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A SUPERHOME in Christchurch Under Winter Conditions: Real
Performance Through Post-Occupancy Evaluation

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Abstract

The profile of energy-efficient, high performing, ‘sustainable’ buildings have greatly increased in recent years in response to the need for change in design, construction, and maintenance of the built environment. Residential buildings in particular have been in the spotlight when it comes to the application of ‘green’ building concept. Although it is generally understood that a ‘green’ home provides a healthier and more comfortable housing environment to its occupants aside from generating energy efficiency, little is known about the extent to which such a home actually performs while in use. In New Zealand, a nationwide industry led initiative, known as the ‘Superhome Movement’, was established to promote the designing and building of environmentally sound, healthier, more energy-efficient and overall high-performing homes known as SUPERHOMES. This research investigated the post-occupancy performance and indoor environment quality of a SUPERHOME under winter conditions. This study incorporated the analysis of energy use, monitoring of IEQ, and the surveying of building occupants. Results suggest that (1) the study building has not achieved its design potential with regards to electricity use in the first winter that it is occupied; (2) a SUPERHOME achieves a high level of thermal performance and provides adequate IAQ in winter conditions; and, (3) occupants’ overall perceptions towards the post-occupancy and winter performance of a SUPERHOME are positive. These findings lead to a realization that the ‘green’ status of a build should not be limited to ratings by third-party certification.

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Abbreviations

BRANZ	Building Research Association of New Zealand
BRS	Building Rating Scheme
BUS	Building in Use Studies
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
dB	decibels
dB(A)	A-weighted decibels
GHG	Greenhouse Gas
HEEP	Household Energy End-use Project
IAQ	Indoor Air Quality
IECC	International Energy Conservation Code
IEQ	Indoor Environment Quality
LPM	Litres Per Minute
NIWA	National Institute of Water and Atmospheric Research
NO ₂	Nitrogen Dioxide
NZBC	New Zealand Building Code
NZBCSD	New Zealand Business Council for Sustainable Development
NZGBC	New Zealand Green Building Council
OITC	Outdoor Indoor Transmission Class
PIS	Participant Information Sheet
POE	Post Occupancy Evaluation
PV	Photovoltaic
RH	Relative Humidity
SHM	SUPERHOME Movement
SLM	Sound Level Meter
STC	Sound Transmission Class
TL	Transmission Loss
uPVC	Unplasticized Polyvinyl Chloride
VOC	Volatile Organic Compound
WHO	World Health Organization

Chapter 1: Introduction

A SUPERHOME in Christchurch Under Winter Conditions: Real Performance through Post-Occupancy Evaluation investigated the post-occupancy performance and indoor environment quality of a SUPERHOME Movement exemplar home in Christchurch, New Zealand. This study aimed to demonstrate how well a designed and built above-building-code residential building is performing under occupied conditions. This introductory chapter covers the background, rationale, and the specific context in which this research project was carried out. It describes its objectives and presents the research questions as well as the structure of this thesis.

1.1 The ‘green’ home trend

An extensive range of studies has reported the substantial impacts that the building industry brings about on the environment. Buildings consume resources such as energy, water and raw materials, generate a variety of wastes and emit potentially harmful substances to the environment during their life cycle. In New Zealand, the housing sector is the third biggest consumer of and is responsible for at least 11 per cent of, the country’s total energy consumption (MBIE, 2016). In 2015, around 31.5 per cent – which is equivalent to 12,544 GWh – of New Zealand’s electricity is consumed by residential buildings, accounting for the second largest share of electricity consumption in the country (MBIE, 2016). The residential sector should therefore be a vital focal point for research on energy efficiency and climate change. With the adoption of more energy-efficient technologies within New Zealand homes, a significant amount of electricity could be saved nationwide.

The profile of energy-efficient, high performing, ‘sustainable’ buildings have greatly increased in recent years in response to the need for change in design, construction, and maintenance of the built environment (Bond, 2010; Bond & Perrett, 2012; Bonde & Ramirez, 2015; Eichholtz, Kok & Quigley, 2013). To guide and encourage green building practices, numerous building rating schemes (BRSs) have been developed, each with its own set of criteria and performance standards to minimize environmental impacts and improve indoor environment quality (IEQ). The increasing numbers of buildings being certified under various BRSs worldwide and the growing numbers of publications related to sustainable architecture indicate positive trends of interests

towards sustainability within the property industry. Green' – or environmentally sustainable – building has mainly been associated with energy efficiency and also emission reduction. Residential buildings in particular have been in the spotlight when it comes to the application of 'green' building concept (Cryer, Felder, Matthews, Okrent & Pettigrew, 2006; Jackson, 2014; Kahn & Kok, 2014; Zuo & Zhao, 2014).

In New Zealand, the industry accepted BRS in use for residential buildings is HomestarTM, administered by the New Zealand Green Building Council (NZGBC). Since the introduction of HomestarTM rating system in 2010, HomestarTM has been a pioneer in building ratings to the housing market in New Zealand. Under the HomestarTM rating system, a building is rated on a 1 to 10 scale, with 10 being the highest rating achievable. Houses built to New Zealand's current building codes typically achieve 3 or 4 Stars, which equates to houses that are not particularly comfortable to live in and require high heating costs during the colder months (NZGBC, 2017a). As a matter of fact, the uptake of 'green' homes still encounters resistance across New Zealand. The majority of New Zealand homes, even the newer ones, have been designed and built to the code minimums (NZBCSD, 2008). This indicates how the New Zealand housing stock lags far behind in terms of comfort and energy efficiency.

A nationwide industry led initiative was established to promote the designing and building of homes that would rate a 6 or higher HomestarTM rating, known as the 'SUPERHOME Movement' (Aliento, 2015; Bob Burnett Architecture, 2017; NZGBC, 2015a). The 'SUPERHOME Movement' provides a forum for the sharing of new ideas, technologies and techniques of design and construction of environmentally sound, healthier, more energy-efficient and overall high-performing dwelling (Bob Burnett Architecture, 2017). Bob Burnett, widely recognized for his long-standing dedication to sustainable design and construction, has been instrumental in initiating and promoting the 'SUPERHOME Movement'. The Christchurch-based architect, who is a certified HomestarTM assessor, designed the first SUPERHOME – a 10 Star HomestarTM Built home (Shannon, 2015).

Since its launch in 2015, 17 exemplar homes have been built to model the standard of design and construction of a SUPERHOME; thus to be used as a communication tool for the movement. These demonstration homes present options of innovative and energy

efficient environmental design that could be replicated for future housing projects development across New Zealand. The focus of attention on these homes has been directed towards its design and construction features. Not enough attention is being placed on the operational stage. According to the New Zealand Business Council for Sustainable Development, the in-use phase of a building's lifetime is responsible for approximately four-fifths of the building's total energy use and carbon emissions (NZBCSD, 2008). This finding underscores the need for operational energy performance assessment in building projects.

Although it is generally understood that a SUPERHOME provides a healthier and more comfortable housing environment to its occupants aside from generating energy efficiency, little is known about the extent to which such a home actually performs while in use. It is generally believed that the performance of buildings, especially the certified ones, needs to be constantly monitored and re-evaluated during operations to ensure optimum performance (Birt & Newsham, 2009; Chan, 2015). While the post-construction performance of SUPERHOMEs might have been evaluated, the story could be different as-built and occupied. On-going measures of performance are necessary to make certain that a 'green' building is not only 'green' in its design and construction, but also in its operations. However before now, there is a lack of research that has been conducted which monitors post-occupancy performance of 'green' residential buildings in New Zealand. Research on this matter is key for providing evidence-based validation of actual benefits of SUPERHOME projects.

Besides energy consumption, another important aspect of building performance evaluation is the monitoring of indoor environment quality (IEQ). In New Zealand, it has been estimated that people spend approximately 70% of their time indoors, at home, per day (Khajehzadeh & Vale, 2016). Research has acknowledged the importance of the housing environment to human health (Phipps & Warnes, 2007). The quality of the indoor environment, in particular, is critically responsible for some health threats possibly found in dwellings (Marmot Review Team, 2011; Rudge, 2011; Taptiklis & Phipps, 2017; WHO, 1987). On a more positive note, there is a growing body of evidence of health benefits resulting from improvements of IEQ (Phipps & Warnes, 2007). In the housing context, the health benefits associated with better IEQ is the stronger driver to the adoption of green building practices than energy efficiency and reduced environmental impacts (Underhill, 2007, as cited in Phipps & Warnes, 2007).

In building studies, IEQ of a building is commonly measured in terms of temperature, relative humidity (RH) and carbon dioxide (CO₂) levels, as well as acoustic quality, thermal fitness and air tightness (French, Heinrich, Jaques, Kane & Pollard, 2007; Jaques, Pollard, Berg & Huang, 2017; Mumovic et al., 2009; Pollard, French, Heinrich, Jaques & Zhao, 2008; Silva, Maas, de Souza & Gomes, 2017).

According to Bonde & Ramirez (2015), performance evaluation of an occupied building should incorporate not only technical assessments, but also assess the experience of occupants. One way to achieve this is through performing a post occupancy evaluation (POE) – a method for assessing an occupied building’s performance, taking account of the occupants’ perspectives (Agha-Hosseini et al., 2013; Bonde & Ramirez, 2015; Preiser, 2001; Zimring & Reizenstein, 1980). POE is a key practice to verify actual performance of buildings against design expectations. The POE method goes beyond assessment of technical performance of the building and takes into consideration the needs and points of view of the occupants. POE has been widely used to measure satisfaction levels of building users over the technical and functional performance of occupied facilities – both residential and commercial (Bonde & Ramirez, 2015).

It was clear from early studies that changes in microclimate conditions have direct influence to a building’s energy consumption and IEQ (French et al., 2007; Isaacs et al., 2010; Lloyd & Callau, 2006; Pollard et al., 2008). Winter performance, in particular, is highly influenced by increased use of space heating, water heating and lighting, which translates to increased energy use. Isaacs et al. (2010), found an increase in winter energy consumption in New Zealand households by as much as three times the consumption during summer. In addition to that, solar gains are reduced during winter months, therefore these months are less effective for homes that rely on solar energy for water heating for example. Seasonal changes also bring inevitable changes to the indoor environment. During cold weather, airflow access tends to be sealed off to hold heat in the building. This, as a consequence, seals off the home from receiving fresh air, which raises contaminants concentrations indoors. Given the end results that wintry conditions may have on the overall operational performance of buildings, it is fair to assume that a building’s energy performance and IEQ are most vulnerable in wintry conditions, which therefore suggests that monitoring of IEQ is most impactful if carried out during winter.

As evident in the literature the SUPERHOMEs have not been evaluated under occupied and winter conditions. This thesis was carried out to investigate the post-occupancy performance and IEQ of an occupied SUPERHOME in Christchurch, New Zealand. This research aimed to see how this building performs under winter conditions. The evaluation was carried out across three key areas, which include operational energy performance, indoor environment quality and occupants' satisfaction.

1.2 Research statement

This research investigated the post-occupancy performance of a SUPERHOME Movement exemplar home. The evaluation was done involving one SUPERHOME building in Christchurch. By conducting a case study of the building, the researcher sought to gain insight into how one SUPERHOME performed in regards to energy usage, indoor environment quality and occupants' comfort. This home is expected to be representative of SUPERHOMEs in general. Due to the stringent standards however it was not possible to verify this assumption.

Based on the research statement, three research questions were developed:

1. What is the winter energy consumption performance of a SUPERHOME?
2. What is the operational winter indoor environment quality of a SUPERHOME?
3. How has the post-occupancy and winter performance of a SUPERHOME been from the perspective of occupants?

As SUPERHOMEs are designed and built to be more energy efficient and comfortable than homes built to the current building code, it is hypothesized that a SUPERHOME requires less energy for maintaining a thermally comfortable and healthy environment and fulfils the needs for comfort of occupants. A SUPERHOME is energy-efficient, thermally efficient, and comfortable to be in during winter conditions.

1.3 Significance of research

The purpose of this research is to provide an in-depth evaluation of post-occupancy performance of a residential building designed and built to SUPERHOME standard, specifically the environmental and social implications generated by the building. Three underlying questions shaped the focus of this research as pointed out in section 1.2.

