apartments were all of the same type and were spread across the four separate blocks.

For the pre-renovation apartments, their low levels of insulation and limited purchased heating resulted in frequent low temperatures. It is also likely these apartments would be subject to high humidities, so the pre-renovation Kōtuku Apartments would provide a useful dataset of households that are more likely to have moisture problems. The post-renovation dataset could also provide some information on the extent to which improvements to the insulation could help mitigate the high moisture levels.

The Key Energy Uses (KEU) project (Burrough et al., 2015) looked at the use of heat pumps and the resultant indoor temperature and relative humidities from their use. This project included around 160 randomly selected households throughout New Zealand that had at least one heat pump. The temperature and relative humidity were measured in the room in which the heat pump operated. The bedroom was seldom part of the monitoring. Another problem with this study was that homes with heat pumps tend to be heated to a higher level and at different times of day. (Households with heat pumps are more likely to heat in the mornings.) These factors tend to reduce the likelihood that high humidities will be widespread within the KEU sample and may provide a useful contrast to the Kōtuku Apartments.

3. Exploring humidity data

To examine techniques to explore underheating, temperature and humidity data was collected from a test home for 63 days from 12 April 2017. This test home was selected for its ease of access and because it was reported as being somewhat damp in some rooms. The house was an approximately 170 m^2, 3-bedroom 1980s house being rented in Wellington. The house had a slab-on-ground floor (likely, uninsulated). The insulation in the roof space was thin but had recently been topped up. Given the age, there was likely to be some insulation in the walls but was likely to be in poor condition. The windows were original 1980s single-glazed aluminium and were in poor condition. The house has no fixed heaters, and portable electric heaters were used throughout. The house was occupied by a working couple with two children. The children shared a bedroom, with the third bedroom being a spare room for storing items.

The cumulative temperature distributions for each of the rooms in the home is shown in Figure 2. For each temperature between 10°C and 22°C, the value of the graph gives the percentage of the time that the temperature is below that particular temperature. The proportion of the time the temperature in the lounge is below 16°C is around 30% of the time, while the temperature in the spare room is below 16°C for around two-thirds of the time.

Overall, the temperatures in the home are low, reflecting to an extent that the home is not occupied (or heated) during a large part of the day. The lounge is heated in the evenings and is seen to the right of the other curves. The outdoor temperature is partly shown to the left of the other curves. The lowest temperatures from the rooms are the main bedroom and the spare room. Both of these rooms were unheated.

The partly heated second bedroom, dining room and bathroom curves fit in between the lounge and the unheated rooms (Bed1 and Spare) and show interesting variations at the ends of the scale as well in the steepness in the middle of the range.

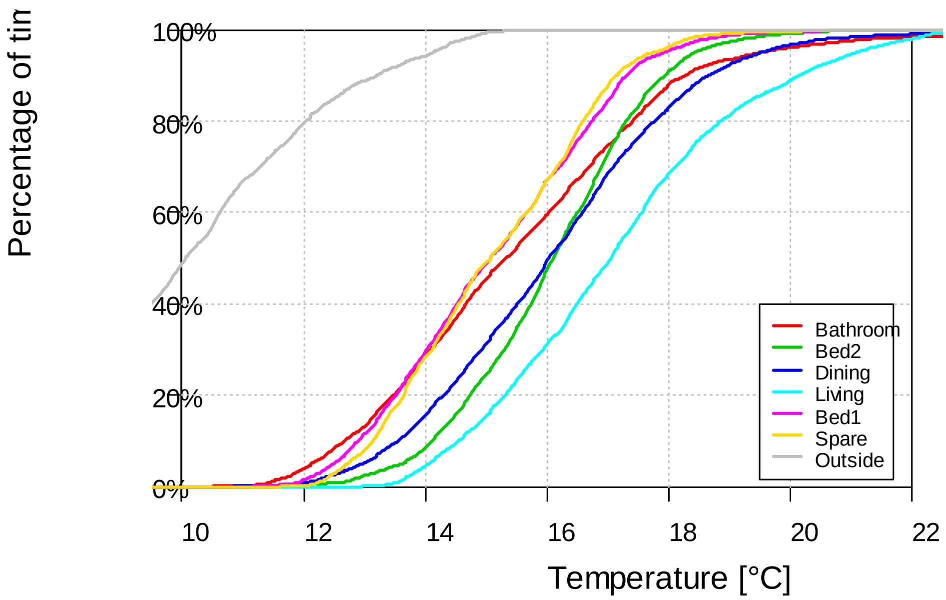


Figure 2. Cumulative temperature distributions for each room in the test home.

The cumulative relative humidity distributions for the rooms in shown in Figure 3.

This time, the cumulative distribution is shown in reverse order so that the graph shows the proportion of time that the relative humidity is above that particular value. This is because, unlike the temperature where you typically want to be above a minimum value (for wintertime heating), for relative humidity, you want to be below a maximum value.

In Figure 3, we can see that the relative humidity in the lounge is above 70% for around one-quarter of the time, while it is above 70% in the main bedroom around 87% of the time. The relative humidities in this home are high. The desirable (drier) response would be for the proportion of time above the particular relative humidity to drop off quickly so that the preferred curves are to the left of the graph, opposite to that for the temperatures.

In Figure 3, the lounge and dining provide the best response dropping away first, while the unheated main bedroom, spare room and bathroom are slower to fall away. The partially heated second bedroom is an intermediate response, having an interesting shallower curve (resembling the lounge curve) as it drops away.

