Study Report

SR369 [2017]

Retrofit performance measurement of Kotuku Apartments

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Preface

This is the second of a series of three BRANZ study reports prepared on the upgrading of Wellington City Council's four low-rise Kotuku Apartments, located in the suburb of Kilbirnie, Wellington, New Zealand. This report's focus is on the actual building performance transformation via a suite of in situ experiments executed to quantify aspects related to comfort, cost and liveability.

The first BRANZ study report (Buckett & Jaques, 2016) focused on examining the apartments' thermal performance only – both existing and that resulting from various possible design upgrades. Existing performance was examined using thermography, while computer thermal simulation was used to compare various possible design upgrades.

The third and final BRANZ study report (Pollard, Saville-Smith & Jaques, 2017) focuses on the measured thermal performance within individual apartments, with a commentary around the implications, experiences and aspirations of residents based on interviews.

Acknowledgements

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BRANZ Study Report SR369

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Reference

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Abstract

This project looks at increasing the performance of low-income dwellings in the rental sector, using the recent renovation and upgrade of Kotuku Apartments located in Wellington, New Zealand, as an example. The work was carried out over the 2014–2017 period. A suite of in situ measurements was carried out to quantify changes in building performance related to comfort, cost and liveability.

The main in situ performance aspects examined were:

- whole-building external envelope thermal ability (via thermography)
- detailed element-only thermal resistance (via heat flux tests)
- individual apartments' comfort (via co-heating experiments)
- uncontrolled external-internal air exchange (via blower door tests)
- shower utility (via flow rate measurements and online energy efficiency tools).

It was found that, quantitatively, there were marked improvements to whole-building thermal envelope performance in terms of uniformity and a raised level of thermal resistance. However, it was also found that, quantitatively, while there was an improvement for individual apartments to provide thermal comfort, its exact extra level was difficult to determine. The utility of the showers, in terms of flow rate, was improved while still maintaining acceptable water efficiency levels. Lastly, it could not be established whether there were any significant improvements to the background uncontrolled ventilation (i.e. draughts) that is naturally provided by the building, due to shortcomings in the available data.

Keywords

Performance monitoring, retrofit, building metrics, thermal improvements.

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1. Background

New Zealand has persistently had one of the least-affordable housing stocks in the world. It is less affordable to buy a house in Auckland than in New York, Los Angeles or Tokyo (Demographia, 2015). Housing costs in Auckland relative to incomes are at unprecedented levels – approaching 12 years of income to purchase a median price house (Child Poverty Action Group, 2015).

Falling rates of home ownership in the last two decades is indicative of those problems. The rental market has not delivered a liveable, affordable alternative to home ownership. The rental-housing infrastructure is in poor condition (Buckett, Jones & Marston, 2012). Tenure insecurity is high and often generated by landlord churn and landlords accepting low yields (Lundberg et al., 2015). Unaffordability causes varied by region – Auckland was unaffordable because of high rents, while low incomes affected affordability in Northland and Bay of Plenty (Statistics New Zealand, 2013). Most private rental dwellings are occupied by low-income or middle-income households who cannot access public housing, are employed but are unable to afford home ownership.

Inability to access affordable housing stock, irrespective of tenure, is associated with a raft of poor economic and social outcomes for individuals and their families. Like dwellings that are costly to operate, unaffordable housing access generates externalised costs in the health and welfare sectors. Unaffordable access to dwellings also drives fiscal expenditure. It is accepted overseas that undersupply of affordable housing is a barrier to economic growth, labour supply and global competitiveness (Property Council, 2011). That conclusion is now more widely accepted in New Zealand. The impacts are significant even within regional economies. Research shows that unaffordable housing has inhibited economic growth and attraction and retention of workers in Queenstown, Marlborough, Tasman and Nelson districts (Motu Project Team, 2006).

This shortage of homes that meet the needs of low income New Zealanders is especially worrying. It often leads to overcrowding, and as these homes have high running costs, the occupants struggle to provide healthy conditions, such as an internal temperature of at least 18°C. This can lead to poor health, extra costs for our health system and sick days for the occupants (Howden-Chapman et al., 2008).

2. Introduction

Several projects have been carried out on housing affordability in New Zealand by groups such as the Productivity Commission, CHRANZ and the Auckland Regional Council (New Zealand Productivity Commission, 2012; Dunbar & McDermott, 2011; CRESA, 2007). This multi-disciplinary BRANZ project – Building Good Affordable Homes (BGAH) – brings together previous work, providing an opportunity to show practical solutions in the affordability space. The closest New Zealand project to this BGAH work is the BRANZ Papakowhai study (Burgess et al., 2008), which was a smaller 'before and after' retrofit study, with all the dwellings being owner-occupied. The upgrade priorities and solutions were therefore different to rental housing.

In late 2013, Wellington City Council (WCC) expressed an interest in improving its decision-making and specification process around upgrading its rental housing stock as part of its ongoing operations. By using some of WCC's stock as a real-life case study, BRANZ saw research into this area as an opportunity to assist all rental service providers with larger portfolios by providing more targeted advice. The experimental approach taken was mainly based on a combination of computer modelling, fieldwork and one-on-one interviews.

The aim of the project is to better understand the best opportunities that have the most benefit in low-income existing rental dwellings in terms of energy and thermal performance, operating costs and occupant satisfaction. The most promising retrofit solutions can then be communicated to industry. The project also looks to understand how the industry can best retrofit these homes, and understand landlords and their decision-making processes.

Specifically, the aims of the BGAH project are to:

- explore what opportunities there are for New Zealand to improve housing affordability
- understand the key features for increased performance (dwelling condition, energy use and occupant satisfaction) in low-income housing
- explore how new approaches to building and construction can support improved housing affordability
- understand and evaluate housing providers' decision-making processes used when upgrading housing.

In terms of indoor performance, the case study dwellings have been monitored for indoor temperature, envelope heat flows and energy, both before and after being retrofitted. The renovation features that have the most value in terms of energy and indoor environment performance, occupant satisfaction and operating costs will then be able to be determined.

This project is looking to increase performance of low income-dwellings in the rental sector. It is of interest to landlords, particularly those with a large portfolio including low-income tenants, who wish to upgrade and protect their housing investments. It is also of interest to tenants, health boards, education providers and the building industry, given the importance of retrofits in the industry. This recognises that most of current stock will still be in use for decades to come. The project is expected to provide information to increase industry and investor knowledge about which features are most important for increasing the energy and indoor environmental performance of low-income housing.

Intended outcomes include:

- housing for low-income New Zealanders that is of good quality, good internal environment and low operation costs (at least in our case study areas)
- industry is stimulated into providing good homes that meet the needs of low-income households
- rent and operation costs will be a smaller proportion of people's incomes in the case study homes
- homes will be better performing with healthier conditions and lower operating costs
- long-term maintenance plans will be in place and approximate costs known for features that affect the energy and indoor environment
- better-informed tenants.

For this research project, a case study was undertaken of Wellington City Council's Kotuku Apartments in Kilbirnie, Wellington.

This report follows on from BRANZ study report SR262 (Buckett & Jaques, 2016), which investigates aspects of the Kotuku Apartments' thermal performance – both prior to the renovation as well as the theoretical implications of various upgrades. This report precedes BRANZ Study Report SR373 (Pollard, Saville-Smith & Jaques, 2017), focusing on the measured thermal performance of individual units with a commentary around the implications and the experiences and aspirations of residents.

The size and shape of the four blocks that make up Kotuku Apartments is shown in Figure 1. The construction of each block, in terms of materials, is essentially identical.

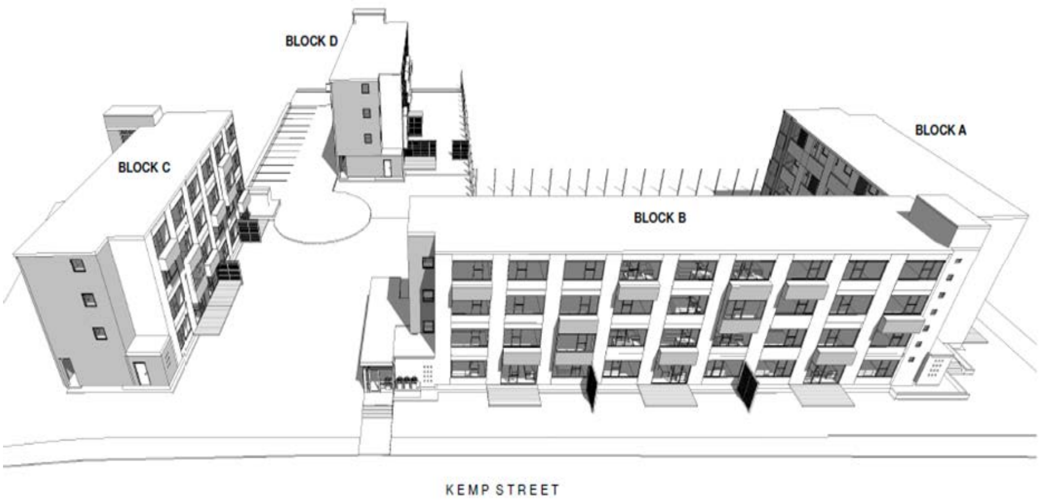

Figure 1. Kotuku Apartments, looking west. (Source: Opus Architecture, Wellington Studio)

3. Performance measurements

A suite of in situ measurements were carried out to quantify any changes in building performance related to some key areas associated with apartment comfort, operating cost and liveability. The main pre-renovation and post-renovation measurements and their focus were:

- thermography – external envelope thermal ability
- heat flux – element-only thermal resistance
- co-heating – individual apartment thermal comfort
- airtightness – apartment uncontrolled external-internal air exchange
- shower utility – effectiveness of showers.

The measurements should be read in association with the two related BRANZ study reports – SR362 (2016) and SR373 (2017) – to provide a more complete picture of the theoretical, social and physiological impact the renovations have had.

3.1 Thermography

3.1.1 Background

Thermography or thermal imaging can be used to identify areas of heat loss in existing buildings. This is done by the use of an infrared camera that takes images of heat radiating from a surface and translates it into temperatures. These images can then be analysed to attribute the heat energy loss across the surface. Often this technique is used in building performance as a rapid and straightforward way to identify areas where heat loss or gain is abnormally high. Thus, it is a useful tool for quality control checks on new homes and building inspections on existing homes.

Thermal cameras are sensitive to longer wavelength radiation than human eyes can perceive. These waves represent a large portion of the heat emitted by surfaces with near-ambient temperatures. The primary benefit of infrared cameras is that they allow thermal differences to be located, and they can also allow the actual surface temperature to be determined (Overton, 2010).

Thermal imaging cameras are very useful for complementing other tools that building surveyors possess. They require skill in both conducting surveys as well as in the interpretation of the resultant thermal images. The main stumbling block for an inexperienced user is that many things can result in both the real and apparent temperature differences across a surface that may have nothing to do with the thermal attributes of the surfaces being examined. These can be, for example, caused by things such as material surface moisture variations, airflows, reflectivity variations or partial shading of the wall (Taylor, Counsell & Gill, 2013). Specific environmental conditions are laid out in BS EN 13187:1999 *Thermal performance of buildings. Qualitative detection of thermal irregularities in building envelopes. Infrared method*.

The images in this section can be interpreted by the colouring on the subjects. Colours in the images indicate the amount of infrared radiation coming from a surface, thus indicating the surface temperature (Figure 2). The cooler temperatures (usually indicating low conductivity) are black, then purple, while the warmer temperatures (usually indicating high conductivity) are white then yellow. It should be noted that window surfaces appear to be cooler than they are because glass reflects the cold temperature radiation coming from the sky (i.e. the background radiation from our solar system). This is true for other highly reflective surfaces as well.