Primarily, the findings presented in this research will be useful for the SUPERHOME Movement, as they will inform the operational – or in occupied conditions – performance of their exemplar home. While the SUPERHOME Movement assessors might have explored and made assumptions or estimates of performance of the building at the design and construction stage, evaluation on the operational reality of the building might have not been carried out.

The results of the monitoring and information gained can also be useful to a wide range of industry groups including designers, manufacturers, and regulators to provide information on the marketability and benefits of SUPERHOMES. They will be able to gain conclusions of what may be achievable when sustainability is incorporated in the design and construction of residential properties.

Last but not least, the owner and occupants of the property participating in this study, will benefit from the outcomes of the monitoring since they might be informed of issues or flaws, if any, that exist in the building as well as recommendations on how to mitigate.

1.4 ‘Green’ houses

The incorporation of sustainability into building industry practices develops in response to the growing awareness in the building sector being largely responsible for the world energy consumption and greenhouse gas (GHG) emissions. The building industry is regarded as one of the biggest – if not the biggest – contributor to climate change (Allouhi *et al.*, 2015; Bound & Flemmer, 2014; Dahl, 2008; Deuble, 2012; IEA, 2016; Metz, Davidson, Bosch, Dave & Meyer, 2007; Urge-Vorsatz, Koepfel & Mirasgedis, 2007; Zuo & Zhao, 2014). As had been reported in a number of studies, buildings consume 30-40 per cent of energy produced worldwide and are responsible for at least a third of global greenhouse gas emissions, two-fifth of total global CO₂ emissions, and two-fifth of solid landfill waste (Allouhi *et al.*, 2015; Arnel, 2010; IPCC, 2014; Pellegrino *et al.*, 2016; Razali, Kamarudin, Zainuddin & Othman, 2015, p. 134; Shaikh, Nor, Nallagownden, Elamvazuthi & Ibrahim, 2014; Watson, 2015; WBCSD, 2007). The CO₂ emission of buildings is predicted to reach 42.4 billion metric tonnes in 2035 – a 43 per cent increase from what the rate was in 2007, due to growth in global population (Dixit, Fernandez-Solis, Lavy & Culp, 2010; EIA, 2010, as cited in Zuo &

Zhao, 2014). In regards to this, the mitigation of the environmental impacts of buildings is a major concern (Franzoni, 2011).

The literature on climate change puts forward the belief that there is a great deal of potential for the reduction of GHG emissions to take place in the property sector (Amitrano et al., 2014; Bond, 2010; de Paola, Ortolani, Re, Anastasi & Das, 2014; Deutsche Bank Research, 2010; Eichholtz et al., 2013; Enkvist, Naucler & Rosander, 2007; Gou, Lau & Chen, 2012; Jimoh, 2011; Klein, Drucker & Vizzier, 2009; Stern, 2008; UNEP, 2010; Watson, 2015). The level of sustainability of buildings has large influence on GHG emissions and on energy efficiency in the economy (Thomas, 2010). Thus, small improvements to the ‘sustainability’ of buildings can greatly reduce reliance on GHG emitting energy sources, and certainly cut emissions (Eichholtz et al., 2013). There is, ultimately, a growing market pressure on the property industry to respond to these concerns by implementing sustainable principles, policies and practices (CBRE, 2009). A ‘green’ building is designed to reduce the overall impact of buildings/or building materials on the environment (Reed & Wilkinson, 2007).

‘Green’ houses are houses that are designed and constructed to be environmentally friendly and efficient in its use of energy, water and materials. There is no universal agreement upon what constitutes a ‘green’ home. In this section, key concepts drawn from the literature relating to the definitions and benefits of ‘green’ homes are reviewed to serve as background information for this study.

1.4.1 Definitions of ‘house’

The term house refers to a “building for human habitation, especially one that consists of a ground floor and one or more upper storeys” (Oxford University Press, 2017). Under the New Zealand Building Code (NZBC), house is a residential building and can be classified into three categories: detached dwelling, multi-unit dwelling and group dwelling (MBIE, 2014). As used throughout this thesis the term ‘house’ is interchangeable with the terms ‘home’, ‘dwelling’ and ‘residential building’.

1.4.2 Definitions of ‘green’ building

The concept of a 'green building' was developed in the 1970s – during the aftermath of the energy crisis – in response to the need to develop energy efficient and sustainable buildings (Haapio & Viitaniemi, 2008; Howell, 2005, all as cited in Yu & Kim, 2011). Since then, there have been extensive definitions of the term 'green' building. Understanding of the term 'green' building diverges depending on the context in which it is discussed. According to Paetz (2008), although the principles of the term 'green' building are the same, the view of the term can differ and be very flexible. For example, the term 'green' may be associated by some with less energy use while may also be associated by others with the use of sustainably-sourced materials. Paetz (2008) defines 'green' buildings in broad terms as “any building that has significantly lower negative impacts than traditional buildings” (p. 78).

For some, buildings are deemed 'green' when environmentally sustainable measures are incorporated during the design and construction phases. A 'green' building, used interchangeably with the term 'energy-efficient building', is defined by Berardi (2013) as “a healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community” (p. 76). Similarly, Kibert (2016) acknowledges 'green' building as: “... healthy facilities designed and built in a resource-efficient manner, using ecologically based principles” (p. 9).

Others view the ideal 'green' building as a building in which the incorporation of sustainable measures does not end at the design and construction stages, but extends to operations. The US Environment Protection Agency (EPA, 2016) refer 'green' building to as “the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle from siting the design, construction, operation, maintenance, renovation and deconstruction” (§ 1). Moreover, as suggested by Deuble & de Dear (2012), a 'green' building is one that reduces “their environmental impact by using less energy in its whole life cycle, including construction and operation” (p. 21).

Some associate 'green' with design intelligence. According to the Intelligent Building Group (IBG), the concept and goals of a 'green' building correspond to those of an 'intelligent' building, defined as a building that “provides a sustainable, responsive, effective and supportive environment within which individuals and

organizations can achieve their objectives” (ibgroup, 2007, as cited in Cole & Brown, 2009). Cole & Brown (2009) are also of the same opinion. They argue that green building “is not simply about attaining higher environmental performance standards or investing in new values; it is also about rethinking design intelligence, and how it is placed in buildings” (p. 41).

As attention to – therefore demand for – ‘green’ buildings grows, the focus of ‘green’ buildings should not just be about having smaller impact on the environment but also to create a comfortable and healthy environment for its users. Weiss, Williams & Heerwagen (2004) pointed out that the successful delivery of ‘green’ buildings requires a balance between the optimization of energy and resource efficiency – as reflected in mainstream green building rating system –, and the provision of comfortable, healthy but productive environment. This concept of ‘green’ buildings is supported by Bound & Flemmer (2014) who also recognize the importance to make sure that the efficient use of energy and resources in ‘green’ buildings “does not come at the expense of the occupants’ experience” (p. 2). In other words, generally buildings that are designed and built to be ‘green’ should aim to minimize effect on the environment throughout its life cycle while providing a healthy and effective environment. A ‘green’ building should minimize consumption without compromising on comfort.

There are numerous other definitions which highlight the characteristics and functions of ‘green’ buildings. Yu & Kim (2011, p. 5-6) came up with a list of characteristics typically found in ‘green’ buildings. A ‘green’ building should have some of the following characteristics in regards to land use, site locations, materials used, energy efficiency, water efficiency, surface water management, pollution, and health and wellbeing of occupants:

- Effective use of existing landscapes
- Site use, community development and transport requirement
- Use of energy efficient and eco-friendly equipment
- Used of recycled and environmentally friendly building materials
- Indoor air quality for human safety and comfort
- Efficient use of water
- Use of non-toxic and recycled materials

- Use of renewable energy
- Effective controls and building management system
- Effect on bio-diversity of the present ecosystem

Robichaud & Anantatmula (2010, as cited in Zuo & Zhao, 2014, p. 272) acknowledged that there are four fundamental pillars of ‘green’ buildings. These include minimization of environmental impacts; improvement on the health of occupants; the return on investment to developers and local community; and, the life cycle consideration during the planning and development process.

Fullbrook, Jackson & Finlay (2005), in a report presented for the New Zealand Ministry for the Environment, describe ‘green’ buildings as having the following characteristics (p. 1):

- radically reduced energy consumption;
- improved resource efficiency;
- reduced environmental impacts;
- improved indoor environment;
- lower impact on local infrastructure; and,
- being easier to manage.

Van Uden (2008) lists typical features of ‘green’ buildings including, but not limited to, generous eaves, green roofs, double-glazing, solar hot water panels, locally sourced materials, renewable building materials, permeable paving to minimize impermeable areas, water tanks, onsite wastewater treatment and dispersal, greywater collection, photovoltaic panels for electricity generation, use of natural or low-VOC paints, and insulation.

The numerous and differing examples of definitions mentioned above, indicate extensive variances of perspective amongst industry professionals on what constitutes a ‘green’ building. This lack of clear and universal definition of ‘green’ building, as argued by Onyeizu (2014), can leave the term ‘green building’ exposed to “interpretation or even misinterpretation” (p. 4), which in turn presents itself challenges when promoting and implementing ‘green’ building practices (Zuo & Zhao, 2014).

It is important to note that the terms ‘energy-efficient’ building, ‘green’ building and ‘sustainable’ building, although often used interchangeably, differ in meanings. As Pan & Ning (2015) suggest, the term sustainable building tends to be more holistic in scope as it embodies aspect of, not only, environmental sustainability but also, social and economic sustainability. The term ‘green’ building, on the other hand place focus only on environmental issues. Energy-efficient buildings consider only one element of green building – i.e. energy.

So ‘what makes a home green?’. Paetz (2008) and Yudelson (2008) acknowledge how ‘green’ buildings, in some countries, are defined in more precise terms through rating systems. In New Zealand, the rating system most-commonly in use for residential buildings is the NZGBC’s HomestarTM. HomestarTM rates dwellings on a scale of 1-10. A Star rating of 6 represents a level of practice that well-exceeds minimum requirements of the building code (NZGBC, 2014). A typical 6-Star home is significantly warmer, drier, more energy efficient, and environmentally friendly than a home constructed to Building Code standards. Based on the understanding of ‘green’ by Paetz (2008) and Yudelson (2008), a ‘green’ home in New Zealand is a residential building that would achieve a minimum of 6 Star rating under the HomestarTM Built Rating. This thesis aimed to challenge this definition of ‘green’, by hypothesizing that non-HomestarTM-rated homes – like SUPERHOMES – can also be regarded as ‘green’ homes.

1.4.3 Benefits of ‘green’ houses

The residential property sector has been witnessing increased importance of sustainability in recent years. ‘Green’ homes are well known for its associated tangible and intangible benefits – including environmental, economic and social benefits (Tan, 2014) (see Table I-1). Tan (2014) claimed that the primary driver for implementing environmentally sustainable practices into the design of buildings – including houses – is the reduction in energy consumption and hence the subsequent reduction in the use of fossil fuel to produce that energy. Other significant benefits of ‘green’ homes include lower operations and maintenance (O&M) costs, less building-related illnesses, as well as reductions in waste and pollution. The comfort – thus, health – of occupants is also expected to be better in ‘green’ homes (Colton et al., 2014; Roberts, 2003). In addition, evidence is emerging that houses with green

label or rating represent smart financial investments. A green rated dwelling translates into lifted capital value thus higher resale price (ADEWHA, 2008; Kok & Kahn, 2012). On the whole, ‘green’ homes present the opportunity to use resources wisely – hence address climate change –, cut operational and maintenance expenditure, increase investment value – thus have greater rental and selling rates –, while creating healthier environments for occupants to live in.

Table I-1: The Benefits of Green Homes.

Environmental	Social	Economic
Reduction in waste ending up in landfill	Improved health and comfort benefits for occupants	Potential for increased capital value and rental returns
Increased material re-use and recycling		Reduced operating and energy costs
Produce less to zero GHG emissions		Reduced sick leave from work, resulting in greater income
		Less hospital visits and reduction in medical expenses

Global climate change has become more evident over the last few decades. The existence of climate change is factual considering that global temperatures are increasing, patterns of rainfall are changing and extreme weather conditions are occurring more often. Buildings over their entire life cycle contribute largely to global GHG emissions and hence to the occurrence of climate change (Deutsche Bank Research, 2010); therefore, the housing industry has an effective role to play in tackling climate change (Lovell, 2004; Seelig, 2011). ‘Green’ homes are designed to consume less energy and water – thus generate less GHGs –, and use materials efficiently – thus have lower outputs of waste.