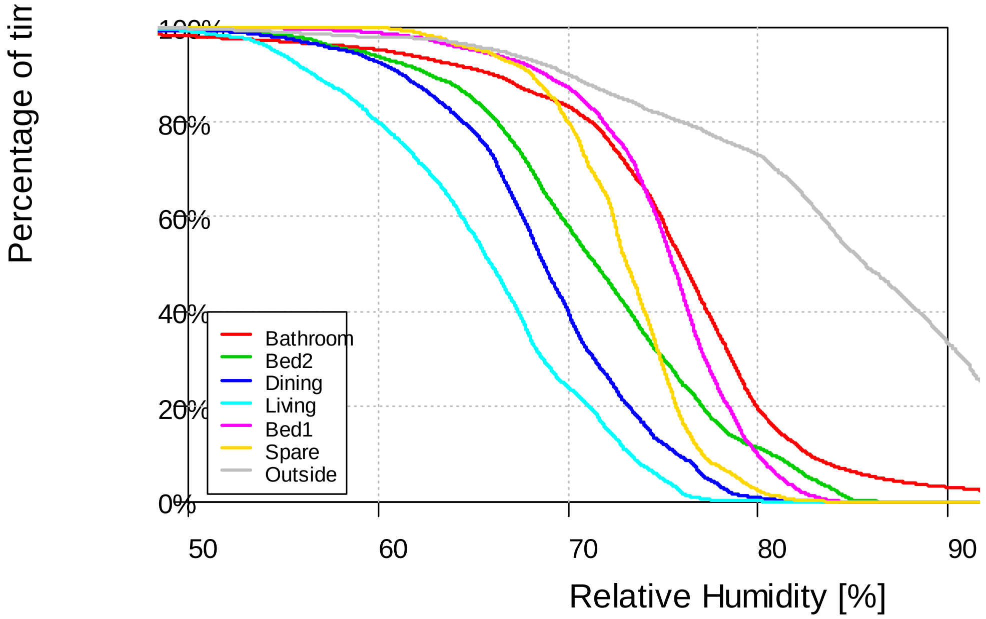


Figure 3. Cumulative relative humidity distributions (reverse) for each of the rooms in the test home.

The cumulative humidity ratio distributions, again in reverse order, for the various rooms are shown in Figure 4.

The humidity ratio curves for each of the rooms are very similar to one another. However, the outdoor humidity ratio is appreciably lower, indicating that being inside is a dominant factor. The bathroom is subject to episodic wet events, with many periods of time well above a humidity ratio of 10 g/kg.

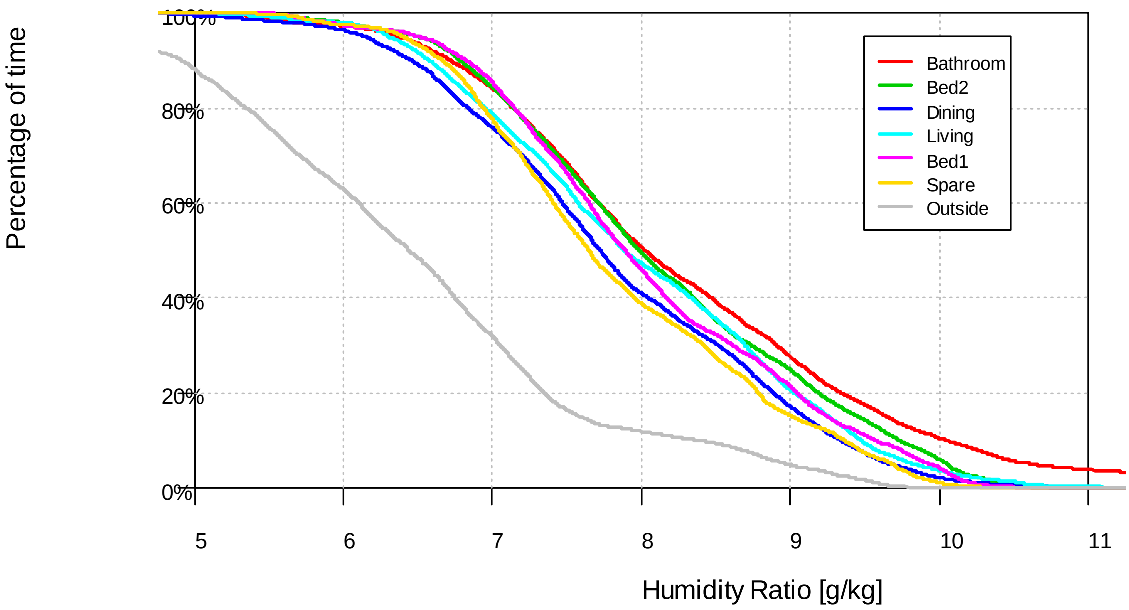


Figure 4. Cumulative humidity ratio distributions (reverse) for each of the rooms in the test home.

3.1 Temperature-modified scenarios

Having obtained data on the temperature and relative humidities in a particular home, a technique is required to explore the impacts of different temperature levels on the relative humidity.

Increasing the temperature of room air without changing the moisture content will reduce the relative humidity of the room air. Heating, such as electric resistive heating, is the obvious means to increase the temperature of the room air. However, it is important to remember that some types of heating, such as unflued gas heating, will also impact on the moisture content within that room. The rest of this report will consider only this first type of heating, which does not impact of the moisture content.

Linking an amount of heating to a change in room temperature and moisture content is non-trivial. The amount of insulation and level of air infiltration of the room and the rest of the house will dictate how quickly heat is lost from that space. It will also dictate how the room temperatures and moisture levels will be impacted.