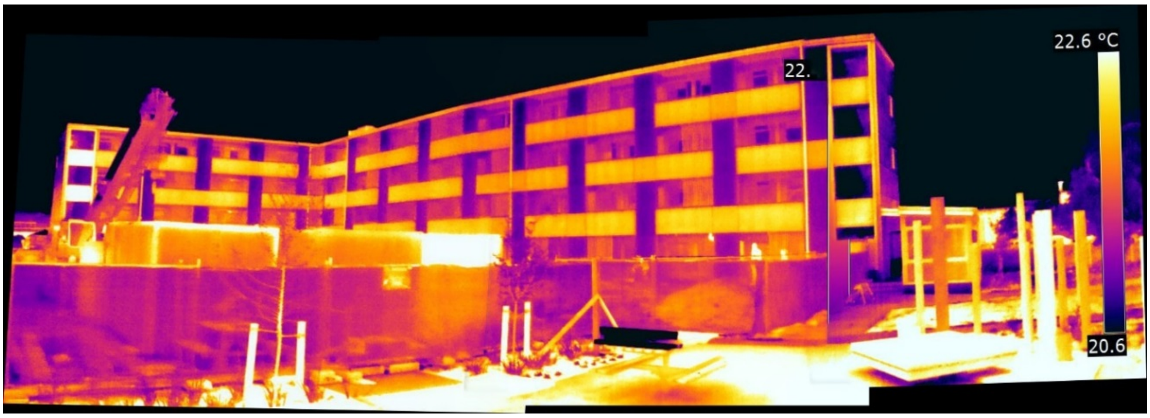

Figure 2. Apartment Blocks A and B in early 2016 during renovation.

Note that educating readers on detailed thermal imagery interpretation is beyond the scope of this report. There are many useful sources of thermographic instruction for building surveying that can be pursued for the curious reader,[1] including the previous BRANZ study report (Buckett & Jaques, 2016).

3.1.2 Methodology

A FLIR P640 thermal imaging camera was used for the Kotuku Apartments field experiments. The FLIR camera has a 640 x 480 image resolution and a sensitivity of 30 mK. Both BRANZ camera operators had specialist thermal imaging training (i.e. Level 2 ASNT equivalent certification or higher) to ensure competent usage. The initial thermal images were taken in September and October 2013 before Kotuku Apartments were renovated. The second set of images, post-renovation, were taken in mid May 2016 around noon. The weather targeted was close to ideal for thermographic examination – overcast, with low contrast to reduce reflection, and no surface moisture for both field visits. A more regular picture of an external wall façade is shown in Figure 3 .

Figure 3. Kotuku Apartments (left: pre-renovation and right: post-renovation).

[1] www.flirmedia.com/MMC/THG/Brochures/T820325/T820325_EN.pdf

3.1.3 Results

A series of thermographic 'before the renovation' and 'after the renovation' images are shown of various external sections of Kotuku Apartments Block D. Once again, the interior and exterior surfaces of the apartments were checked for air leakage, thermal bridging and general weak points in the thermal envelope.

Thermal images from 2013 suggested there may have been an issue with water-saturated polystyrene insulation on the exterior concrete spandrel panels (Figure 4 and Figure 5). This is demonstrated via irregularities in the insulation panels' infrared thermal profiles, likely due to water ingress and consequent saturation.

Note that the 'before' colours (and therefore temperatures) do not match the 'after' colours in these and all the remaining pictures. Thus, the rate of heat loss can only be compared within a picture rather than between pictures.

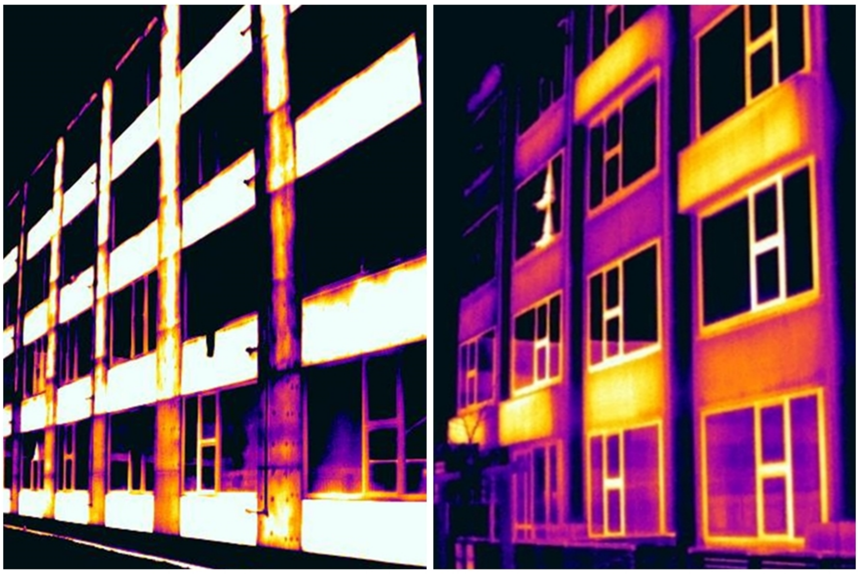

Figure 4. Polystyrene wall panels (left: pre-renovation and right: post-renovation).

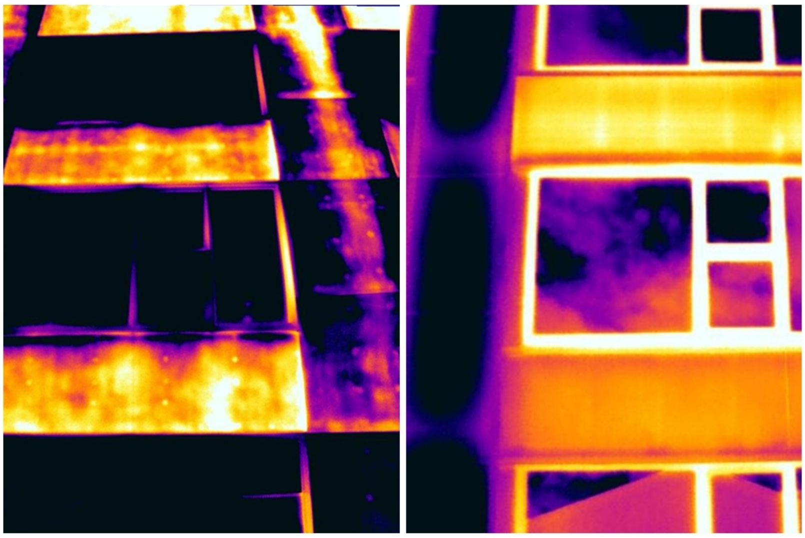

Figure 5. Water ingress in exterior wall panels (left: pre-renovation and right: post-renovation).

Saturated insulation is far less effective than dry insulation in providing thermal resistance. It was estimated that the compromised polystyrene sheet insulation shown would be approximately half as effective than if it was dry (I. Cox-Smith, personal communication, 20 April 2014). Since the saturated spandrel panels were replaced as part of the renovation, the resulting thermal performance of the wall system should have been significantly improved. This expectation was confirmed by the results from the in situ R-value measurements using heat flux transducers.

The Figure 5 'after' image shows the saturated insulation panels have been replaced, demonstrated by the even colour tones. The invisible spectrum (infrared) surface temperature difference between the panels is due to the visible spectrum colour of the newly painted panel surface. Some were painted with dark colour and therefore absorbed more heat and were warmer than the others painted in lighter colours (see Figure 3 post-renovation). Insulation has also been added in the soffit to reduce heat loss (see Figure 6). However, there was still some heat loss through the base of the wall where the cladding meets the concrete floor (see the arrow in Figure 7).

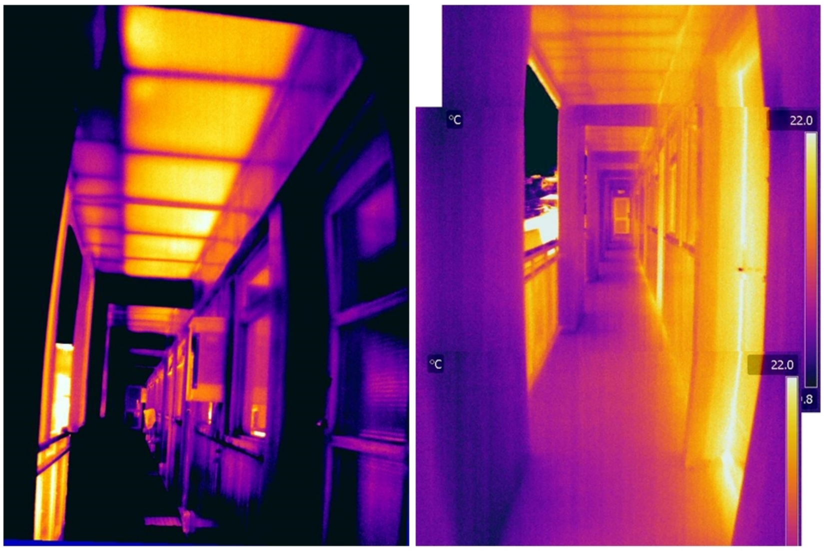

Figure 6. Heat loss through soffits above open walkways (left: pre-renovation and right: post-renovation).

Figure 7. Post-renovation heat loss through wall adjoining open walkway.

Figure 8 shows the impact of insulating the wall adjacent to a staircase, in terms of reducing heat loss, post-renovation. The renovated wall shows dark pink (i.e. a cooler temperature) over most of the wall apart from the floor-wall intersection (arrowed). This shows that the installed wall insulation has been effective at minimising the heat transfer through the wall. This is true for everywhere apart from the junction, which acts as a thermal bridge and cannot be easily thermally rectified using this type of renovation.

Figure 8. Heat loss in stairwell (left: pre-renovation and right: post-renovation).

Before renovation, the top floor unit appeared to be cooler because of lack of insulation (Figure 9). Previous thermal simulation parametric studies (Buckett & Jaques, 2016) have shown that the top floor in this building was especially vulnerable thermally. This is due to its lack of any significant ceiling roof insulation, not having the potential benefits from heated apartments above it to minimise heat losses and receiving the strongest wind effect of all the levels. Post-renovation, this situation has changed dramatically, as demonstrated by the considerably more even thermal gradients between floors.

Figure 9. Slab junction bridging (left: pre-renovation and right: post-renovation).

3.1.4 Discussion and conclusion

The results of the thermal renovations to Block D when examined with high-quality infrared thermographic equipment have supported and reinforced the previous results in the wall R-value determination field experiment. The results confirm considerable thermal improvement to Kotuku Apartments resulting from the 2016 renovations.

3.2 Heat flux

3.2.1 Background

Heat flux transducers (HFT) are a way of measuring the actual in situ thermal resistive performance (i.e. R-value) of a construction element accurately and quickly (Cox-Smith, 2008). Building element R-values would be impossible to measure otherwise, even if the elements were replicated under laboratory conditions, as ventilation or moisture conditions (and therefore contributing impacts) are not known. In addition, the properties of thermal mass complicates the steady-state R-value. BRANZ has been using HFTs for field measurements of heat flow since the 1970s, and they are an important part of many research projects.

An accurate R-value measurement requires:

- an inside-outside temperature difference of at least 10 K
- at least 7 days of data
- minimal air exchange into or out of the area being measured
- no lateral heat flow into or out of the area being measured
- the area being measured shaded from direct sun (both inside and outside)
- the HFT panel not to be subjected to radiant heat.

In general, the longer the measurement period, the greater the accuracy. More stable internal and external temperatures mean a less dynamic heat flow, and this also improves accuracy.

3.2.2 Methodology

The BRANZ transducer system used in situ at Kotuku Apartments consists of:

- a 600 x 600 mm main panel
- four 150 mm wide surround edge panels of similar R-value to minimise edge errors
- a data acquisition unit or wireless Wi-Fi logger to record HFT output, and
- either type-T thermocouples or wireless Wi-Fi temperature loggers to measure concurrent indoor and outdoor temperatures (see Figure 10).

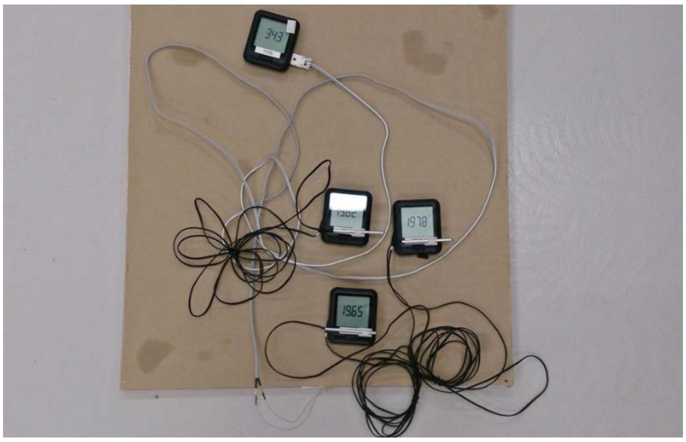

Figure 10. The BRANZ 600 x 600mm HFT panel (light brown) and Wi-Fi loggers.