Although the cost of developing a ‘green’ building may be more than that of a conventional building, there is mounting evidence that implementing sustainability approaches into the design and construction of buildings will benefit owners through greater financial savings and gains. The financial advantages associated with ‘green’ buildings are believed as motivating drivers to the green building movement (Tan 2014). Compared with conventional homes, houses with environmental certification command higher rental and selling rates, hence greater capital values. For example, a study by the Department of the Environment, Water, Heritage and the Arts of

Australia showed that each half-star increase in the energy-efficiency rating of houses added up a 2% increase in capital value (ADEWHA, 2008). Furthermore, Kok & Kahn (2012), in their study, examined the economic impact of 'green' rating on the sales price of a home, and discovered buildings with 'green' rating delivering a 9% green premium in value. A similar finding was reported in the Griffin, Kaufman & Hamilton's (2009) study in which a premium of 9.6% is added to the average sales of certified homes in the Seattle metro area. Other economic performance potential of 'green' homes include tangible improvements in occupants' health (NZBCSD, 2008). Improved occupant health means reduced building-related illnesses, which ultimately results in less spending on medical and healthcare services. A study carried out by the NZBCSD, came up with estimates of the significance of building 'green' homes in New Zealand. The study found out that warmer, drier and more energy- and water-efficient homes could help the country avoid up to 50 people per day getting sent to hospital with respiratory conditions – saving at least \$54 million in hospital admissions a year. Healthier homes also means fewer days off work, recovering the number of days people do not turn up to work due to sick leave, thus improving productivity, which equates to at least \$17 million of extra income a year.

Besides the above-mentioned financial benefits of 'green' homes, there are other corresponding benefits including utility cost savings for energy and water, and maintenance cost reductions. Studies have revealed cost savings in utility bills as the most appealing benefit of owning 'green' homes (Ling & Gunawansa, 2011; Raisebeck & Wardlaw, 2009; Tan, 2014). As 'green' homes command less consumption of energy, there is potential for savings through reduced operations and maintenance (O&M) costs. According to Goering (2009), the energy saving potential from typical 'green' certified buildings, in most cases, will be in the range of 20-35 per cent annually compared to energy use from comparable average buildings. Similarly, Watson (2009) reports that there can be as much as 25 per cent of potential savings in energy consumption in 'green' buildings than in similar regular buildings. eCubed, a New Zealand-based sustainable buildings consultancy firm, carried out a cost benefit analysis of HomestarTM rated buildings of 5, 6 and 7 ratings. Their study found that over a period of seven years, annual savings on O&M expenditures of as much as \$948 can be made from complying with HomestarTM standard of 6 Star and

\$1429 from complying with 7 Star standard (eCubed Building Workshop Ltd, 2013). The savings made during the operation and maintenance stages of a building life cycle will ultimately help offset the initial costs required for adopting sustainable features during the design and construction stages (eCubed Building Workshop Ltd, 2013; Tan, 2014; Zuo & Zhao, 2014).

Based on the afore-mentioned advantages it can be concluded that ‘green’ homes simply mean homes designed and constructed to save energy and resources, that enhance the well-being of the occupants and that support the stewardships of the natural environment.

1.4.4 The New Zealand context

In response to the growing pressure on the property industry to respond to climate change issue, New Zealand is dedicated to driving its economy towards sustainability and to start implementing sustainable principles in their industry practices (MFE, 2007). ‘Green’ building, in particular, is a growing trend in the country. New Zealand is believed to hold “an excellent position to become leaders in sustainable building” (Fullbrook et al., 2005, p. 2). The market for ‘green’ buildings in New Zealand, according to NZGBC (2015b), is currently ‘buoyant’ and has ‘strong’ industry support. Furthermore, public’s interest and knowledge in ‘green’ homes are developing. News and information that are green homes related, are being brought up in the media more often (Aliento, 2017; Cairns, 2014; Dungey, 2015; Shannon, 2015).

HomestarTM has been the sustainability standard for home design and construction in New Zealand. In the following, a short overview of HomestarTM is presented followed by an overview of the SUPERHOME movement – a nationwide campaign towards green, high-performing and energy-efficient housing.

1.4.4.1 HomestarTM

HomestarTM is a rating system that is specifically designed to assess the level of sustainability of residential buildings in New Zealand. Developed by the NZGBC in collaboration with Building Research Association of New Zealand (BRANZ), Beacon Pathway, and various industry experts, the HomestarTM rating tool was

launched in 2010 after extensive industry consultation. It was developed based on various successful international rating tools and has been adapted for New Zealand's specific conditions (NZGBC, 2017a). The development of the Homestar™ rating tool was initiated in early 2009, in response to the emerging need for making New Zealand's residential sector more sustainable. The findings of NZBCSD's study – mentioned in section 1.4.3 –, in this instance, led to an industry-wide support for the development of an industry-developed residential rating tool that would help homeowners understand their home's performance and make informed decisions which then led to the launching of Homestar™ (Homestar, n.d.; NZGBC, 2015c). There have been several revisions of Homestar™ since 2010. Version 4 was launched in mid 2017 (NZGBC, 2017b).

To date, NZGBC is the authorized institution to grant Homestar™ certifications in New Zealand (NZGBC, 2017a, 2017b). Besides Homestar™, other BRSs initiated by NZGBC are Green Star and NABERSNZ – for commercial buildings. The NZGBC was established in July 2005 and since then has been actively involved in the development of sustainable buildings in New Zealand. The organization's work programme addresses both residential and commercial buildings (NZGBC, 2015d).

The Homestar™ rating tool rates a building on a scale of 1-10 Stars. A rating of 1 Star would mean the house has very insufficient or no insulation, would be highly susceptible to draughts and condition-wise is damp, mouldy and unhealthy; therefore, major improvements are necessary. Houses with a rating of 10 Star would have extra insulation to what is required in the Building Code, well-sealed doors and windows, renewable energy generator – such as photovoltaic solar panels – on site and have been completely self-sufficient with water; therefore, they represent international best practice (Kirpensteijn, 2017). Most existing New Zealand houses achieve a 1 to 5 Homestar™ rating and even a new house based on the NZBC standard would be expected to achieve only 3 to 4 Stars (NZGBC, 2017a).

The Homestar™ Built rating tools work by evaluating environmental attributes – not operations – of a building based on the building performance in terms of its,

(1) energy, health and comfort; (2) water; (3) waste; (4) home management; (5) materials; and (6) site (NZGBC, 2017a, 2017b).

Under the ‘energy, health and comfort’ category, the Homestar™ targets satisfying conditions in the dwelling attributes that contribute to reduction in energy use and to a good thermal comfort and essentially the well-being and the health of the occupants. Under this category emphasis is placed on the heating, ventilation and air conditioning (HVAC) system, lighting, indoor air pollution and other indoor environmental features that directly and indirectly affect energy usage and occupants’ comfort towards the indoor environment (NZGBC, 2017a).

Credits under the ‘water’ category are obtained based on the manner in which water consumption in the building is minimized. Through the ‘water’ category of the Homestar™ rating tool, the NZGBC encourages initiatives to reduce potable water usage by prescribing efficient design of building systems, rainwater collection and water reuse and also through the installation of attributes such as low water flow taps and toilets (NZGBC, 2017a).

Waste is an important category to address under the Homestar™ certification scheme. The ‘waste’ category targets efforts that are aimed towards reducing the amount of natural resources used, and optimize the reuse and recycling of materials, thus minimizing the amount of used materials that go into landfills (NZGBC, 2017a).

In the ‘home management’ category, attention is directed towards attributes that contribute to maintenance and management of safety, security and adaptability of the dwelling. Examples of such attributes include a home user guide (HUG), smoke alarms, motion-censored outdoor security lighting, fire extinguisher, and secure locks. This category also covers the manner in which construction actions, if taking place, are carried out, managed and supervised to minimize pollution and maximise protection of the environment (NZGBC, 2017a).

‘Materials’ is a category in which the NZGBC specifically encourages the use of sustainably-sourced products and materials that have lower impacts on the environment and the health of occupants and the reduction in use of harmful by-

products that contribute to the carbon footprint of the building’s occupants and ultimately to global warming (NZGBC, 2017a).

The ‘site’ category specifically rewards a dwelling based on where it is located and how spaces around the outside of the dwelling is utilized and contribute to local ecology (NZGBC, 2017a).

The ‘innovation’ category is included in the Homestar™ rating scheme as a means of encouraging, acknowledging and rewarding the application of innovative technologies, designs, processes, and strategies that impact upon environmental performance. In this category, the NZGBC targets projects that demonstrate application of sustainable development principles in a broader scope of designing and procuring a building. This looks beyond the building itself and may include initiatives or strategies that result in positive sustainability outcomes – environmentally, socially and economically (NZGBC, 2017a).

Under each of the categories, a certain amount of credits are available to be awarded (see Table I-2). Points scored in the Innovation category are not weighted, but are added to the overall score, resulting from the six main categories (NZGBC, 2017a). Based on the total points collected, the Homestar™ certification is then awarded according to the rating categories presented in Table I-3.

Table I-2: Weighted categories for Homestar™ Built v4 rating system (NZGBC, 2017b).

Environmental Category	Weightings
Energy, Health and Comfort	50%
Water	12%
Waste	5%
Home Management	5%
Materials	12%
Site	10%
Innovation	9%
Total Score Available	120 + 10

Table I-3: Homestar™ Star bands and required scores (NZGBC, 2017b).

Overall Points	Rating
60 – 69.9	6 Star
70 – 79.9	7 Star
80 – 89.9	8 Star
90 – 99.9	9 Star
100+	10 Star

The NZGBC does not believe in the idea of buildings having to renew their Homestar™ certification at periodic intervals. Once certification is achieved, unless refurbishment/redevelopment takes place, the certification lasts indefinitely.

A major barrier to obtaining the Homestar™ Built certification is perhaps the cost of obtaining the certification. The cost of getting a Homestar™ rating ranges from \$680 – \$1,180, for certification and assessment fees (Cutler-Welsh, 2014). Although the cost of obtaining certification may be relatively small compared to the overall project cost, investors are likely to perceive this to be an obstruction to the uptake of the rating. Moreover, since the rating tool is still relatively new to the housing market in New Zealand, having only been in existence for six years, and since there are no requirements for mandatory disclosure of an energy rating for the selling of residential property in New Zealand, the uptakes of the rating remain low (Kirpensteijn, 2017).

1.4.4.2 SUPERHOME Movement

The SUPERHOME movement (SHM) is a non-for-profit organization that aims to encourage the building of healthier, more energy efficient and environmentally sound homes, through open-source sharing of design, new technologies and construction information. The initiative was first launched in August 2015 in Christchurch at the cutting of the ribbon of the first SUPERHOME which was rated 10 Star under the Homestar™ Built rating (B. Burnett, personal communication, July 10, 2017). Launching of the movement continued in other parts of New Zealand; for example, Wellington and Auckland in late 2016, and Queenstown in May 2017. SUPERHOMES have been designed and built with affordability, design integrity, energy efficiency, earthquake resilience,

durability, thermal comfort and a healthy indoor environment as key considerations (Aliento, 2015).

1.5 Design features of study home

1.5.1 External Walls

External walls are a very important component in building insulation. The study home is enclosed in SIPs. The external walls are clad with vertical shiplap weatherboards installed over a 45mm drained cavity on 9mm H3 structural plywood clothed with FPS® EUROTOP N15, insulated with R.3.2 (140mm) stud frame walls at 600mm centres, fixed tightly to FPS® ACTIV V110 vapour controlling membrane and R1.2 (70mm) masonry wall strapping at 600m centres covered with a 10mm plasterboard lining. The insulation used is wool insulation. A vapour controlling membrane is installed to prevent moisture damage on the structure.