Building simulation software, such as WUFI® PLUS (www.wufi.co.nz), can accurately predict the change in room temperature and moisture content from the operation of a particular heater. This requires a detailed description of the building, the heater and their operation.

Rather than trying to get involved with the details of the intervention (the heating), it may be helpful to consider only the outcome of the heating on changing the temperature and moisture content of the room.

- What would be the impact on the relative humidity if the room was kept 1°C warmer?
- What would be the impact on the relative humidity if a 500 W heater was left on within the room?

This outcome method is removed from the means of the intervention. In the above example of keeping a room 1°C warmer, the amount of heating required to keep a small, well insulated (only one external wall) lounge with good sun 1°C warmer may be quite different from the heating required for a large bedroom with a lower insulation level (two external walls) and bad sun.

Rather than increasing the temperature consistently, as per the example, a more effective relative humidity management process may be to ensure that the room temperature does not fall below a particular value. This outcome description is similar to the action of a thermostat on the heating, but in this case, the capacity of the heater is not limited.

The calculation for the impact on the relative humidity using the thermostat outcome is described as follows.

The measured temperature and relative humidity of the room air can be used to calculate the humidity ratio of the room air. This data is a time series, and when it falls below the thermostat temperature (either 16°C, 18°C or 20°C), the actual room air temperature is replaced with the managed temperature, simulating the addition of heating.

As no moisture is added to the air, the humidity ratio for the managed air remains the same. From the managed air temperature and humidity ratio, the new managed relative humidity can be calculated.

The resultant time series of the relative humidity values will be a combination of actual relative humidity (when the temperature is above the thermostat temperature) and the managed relative humidity (when the temperature is below the thermostat temperature).

This is summarised in the following equation:

$$\varphi(t_i) = \begin{cases} \varphi(t_i), & T(t_i) > T_{set} \\ \dfrac{p_w(t_i)}{p_{ws}(t_i)}, & T(t_i) \leq T_{set} \end{cases} \tag{3.1}$$

where

$\varphi(t_i)$ is the new relative humidity at time t_i

$T(t_i)$ is the original temperature at time t_i

T_{set} is the thermostat setpoint temperature

$p_w(t_i) = \frac{pW}{0.62198+W}$ = water vapour partial pressure in terms of p and W (3.2)

p is the total pressure

W is the humidity ratio

$p_{ws}(t_i) = p_{ws}(t_i, T_{set})$ = saturation pressure of water vapour (3.3)

(the saturation pressure of water vapour is an empirical function of temperature and is available from sources such as ASHRAE (2013))

Having obtained a new relative humidity time series, it is possible to calculate a new cumulative relative humidity distribution for the new data.

Figure 5 gives the cumulative relative humidity distributions for each of the three thermostat setpoints of 16°C, 18°C and 20°C for the temperature and humidity data from the main bedroom.

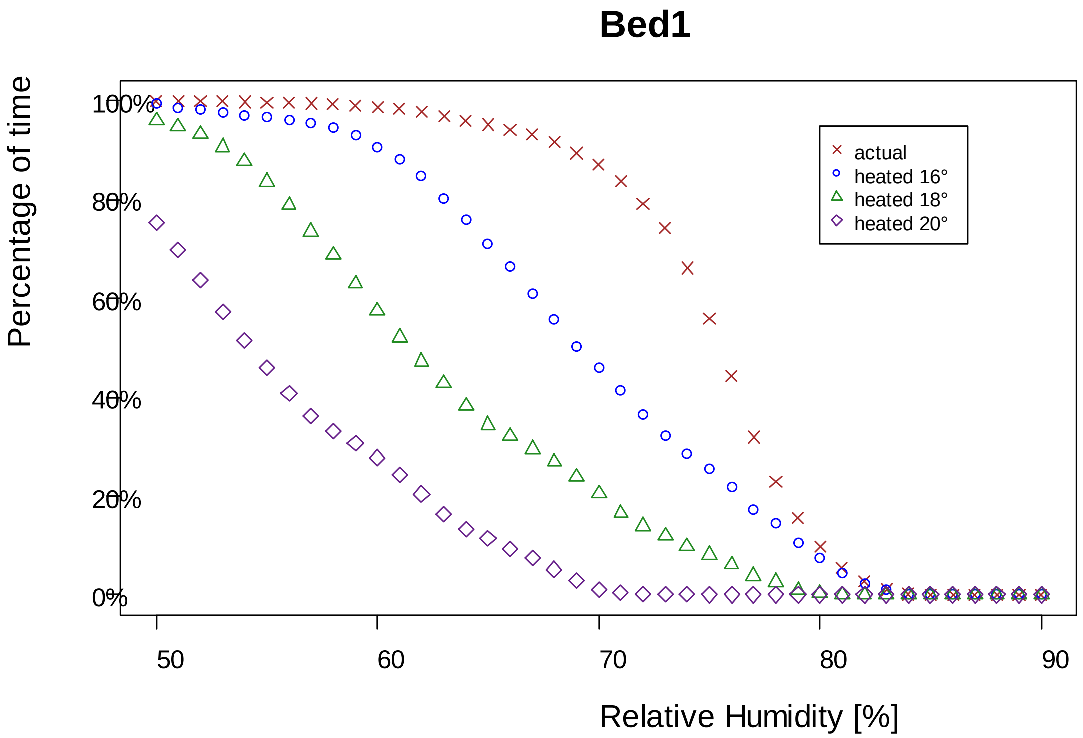


Figure 5. Cumulative relative humidity distributions (reversed) for the main bedroom subject to a range of minimum temperature scenarios.