Three to four calibrated HFTs were set up in the end units in Block D on Level 1 and 3 for several days in May/April 2014 and then again in May 2016 to compare the thermal performance before/after renovation (see Figure 11). In 2014, type-T thermocouples were utilised. These were replaced in 2016 with Wi-Fi temperature loggers and a data acquisition unit to record HFT output to bypass the need to drill the steel entry door for cabling.

Figure 11. Set-up in the apartment, showing physical supporting mechanism.

The system thermal resistance (in this case, the wall R-value and the HFT R-value) is determined by the sum of the temperature difference divided by the sum of the heat flow. The wall R-value is determined by subtracting the thermal resistance of the HFT (approximately R0.35 m^2°C/W).

The instantaneous R-value is of little value due to the dynamic nature of heat flow, storing or releasing heat from thermal mass. By accumulating data over a period of several days, the thermal mass effects are accounted for. For these multi-day experiments, typically the initial R-values determined will be inaccurate but will soon converge to a reasonably accurate value 'system' R-value. The accuracy for the method is typically within 10% of the true value.

3.2.3 Results

The average heat flux (i.e. rate of heat flow for an area) of the wall system in 2014 was approximately 10–15 W/m^2 (see Figure 12). This is shown by the dotted lines in each of the graphs. In 2016, after renovation, the average heat flux of the wall system was decreased to approximately 10 W/m^2 (see Figure 13).

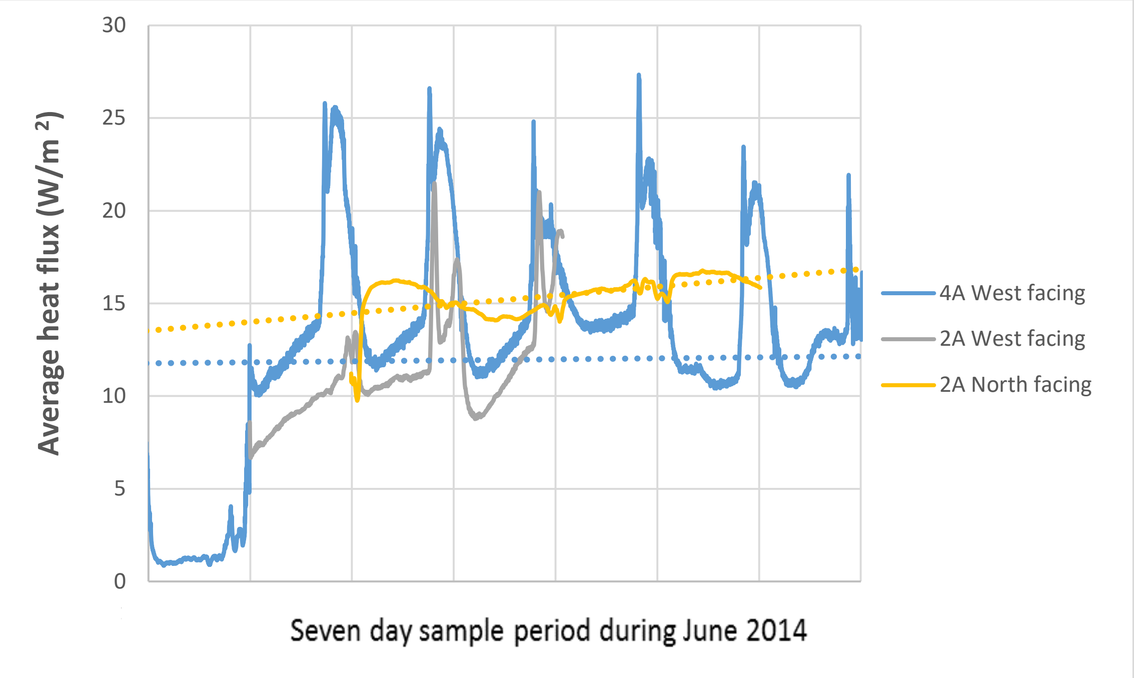

Figure 12. Hourly average heat flux (W/m^2) before renovation.

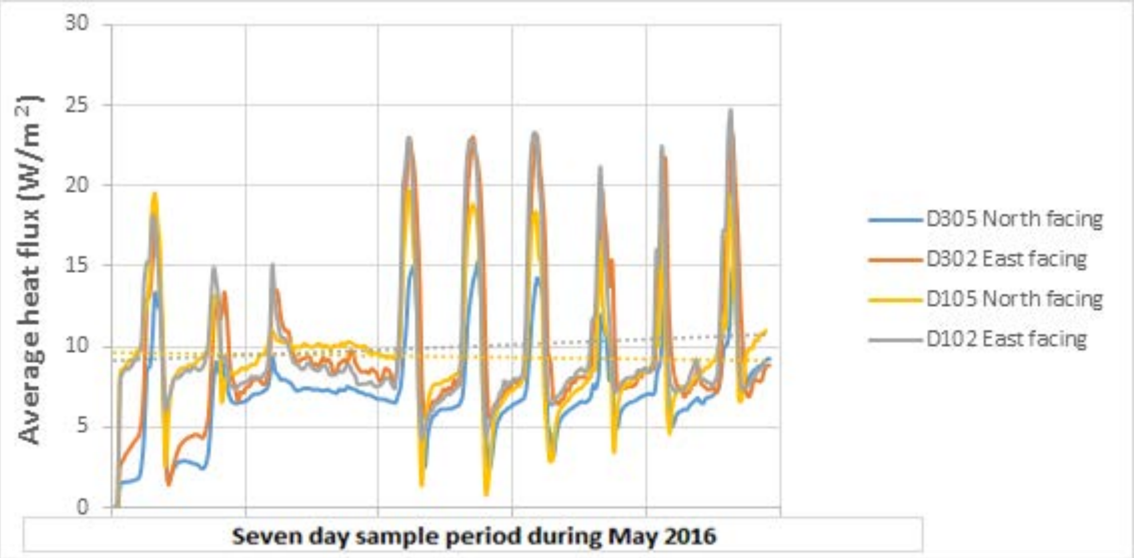

Figure 13. Hourly average heat flux (W/m^2) after renovation.

The average indoor-outdoor temperature difference in 2014 was approximately 12 K during testing. Post renovation in 2016, it was approximately 13 K for heated apartment units (i.e. east-facing walls) and approximately 10 K for unheated apartment units (i.e. north-facing walls). Thus, it met the preferred experimental inside-outside temperature difference of 10 K.

The average R-value of the walls in 2014 was approximately 0.6 m²K/W (see Figure 14). After the renovation in 2016, the average R-value of the walls increased to approximately 1.0 m²K/W for heated apartment units (i.e. east-facing walls) and approximately 1.1 m²K/W for unheated apartment units (i.e. north-facing walls) (see Figure 15).

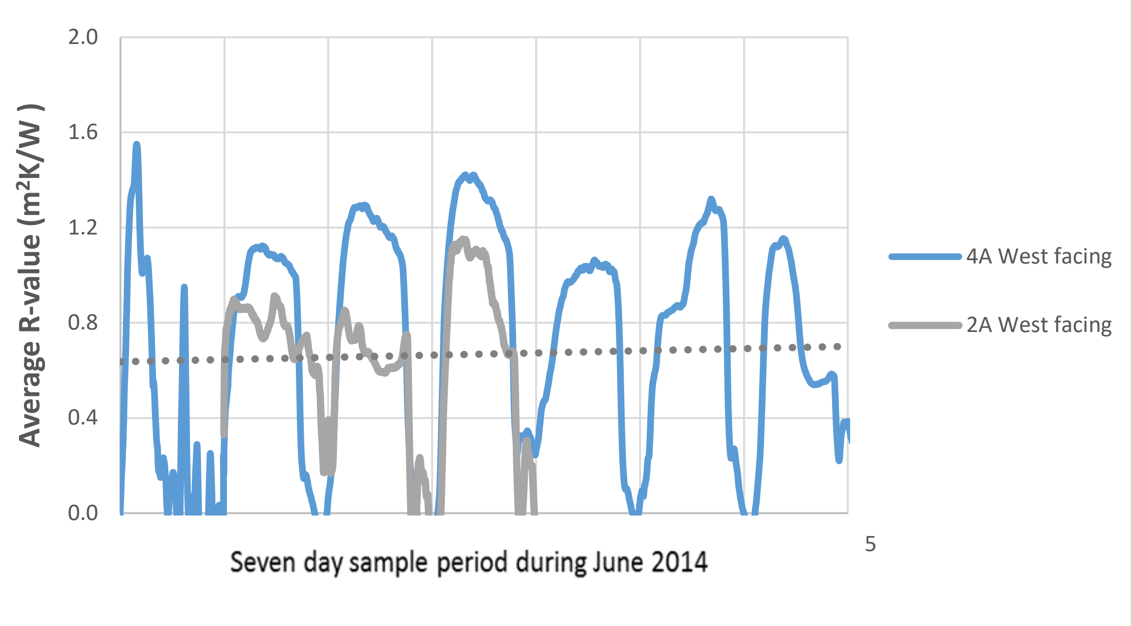

Figure 14. Average hourly R-value (m²K/W) before renovation.

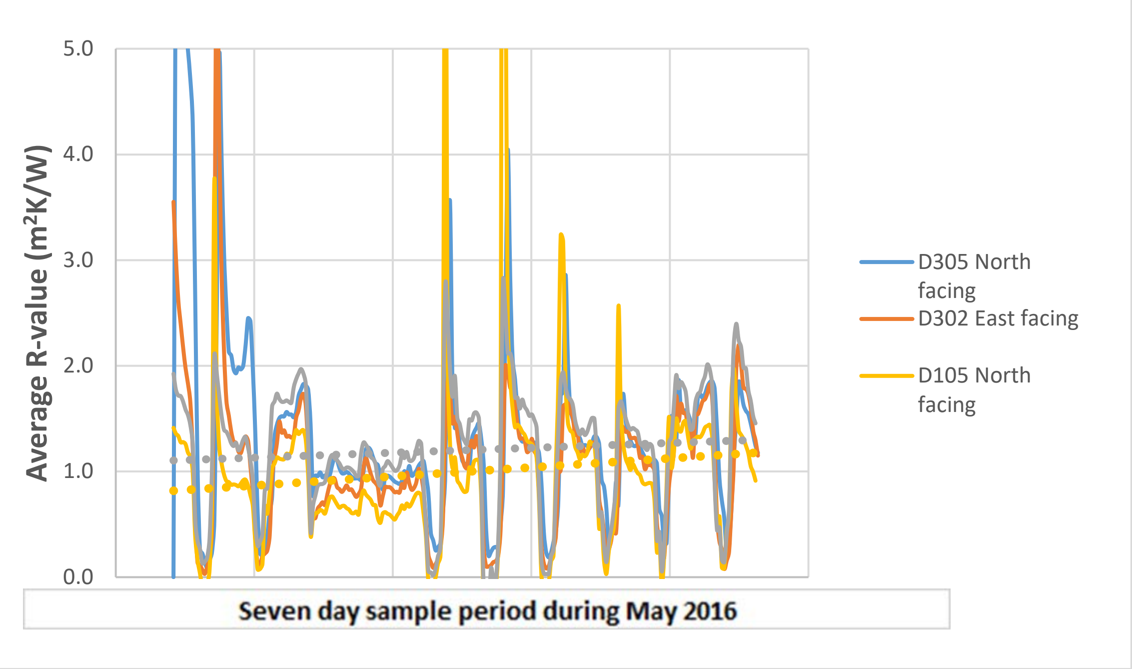

Figure 15. Average hourly R-value (m²K/W) after renovation.

3.2.4 Discussion and conclusion

The thermal renovations to Block D resulted in an R-value increase of 66%, i.e. pre-renovation = R0.6 and post-renovation = R1.0 for the external wall systems examined. This result accounts for the influence of the high-mass concrete panels. Thus, the heat loss for these wall elements has reduced considerably.

Given that this improvement is consistent in all the walls in all the four apartment blocks, it follows that there will be an improvement in comfort and reduced heating loads during the colder seasons. This improvement should be undertaken in parallel with upgrades to other building elements.