1.5.2 Windows and Doors

Glass is a very good thermal conductor. The building employs uPVC (Unplasticized Polyvinyl Chloride) windows with clear double-glazing and Low E (low emissivity), plus argon filled with thermex internal spacer. The windows in bathrooms are frosted. This should provide very good winter heat retention and protection against summer overheating and fading damage. uPVC windows and window frames are very good heat insulators which can dramatically reduce the possibility of condensation. Apart from minimizing internal heat loss through glazing, clear Low E coatings reduce the amount of ultraviolet and infrared light transmitting through glazing without reducing visible light. Ultraviolet light contributes to fading of interiors, whilst infrared light carries heat energy. Argon is the gas used between panes in a multiple-glazed window. Besides providing more thermal efficiency than air, the presence of Argon slightly improves noise insulation performance (NK Windows, 2016).

1.5.3 Roof

The roof is covered with Trimrib® profile longrun roofing over 70 x 45 at 600m centres H1.2 timber purlins on 20 x 45 at 900m centres H1.2 timber cross battens,

insulated with 90mm thick R4.09 PIR foam clothed with FPS® EUROTOP N35 over XLam cross-laminated timber (CLT) roof panels.

1.5.4 Flooring

The ground floor is a concrete slab construction with timber overlay, except carpet to bedrooms and tiles to bathroom. The slabs have embedded underfloor heating systems. The first floor is constructed with CLT panels manufactured by XLam. Bathrooms' floor construction uses the 19mm Scyon Secura® flooring supported at 400mm centres, pre-sealed with a water resistant coating.

1.6 The Climate of Christchurch

Christchurch, the third most populous urban area in New Zealand, is situated on the east coast of the South Island – at 43° 31' 32.3400" S, 172° 38' 23.4492" E. The climate of Christchurch is largely influenced by the presence of complex elevated topography surrounding the region including the Southern Alps to the west, as well as the Port Hills and Bank Peninsula to the southeast and due to close proximity to the Pacific Ocean to the east (McGann, 1983).

Christchurch has a dry, temperate climate. The area is warm in summers and cold in winters (see Figure 1.1). The summer months of December to February can be described as mild – i.e. mostly warm with very low humidity. The warmest month of the year is in January with mean daily maxima of 22.7°C and mean daily minima of 12.3°C. The highest temperatures in the Christchurch area are centred near the Cathedral Square area. Winters are quite cold with frequent frosts, particularly in July, with temperatures reaching 11.3°C generally during the day, with overnight lows of 1.9°C. Christchurch averages 70 days of ground frost per year, mostly occurring during the wettest months between June and July. Fogs are most common in winter and occur mostly around the rivers, near the ocean and in Hagley Park. September, or during the transition from winter to spring, is the driest period during the year.

The rainfall pattern at Christchurch is largely influenced by the presence of the Southern Alps and to a much lesser extent the Banks Peninsula for sheltering the Christchurch area. Rainfall is fairly evenly distributed throughout the year, with a modest tendency towards a winter maximum. Mean annual rainfall is relatively low compared with other

regions in New Zealand, with total annual precipitation varies between 600 to 700 mm. Christchurch’s sunshine hours are comparable to many other areas of the country. In average there are 2142.5 hours of bright sunshine per year. The monthly average sunhours for Christchurch over the 1981-2010 are shown in Figure 1.2.

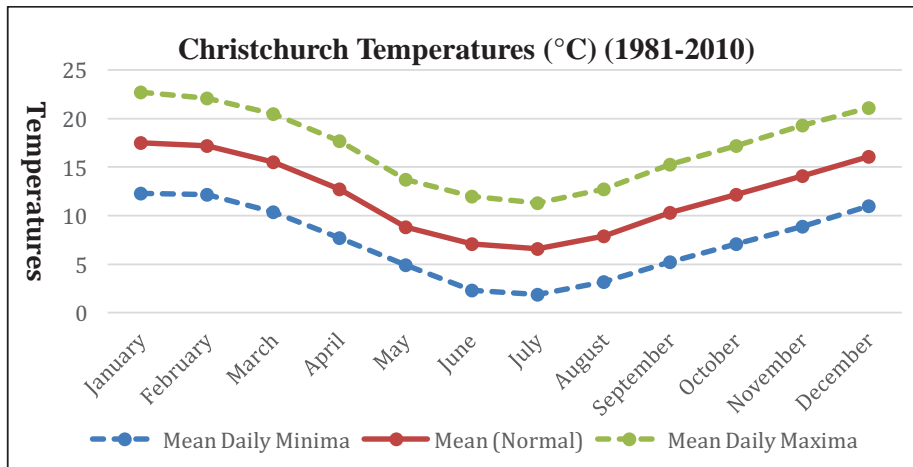


Figure 1.1: Christchurch’s average daily temperatures by month with average daily maxima and minima (NIWA, 2016).

Because of the relatively high frequency of dry, frosty conditions during winter, and due to light winds and sufficient sunlight – hence, clear skies –, which thus results in temperature inversions, Christchurch is susceptible to air pollution. The source of pollutants includes smoke from domestic fires, sulphur dioxide, ozone and oxides of carbon and nitrogen, and lead – from combustion of petrol in motor vehicles. Health Department measurements show that the concentrations of all pollutants reach their maximum in the evening and again to a much lesser extent in the morning – i.e. during traffic peak hour, times when people travel to and from work (McGann, 1983).

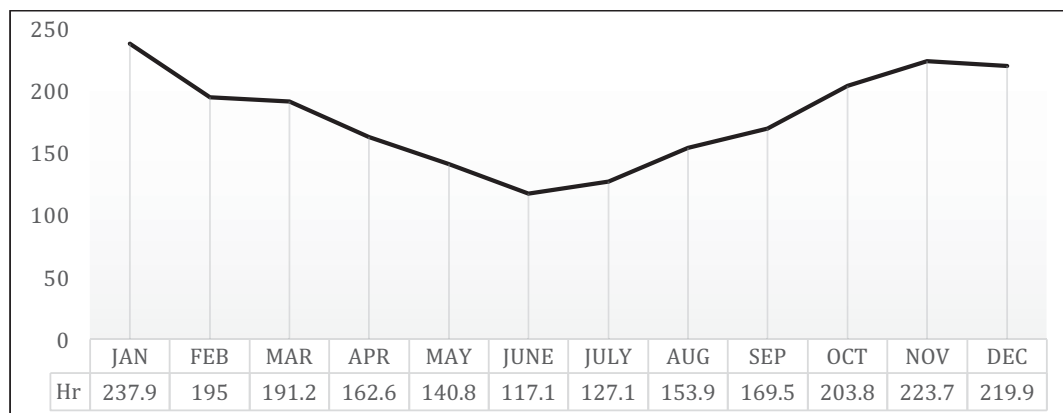


Figure 1.2: Christchurch’s Mean Monthly Total Sunshine Hours (NIWA, 2016).

1.7 Outline of Thesis

This thesis is divided into five chapters, consisting of an introductory chapter, a literature review chapter, a methodology chapter, a result-and-discussion chapter, and a concluding chapter. An overview of all the six chapters is presented below.

Chapter 1, is the introduction chapter, provides the background, rationale and the specific context in which this research project was undertaken, leading up to the research statement and the aim and objectives.

Chapter 2, reviews key concepts in the literature associated with indoor environment quality, the New Zealand housing stock, and POE. The literature review includes discussions on knowledge related to the different tools and techniques that can be used to monitor operational performance of residential buildings.

Chapter 3, describes the methodological approach chosen for the research and the procedures for conducting the study, case study selection, the monitoring parameters, ethical consideration issues, data collection and processing approach as well as the limitation and potential problems of the chosen research approach. The justification for choosing the methodological approach is also addressed.

Chapter 4, answers the Research Questions. This section looks further at demonstrating the post-occupancy performance and IEQ of the SUPERHOME that were monitored.

Chapter 5, is a discussion chapter. This section looks at the themes that emerged from the findings presented in chapter 4.

Chapter 6, highlights the key findings of the research, including the answers to the research questions. This section concludes the strengths as well as the limitations of the research. Recommendations for future research are proposed.

Chapter 2: Review of the Literature

2.1 Introduction

This chapter is a review of recent research on indoor environment quality (IEQ), New Zealand housing and post occupancy evaluation (POE). Relevant articles were partly accessed electronically from various databases and – for the most part – consisted of peer-reviewed journals, articles, books, reports, and Master’s and Doctoral dissertations. This review begins by exploring basic knowledge on IEQ. A review of literature concerning the importance of IEQ to home environment is presented. This literature review chapter continues by drawing on what past studies have indicated in regards to New Zealand housing and indoor environments. This is intended to provide an overview of the environmental conditions of New Zealand homes, specifically in regards to insulation, heating, and ventilation. The literature on the above-mentioned two subjects contributed as the basis to the analysis of results of the IEQ monitoring that were carried out in this research. A review of literature concerning the use of POE as a tool for assessing building performance is then presented. A part of this focuses on exploring the different tools and techniques that can be used to assess operational performance of residential buildings

The literature review continues with a couple of other questions in mind:

1. Based on previous research, how have green residential buildings performed during operations?
2. What factors cause gaps between design expectation and operational reality of residential buildings?

This chapter ends with a conclusion that summarizes the reviews covered.

2.2 Indoor environment quality

Besides energy efficiency, cost efficiency and environmental sustainability, ‘green’ building has also been associated with comfort. Comfort has always been and will remain a vital necessity that any building, in particular residential building, has to provide. Key to determining occupants’ level of comfort in a building is IEQ. IEQ, such as thermal, noise, light and indoor air quality, are continuously associated with

occupants' comfort and health (Al-Horr, Arif, Katafygiotou, Mazroei, Kaushik & Elsarrag, 2016; Sakellaris et al., 2016; Taptiklis & Phipps, 2017).

People spend a significant amount of time indoors. People spend more than 90 per cent of their time inside buildings – either at home, workplace, or in an educational facility (Frontczak & Wargocki, 2011; Koistinen et al., 2008). According to a study by Khajehzadeh & Vale (2016), New Zealanders, in particular, spend a total of 69.7% of time at home indoors. The quality of the indoor environment has therefore widely applicable effects on their comfort, health, and hence their overall well-being (Dykes, 2012; Frontczak & Wargocki, 2011; Shaikh, Nor, Nallagownden & Elamvazuthi, 2013; Taptiklis & Phipps, 2017).

This section draws on what past studies have found in regards to IEQ of home environments. The literature search was undertaken for articles presenting the results of studies that were performed in non-industrial buildings including homes, offices and schools. It is pertinent to reiterate the relative importance of IEQ components to overall satisfaction of the occupants towards a building and therefore their response to the satisfaction survey.

2.2.1 IEQ features

Comfort towards IEQ is largely affected by features of the indoor environment. One dominant comfort feature of IEQ is thermal comfort, defined as “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE, 2004a). Thermal comfort, according to Zuo & Zhao (2014), comprises of complex dynamics of air temperature and humidity. The thermal comfort of a building, as described in Standards ISO 7730, concern four IEQ variables including air temperature, mean radiant temperature, relative air velocity, and air humidity, and two human-factor variables including activity level and clothing (Dall, 2013; ISO 7730, 1993, as cited in Frontczak & Wargocki, 2011). The building features – insulation, heating, and ventilation – as well as the outdoor environmental conditions have an effect on these IEQ variables. Thermal comfort can only be reached if building occupants are undisturbed by thermal errors such as draught, too warm or too cold internal temperatures, too high radiant temperature asymmetry, or too high vertical air temperature difference (Frontczak & Wargocki, 2011). Occupants in

buildings that are thermally comfortable, will be satisfied with the four physical thermal variables mentioned above and will wish to feel neither cooler nor warmer conditions, when asked about thermal preference.

Another vital IEQ comfort parameter is indoor air quality (IAQ). Basically the term 'air quality' is used to convey the level of contamination of the clean air. IAQ reflects the physical, chemical and biological characteristic of the air in the indoor environment (Leardini & van Raamsdonk, 2010). The direct impacts that IAQ has on well-being of the building occupants are associated with poor IAQ, which include the symptoms of flu, asthma, sick building syndrome, allergies, respiratory infections, headaches, cancer and colds (Taptiklis & Phipps, 2017). According to the World Health Organization (WHO, 2017), 4.3 million people die from causes relating indoor air pollution each year. Indoor air contamination is a result of a combination of outdoor and indoor pollutants (Phipps & Warnes, 2007; Taptiklis & Phipps, 2017). Studies have found that indoor air is likely to have higher concentrations of pollutants than outdoor air and that exposure to outdoor air pollution is likely to occur indoors, where people spend most of their time (Swankin, 1989; Brown, 1997; Bennet et al., 2002; Smith, 1988; Lai et al., 2000, all as cited in Phipps & Warnes, 2007; Taptiklis & Phipps, 2017).