The crosses in Figure 5 give the original relative humidity data from the measurements from the room. As previously discussed, the response 'extends' along the top of the graph before it drops away after passing around 70% relative humidity.

The circles in Figure 5 give the values of the cumulative relative humidity distribution as would be obtained if the room air was maintained at a temperature of at least 16°C using equation 3.1. The circles drop off more quickly than is the case for the original relative humidity data. Rather than dropping off after 70%, as was the case for the original data, the relative humidities start dropping around 60%.

The gap between the circles and crosses begins to converge when the relative humidity gets high and overlaps for values over 80%.

Increasing the temperature setpoint to 18°C (shown by the triangles in Figure 5) further increases the effect of dropping away sooner, appearing to reduce from the start of the scale at around 50%. The 18°C curve remains separate from the actual and the 16°C curve and reaches the end of its scale before overlapping with the other two scales.

Diamonds are used to distinguish the curve for the 20°C temperature setpoint. This curve already starts with a steep descent, so the drop-off is likely to start with relative humidities around 40–50%. This curve remains distinct from the other curves and looks to top out around the 70% relative humidity mark.

The data in Figure 5 shows support for the suggestion that increasing the minimum temperature within a room can reduce the amount of time the relative humidity is too high.

Table 4 provides some comparisons of this data using relative humidities over 70% as a reference point. While the actual relative humidities in the main bedroom are over 70% for 87% of the time, this percentage of time rapidly reduces as minimum temperatures of 16°C, 18°C and 20°C are applied.

When heated to 20°C, the relative humidity is over 70% for less than 1% of the time.

Table 4. Percentage of time the relative humidity in the main bedroom is over 70% subject to a range of minimum temperatures scenarios.

Temperature scenario	Percentage of time relative humidity greater than 70%
Actual	87.2%
Heat to 16°C	46.1%
Heat to 18°C	20.4%
Heat to 20°C	1.0%

Figure 5 is repeated for each of the rooms of the house in Figure 6. For the heated rooms (lounge, dining), the top curves appear to be pushed down on the lower curves, closing the gap between the curves. For the unheated rooms (main bedroom, spare room and bathroom), the gap between the curves is extended.

The lower 20°C curve appears fairly consistent between the rooms, being above 50% relative humidity for around 75–80% of the time. All of the data is below 70% relative humidity except for the bathroom, which can get up to around 75% relative humidity.

Most of the interesting changes occur for relative humidities between 60% and 80%, so that an intermediate value of 70% may be a useful reference point. The heating to 16°C setpoint curve shows some reduction in the percentage of time the relative humidity is over 70%. However, the 16°C curve and the actual curve merge at higher relative humidity.

A more effective control temperature is the 18°C curve, which maintains a separation from the actual curve at high relative humidities. The reference comparison would therefore be to compare the percentage of time the relative humidity is over 70% when the temperature is controlled to a temperature of at least 18°C.

In order to compare different rooms on one graph, the percentage of time the relative humidity is above 70% can be plotted on one axis. The percentage of time the relative humidity is above 70% when the temperature is maintained with a minimum of 18°C is plotted on the other.