3.3 Co-heating

3.3.1 Background

Co-heating is used to determine thermal envelope performance of a building or part of a building. It involves heating the building interior to an elevated constant temperature (T_i) over an extended period, while the exterior temperature fluctuates (T_e). Knowing the thermal energy input and accounting for the inside-outside temperature difference (ΔT), thermal transmission and infiltration heat losses via the exterior envelope of the building can be calculated.

Once the internal heating commences, the indoor environment must be left to obtain a steady state where the desired elevated indoor temperature is reached and then stabilised via thermostatic control. This is to ensure that overly humid spaces and high thermal mass contributions do not inflate the heating load. Steady state may take several days to reach, depending on the heat capacity of the building. The interior space is then monitored 24 hours a day for a period of at least 1 week after the steady state occurs. The external temperatures are logged concurrently.

Co-heating experiments are usually conducted in the winter months to minimise solar radiation effects (Johnston, Miles-Shenton, Farmer & Wingfield, 2013) due to the likelihood of lower levels of solar irradiance and cloudy days. The building under examination must remain unoccupied and have access restricted to avoid ventilation-related heat losses via open doors and windows. Before the heating begins, a pressure test is done to establish the air leakage of the space.

The concept of co-heating was introduced in the 1970s. However, it is recognised that "the methodology is very much in its infancy, and in the UK, is currently the subject of much research and debate" (Johnston et al., 2013). It is very resource intensive to set up and conduct, which makes it a less commonly applied in situ thermal experimental method.

The Centre for the Built Environment at Leeds Metropolitan University has been one of the more active proponents of experimental co-heating. Their published test protocols (Johnston et al., 2013) recommend the tests be conducted when ΔT is at least 10 K. This aligns well with other researchers, such as (Asdrubali, Baldinelli & Bianchi, 2012) who advised a 10–15 K ΔT for their co-heating tests documented in their methodology for evaluating thermal bridging. The Leeds Metropolitan University protocol was largely followed in the Kotuku Apartments experiments.

3.3.2 Methodology

Block D was used as a proxy for the co-heating testing, being essentially very similar in construction to the other three blocks (see Figure 16). In addition, it had the advantage of being the first block scheduled to be renovated and then reinhabited, so testing could be completed sooner than the other apartments. It is the westernmost block, having by far the bulk of its glazing north-facing, and four storeys high. The co-heating tests were conducted during complete vacancy for 2 weeks before the start of renovations (in June 2014) and then again for 2 weeks after the renovations rehabilitation (in May 2016).

Figure 16. Apartment Block D, prior to renovations, looking east.

Originally, it was thought that monitoring the entire 24 apartments contained within Block D would be possible. However, this proved to be impractical due to the amount of duplicate monitoring-related equipment necessary in addition to the marginal usefulness of the extra monitoring. Thus, only a single wing (the east-side for the pre-renovation and west-side for the post-renovation) was examined for the co-heating study.

The experimental intent was to examine the same apartment units before/after the renovations. However, in some cases, the units where tenants agreed to give access pre-upgrade underwent layout changes as part of the reconfiguration of the buildings (such as merging of adjacent units). This required the post-renovation units used for co-heating being switched to adjacent identical apartments within the same block. This situation was less than ideal but applicable for the field experimentation carried out, due to the very repetitive nature of the building. Thus, the bulk thermal attributes of the switched apartments – such as solar orientation, links to the open southern walkway, volume and physical relationship to other units – were unchanged from the original selected apartments.

Both the before and after experimental set-ups comprised the internal temperature stabilising of three adjacent apartments (by floor) for over a week. Multi-floors were set up this way so that a vertical central core would be effectively thermally cocooned by the adjacent apartments. Each unit consisted of two space heaters, an air circulation fan and several temperature/humidity data loggers. The central unit also contained various extra switching controls and loggers. A schematic of the central unit equipment layout is shown in Figure 17. (Key: pulse = pulse logger, TC = thermocouple wire stands, heater = convection-type space heater, fan = standard oscillating mixing fan). Not shown are the two temperature and humidity loggers located on the eastern living room wall and on the kitchen door.

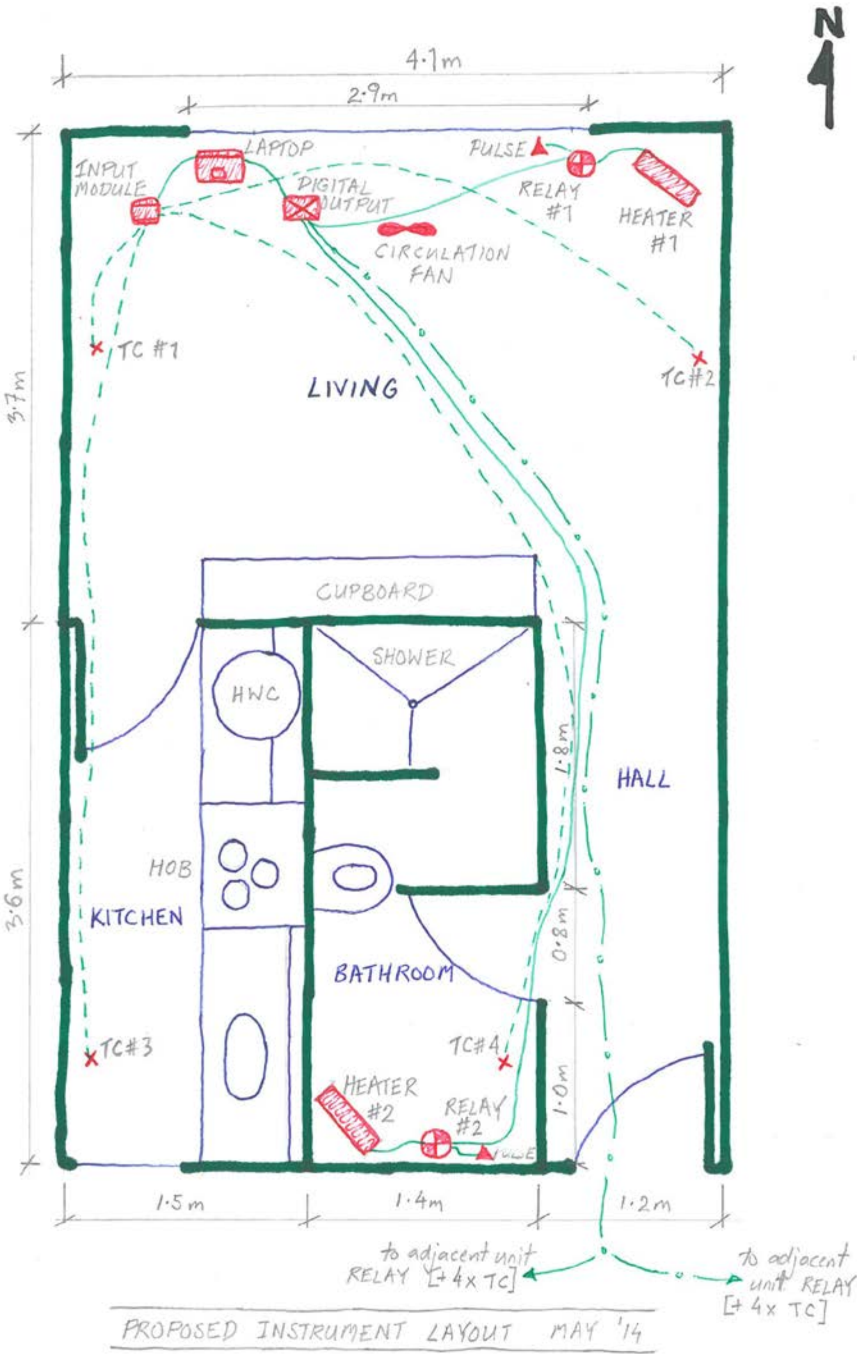

Figure 17. Typical instrument set-up (pre-renovation) for central apartment co-heating layout.

Post-renovation, wireless protocols were used to communicate between units to control space heater switching, so no inter-unit communication cabling was needed. The shift to wireless was necessary as metal security doors replaced (as part of the upgrade) the original timber doors, removing the opportunity for drilling any holes for conduit. Convective heaters were used to warm the apartments to 27°C, which provided an indoor-outdoor ΔT of at least 10°C.

The convective heaters were thermostatically controlled via thermocouples placed 0.85 m above the ground (see Figure 18) and also away from any direct heat, draughts or sunlight. Appendix A shows the new apartment layout.

Pulse loggers attached to the heaters tracked the on-off switching necessary for long-term indoor temperature stabilisation, therefore enabling the calculation of total energy requirements (see Figure 19).

Figure 18. Typical thermocouple wire at 0.85 m height supported by timber stand.

Figure 19. Heater relay and pulse meter box. (Photography: Neil Price)

Originally, a small HOBO Onset weather station was established on the rooftop. Within days of its erection, high wind gusts proved to be too severe, and it was destroyed. Fortunately, the Kotuku Apartments are located very close to the NIWA site at Greta Point so reliable and accurate simultaneous hourly outdoor temperatures could be easily established.

The co-heating test started in earnest only when the medium-mass building reached a steady state internal temperature, which was after about 3 days. Once a steady state had been reached, both the before and after tests ran continuously for 8 days. During this time, access to the heated indoor spaces was restricted to minimise extraneous heat losses (i.e. through door ventilation).

Space heaters were logged at 1 minute intervals while temperature and humidity were also logged at 1 minute intervals. In the post-renovation set-up, all the space heater-related logged data was pushed via a cellular connection to a database server at BRANZ for back-up, remote access and dynamic troubleshooting.

Figure 20. Temperature and relative humidity sensor/logger on kitchen door. (Photography: WCC)

Figure 21. Block D post-renovation, looking west.

Figure 22. Cable runs (in plastic conduits) from base of central unit door to adjacent units.

3.3.3 Results

Both the pre-renovation as well as the post-renovation co-heating performance will be examined together in this section.

3.3.3.1 Providing a stable indoor environment (pre-renovation)

Figure 23 gives the temperatures within each of the apartments as well as the outside temperature (measured on site) during the 2-week pre-renovation period (June 2014). Owing to equipment limitations, the three edge apartments and those on the ground floor were not able to be temperature controlled very accurately using computers. Instead, these apartment heaters were reliant on their (less-accurate) space heater thermostats.

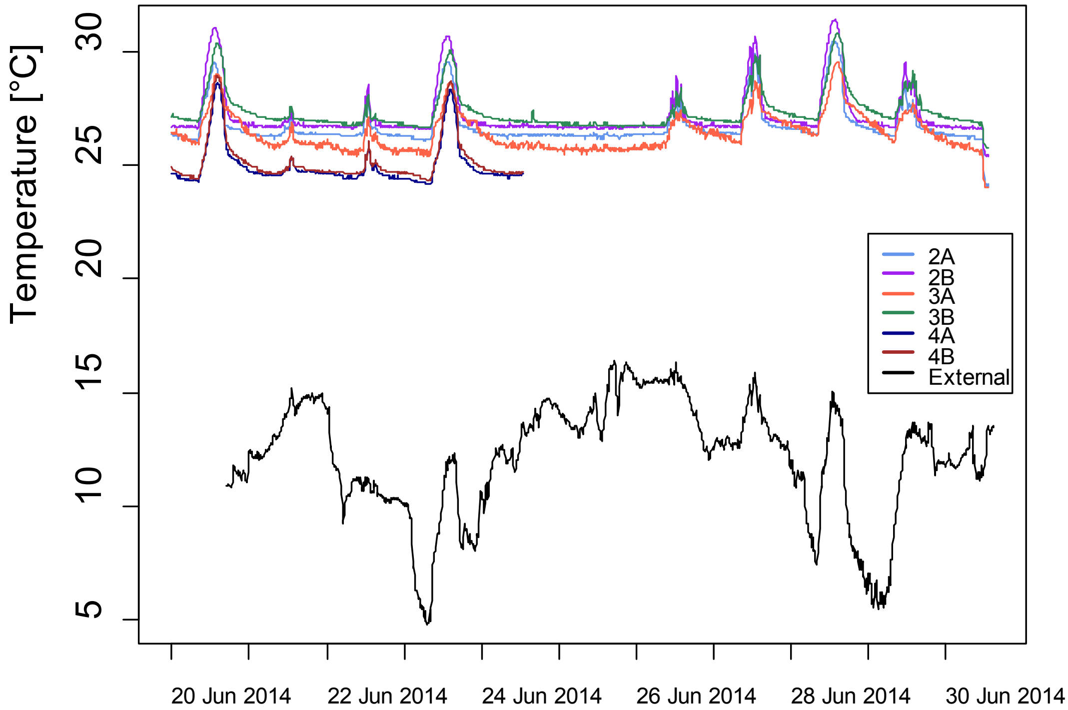

Figure 23. Outside temperature and temperatures within each apartment under test during the pre-renovation period (June 2014).