The acoustics of a building also plays a role in determining occupants' level of comfort. Navai & Veitch (2003) referred acoustic comfort to as "a state of contentment with acoustic conditions" (p. 2). Noise is one of the major concerns to achieving acoustic comfort. Noise control determines the quality of the acoustic environment shaped by properties of indoor environmental acoustics such as sound insulation, absorption and reverberation time (Cowan, 1994). Noise pollution can be generated outdoors – such as, by traffic and construction activities – and indoors – such as the HVAC systems. Research shows that excessive levels of noise can result in the loss of hearing, trigger mental stress and produce a variety of other health problems such as, irritation, fatigue, disturbed sleep, headache, etc. (Phipps & Warnes, 2007; Sanni-Anibire, Hassanain & Al-Hammad, 2016).

Another major comfort feature of IEQ is visual comfort, referred to as "a subjective condition of visual well-being induced by the visual environment" (BS EN 12665, 2011). Visual comfort are influenced by parameters such as luminance distribution,

illuminance and its uniformity, glare, colour of light, colour rendering, flicker rate and amount of daylight (BS EN 12464-1, 2011). Lighting – both artificial and natural – plays a crucial contribution to ensuring comfortable visual conditions in buildings which seem to contribute to the improvement of occupants' comfort (Sakellaris et al., 2016). Appropriate light levels are generally important in shaping how well occupants can see; similarly, increasing levels of natural light can also be mood-enhancing (Edwards & Torcellini, 2002, as cited in Sakellaris et al., 2016). Failure to provide adequate day lighting and artificial lighting provision levels can lead to visual discomfort. Exposure to natural light, however, takes place during daytime hours, when homes are likely to be left unoccupied (Cole, 2014; Portland State University, 2010). It is fair to assume therefore that the impact of day lighting on comfort in home environment is minimum. Measurement of daylight illuminance – i.e. the amount of exposure to daylight – is unsuitable for home monitoring.

2.2.2 Relationship between IEQ and occupants' health

The conditions of the indoor environment have been shown to have quite an effect on the health and comfort of occupants. Research across a range of disciplines has shown that the levels of satisfaction that occupants have with IEQ are strongly associated with overall comfort and perceived health. In majority, sources of dissatisfaction that occupants experience in most buildings have been associated with poor IEQ – e.g. dry, stuffy and still indoor climate, poor glare (visual disruption), too much artificial light/too little natural light, too noisy, smelly, etc. (Leaman & Bordass, 2007). Poor IEQ can trigger negative stress, which in turn can cause both physical and mental health problems – short- and long-term (Bluyssen, Aries & Dommelen, 2011).

The fact that IEQ has impacts on occupants' health has been proven in a number of studies. The IEQ of a building sets the climate of the indoor environment. There is good enough evidence to link poor IEQ and increased respiratory symptoms. Indoor air contaminants such as PAHs and nitrogen dioxide, produced from the burning of solid fuels, have been shown to associate with respiratory and cardiovascular symptoms (Taptiklis & Phipps, 2017). Also, a building's IEQ can have impacts on hormones. A study by Duffy & Wright (2005), about the effect of light on the production of melatonin, implies that poor lighting can cause sleep distortions, trends

of depression and loss of concentration which essentially lead to health problems. The conclusion is that healthier IEQ in buildings ultimately means improved health of occupants; therefore, providing a comfortable indoor climate is key to avoiding major health problems amongst building occupants.

The impacts the IEQ has on the health of the occupants could be demonstrated in commercial means, as it has a direct financial implication. Financial benefits would result from reduced hospital admissions and medical expenses, and for people in the work force, fewer days off work, thus more income. Each day 50 people get sent to hospital because of health problems caused by their homes. With one public hospital bed costing \$3000 a night, a total savings of \$54 millions can be made annually through healthier homes (NZBCSD, 2008).

2.2.3 Sources of indoor contaminants

The development of indoor contaminants can originate from within the building or be drawn in from outdoors. The concentration of contaminants within the indoor space increases where there is poor IAQ. Fundamentals to maintaining the air quality of the indoor environment are insulation, ventilation, and heating and air-conditioning of the building. Insulation keeps heat from entering into and escaping from the indoor space, and hence is what keeps a home a confined space. Ventilation allows air to come into and escape out of the indoor space, and hence is what keeps the indoor air fresh and clean. Space heating is the process of producing heat within an indoor space whilst air-conditioning removes heat. These three features all together are responsible for the production and removal of heat and moisture which are vital precursors to high levels of contaminants (McNeil, Plagmann, McDowall & Bassett, 2015; Phipps & Warnes, 2007; Taptiklis & Phipps, 2017). Insufficient dehumidification, for example, may results in high levels of dampness and humidity, enough to trigger certain indoor pollutants such as mould and dust mites to grow on interiors within the space (Seppänen & Kurnitski, 2009). The forms of heating and air-conditioning used can also affect IAQ. For example, the use of wood burners for heating can be a significant contributor to particulate contamination, while unflued gas heating increases the amount of gases – i.e. carbon monoxide, nitrogen dioxide – and chemical contaminants given off through floors and ceilings (Phipps & Warnes, 2007; Taptiklis & Phipps, 2017).

Besides indoor climate, building materials, finishes and furnishing used within the space also give off contaminants. For example, building furnishings, appliances and equipment that contain toxic substances – and, if maintained poorly – are often large sources of contaminants such as volatile organic compounds (VOCs), odours and mould spores (Clausen, 2004; Jones Lang Lasalle, 2011; Taptiklus & Phipps, 2017). Moreover, high concentrations of toxic particles are emitted by household cleaning products when in use. The intensive use of cleaning products contributes significant amounts of VOCs to indoor environment (Bari et al., 2015; Kwon, Jo, Lim & Jeong, 2008; Moran et al., 2012; Steinemann et al., 2011; Taptiklis & Phipps, 2017).

Occupants themselves are also sources of pollutants of the space. They give off contaminants such as, heat, CO₂, moisture, bio-effluents, viruses, etc. (Dykes 2012; French et al., 2007; Hathway, Noakes, Sleigh & Fletcher, 2011; Olmedo, Nielsen, Adana, Jensen & Grzelecki, 2012; Taptiklis & Phipps, 2017), which affect IAQ. For example, cooking, showering and breathing all produce moisture, which without adequate ventilation would create conditions likely for the proliferation of moulds and bacteria. As occupants move around indoors, these pollutants are continuously dispersed throughout the building (Choi & Edwards, 2012; Spitzer, Marr & Glauser, 2010; Wang & Chow, 2011). Pollutants are also distributed through events of inter-occupant contact, such as cough and sneeze (Redrow, Mao, Celik, Posada & Feng, 2011). Self-evidently, the building systems need to be catering for the right amount of people as overcrowding will not only increase the need for fresh air (Dykes, 2012), but also increases the intensity of these pollutant sources (Firdaus & Ahmad, 2012; Taptiklis & Phipps, 2017).

The building's outdoor environment may as well be partly responsible for indoor pollution. Pollutants produced in the outdoor environment – e.g. vehicle emissions – are brought indoors through ventilation (Hodas et al., 2012; Sangiorgi et al., 2013; Shi & Zhao, 2014). Factors that determine concentration levels of pollutants coming into the indoor space from the outdoors include the proximity of the building to the outdoor sources (Amato et al., 2011) and the timing in which the episodes of air exchange take place (Haas et al., 2013; Menut, Goussebaile, Bessagnet, Khvorostiyarov & Ung, 2012). Buildings located near – i.e. specifically within 700 metres of a – busy traffic are more likely to receive traffic related contaminants and even more on rush hours (Coulson, 2015, as cited in Taptiklis & Phipps, 2017).

Table II-1 summarizes common pollutants found in homes and their respective sources as well as the potential health risks associated with them. The extent of the health drawbacks depends upon many factors, including the type and amount of pollutants, the level of exposure and the length of time of exposure to them.

Table II-1: Indoor air Pollutants, sources and health impacts (Leung, 2015; Phipps & Warnes, 2007; Taptiklis & Phipps, 2017).

Pollutant	Sources	Potential Health Drawbacks
Carbon Monoxide (CO) - <i>colourless, odourless gas produced in incomplete combustion of carbon fuels indoors and outdoors</i>	<ul style="list-style-type: none"> • Heating Equipment (Unflued-gas heating) • Motor Vehicle Exhaust • Tobacco smoking • Open fireplaces/wood-burners; Coal burning 	<ul style="list-style-type: none"> • Headache; Fatigue; Nausea; Mental confusion • Heart attack • Flu-like symptoms • Very high levels can cause death
Nitrogen Dioxide (NO ₂) - <i>pungent gas formed indoors and outdoors</i>	<ul style="list-style-type: none"> • Cookers 	<ul style="list-style-type: none"> • Impairment of respiratory tract and lungs • Wheezing; coughing; colds; flu; and, bronchitis. • Increased asthma exacerbations
Sulphur Dioxide (SO ₂) - <i>gas formed and primarily present indoors</i>		<ul style="list-style-type: none"> • Irritation of eyes, nose and respiratory • Increased blood viscosity; Heart disease.
Ozone - <i>a secondary pollutant formed in the presence of sunlight with precursor pollutants such as VOCs or oxides of nitrogen</i>	<ul style="list-style-type: none"> • Traffic emissions • Air cleaners (ionisers) 	<ul style="list-style-type: none"> • Asthma • Eczema
VOCs - <i>airborne chemicals predominantly produced by household products and by indoor activities and processes.</i>	<ul style="list-style-type: none"> • Household cleaning products • Personal care products and fragrances • Tobacco smoking • Paints • Traffic emissions 	<ul style="list-style-type: none"> • Asthma • Cancer • Eye, nose, throat irritation • Damage to liver, kidneys, and brain
Formaldehyde - <i>colourless but pungent gas released into air</i>	<ul style="list-style-type: none"> • Tobacco smoking • Personal care products • Pressed wood products (plywood, chipboard and medium-density fibreboard) • Urethane coatings and building foams (fillers) • Carpet, furniture • Unflued gas heaters or cookers 	<ul style="list-style-type: none"> • Cancer a possibility • Allergic reactions • Nausea, dizziness • Headaches • Eye, skin, nose and throat irritation • Respiratory impairment

Benzene - <i>a component of petrol</i>	<ul style="list-style-type: none"> • Tobacco smoking • Unflued gas heating • Building materials (paints, adhesives and cleaning products) • Traffic emissions 	<ul style="list-style-type: none"> • Childhood leukaemia • Cancer
Respirable Particulates - <i>Particulate matters small enough to inhale released from wood smoke, cigarette smoking mould spores, etc.</i>	<ul style="list-style-type: none"> • Traffic emissions • Tobacco smoking • Vacuum cleaning and house dust • Wood burners • Soap powders, pollen, cooking sprays 	<ul style="list-style-type: none"> • Eye, nose, through and lung irritation • Respiratory infections and bronchitis • Lung cancer, heart attacks, strokes
Lead - <i>Natural element once used as a component in petrol and building paint</i>	<ul style="list-style-type: none"> • Lead-based paints • Outdoor soils 	<ul style="list-style-type: none"> • Damage to brain, heart and kidneys. • Stomach pains, sleeping difficulties, constipation • Anaemia
Environmental Tobacco Smoke - <i>Secondhand smoke</i>	<ul style="list-style-type: none"> • Cigarettes, Cigar, Pipes 	<ul style="list-style-type: none"> • Respiratory irritation (wheezing, coughing) • Bronchitis and pneumonia • Increased risk of lung cancer • Eye, nose and throat irritation
Biological Contaminants - <i>Fungi, Bacteria and Viruses, Dust mites, Invertebrates and Rodents</i>	<ul style="list-style-type: none"> • Poor ventilation, insulation, heating, air-conditioning, humidifier, dehumidifier • High levels of moisture and humidity • Carpets and home furnishings • People and animals • Bedding 	<ul style="list-style-type: none"> • Allergic reactions • Infectious diseases (influenza, measles, tuberculosis, chicken pox) • Headaches

2.2.4 Winter IEQ

This section reviews existing findings of IEQ in New Zealand houses in the winter. The literature search on winter IEQ was limited to temperatures, relative humidity (RH) and CO₂ concentrations. The findings reviewed were analysed and compared against international standards. All New Zealand monitoring studies to date indicated that average New Zealand homes are cold, susceptible to high humidity levels and exposed to high to very high concentrations of carbon dioxide during winter months.