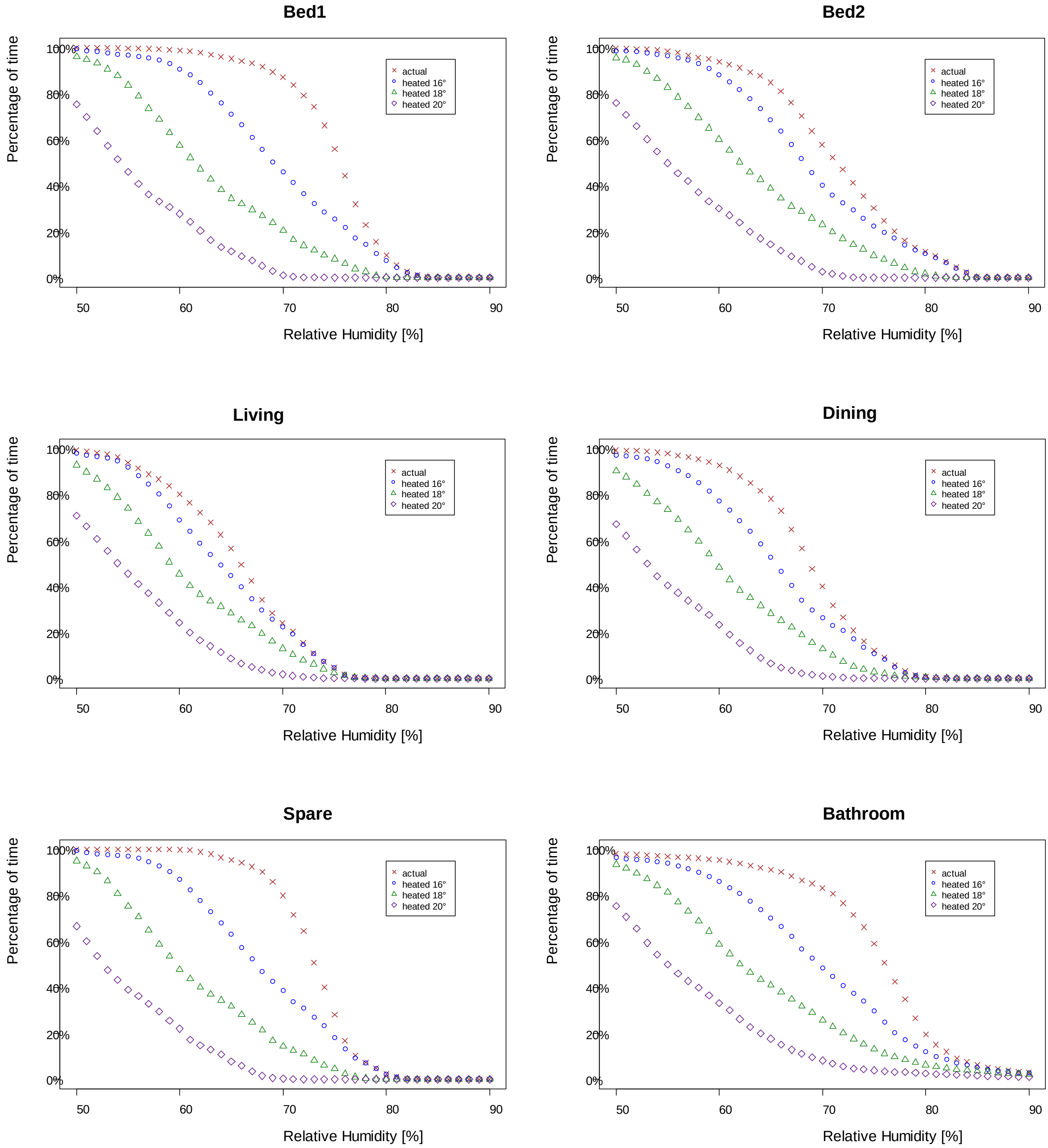


Figure 6. Cumulative relative humidity distributions (reversed) for the rooms indicated in the graph title, subject to the range of minimum temperatures scenarios.

Figure 7 shows this type of plot for the test house where the actual percentage is shown on the x-axis and the percentage when heated to at least 18°C is shown on the y-axis.

Ensuring that there is a minimum temperature within the room will, at worse, have the same percentage of time above the threshold relative humidity.

This situation would have the point representing that room in Figure 7 along the dotted ‘same as before as after’ line. When having a minimum temperature reduces the percentage of time the relative humidity exceeds the threshold value, the value will lie between the x-axis and the dotted line.

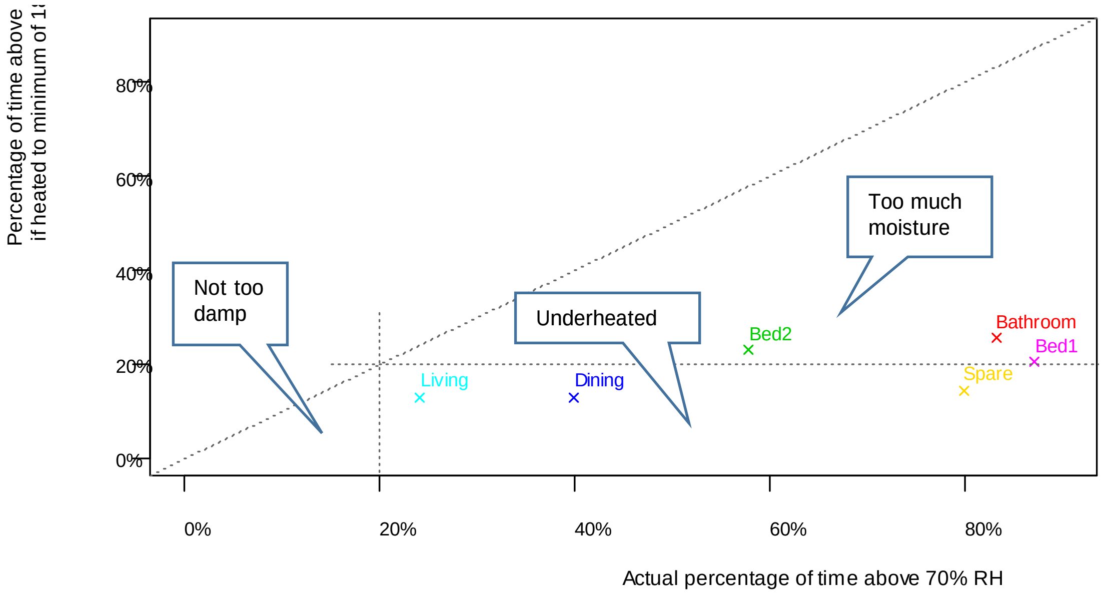


Figure 7. Comparison of the percentage of time the relative humidity is above 70 % and the percentage of time the relative humidity is above 70 % if the room were to be heated to a minimum of 18°C for each of the rooms in the test house.

For the test house, heating to 18°C in any of the rooms tends to reduce the percentage of time the relative humidity is greater than 70% to around 20%. The 20% lines can be used to partition the data into regions as described by the speech blurbs in Figure 7.

Where the actual percentage of time when the relative humidity is above 70% is less than 20% of the time, the resultant environment may not be too damp. When the actual percentage of time above 70% relative humidity is greater than 20% of the time, the environment may have some moisture issues.

When heated so that the temperature is a minimum of 18°C, if the relative humidity is over 70% for less than 20% of the time, the environment is too cold or underheated. The periods of high relative humidity are resolved by increasing the temperature.

After heating the environment to a minimum of 18°C, if the period of time above 70% relative humidity remains above 20% of the time, there may be moisture sources or too much moisture present within the room.

4. Examining humidity datasets

The criteria that will be used to examine the underheating risk or homes with high moisture levels that have temperatures that are too cold will be to use graphs like Figure 7 to assess if the percentage of time the relative humidity is above 70% is reduced by a large degree when a minimum temperature level of 18°C is employed. In the visual representation, this is saying that, in graphs like Figure 7, there are present data points in the bottom right-hand corner. For quantification purposes, durations longer than 20% of the time over a relative humidity of 70% will be used as an indicator of high humidity levels.