The intent was to stabilise the temperatures within each apartment to 27°C. However, some apartments struggled to achieve this pre-renovation. Despite their small size (at around 30m^2) and the use of 4 kW of heating, the externally exposed apartments (on the top level and at the end of the block) struggled to achieve this temperature continuously. This was due to these apartments having large, poorly insulated surfaces exposed to outside conditions. The two core units (3B and 2B) that were surrounded by conditioned apartments can be seen in Figure 23 to be the closest to the 27°C set point temperature.

During the day, solar gains through the north-facing windows pushes the internal temperatures above the 27°C set point, reaching over 30°C several times in a number of units. Ideally, co-heating studies reduce the influence of solar gains by covering all external glazing with reflective foil – unfortunately, this was not practicable for this project.

To artificially remove the influence of the solar gains, only overnight data (i.e. 6pm–6am) was examined. Figure 24 shows a close-up of the overnight temperatures in each of the monitored apartments. Rather than being flat for the duration of the overnight period, many apartments show a steady reduction in temperature throughout the night. By comparing Figure 24 and Figure 23, this effect is particularly pronounced when the preceding daytime temperature was high. This response is what would be expected when there is an interplay between the thermal mass of the building and the air temperature within the apartments. Heat from the day charges the thermal mass within the room to be later released at night-time when the room cools down.

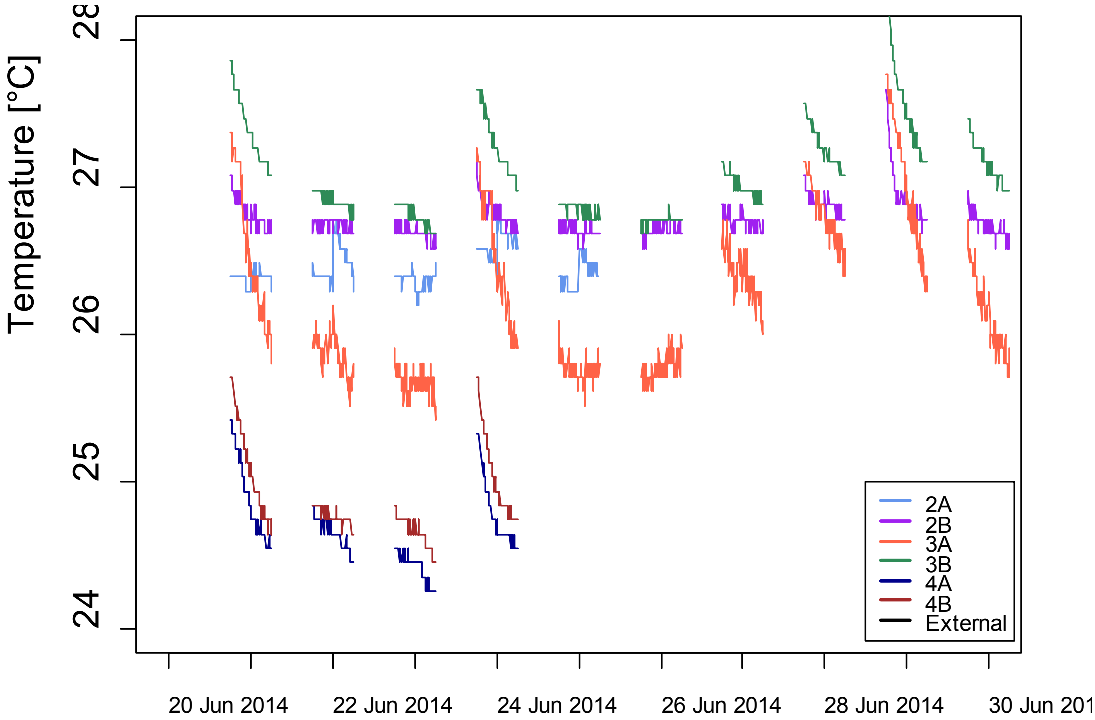

Figure 24. Temperatures within the monitored apartments showing only the overnight (6pm–6am) temperatures.

3.3.3.2 Providing a stable indoor environment (post-renovation)

Figure 25 shows the outside temperature as well as the temperatures in the equivalent apartments after the renovations during the monitored period of May 2016. The average outside temperature during the pre-renovation was considerably colder (at 11.7°C) than the post-renovation period (at 15.4°C).

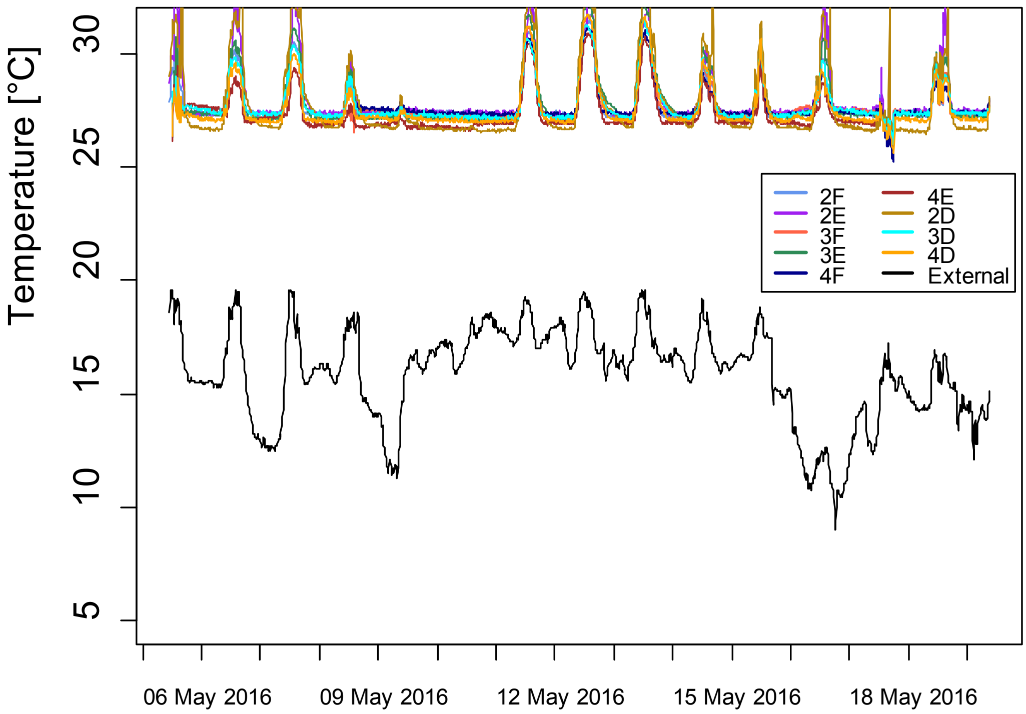

Figure 25. Post-renovation temperatures.

The achieved indoor temperatures in the apartments during the 2016 monitoring period are much more consistent than those achieved in 2014. This is reflected in the smaller overnight temperature range. Although daytime solar gains still result in temperatures peaking over 32°C, the overnight temperatures are considerably more stable – in most cases almost flatlining (see Figure 25). The required space heating for the overnight periods is shown in Figure 26 and Figure 27.

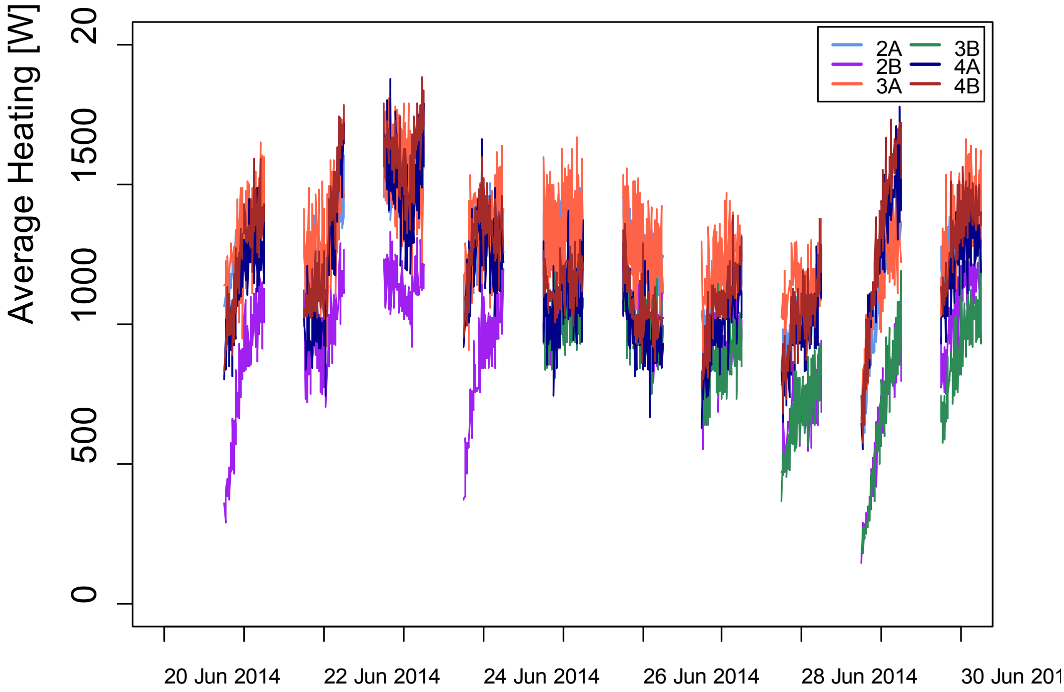

Figure 26. Overnight heating (averaged over 10-minute periods) before the renovations.

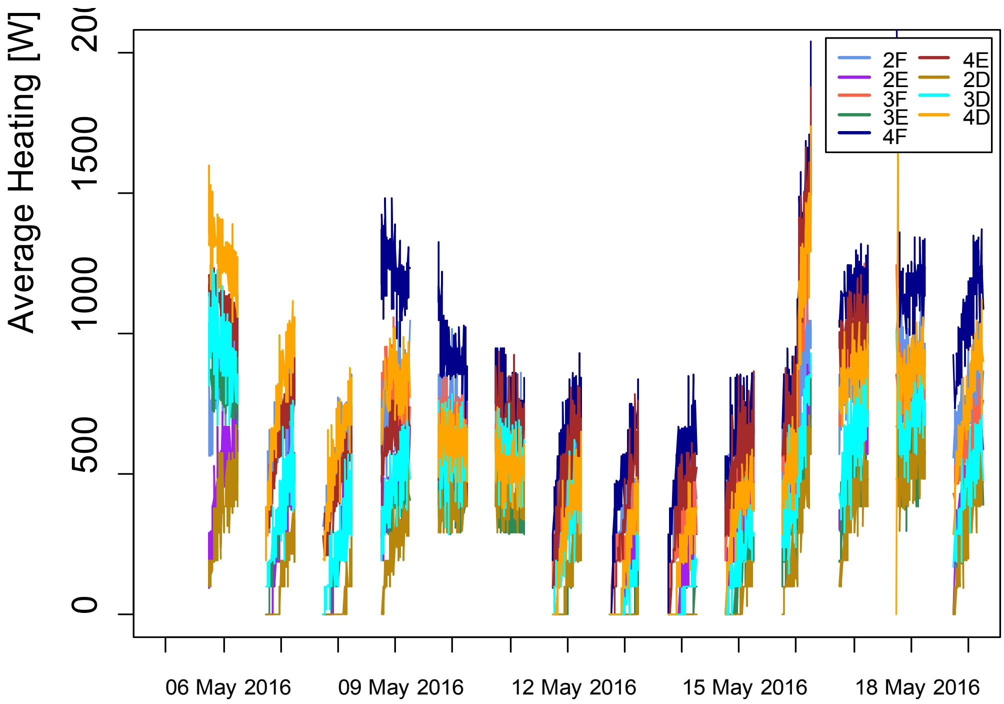

Figure 27. Overnight heating (averaged over 10-minute periods) after the renovations.