2.2.4.1 Temperatures

Indoor temperatures are typically affected by the ambient weather variations throughout the year (Lloyd & Callau, 2006). In New Zealand, winter temperatures are reached during the period of June through to the end of August (French et al., 2007; Lloyd & Callau, 2006). The indoors of a typical New Zealand house is warmest in the evening due to elevated use of heating. During this time of the day, internal heat gains are high because of increased presence of occupants and their interactions with the building (French, Camilleri, Isaacs & Pollard, 2006). Living rooms' temperatures on average always seem to be higher than the bedrooms' – of as much as 2.8°C. This is most likely because heating is common in living rooms and typically very little – or not available – in the bedrooms (Isaacs et al., 2010). A major study was conducted by BRANZ, entitled as the Household Energy End-use Project (HEEP), involving indoor temperature monitoring of 397 sample houses nationwide over the course of 10 years. Through HEEP, it was found that New Zealand houses had lower winter temperatures than those expected in other temperate climates, with a mean living room evening temperature of 17.9°C. Results released indicated a mean winter living room evening temperature of 16.1°C for Christchurch, in particular (Isaacs et al., 2010).

Monitoring results from HEEP indicated that average New Zealand homes were not warm enough in winter. As recommended by the WHO, a minimum indoor air temperature of 18°C and a minimum of 20°C – for houses occupied by vulnerable populations, e.g., young children, elderly people or ill people – should be maintained (Jiang, Grey, Poortinga & Tweed, 2015; Rudge, 2011; WHO, 1987). According to the WHO (1987), there is no demonstrable health risk to living in indoor spaces with air temperature range from 18°C to 24°C.

The health risks associated with living in cold conditions should not be taken lightly. Low indoor temperatures have been shown to be a contributing factor to poor respiratory, circulatory and mental health, as well as excess winter deaths – i.e. rates of mortality occurring in the winter months (Howden-Chapman et al., 2007). Indoor temperatures lower than 16°C appear to increase the risk of respiratory infections and below 12°C place stress on the cardiovascular system (Marmot Review Team, 2011; Rudge, 2011).

2.2.4.2 Relative humidity

Relative humidity, expressed as a percentage, is a measure of the amount of water vapour contained in the air at a given temperature relative to the maximum amount of moisture the air could contain at the same temperature. A humidity level of 100% means that the air has fully absorbed and cannot hold any more water vapour. RH varies with temperature; in other words, a rise of indoor temperature will generally result in the reduction of RH (Byber et al., 2016; French et al., 2007; Lloyd & Callau, 2006; Wang, Rao, Wu, Zhao & Chen, 2015).

Moisture is formed as a result of either internal condensation or external dampness penetrating into the house. Moisture can be generated internally from everyday activities such as cooking, clothes washing and drying, showers and baths, heating and cooling, and breathing. Moisture can also enter a house through rain falling on a leaky roof, and penetrating around window and door frames, leaking of water through cracked pipes, spilling from a blocked gutter, or waste overflows (Seppänen & Kurnitski, 2009; EPA, 2013).

Condensation occurring on inside surfaces is a common wintertime occurrence. Condensation forms on any surface when the temperature of that surface is below the dew-point temperature. Window construction often has the highest susceptibility in a thermal sense and hence is the component of the building enclosure with the lowest inside surface temperature. Repeated wettings typically result in mould infestation and subsequent occupant exposure to mould. Condensation on window surfaces can occur on the glazing and the frame. To be resistant to the formation of condensation, it is important that each component of the window is thermally efficient (Godish, 2010; Phipps & Warnes, 2007). The thermal performance of each must be separately considered. Condensation on window surfaces can be reduced with double-glazing, low emissivity glass and thermal window fabrics – such as PVC-U window frames (NZBCSD, 2008)

RH affects the air quality of the indoor environment and hence is an important performance parameter to measure. Very few studies of RH however have been carried out in New Zealand houses. To date, there is no monitoring study of RH

on a nationally representative sampling of New Zealand homes. A post-occupancy monitoring study was done on a NOW Home® in Waitakere. Learning from the second year of occupancy indicated that winter RHs were lower than during summer with a living room value averaging at 51.3% (Pollard et al., 2008). The same monitoring was done on a NOW Home® in Rotorua and the results showed an average winter RH value of 60% for the living room (Pollard & Jaques, 2009). A slightly similar result was found for a monitoring study done over houses located in the southern part of the New Zealand's South Island. Occupants were found to be exposed to living room relative humidity of approximately 57% over winter (Lloyd & Callau, 2006). The humidity levels in these homes had not met the WHO's recommended standard of humidity (WHO, 1987).

The WHO recommends a humidity level between 30% and 50% for indoor temperatures between 18°C and 24°C (WHO, 1990; WHO, 1987). Failure to maintain humidity levels within this range can impose health hazards to occupants. 50% and greater RH can start and proliferate the growth of mould especially where ventilation is insufficient (Fisk, Lei-Gomez & Mendell, 2007; Phipps & Warnes, 2007; Seppänen & Kurnitski, 2009; WHO, 1990). Mould growth appears to be associated with respiratory infections, reduced lung function and potentially chronic diseases like asthma exacerbation (Taptiklis & Phipps, 2017; Mendell et al., 2009; WHO, 1990). Exposure to low level of humidity at home – i.e. below 30% - may induce dryness and irritation symptoms of the eyes, throat and skin (Byber et al., 2016).

2.2.4.3 CO₂ levels

There is a lack of monitoring of CO₂ levels in New Zealand houses. All studies to date found that CO₂ levels are relatively higher in New Zealand homes during winter than in summer. The second-year monitoring study of the Waitakere NOW Home® found out an average concentration of CO₂ of around 492 parts per million (ppm) during winter, compared to 438 ppm during summer (Pollard et al., 2008).

Indoors, CO₂ is a byproduct of combustion products including unflued space heating, unvented gas cooking and smoking. Occupants are also responsible for the generation of CO₂ indoors through breathing (Boulic, 2012). Typically, CO₂ is a key indicator of IAQ since the level of CO₂ indoors corresponds directly to level of occupancy within the space – thus, breathing rate – as well as the amount of human-generated odours based on occupants' activity level in the building (Hesaraki, Myhren & Holmberg, 2015; Mumovic et al., 2009). In addition, the concentration of CO₂ is frequently used an indicator of airtightness. Through CO₂ measurements, a lot can be learned about the effectiveness of the ventilation system (Mumovic et al., 2009; Taptiklis & Phipps, 2017).

The WHO has not released a guideline relating to indoor CO₂ concentrations (Boulic, 2012). It is worth mentioning that CO₂ at levels commonly encountered indoors has not been shown to be harmful to human health. CO₂ is considered harmful at concentrations above 5000 ppm, which seldom is the case in residential buildings (Hesaraki et al., 2015). However, CO₂ can be considered as a surrogate indicator of ventilation efficiency. To assure a sufficient ventilation rate, the concentrations of CO₂ within the indoor space should not exceed 1000 parts per million (ppm) (New Zealand Standard, 1990, as cited in Boulic, Hosie & Phipps, 2010). This standard was based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62:1989 Standard with modifications to suit New Zealand conditions (Boulic, 2012).

2.2.5 Noise

Noise is produced when objects vibrate in air (Hansen, 2001). Knowledge on the effects of noise exposure has greatly increased (Naim, Gulliver, Fecht & Hansell, 2017; Phipps & Warnes, 2007; Sanni-Anibire et al., 2016). Noise had been associated with various health impacts from sleep disturbance, hearing impairment, cardiovascular diseases, to stroke. Proximity to outdoor noise sources, window opening habits and sound insulation influence noise exposure levels indoors (Naim et al., 2017). Despite growing research interest in health effects associated with noise, very little to almost no research has been undertaken on noise levels in residential buildings in New Zealand (Phipps & Warnes, 2007).

Noise levels are expressed in decibels (dB). ‘Transmission loss’ (TL) – a term used to indicate the reduction of noise – is also expressed in dB. TL is determined by the amount by which noise transmitted from one space to another is reduced by a separating construction (Ziobroski & Powers, 2005). TL is important because the higher the reduction in noise transmission the more comfortable the living environment. Based on the WHO’s Guidelines for Community Noise, in residential environments, continuous indoor noise levels should not exceed 35 dB LAeq daytime (07:00-22:00) and 30 dB LAeq nighttime (22:00-07:00), if the negative effects on sleep disturbance are to be avoided. The L_{Amax} of sound events during the night should not go above 45 dB indoors. The WHO also recommends that daytime LAeq level remain less than 50 dB outdoors to minimize annoyance (Berglund, Lindvall & Schwela, 1999).

The literature provides examples of TL measurement (Mumofic et al., 2009; Olafsen, Bard, Strand & Espejo, 2015). These measurements were performed by producing a noise outdoors and measuring the dB on each outside and inside of the building. The difference between the two sound levels recorded represents the TL value. The most common methods use a loudspeaker as an artificial sound source. The loudspeaker is placed outside at an angle of sound incidence equal to $(45\pm 5)^\circ$ from the testing specimen – i.e. facade. The average sound pressure level (SPL) outdoors is measured at a two metre distance from the façade (BS EN ISO 16283-3, 2016).

In 1961, STC was introduced as the method to rate how well building partitions attenuate airborne sound. The NZBC specifies a minimum requirement for STC of no less than 50 dB based on field measurements (Mahn, Davy & Pearse, 2011; Walther & Beattie, 2013). STC is derived from the TL values tested at 16 standard frequencies from 125 Hz to 4000 Hz and plotted on a sound pressure level graph, which curve is then compared to standard STC reference curves (Hassan, 2009). The STC however only considers TL values at frequencies down to 125 Hz; hence the range of noise sources covered is limited. This measurement can be misleading as most noise complaints are from noise sources with low frequency energy below 125 Hz.

An alternative standard for determining the rate of transmission of sound between outdoor and indoor space in a structure is outdoor-indoor transmission class (OITC).

The OITC defines the ability of exterior walls and façade elements – e.g. windows and doors – to reduce noise energy getting transmitted indoors. This method requires TL test data in one-third octave bands from 80 Hz to 4000 Hz. Calculating OITC involves the subtraction of the logarithmic summation of the TL values from the logarithmic summation of the A-weighted Reference Spectrum (AWRS) at all test frequencies (Firesheets, 2012; Hassan, 2009) (Table II-2).

Table II-2: Reference spectrum values to calculate OITC, and the corresponding A-weighted reference values (Hassan, 2009).

Frequency (Hz)	Transmission Loss (dB)	A-weighted correction (dB)	AWRS (dB)
80	103	-22.5	80.5
100	102	-19.1	82.9
125	101	-16.1	84.9
160	98	-13.4	84.6
200	97	-10.9	86.1
250	95	-8.6	86.4
315	94	-6.6	87.4
400	93	-4.8	88.2
500	93	-3.2	89.8
630	91	-1.9	89.1
800	90	-0.8	89.2
1000	89	0	89.0
1250	89	0.6	89.6
1600	88	1	89.0
2000	88	1.2	89.2
2500	87	1.3	88.3
3150	85	1.2	86.2
4000	84	1	85.0

The OITC can be obtained using a mathematical equation. The value of 100.13 is the logarithmic summation of the AWRS.

$$OITC = 100.13 - 10 \cdot \log \left\{ \sum_{i=80 \text{ Hz}}^{4000 \text{ Hz}} 10^{\frac{(AWRS_i - TL_i)}{10}} \right\}$$

There are two ways in which sound can be transmitted into buildings – i.e. through the air or through the building’s structure. Since sound transmission can happen through air, openings in doors, windows, leaks, etc. will allow for easy transmission of sound. When all openings are sealed – to prevent the transmission of sound through air – windows will become the controlling sound paths since windows typically have lower transmission loss performance than other façade elements, especially at low frequencies. In a multi-glazed window structure, air trapped between the panels acts as a resonance, known as the mass-air-mass resonance. The

larger the cavity, the lower the frequency at which resonance occurs. The decrease of outdoor-indoor transmission loss happens when the resonance frequency is above the frequency of the sound generated outdoors (Firesheets, 2012; Robinson, Bernhard & Mongeau, 2008). In addition, the transmission of noise through windows may strongly be affected by the angle of incidence – from the noise source to the façade elements (Jean & Rondeau, 2004).