One of limitations of the larger sample size datasets of indoor conditions is that, in order to increase the sample size, the number of locations that are monitored within each home often becomes more limited. In New Zealand, homes seldom have centralised heating systems, and rooms are frequently heated on a one-by-one basis (French et al., 2007). Whether a room is heated may depend on whether it is occupied and what the heating expectations are. We can see from Figure 7 that underheated rooms (master bedroom, spare room and bathroom) as well as sufficiently heated rooms (lounge) are occurring within the same home. Had the monitoring been restricted to just the lounge, the home may not have been considered as problematic, whereas the cold rooms suggest a degree of underheating is occurring within this home.

The Occupant Behaviour project, done on a subsample of the 2015 BRANZ House Condition Survey (White et al., 2017), collected winter data for 66 homes. Measurements were made in 222 rooms as shown in Table 5. As the focus of this project was on studying ventilation behaviour as it relates to moisture management, the bedrooms and bathrooms were the primary rooms of interest.

Table 5. Room types in the Occupant Behaviour project.

Code	Room description	Number	Percentage
fr	Family room	27	12%
kt	Kitchen	4	2%
of	Office	10	5%
bd	Bedroom	116	52%
bh	Bathroom	65	29%

Figure 8 provides a graph of the underheating risk from the 222 rooms from the Occupant Behaviour project. The room codes from Table 5 have been used as plotting symbols. Many of the data points below 20% on the x-axis are overprinted and are hard to distinguish. These points represent a low occurrence of high moisture levels, and their closeness to the one-to-one line is not important.

Those points over 20% on the x-axis are more easily distinguished, with 116 rooms in this range. Of these 116 rooms, however, 21 would still have had a relative humidity over 70% for more than 20% of the time if heating had been to a minimum of 18°C. These cases have persistent high moisture levels, which could be due to excessive moisture generation or ineffective moisture removal (such as too little ventilation) in these rooms. The 95 remaining rooms (43%) are cases where the measured higher moisture levels (over 70% RH for more than 20% of the time) would not occur had the room been heated to a minimum of 18°C.

When considering homes, more than 65% of them had at least one room with high moisture due to underheating. If a minimum temperature of 18°C was applied throughout these homes, around 21% of homes would still have at least one room with a high humidity level (over 70% RH for more than 20% of the time).

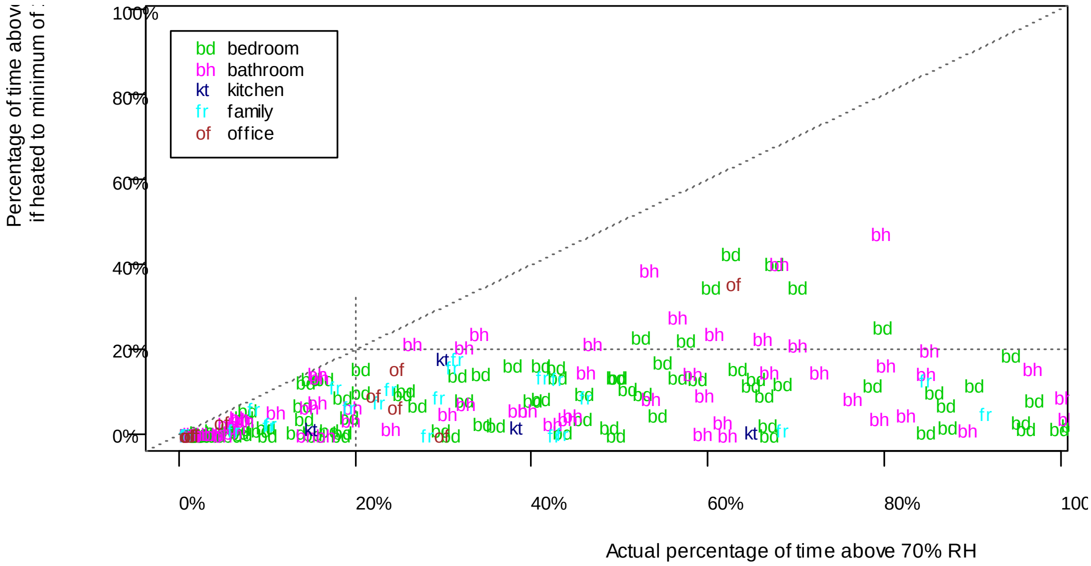


Figure 8. Underheating risk for 222 rooms in 66 homes from the Occupant Behaviour subset of the House Condition Survey.