The average overnight heating from the external side apartments before the renovations was 1121 W per apartment and 725 W per apartment after the renovations. The two primary factors influencing this post-renovation space heating reduction are the upgraded thermal insulation and the higher outside temperatures experienced. It is not possible to determine the proportional influence of each from this data alone due to the unknown contributions of mass and solar irradiation.

3.3.3.3 Comparing heating and temperature differences

The co-heating methodology can deal with outdoor temperature fluctuations as only the temperature indoor-outdoor differences are considered. However, when there is a large amount of heat flowing into and out of a building's thermal mass, the co-heating methodology does not work as well. Unfortunately, for the pre-renovation situation, there is a large influence from the mass overnight with temperatures varying during the night. The co-heating methodology determines building envelope heat loss by plotting the temperature difference between the inside and outside of the space of interest and the heating required. The resulting slope is then the heat loss for that space – the steeper the slope, the greater the heat loss.

Figure 28 shows the comparison of the space heating and temperature difference from the core apartment on level 3. The pre-renovation data (for 3B) is shown as blue circles, while the post-renovation data (for 3E) is shown with filled red triangles. This core apartment (3B or 3E) is surrounded by heated apartments above, below and to the sides. As these other apartments are heated to the same level, there should be minimal heat flow through the walls, floors and roof. The renovation changed the north elevation by including double glazing as well as internally insulated plasterboard for the remaining wall area. The south elevation had fibreglass insulation added to the framing and a new security door, while the single glazing was retained.

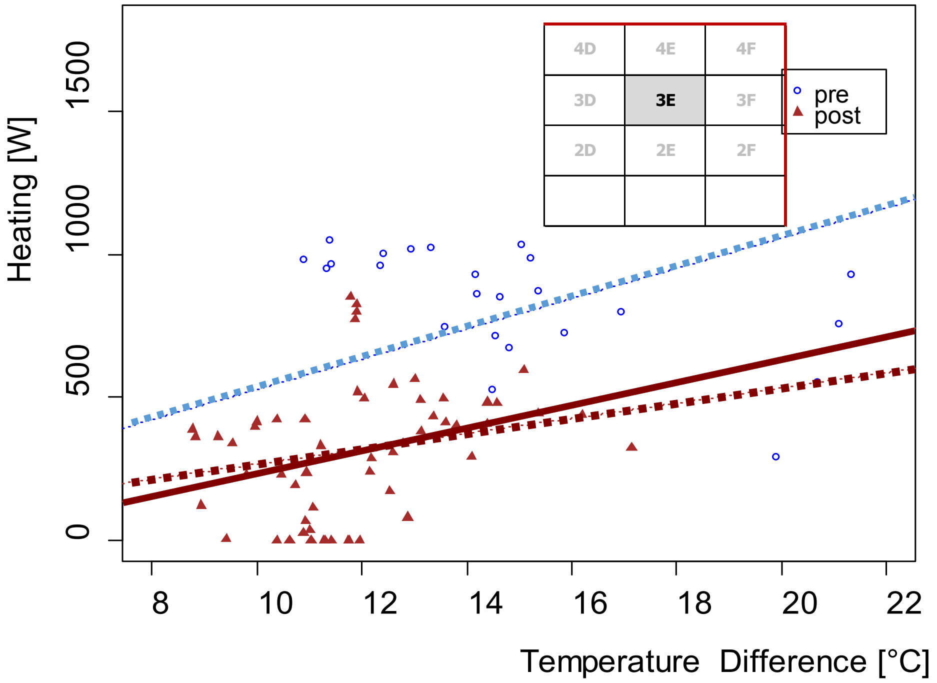

Figure 28. The space heating requirements for the central (core) level 3 apartment (3B pre-renovation ≡ 3E post-renovation). The solid red line is the least squares fit through the post-renovation data. The blue dotted line and the red dotted line are

least squares fitted lines that also go through the origin for the pre-renovation and post-renovation cases respectively.

For the pre-renovation data (blue circles), it is difficult to establish if there is a change of heating with increasing temperature difference. There appears to be an increasing variability of heating requirements as the temperature difference increases, which suggests a more complicated process is involved. The dotted blue line is the least squares fit, which also goes through the origin. In this case, this fitted line does not describe the behaviour of the heating in the range of temperature differences seen over the monitored period, and an estimate of the heat loss from this apartment is not possible. Rather than extending the theory in more detail, it may be useful to consider the heating as a fixed value of 843 W rather than as a dynamic quantity.

This reason for the increase in variability with increasing temperature difference displayed in Figure 28 is unknown, but the following is a hypothesis. When the temperature difference is large, the mass may be cooling down or warming up and consequently would require more heating or less heating than the average. When the temperature difference is smaller, the required heat flows into or out of the thermal mass would be smaller and the variability around the average amount of heating would be reduced.

For the post-renovation data in Figure 28 (red triangles), the correlation between the heating and the temperature difference is also poor. The dotted red line is the least squares fit, which also goes through zero heating when the temperature difference is zero and is roughly representative of the data. The solid red line is a 'least squares fit' and is similar in slope to the dotted red line. The slope of this dotted red line is 26.6 W/K, which could be taken as a rough approximation of the heat loss for this apartment. The average of the heating for the range of temperature differences observed was 314 W or 63% less than the average heating for the level 3 core apartment before the renovations were undertaken.

The other core apartment immediately below this apartment (2B pre-renovation and 2E post-renovation) is similarly surrounded by heated apartments[2].The level 2 core apartment showed a similar level of reduction of heating demand, this time reducing by 56%, lowering from a heating level of 909 W pre-renovation to a level of 314 W post-renovation. The heat loss from the straight line fitted to the post-renovation data (through the origin) was 32.8 W/K. As both the level 3 and level 2 core apartments (3B ≡ 3E and 2B ≡ 2E) are surrounded by heated apartments on the east and west, space heating requirements will be primarily due to heat loss through the north and south faces as well as via infiltration losses.

3.3.3.4 Impacts of thermal mass

Co-heating tests require a very high artificial set point, considerably higher than what apartment occupants will characteristically heat their apartments to during cold spells. Typically, given the average Wellington July temperature is around 10°C, the temperature difference needed to achieve indoor thermal comfort (say 18°C) will therefore be closer to 8°C. As the indoor-outdoor temperature difference lowers, there

[2] The apartment directly below apartment 2E was not heated, but there was an increased level of insulation between these two apartments post-renovation.

is an increasing gap in space heating power needed between the pre-renovated and post-renovated apartments.

Figure 29 illustrates this using the data from the level 2 side apartment as an example. Here, the pre-renovation period is shown by the flat blue line, and the post-renovation requirements are shown by the brown line. Thus, the positive benefits of the thermal improvements from the renovations can be seen, being especially useful when the temperature differences are small.

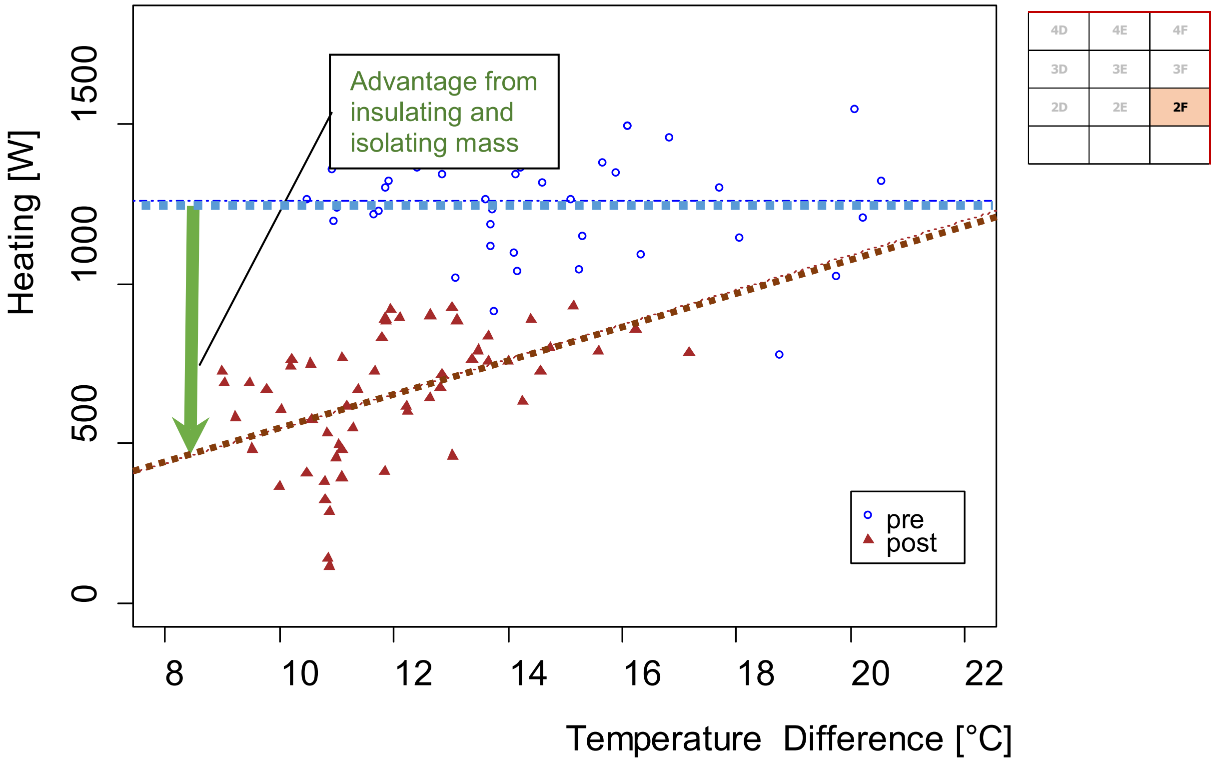

Figure 29. Level 2 side apartment (2A pre-renovation ≡ 2F post-renovation). The blue line is the average value of the heating for the pre-renovation data while the brown line is least squares fit forced through the origin.

It should be noted that the level of influence that the thermal upgrades have are dependent on the apartment of interest. This is best illustrated in the thermal simulation studies carried out in the previous BRANZ study report (Buckett & Jaques, 2016), where comfort performance – via both passive and active heating – is examined. This introduces some interesting equality issues according to where the occupants are situated. Other issues, such as whether their neighbour chooses to heat or not, further complicate the issue.

The key construction change between the pre-renovation and post-renovation side apartments was the addition of insulated plasterboard on the interior of the solid concrete external wall. This insulated plasterboard has two effects. The first is that the added thermal resistance reduces the heat flow through the wall. The second is the increased isolation of the thermal mass, limiting the heat exchange between the apartment air and the thermal mass.

In solar design, 'accessible' thermal mass may be seen as a good feature, depending on placement. Thermal mass can moderate heat flows, soaking up excess solar heat during the day and releasing at night. The impact on the air temperatures is to moderate the fluctuations, providing a more even temperature within the space. The degree of moderation depends on both the thermal resistance (R-value) and thermal mass (the heat capacity of the wall, which usually equates to the mass of heavy construction materials) accessible to the space. To make the thermal mass accessible to the space, it is usually necessary to place the insulation on the exterior of the thermal mass.

As the Kotuku Apartments were constructed when there was limited experience with the need for insulation, the concrete (thermal mass) in the construction was uninsulated. Later retrofitting of insulation to the exterior of the apartments was undertaken. However, this insulation was largely ineffective due to water ingress behind the polystyrene insulation. Consequently, the impact on heating for the pre-renovation apartments with accessible poorly insulated mass was to require long periods of heating, which also had minimal impact on the temperature within the apartments.

Where both sides of the thermal mass are within the thermal envelope of the building, there is no direct loss of heat to the exterior. This is the situation when there are heavy mass interior walls within the apartment or when heavyweight walls are used between apartments. When heavyweight walls are used between apartments, the temperature of the mass will tend to an average of the temperature between the apartments. This can cause an imbalance in the heating demands in two adjacent apartments. For example, where one apartment's occupant does not heat, the occupant in the adjacent apartment will need to heat theirs to a higher level to compensate.