2.3 New Zealand housing

There is widespread agreement in the literature that housing, as shelter, is a fundamental necessity to which all humans need access in order to maintain a basic level of comfort. There are currently almost 1.8 million private dwellings in New Zealand of which 10 per cent or about 185,000 are unoccupied (Statistics New Zealand, 2014, 2015). Given a population of 4.8 million, this is an average of 2.7 people per household. New Zealand housing stock has grown at an average annual rate of 1.2 per cent. This equates to about 21,600 dwellings per annum (Statistics New Zealand, 2015).

2.3.1 Energy use

The HEEP has analysed the energy consumption trend in New Zealand dwellings and has found a statistically significant association between energy use, dwelling floor area, and household size (Table II-3). The average total energy use of a dwelling between 151-200 sq metres with 2 to 3 household members is 12,220 kWh annually (Isaacs et al., 2010).

Energy consumption peaks during winter. The HEEP has found that energy use during winter is nearly three times as much as the consumption during summer – i.e. from December through to end of February (Isaacs et al., 2010).

Table II-3: Average annual energy consumption by dwelling and household size (Isaacs et al., 2010).

Sq Metres	Household Size		
	1 person	2-3 people	4 or more people
≤100	5944	8738	11410
101-105	7437	11279	13717
151-200	10355	12220	17573
≥201	-	9092	18326

2.3.2 Water use

The average daily water use of a four-person dwelling in New Zealand is 720 litres. Reducing household water consumption has both environmental and economic benefits. Reduction in demand for water lowers pressure on water sources and thus the development of water supply and treatment facilities become unnecessary. In turn, costs for wastewater collection and treatment facilities and pumping are lowered (NZGBC, 2017b).

The shower accounts for the largest water end use in homes (French et al., 2007; Heinrich, 2007; Heinrich & Roberti, 2010). To achieve a 6 Star rating under HomestarTM, the required maximum flow rate of showers is 9 litres per minute (LPM) (NZGBC, 2017b).

2.3.3 Housing condition

New Zealand has a poor reputation when it comes to housing condition (Buckett, Jones & Marston, 2012). It is evident that a large portion of New Zealand homes is ineffectively insulated, heated and ventilated and consequently prone to damp, cold, mould and rot (McKechnie, 2010). Housing condition is a very general and perhaps unhelpful term (Taptiklis & Phipps, 2017). In this study it is used to refer to the condition of features that have impacts on the overall indoor environment of the facility. The following sub-sections describe the state of New Zealand housing condition in regards to insulation, space heating, ventilation and airtightness.

2.3.2.1 Insulation

Insulation is a vital component to a building's health, thermal performance and energy use and hence is important for creating a sustainable home environment. A great deal of research has addressed the range of benefits from sufficient insulation (Boulic, 2012; Howden-Chapman et al., 2007; McChesney & Amitrano, 2006; McChesney, Cox-Smith & Amitrano, 2008; Phipps & Warnes, 2007). Also referred to as thermal resistance, insulation provides substantial resistance to heat transmittance between the conditioned indoor space and outside of a building (Ministry of Education, 2007). Insulation acts to stop air from escaping or, in summer, heat from entering, which helps to keep the home at a comfortable range of thermal conditions. This reduces the need to provide supplementary energy – thus costs – for either heating or cooling. A number of

New Zealand studies reported that an insulation upgrade can result in temperature increase in a range of 0.4°C – 1.4°C, decreased RH in a range of 2.3% - 7%, and reduction in the need for space heating – thus, decreasing winter energy use by as much as 10% (Howden-Chapman et al., 2007; Isaacs et al., 2010; Lloyd, Callau, Bishop & Smith, 2008). RH monitored in an insulation study found that adding a small amount of insulation reduce exposure to high – i.e. above 75% – RH by 2.13 hours each day (Howden-Chapman et al., 2007).

Various estimates have been made of the status of insulation in New Zealand homes and the inevitable conclusion is that large numbers of dwellings throughout the country have inadequate insulation (McChesney et al., 2008; NZBCSD, 2008). Insufficient insulation is a very common problem in older homes, which were generally built when insulation was not a requirement under the building codes. A large number of New Zealand homes, accounting for approximately 1.04 million houses, were built before requirements for thermal insulation were made mandatory in 1978. Two-thirds of these homes were either not insulated or inadequately insulated (McChesney et al., 2008; NZBCSD, 2008). The 1978's insulation standards required newly-constructed dwellings to have a thin layer of ceiling insulation installed. Insulation upgrades have been widely practised across the country following government's decision to making subsidies available for insulation upgrades in 2008. Despite high take-ups of the insulation grant, there are still several hundred thousand homes lacking sufficient insulation, most of which are rentals (Taptiklis & Phipps, 2017).

New Zealand is divided into three climatic zones for the purpose of insulation requirements. Climate Zone 1 applies to the northern part of the North Island, Climate Zone 2 covers the southern part of the North Island apart from the central plateau area and Climate Zone 3 consists of the South Island and the elevated central plateau, in the central North Island. Christchurch – where the study home is located – falls within Climate Zone 3. Table II-4 shows the minimum thermal resistance requirement for each climatic zone. R-value is a measure of thermal resistance used in the building industry; the higher the R-value, the greater the thermal resistance.

Table II-4: NZBC insulation requirements for non-solid construction house and solid construction house (Department of Building and Housing, 2007, as cited in Boulic, 2012).

	Thermal Resistance R-Value (m^2C/W)		
	Climate Zone 1	Climate Zone 2	Climate Zone 3
Non-solid construction house (light timber frame, brick veneer)			
Roof	R2.9	R2.9	R3.3
Wall	R1.9	R1.9	R2.0
Floor	R1.3	R1.3	R1.3
Glazing	R0.26	R0.26	R0.26
Solid construction house (masonry concrete – excludes solid timber)			
Roof	R3.5	R3.5	R3.5
Wall	R0.8	R1.0	R1.2
Floor	R1.5	R1.5	R1.5
Glazing	R0.26	R0.26	R0.26

2.3.2.2 Space heating

Space heating is one of the key housing components that ensures comfort within the indoor environment (McNeil et al., 2015). Typically over one-third of energy used in a New Zealand household is for space heating (Isaacs et al., 2010; McChesney et al., 2008). The purpose of heating in a building is to provide indoor thermal comfort no matter the outdoor conditions. A building's indoor temperature is primarily determined according to heat gain from the sun and thermal resistance of the structure as a whole. Indoor temperature is also affected by heat from intrinsic sources such as occupants, lighting, and electronics (Ministry of Education, 2007).

A range of between 18°C and 24°C is well established as the required indoor temperature for households (WHO, 1987). New Zealand dwellings regularly fall outside this range, even when space heating is installed. Only about 5% of New Zealand homes have central heating systems. The rest adopt zone-heating systems, with the most common space – or area – heated being the living room (Isaacs et al., 2010). The HEEP report showed that the average winter temperatures achieved in South Island living areas was 17°C and nearly one third of households were identified as having an average winter evening living room temperature below 16°C (Isaacs et al., 2010).

In New Zealand, there are various sources of energy used to warm homes, including electricity, mains gas, bottled gas, wood, coal, solar power, etc. Electricity is the primary source of energy used for space heating. Nearly four-

fifths of occupied private dwellings across the nation use electricity as heating fuel. Wood comes at second place with 36.8 per cent. Despite the considerable health nuisances involved, wood burners are more preferable than electricity-powered heater for some family primarily due to economic reasons and their ability to warm homes sufficiently (Taptiklis & Phipps, 2017). As of 2013, 4.1 per cent of New Zealand homes were still heated by burning coal (Statistics New Zealand, 2014). Table II-5 shows data from the last three Censuses, indicating trends of houses using various fuel types for space heating. As can be seen from the table, there has been consistent decline in the number of houses relying on solid fuels – i.e. wood and coal. Solar power remains a marginal energy source. Despite the majority of dwellings having heating systems in place, there remain homes without a heating source. In 2013, 44,832 households did not have heating at all in their dwelling, which make up three per cent of occupied private dwellings.

Table II-5: Percentage of housing stock using various fuel types for space heating (Statistics of New Zealand, 2014).

Fuel Types	Per cent of households%		
	2001	2006	2013
Electricity	72.0	74.8	79.2
Mains Gas	13.5	13.2	12.0
Bottled Gas	28.3	27.7	15.4
Wood	44.7	40.9	36.8
Coal	9.3	7.0	4.1
Solar Power	0.9	1.1	1.6
No fuels used in this dwelling	2.8	2.4	3.0
Other fuel(s)	1.1	2.1	1.6

2.3.2.3 Ventilation

Ventilation moves air into, within and out of a building or a room. It plays a major role in removing indoor air contaminants as well as reducing water vapour production indoors. Studies have shown that contaminant levels are much higher indoors than outdoors (Taptiklis & Phipps, 2017; Phipps & Warnes, 2007). Hence, it is essential to have sufficient ventilation.

Ventilation exists in active and passive forms. Active ventilation refers to ventilation where air distribution solely results from purpose-built openings – opening windows and doors – and the use of mechanically-driven equipment, i.e. an extractor fan. Passive ventilation is ventilation through unintentional, uncontrolled building envelope openings such as, via weep holes and trickle ventilators and through construction joints or flaws in the structure (Hesaraki et al., 2015; Taptiklis & Phipps, 2017).

International guidelines on IAQ consider a minimum ventilation rate of 0.35 to 0.5 ACH of fresh air to be sufficient to maintain indoor air freshness (ASHRAE, 2004b; Swedish National Board of housing, 2010, as cited in Hesaraki et al., 2015; Quaglia & McNeil, 2011). As already mentioned, ventilation performance can be determined by contaminant levels indoors, primarily CO₂ (Mumovic et al., 2009; Taptiklis & Phipps, 2017). New Zealand Standard 4303:1990 for housing ventilation requires a minimum ventilation rate with an approximate complete air change of once every three hours, to be distributed throughout the house, in order to maintain less than 1000 ppm of CO₂ (New Zealand Standard, 1990, as cited in Bond, 2013; Boulic et al., 2010; Isaacs et al., 2014).

Finding from the Overton et al.'s study (2013, as cited in Overton 2013) indicates that passive ventilation alone will not generally provide adequate ventilation for most New Zealand homes which could have an effect on the IAQ and moisture control in these houses. This implies that keeping windows and doors open for some time every day may be necessary to provide adequate air and dilute moisture and other indoor contaminants.

Reliance on window opening for ventilation, however, may not be adequate especially considering the fact that many households are empty during work hours, and for security purposes, consequently windows are shut all day. With houses more commonly left unoccupied most of the time, primary ventilation may no longer be sufficient as a ventilation source for moisture control and IAQ (McNeil et al., 2015; Phipps & Warnes, 2007). Other potential factors that contribute to ventilation behaviours include outdoor noise and proximity of the building to the outdoor sources. To illustrate, houses located near busy traffic are more likely to have windows and doors closed at most times to reduce outdoor

pollutions entering the indoor space – e.g. noise, smokes, dusts, etc (van Renterghem & Botteldooren, 2012). More research is recommended in this area.

2.3.2.4 Airtightness

Air leakage through the building envelope wastes energy and increases utility costs. As outside air leak into a building, more energy may be required to maintain the desired indoor conditions for comfort. Air leaks can also cause condensation to form indoors, which in its turn can impact IAQ (Seppänen & Kurnitski, 2009).

The quantity of air leakage in a building envelope is widely represented as airtightness. In the simplest terms, building airtightness defines a building's resistance to air leakage through passive ventilation, which negatively correlates to infiltration rate (Fennell & Haehnel, 2005). Airtightness is commonly expressed in terms of building air changes per hour at 50 Pascal's air pressure difference across the building envelope, measured as ACH@50 Pa. From the airtightness measurement, an estimate of the mean infiltration rate can be worked out by simply dividing the airtightness value by 20 (McNeil, Plagmann, McDowall & Bassett, 2015).