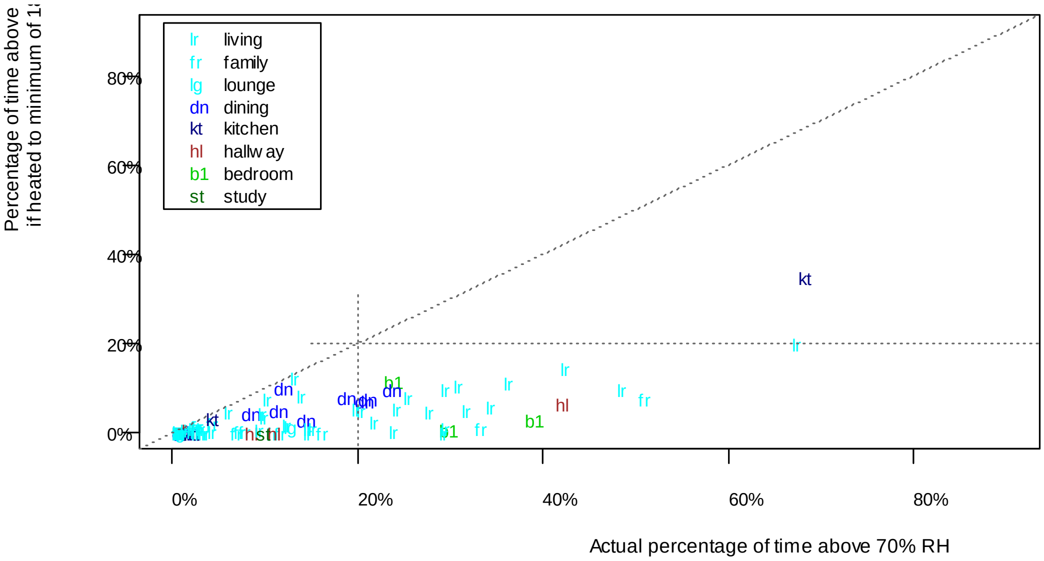
One of the larger relative humidity datasets available was from the KEU study (Burrough et al., 2015). The KEU study focused on the operation of heat pumps so only the conditions within the room with the heat pump was recorded. Table 6 provides a breakdown of the room types encountered. The living room and family room were two different descriptors for the same room type, while the lounge was a more formalised space that was anticipated to be less occupied. Around three-quarters of the heat pumps were installed in one of these spaces. Around 18% of the heat pumps were installed in a dining room or kitchen, while 6% were installed in a hallway. Just 2% of heat pumps were installed in a main bedroom.

Table 6. Room types in the Key Energy Uses project.

Code	Room description	Number	Percentage
lr	Living room	62	46%
fr	Family room	35	26%
lg	Lounge	2	1%
dn	Dining	17	13%
kt	Kitchen	7	5%
hl	Hallway	8	6%
b1	Main bedroom	3	2%

Source: (Burrough et al., 2015)

The underheating risk graph for the 134 heat pump houses is shown in Figure 9, again with the room code being used as the plotting symbol. Despite the room being heated by a heat pump, which makes it more likely to be heated than other rooms of the house, there is an appreciable amount of data a long way below the one-to-one line indicating some degree of underheating taking place.



Source: (Burrough et al., 2015)

Figure 9. Underheating risk for 134 households with heat pumps throughout New Zealand using the room in which the heat pump is located.

The three bedroom measurements all have an actual relative humidity above 70% between 20% and 40% of the time, indicating this room type as being particularly problematic. This further adds weight to the argument that, when underheating risk is being examined, the measurements should come from a room type that is less likely to be heated appropriately.[1] To better examine the lower end of the percentage of time the relative humidity is above 70%, this number is plotted against the proportion of the sample of heat pump households as in Figure 10.

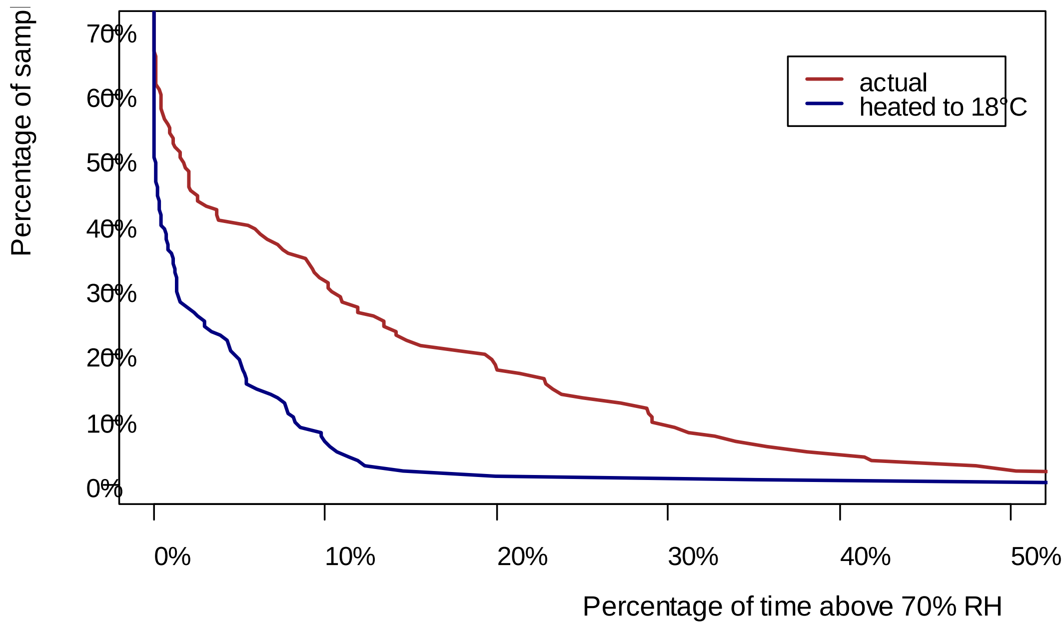


Figure 10. Percentage of the number of heat pump households that have at least that percentage of time the relative humidity exceeds 70% for the actual conditions and the conditions when heated to at least 18°C.

[1] The bedrooms would be a candidate for underheated rooms but it can be conceived this is not always the case, especially when the bedroom is heated regularly for babies or small children.