In dealing with old existing buildings that have heavy construction (thermal mass) that is not well insulated, it is important to make them easier to heat. This includes providing sufficient insulation. If sufficient heating is not used to lift the temperatures within the building to an adequate level, efforts should be made to reduce the effect of the thermal mass to absorb. Placing insulation on the interior of thermal mass in exterior walls can increase the isolation of the thermal mass.

3.3.4 Discussion and conclusion

The pre-renovation and post-renovation co-heating tests proved to be very challenging for a number of reasons. As previously mentioned, co-heating is seen as a new science and therefore 'in development'. Specifically, for this test, there were the following challenges:

- A large amount of heat flowing into and out of the thermal mass within the building, influencing overnight temperatures of interest.
- The inability to account for (and therefore mitigate) the effects of solar gains through the glazing.
- The inability to account for infiltration losses, which could be considerable for this very exposed site.
- The unexpected large heat losses in the most exposed pre-renovation apartments, making the achievement of a stable temperature set point difficult.
- The change in the original construction plans leading to the amalgamation of the original studio apartments in Block D, necessitating a 'mirror apartment' substitute from west wing to east.

- Some unexpected equipment failures during the pre-renovation tests.

To effectively examine thermal performance changes of a renovation, it is suggested that there are other, less challenging and more robust tests that can be conducted for considerably fewer resources.

That said, the following was gleaned as a result of the co-heating tests:

- The difficulty in reaching a set point temperature in the most exposed apartments reflects the simulation findings in the previous BRANZ study report (Buckett & Jaques, 2016) results.
- Similarly, the level of influence that the thermal upgrades have is very much dependent on the apartment of interest, reflecting the previous BRANZ study report (Buckett & Jaques, 2016) results.
- A priority thermal upgrade in this style of building is to increase the insulation value of the walls. Insulating the external concrete walls internally helps to isolate the thermal mass, reducing the concrete wall's ability to soak up ambient heating.
- A better investigative approach to examining the influence of thermal improvement to a building envelope is needed, which requires far less time and experimental set-up, execution and analysis while being robust. Ideally, this should be a combination of infrared thermography, elemental heat flux and computer-based thermal simulation.

3.4 Airtightness

3.4.1 Background

The airtightness of New Zealand dwellings has been increasing over time. Air leakage/infiltration is often described as uncontrolled ventilation and is caused by small gaps across the building envelope providing entry pathways for external air and exit pathways for internal air. The recent change in building airtightness is largely due to a change in some key 1960s construction practices – a shift from suspended tongue and groove timber flooring to sheet floor construction or slab on grade, tighter aluminium frames and rubber sealed windows and the reduction in the number of open fireplaces (McNeil et al., 2015).

A poorly sealed dwelling can result in uncomfortable draughts during the colder months when cold air leaks in from the outside. In highly exposed environments, such as Kilbirnie, Wellington, heat losses due to high winds can be considerable. To put Wellington's wind resource into context, it is recognised as the windiest city in the world,[3] with a mean wind speed of 22 km/hr and having 22 gale days per year. Gale days are defined as being when the mean wind speed for the day exceeds 63 km/hr,[4] with gusts well exceeding this figure. For comparison, the mean wind speed for the rest of New Zealand's 28 urban areas is 13.8 km/hr, having 5 gale days a year.

The blower door test measures the airflow through a specifically sized opening located on the external envelope, which is driven by a powerful extraction fan. Blower doors

[3] https://www.theguardian.com/cities/2015/oct/15/where-world-windiest-city-spoiler-alert-chicago-wellington

[4] Data is mean annual values for the 1971–2000 period for locations having at least 5 complete years of data. Source: www.niwa.co.nz/education-and-training/schools/resources/climate/summary

typically consist of several form-fitting plastic panels, a powerful fan with various-sized interchangeable openings and a control/monitoring unit.

Figure 30. BRANZ scientist installing blower unit in the base of entry door.

The panels and the fan are placed within the door frame, ensuring a tight fit to minimise the likelihood of extra air leaks (see Figure 30).

The fan is then cycled through a range of pressures while a data logger monitors the flow rates achieved. By stabilising the indoor-outdoor pressure difference, a known airflow rate and hence airtightness value can be estimated.

Airtightness can be taken as a proxy for mean infiltration rate. At a 50 Pa pressure differential, the mean infiltration rate over a year would typically be approximately 1/20th of the airtightness during the blower door test.

In reality, the infiltration rate is dynamic, according to the outside wind conditions, topography and general exposure of the dwelling.

Blower door testing can be a useful verification tool but is usually only applied to small buildings due to the challenges associated with examining more complex buildings.

Internationally, there are some jurisdictions that mandate its application on new residential buildings. For example, the 2015 International Energy Conservation Code[5] calls for residential buildings to be blower door tested and verified as having an air leakage rate not exceeding 3–5 air changes per hour (ACH) @ 50 Pa, depending on climate.[6] There is no such requirement in the New Zealand Building Code.

3.4.2 Methodology

To quantify the airtightness prior to and post-renovations, a blower door test was conducted on the Kotuku Apartments on multiple apartments. Flow rates (in m^3/hour) were measured for a range of pressure differentials across the external envelope before a curve fit to the data points was used to obtain a measurement of airtightness at an indoor-outdoor pressure difference of 50 Pa.

In each case, the blower door was mounted into the frame of the one (and only) exterior door. Prior to the testing, all openings (such as passive vents) were carefully sealed with tape to ensure that a more realistic infiltration figure would be determined. Given the close to identical nature of the units – in terms of volume (at 72 m^3), room

[5] http://codes.iccsafe.org/app/book/content/2015-I-Codes/2015%20IECC%20HTML/Chapter%204%20[RE].html
[6] http://www.greenbuildingadvisor.com/blogs/dept/guest-blogs/testing-air-leakage-multifamily-buildings

layout, construction materials, aspect and configuration – a random sample of units were selected.

As only one blower door was available for the experiment, the compartmentalisation test method was used. This is where a single unit's leakage from the walls, floor and ceiling is quantified, with the operator moving around the building testing each unit individually. As air leakage from other apartments is not accounted for (in contrast to the co-heating test), compartmentalisation quantifies leakage from the exterior walls as well as the interior party walls, floors and ceilings. As exterior leakage is really what matters for energy use, this test is recognised as being not ideal for energy analysis[7] but was one of the better ones practically available.

As with all blower door tests where the dwelling has only one external door available, the tested door's contribution to the overall apartment's air leakage remains unknown. Without going to considerably more expensive test methodology – for example, using SF_6 tracer gas methods – this is unavoidable.

As has been noted, Kotuku Apartments are highly exposed to wind/gusts, not only by being located in a windy zone but also being considerably taller than the surrounding buildings and foliage in all directions. This exposure was reinforced when the high-quality weather anemometer (for measuring wind speed) positioned on top of Block D lasted only a day before being destroyed. Unsurprisingly, there was some difficulty in obtaining a day calm enough in the first lot of testing (prior to the renovations), as high wind loads and gusts were prevalent.

An instructional video demonstrating the co-heating set-up has been made as part of the BRANZ ScienceTalk media communication series. It is publicly available through YouTube www.youtube.com/watch?v=5YzlApl4tPI. ScienceTalk is an occasional BRANZ video series highlighting aspects of applied building science that the BRANZ Knowledge Transfer team releases.

3.4.3 Results

The before and after renovation results for the units are averaged over nine units, using EN 13829:2000 *Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method*, which provides guidance on the determination of air permeability of buildings.

- Before renovation: Blower door ACH = 8.1 @ 50 Pa
- After renovation: Blower door ACH = 8.0 @ 50 Pa

In terms of the before and after changes relevant to infiltration/airflow, the following construction items may have impacted on the infiltration rates (see Table 1).

Table 1. Before and after building aspects that may impact on infiltration.

Item	Before renovation	After renovation
Windows – north side	Steel framed with old 'rubber' seals	Aluminium framed with new 'rubber' seals
Hob extractor	None	Installed
Bathroom extractor	None	Installed

[7] http://www.greenbuildingadvisor.com/blogs/dept/guest-blogs/testing-air-leakage-multifamily-buildings

Kitchen cupboard vent	Passive vent	None
Entry door	Timber – no seals	Metal security – no seals

Converting to the mean yearly average infiltration rate over the year (estimated to be 1/20th of this figure) provides a figure of about 0.4 ACH. This means that about 40% of the entire volume of air in the units is replaced by external air every hour due to air leaking through gaps and cracks. This external air may come either from the outside or an adjacent unit – it is unknown what the mix is and would be difficult to determine practically. International guidelines on indoor air quality recommend that the ventilation rate should ideally be 0.35–0.5 ACH. At this rate, ventilation should be enough to effectively remove contaminants but not so high as to compromise energy efficiency (Quaglia & McNeil, 2011).

The mean yearly infiltration rate using the blower door average remained unchanged for the Kotuku Apartments sampled at about 0.4 ACH.

3.4.4 Discussion and conclusion

This infiltration test was always only going to be of marginal value due to the following:

- The change in the original upgrade design plans preventing the same units being examined both before and after the renovations. As a result, the modified experiment assumed all the apartments having very similar infiltration rates so that before/after averages would be a reasonable representation.
- The unknown contribution the corridor/entry door has on the units' infiltration. For apartment buildings, this is difficult to avoid due to the nature of the blower door test. There is evidence that these doors may be the largest single air exchange pathway in apartments (Maxwell, 2016). This test method thus ignores one of the defining characteristics of the apartment envelope and airflow patterns and is therefore potentially a fundamental shortcoming.
- The unknown external air contribution – how much of the replacement air is sourced from outside versus how much is sourced from adjacent (and possibly more polluted) units.

Assuming that replacement air comes from zones that are less polluted than the original (polluted) air, the newly renovated units, on average, provide enough background ventilation for adequate pollutant removal throughout the year. This is all the more likely given the location of the apartments and the lack of seals on the new entry door.

3.5 Shower utility

3.5.1 Background

The originally installed low-pressure (approximately 7–12 psi) electric hot water cylinders (1950s era, 135 litre, with 10 mm hessian insulation) were all replaced as part of the building refurbishment. The new system is a high/mains-pressure (approximately 70 psi) system and consists of electric 135 litre internally insulated (to A grade standard) cylinders. They are located internally in each apartment.

The new cylinders each have individual thermostats and tempering valves, set to 65°C and 55°C respectively. These two temperature controls regulate the temperature of the hot water leaving the cylinder, ensuring the hot water (when set to its hottest mixing setting) is not delivered at a temperature dangerous to the occupants. Temperatures above 60°C are required to the safe storage of hot water to kill any *Legionella* bacteria that may be present. In addition, the temperature of any tap when set to its hottest available setting must be less than 55°C (Pollard, Stoecklein, Camilleri, Amitrano & Isaacs, 2002). 53.2°C was the average temperature measured across all apartments at the tap nearest to the cylinder (when set to the hottest position). This is the tap that would have the highest hot water temperatures. This is due to its close proximity to the cylinder, meaning there is less heat lost through the pipework as the hot water travels from the cylinder to the tap fitting. No individual measurement was recorded about the 55°C safety requirement.

As part of the hot water system upgrade, each shower unit was also replaced. As part of this project's measurement of the performance improvements, the temperature and flow rates of the showers were measured. These measurements were recorded in before and after refurbishment use scenarios. The flow rate and the temperature of the shower hot water is an important factor in the energy and environmental performance of the Kotuku Apartments. Research conducted by Pollard et al. (2002) has shown that heated water typically represents approximately 30% of New Zealand's residential energy, with shower usage being a major hot water user.

3.5.2 Methodology

The shower flow rates were measured by timing the length required to fill a 2 litre container when the shower mixer was set to maximum flow for the temperature categories of coldest, hottest and warm. Note, that the 'warm' was defined by the individual performing the test. Like the individual building occupants, this differs from the before and after refurbishment measurements by +9.1°C where the post-refurbishment tester favoured a hotter temperature (36.8°C versus 45.9°C).

3.5.3 Results and discussion

Table 2 shows the results of the shower flow measurements for the pre-renovation and post-renovation. Overall, the average flow rate across all three temperature categories (cold, warm and hot) increased by 194%, from 5.2 L/min to 9.0 L/min. Simultaneously, the average temperature of the hot category has fallen from 57.7°C to 52.3°C. These results show a likely increase in hot water consumption because of increased shower flow. This is an expected consequence of changing from a low-pressure system to a high/mains-pressure system. However, the pre-refurbishment flow rates were very low in terms of providing a good level of shower utility.

Anecdotally, this resulted in a low-quality shower experience for the occupant, where the stream of water leaving the showerhead had a very low surface area coverage. Therefore, while the refurbishment may lead to an increase in hot water use, this is mitigated by a much-improved personal utility experience by occupants. There is also the possibility that, by improving the surface coverage of the shower, the occupant's showering times may decrease overall as they can more efficiently wash themselves.

Putting the average flow rate of 9.0 L/min into the context of water efficiency strategies, a low-flow showerhead uses 6–10 L/min, whereas an ordinary showerhead will use 10–20 L/min. This proves that the refurbished showerheads, despite increasing the flow rate compared to the pre-refurbishment, are still within accepted water-efficiency measures.

For future refurbishments, more advanced water-conserving showerheads are available (such as Methven's SatinJet[8]). These use technologies that atomise the water leaving the head into many small droplets to provide a far greater surface area water coverage compared to ordinary showerheads. Depending on the system, this can minimise the flow rate to as low as 2.8 L/min (www.nebia.com). This is a 69% reduction compared to the measured 9.0 L/min average post-refurbishment flow rate.

Table 2. Hot water (before and after) renovation performances.

Average	Cold		Warm		Hot		All temperature categories	
	Temp (°C)	Flow rate (L/min)	Temp (°C)	Flow rate (L/min)	Temp (°C)	Flow rate (L/min)	Temp (°C)	Flow rate (L/min)
Before	16.0	7.3	36.8	5.0	57.7	3.2	36.8	5.2
After	17.6	9.2	45.9	9.1	52.3	8.9	38.6	9.0

Extrapolating these before and after refurbishment results, EECA's EnergyWise online water heating systems selection tool (www.energywise.govt.nz/tools/water-heating) has been used to provide an indicative cost per apartment estimation of the hot water use of the showers only.

The results show that the post-refurbishment costs are $520 annually compared to the pre-refurbishment costs of $519 annually. This was based on an electricity price of 28 c/kWh and one 10 minute shower per day based on a single apartment occupancy. Furthermore, the EECA tool would not calculate flow rates below 6 L/min, so this was used instead of the 5.2 L/min average. Based on this calculation, the additional water used in the refurbished showers because of increased shower flow only costs the occupant an additional $1 per year.

Finally, the BRANZ water heating assessment tool (Burgess & Cogan, 2008) was employed to assess the overall energy efficiency of the hot water system. The pre-renovation achieved a Home Energy Rating Scheme (HERS) star rating of 4.0 out of a perfect 10, which equates to a minimal acceptable efficiency installation. A post-renovation HERS revises the star rating to 5.0 out of 10, a slight increase. To achieve higher efficiencies, hot water systems require a renewable energy component to contribute to the heating, for example, using solar thermal or a wetback.

[8] www.methven.com/nz/satinjet

4. Summary and concluding remarks

4.1 Overall summary

This study looked at increasing performance of low-income dwellings in the rental sector using the recent renovation of Kotuku Apartments in Wellington, New Zealand, that finished in 2017. A suite of in situ measurements was carried out to quantify changes in building performance related to comfort, cost and liveability.

The main in situ performance aspects examined were:

- whole-building external envelope thermal fitness for purpose (via thermography)
- detailed element-only thermal resistance (via heat flux tests)
- individual apartments' comfort (via co-heating experiments)
- uncontrolled external-internal air exchange (via blower door tests)
- shower utility (via flow rate measurements and online energy efficiency tools).

The experiment work focused largely on the 4-storey Block D, the westerly most apartment oriented west-east, which was essentially duplicated in construction for the other three blocks. These were the findings:

- **Thermography tests** clearly showed the considerable thermal improvement of the external envelope resulting from the 2016 renovations. Not only was the insulation more effective, it was more consistent and removed the issues with water ingress and accumulation within the insulated panels.
- **Heat flux tests** showed the increase in thermal resistance values of 66% (pre-renovation = R0.6 and post-renovation = R1.0) for the external wall systems examined. This determination accounts for the influence of the high-mass concrete panels. Thus, the heat loss for these wall elements has reduced considerably, resulting in either lower operating costs or better user comfort.
- **Co-heating tests** reinforced the difficulty in heating to a not-unreasonable indoor-outdoor temperature differential – one that would be reflective of a colder winter night – for the more exposed apartments. It also highlighted that the level of influence of the thermal upgrades is very much dependent on where the apartment of interest is positioned in relation to the other apartments.
- **Airtightness tests** were inconclusive, even though an attempt was made to determine the individual apartments' pre-renovation and post-renovation infiltration rates. The main complication with this test is the unknown influence of the entry door on the apartment, which is necessarily blocked by the blower door measuring equipment during the test procedure. Research literature suggests this can be an issue.
- **Shower utility testing** showed that the renovation changes have provided a considerably better user experience while not increasing the ongoing hot water operational costs significantly.

4.2 Concluding remarks

One of the original goals of the renovation was to provide social housing providers of multi-unit apartment-style dwellings with some guidance to achieve better renovation outcomes. The following suggestions are based on BRANZ findings from this Wellington-based case study that could be applied to other multi-unit houses. The recommendations are all practical and cost-effective and provide useful, usable results.

In terms of whole-building examination

The single best action to better understand the pre-renovation and post-renovation thermal building performance, comfort and ongoing space conditioning energy requirements is the use of computer thermal simulation. It provides clear guidance between upgrade options while also delivering a useful comparative benchmark in the original design. The simulation work needs to be carried out by experienced experts using a dynamic (i.e. hourly) simulation program.

In terms of individual building element examination

Thermography provides a very useful complementary tool that can work alongside other building surveying tools. It is especially useful for building surveyors for understanding thermal-related quality control issues both pre-renovation and post-renovation at an elemental level. Thermography does require skill in both conducting surveys as well as in the interpretation of the resultant thermal images, however.

References

Asdrubali, F., Baldinelli, G. & Bianchi, F. (2012). A quantitative methodology to evaluate thermal bridges in buildings. *Applied Energy, 97*(0), 365–373.

Buckett, N. & Jaques, R. (2016). *Kotuku Apartments thermal modelling – design stage*. BRANZ Study Report SR362. Judgeford, New Zealand: BRANZ Ltd.

Buckett, N. R., Jones, M. S. & Marston, N. J. (2012). *BRANZ 2010 House Condition Survey – condition comparison by tenure*. BRANZ Study Report SR264. Judgeford, New Zealand: BRANZ Ltd.

Burgess, J. & Cogan, D. (2008). *A water heating rating tool for domestic construction in New Zealand and Australia*, BRANZ Ltd report EC1475, submitted to EECA (Energy Efficiency and Conservation Authority).

Burgess, J. C., Buckett, N. R., Camilleri, M. J. T., French, L. J., Pollard, A. R. & Hancock, P. J. (2008). *Final monitoring report from the Papakowhai Renovation Project*. BRANZ report TE106/15 for Beacon Pathway Limited. Judgeford, New Zealand: BRANZ Ltd.

Child Poverty Action Group. (2015). Housing briefing paper. Retrieved from http://www.cpag.org.nz/assets/Housing%20briefing%20paper%20-%20May15%20CPAG.pdf

Cox-Smith, I. (2008). Measuring in-situ thermal performance. *Build, 107*, 40–41.

CRESA. (2007). *Local government and affordable housing*. Wellington, New Zealand: Centre for Housing Research, Aotearoa New Zealand and Auckland Regional Council.

Demographia. (2015). *Demographia international housing affordability survey*. Retrieved from http://www.demographia.com

Dunbar, R. & McDermott, P. (2011). *Improving the design, quality and affordability of residential intensification in New Zealand*. Wellington, New Zealand: Centre for Housing Research, Aotearoa New Zealand.

Howden-Chapman, P., Pierse, N., Nicholls, S., Gillespie-Bennett, J., Viggers, H., Cunningham, M., … Crane, J. (2008). Effects of improved home heating on asthma in community dwelling children: Randomised community study. *BMJ, 337*, 852–855.

Johnston, D., Miles-Shenton, D., Farmer, D. & Wingfield, J. (2013). *Whole house heat loss test method (coheating)*. Leeds, UK: Centre for the Built Environment, Leeds Metropolitan University.

Lundberg, J., Carson, S., Setefano, M., Bush, R., Conway, K., Child, A., Kanesha, K. & Harrison, P. (2015). *Exploring security of tenure through co-design*. Wellington, New Zealand: Ministry of Business, Innovation and Employment, Auckland Council and The Auckland Co-design Lab. Retreived from http://www.mbie.govt.nz/publications-research/research/housing-and-property/Rental%20Tenure%20-%20Talkbook.pdf/view

Maxwell, S. (2016). Ventilation: The only way that passive vents will work. *Home Energy, January/February*.

McNeil, S., Plagmann, M., McDowall, P. & Bassett, M. (2015). *The role of ventilation in managing moisture inside New Zealand homes*. BRANZ Study Report SR341 Judgeford, New Zealand: BRANZ Ltd.

Motu Project Team. (2006). *Affordable housing in Nelson, Tasman and Marlborough: Taking action*. Wellington, New Zealand: Centre for Housing Research, Aotearoa New Zealand, Ministry of Economic Development and Work and Income.

New Zealand Productivity Commission. (2012). *Housing affordability*. Wellington, New Zealand: Author. ISBN: 978-0-478-39507-5 (online).

Overton, G. (2010). Thermal imaging – handle with care. *Build*, *116*, 44–45.

Pollard, A., Saville-Smith, K. & Jaques, R. (2017). *Implications of the Kotuku Apartments retrofit on its occupants*. BRANZ Study Report SR373. Judgeford, New Zealand: BRANZ Ltd.

Pollard, A., Stoeklein, A., Camilleri, M., Amitrano, L. & Isaacs, N. (2002). An initial investigation into New Zealand's residential hot water energy usage. Presented at IRHACE Technical Conference, March, Palmerston North, New Zealand.

Property Council. (2011) *Inquiry into housing affordability*. [Letter written to New Zealand Productivity Commission by C. Townsend, 3 August 2011]. Retrieved from http://www.productivity.govt.nz/sites/default/files/Sub%20028%20-%20Property%20Council%20New%20Zealand%20Submission.pdf

Quaglia, L. & McNeil, S. (2011). Changing the air indoors. *Build, 127*, 48–49.

Statistics New Zealand. (2013). *Rental affordability1998–2012: Regional distributions*. Wellington, New Zealand: Author. ISBN 978-0-478-40843-0 (online)

Taylor, T. J., Counsell, S. & Gill. (2013). Energy efficiency is more than skin deep: improving construction quality control in new-build housing using thermography. *Energy and Buildings*, *66*, 222–231.

Appendix A: Post-renovation apartment layout

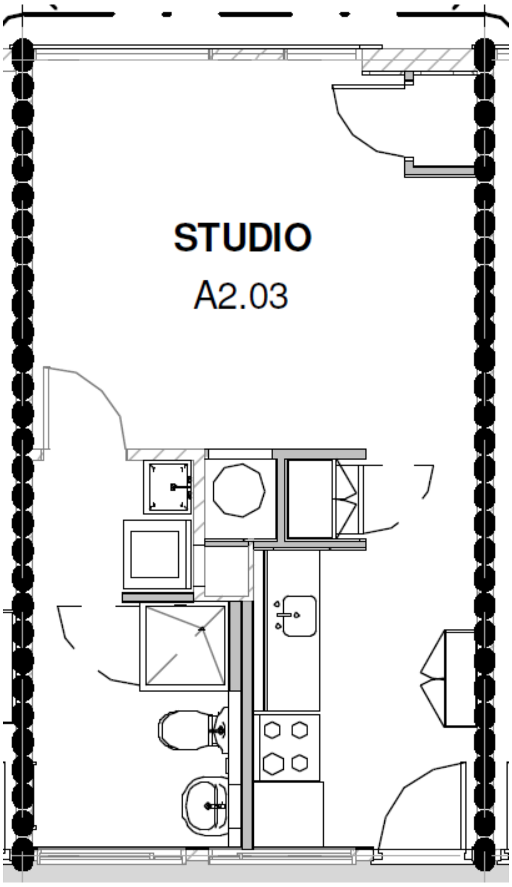

Figure 31. Post-renovation apartment layout, showing bathroom-kitchen swap.