For example, from the actual data (brown curve), the relative humidity of 70% is exceeded 20% of the time by about 17% of the households. When a minimum temperature of 18°C is applied, it is found that the relative humidity of 70% is exceeded 20% of the time in only one household (less than 1% of the homes).

The other temperature humidity dataset that will be examined was from Wellington City Council's Kōtuku Apartments that were introduced in section 2.2. The apartments had a combined living-bedroom space, bathroom and kitchen. Two temperature-relative humidity dataloggers were placed on either side of the living-bedroom. Two loggers were used for reducing the likelihood of missing data. Neither the bathroom nor the kitchen were monitored.

It was thought that the limited heating, extended occupancy within the living-bedroom space and the close proximity of the kitchen and bathroom could result in the moisture levels in the Kōtuku Apartments being too high.

Figure 11 gives the underheating risk for the Kōtuku for the pre-renovation apartments (red) and the post-renovation apartments (blue). For the pre-renovation apartments, about half (five) of the apartments extend out to the right, indicating a potential underheating risk. If these apartments were heated to 18°C, none would be over 70% relative humidity for more than 20% of the time. One well ventilated apartment (KN4B) sits on the x-axis, indicating that if heated to 18°C, it would have no time when the relative humidity was over 70%.

For the post-renovation apartments, all of the cases are close to the one-to-one line at the low end of the scale. This suggests that high moisture levels would not be much of a concern in the post-renovation apartments.

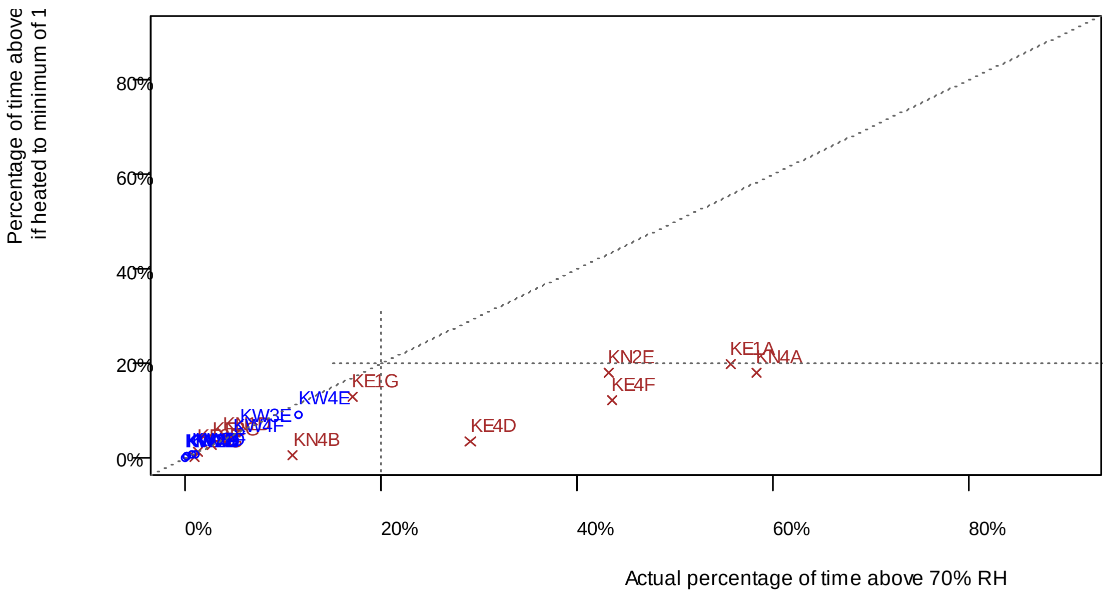


Figure 11. Underheating risk for 11 pre-renovation apartments (red crosses) as well as for nine post-renovation apartments (blue circles).

5. Conclusions

Underheating is a contributing factor to dampness in New Zealand homes.

Heating is unevenly applied across homes. Living rooms are frequently heated and have a lower duration of times with high humidity (relative humidity over 70%). Rooms such as bedrooms, spare rooms and bathrooms, have a much lower likelihood of being heated and tend to have a longer duration of times of high humidity.

A 66-house subset of the House Condition Survey, used to study occupant behaviour, measured the temperature and relative humidity in a number of colder rooms within each of the homes. It was found that around 65% of homes had at least one room where high relative humidity levels (over 70% for more than 20% of the time) were eliminated when the room was heated to at least 18°C.

Other measurement projects have largely focused on heating and have tended to measure the indoor conditions within heated rooms rather than unheated rooms and consequentially underestimate the underheating risk.

The KEU project looked at the conditions within the room in which a heat pump operated in 134 homes throughout New Zealand. As these rooms were very likely to be heated, the proportion of these rooms that have high humidity levels will be likely to underrepresent the extent of these homes that have problems associated with high humidity. Overall, around 17% of the KEU homes had relative humidities that exceeded 70% for more than 20% of the time. Bedrooms were monitored in only three KEU homes, but all of these had relative humidities exceeding 70% for more than 20% of the time.

Wellington City Council has been progressively upgrading their apartment housing stock. The indoor conditions in a number of Kōtuku Apartments were monitored before (11) and after (nine) the upgrades. The apartments were small, having a shared living-bedroom space. Five of the pre-renovation apartments had relative humidities in excess of 70% for more than 20% of the time. If these apartments were subject to an 18°C minimum temperature, none of these units would have a relative humidity higher than 70% for more than 20% of the time. The upgrades included increasing the insulation within the apartments with double glazing to the north side as well as adding insulated plasterboard to the exposed concrete walls. The upgrades were sufficient that all of the post-renovation apartments were in excess of 70% for less than 12% of the time.

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