The trends of air leakage vary considerably through New Zealand's housing stock. Past studies showed that the airtightness of New Zealand homes has increased over time. Newer New Zealand homes, built after 2000, are more airtight than older homes as building technology and construction practices change. Designs of older houses were mostly leaky, having inevitable construction gaps or defects, resulting in higher air infiltration rates. Air infiltration rates in newer constructions, however, are much lower. A study by Overton et al. (2013, as cited in Overton, 2013) has revealed a significant reduction in air infiltration levels of New Zealand homes, from an average of 19 ACH@50 Pa in pre-1960s homes to 4.5 ACH@50 Pa in houses built since 2000. An airtightness result of 4.5 ACH@50 Pa translates to an estimated mean air exchange level of around 0.225 ACH which in principle means that about 22.5% of the total volume of air across a building envelope is replaced by external air every hour due to conversion of air through passive ventilation.

In New Zealand, there is no requirement for airtightness in the building code. For context, this report referenced the 2015 International Energy Conservation Code (IECC), which calls for new housing construction, in Christchurch, to have an infiltration rate of no higher than 3 ACH@50 Pa (ICC, 2014; Jaques et al., 2017; Overton, 2016).

2.4 Post-occupancy evaluation

There are several types of evaluation that can be done as a way to address issues arising during operation phases of a housing project. Typical evaluations have been limited to only technical measures, involving assessments against a set of measurable performance criteria, such as energy consumption, materials use, service life, cleanliness, emissions, etc. Examples of technical evaluations related to operation and management of a building are energy audits, security inspections, and maintenance and operation reviews (Preiser, 2001).

At the most fundamental level, buildings – including houses – are primarily designed and built for occupation (Dykes, 2012; Goins & Moezzi, 2011; Shaikh et al., 2014). It is therefore important that buildings provide healthy, comfortable and functional environments that would allow the occupants to fulfil their needs as well as enhancing their health and well-being. That being said, taking into account the end-users' perspective when it comes to evaluating building performance is essential. Even though technical evaluations address criteria that are important for determining whether a building is performing effectively, they do not address such criteria from the point of view of the occupants and based on its functionality, which are not less important to address.

POE, to this end, provides a systematic quality assurance process that can help designers, architects, constructors and policymakers create better working conditions that fulfil occupants' expectations of comfort (Deuble, 2012). POE is a method of assessment of buildings – of any types –, under occupied conditions, as a way to providing critical feedback for property industry practitioners which can help them better the performance in the future. POE has been found helpful in finding out how a building performs once it is occupied, including whether and how well it has fulfilled its

design intents and how satisfied building users are with the environment that has been established (Federal Facilities Council, 2001).

POEs in general involve ‘the human factor’ in building performance evaluation, hence offer a more complementary element to building evaluation studies. Used extensively worldwide (Deuble & de Dear, 2014), the POE assesses a building in relation to its functionality and how it has fulfilled occupants’ satisfaction (Abbaszadeh, Zagreus, Lehrer & Huizenga, 2006). It justifies the performance of a building from how the occupants feel about its functionality and environment quality.

POE is based on the idea that better living and/or working space can be designed by asking users about their needs. There is no industry-accepted definition for POE nor is there a standardized method for carrying out a POE (Federal Facilities Council, 2001). The following sections discuss the various definitions given for POE, including what the term ‘POE’ means and how POE has been and should be applied in relation to the housing context. Key benefits derived from a POE and limitations undermining its credibility as well-established building performance evaluation tool are highlighted.

2.4.1 Definitions and terminology

There is no universally agreed definition for POE. Various and differing interpretations of the term have been suggested since the term was coined in the late 1960s (Preiser, 2001). According to Preiser et al. (1988, as cited in Preiser, 2001, p. 9), POE refers to “the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time”. POE can also be defined as “any and all activities that originate out of an interest in learning how a building performs once it is built, including if and how well it has met expectations” (Vischer, 2001, p. 23). Another definition of POE was recommended by Zimring & Reizenstein (1980), as “the examination of the effectiveness for human users of occupied designed environments” (p. 1). POE can also be referred to as a tool used to evaluate the performance of a building in terms of their facilities and services as well as in terms of occupants’ satisfaction (Preiser & Vischer, 2005). The various definitions mentioned above highlight POE as a tool that puts forward lessons learned from completed assessments to the general knowledge that are essential for

aiding problems and misfits, thus for successful improvement in future design and construction – hence, building – projects.

The term *post-occupancy evaluation* was intended to reflect that evaluation takes place once a building is under occupation or in use (Preiser, 2001; Zimring & Rosenheck, 2001). Replacement terms such as *environmental design evaluation*, *environmental audits*, *building-in-use assessment*, *building evaluation*, and *building performance evaluation* have been suggested by a number of experts who have disagreed with the use of ‘post-occupancy’ – due to its literal meaning which seems to suggest that evaluation occurs after people had finished occupying the building (Zimring, 2002; Federal Facilities Council, 2001). But the term *post-occupancy evaluation* remains the most commonly used, and it will be as such used in this study.

2.4.2 Introduction of POE

The concept of POE was initiated following the expanding architectural development in the UK in the 1960s. The Royal Institute of British Architecture (RIBA) – a professional association of architects in the UK – recognized the need to gather and disseminate feedback on the performance of buildings after construction completion. They released a report titled the *Handbook of Architectural Practice and Management*, defining ‘feedback’ as integral component to the building lifecycle. Feedback allows architects to track the performance of their completed buildings as a means of ensuring success of their design as well as improving service for future clients (Preiser, 2001; Bordass & Leaman, 2005a, 2005b). POE was brought up based on this need to provide feedback on how well buildings perform (Derbyshire, 2001; Oseland, 2007). However, POE was not largely accepted by the building industry in the UK up until the 1990s. POE was perceived as rather threat to the industry because of its potential to reveal the under-performance of building (Deuble & de Dear, 2014). POE steadily gained recognition as a credible building evaluation mechanism following its use in a large number of housing studies in the USA in the 1970s and 1980s as well as its introduction in Australia and New Zealand in the early 1990s (Preiser & Vischer, 2005).

2.4.3 Benefits and limitations for POE

Besides POEs being conducted with the intention to measure occupants' satisfaction towards a building and to evaluate building performance based on how well it fulfils the needs of the users, the POE is also used for a range of other purposes. The vast majority of researchers agree that POE can provide valuable feedback to the designers of new buildings (Bordass & Leaman, 2005a, 2005b; Meir, Garb, Jiao & Cicelsky, 2009; Menezes, Cripps, Bouchlaghem & Buswell, 2011; Vischer, 2001). It is also a general agreement that POE can be used to improve the design of buildings and stimulate growth in sustainable construction (Baird, 2010; Meir et al., 2009; Nicol & Roaf, 2005). Apart from providing feedback, POE offers a number of other plausible benefits. POE can serve as a testing tool for 'new' concepts or initiatives to determine how effective they are to implement in actual occupied buildings. POE can also function as a mechanism to monitor a building's performance, and therefore to inform whether the building has performed up to an agreed standard (Federal Facilities Council, 2001). To sum up, POE is a useful tool that can help better the performance of buildings and most importantly improve levels of satisfaction amongst occupants.

Whilst the literature contains a great deal of studies that describe the function and benefits of POEs, very few authors have discussed the limitations the POE has as a method of evaluation of buildings. As highlighted by Marley, Nobe & Clevenger (2012), Zimmerman & Martin (2001) and Bound & Flemmer (2014), one limitation of POEs is the lack of standardized protocols and methods, which consequently results in findings being incomparable. There is in fact no agreement on what constitutes a 'good' building in the industry (Sanni-Anibire et al., 2016). Hauge, Thomsen & Berker (2011) observe that POE studies generally have mixed results; some building users are satisfied and some are not. The particular building operation itself may be complex and poorly understood by its occupants and consequently unsatisfactory. A study by Brown & Gorgolewski (2013) suggested that a quarter of the occupants were unhappy with their control of heating, ventilation and air conditioning (HVAC) system in a building but found that the main reason for dissatisfaction was that they had not read the operating instructions and did not know how to use the control. These findings show that problems may not always originate in the operation, management or control systems of the building, but may also originate in the occupants, in regards to their knowledge and behaviour.

Moreover, POE has been viewed traditionally as a one-off or final process evaluation (Bordass & Leaman, 2005a; Preiser & Vishcer, 2005); however, the term post- does not literally reflect the final end phase of a building life cycle. POE is an integral part of the building delivery process and should be treated as rather continual (Federal Facilities Council, 2001; Presier, 2001; Vishcer, 2001). As addressed by Zimmerman & Marin (2001), despite one of the primary goals of POEs is to encourage designers to reevaluate their design, and therefore improve their skills and produce better building designs, actual practice in the delivery process of a facility does not recognize continual involvement of the designers. Performing POE in regular intervals ensures buildings continue to meet expectations of their intended design specifications and, in return, sufficient levels of satisfaction amongst the occupants (Preiser, 2001; Riley, Kokkarinen & Pitt, 2010).

The advantages of conducting POEs seem numerous and self-evident. POEs: (1) provide data that inform the delivery performance thus the success of building and facility management processes; (2) establish organizational learning by allowing decision-makers to build on successes and avoid repeating failures; (3) aid the generation of feedback hence enable communication amongst stakeholders such as designers, clients, end-users, and others; (4) produce mechanisms for quality monitoring where notification gets informed when a building does not perform up to a given standard; and etc. However, many significant barriers exist to the application of POE in building studies. POEs: (1) lack standardized methods for assessing building performance; (2) can be bias, as occupants' opinions and their assessments might be shaped by factors that have nothing to do with the building performance; (3) have barely seen as a necessary inclusion to the process of building monitoring that is done continuously which makes the potential of POE as a process of continual learning unable to be realised.

2.4.4 POE methodologies for housing

Although POE has gained popularity in building studies, POE practice and research for housing remains significantly under-established. POEs of housing facilities are far fewer in numbers compared with non-residential buildings – especially, offices and educational buildings –, even though this have begun to change in the past decades (Leaman, Stevenson & Bordass, 2010).

In earlier – but still in most – applications of POEs, most have failed to implement a holistic approach to evaluating building performance. Most POEs have been carried, as argued by Sanni-Anibire et al. (2016), “in a one-dimensional approach” (p.2), heavily based on users’ perspectives alone. Taking into account their limitations, as identified in section 2.4.3, POEs relying solely on occupant opinions are insufficient and such approach does not convey comprehensiveness that building evaluation requires. The study of building evaluation should be multidisciplinary. POEs, as argued by Deuble & de Dear (2014) should not merely involve the perspective of occupants in the evaluation, but also include the use of physical, technical and environmental data. It is essential that a POE obtains both subjective data – of occupant feedback – and objective environmental data to gain a complete picture of a building’s actual performance from a technical and occupants’ standpoint (Deuble & de Dear, 2014). But again, selection of which method to use depends upon the goals of the POE and how the findings will be used. It is thus necessary that the scope and goals of the POE be identified to determine the variety of data to be collected during the POE site visits.

In recent POE studies of housing, a combination of physical evaluation and qualitative assessment of occupant perception has started to become the more routine practice. Taylor, Littlewood, Geens, Counsell & Petitor (2010) advocated a user-centred, ecological technique for housing POE in which building performance is assessed in relation to: (1) the building’s interaction with its users, and (2) the building’s interaction with the natural environment; in other words, the degree to which the building supports the needs of users and the environmental impacts arising from the use of the building. Measurement of environmental impacts can be performed through physical monitoring such as IEQ monitoring, thermographic surveys and longitudinal energy- and water-use study. Occupant’s experience and behaviour can be investigated through occupant surveys. A number of other studies support these arguments such as that by Sanni-Anibire et al. (2016), who suggested the integration of four methods for POE research, including walkthroughs, IEQ monitoring, occupant satisfaction surveys, and focus group meetings. Another example of housing study that combines the use of multiple evaluation instruments is the study by Silva et al. (2017), who involved questionnaire- and physical measurement-based evaluations in their study of two residential buildings in

Luxemburg, The questionnaire survey was conducted to assess occupant satisfaction in regards to IAQ and ventilation system. The in situ measurements were carried out on CO₂ levels, air temperature and relative humidity.

A critical step in any POE is preparation. When preparing for site visits, it is highly important that the way in which the collection of data – i.e. surveys and monitoring – will be administered is determined. Furthermore, information about the POE including the purpose and schedule of the evaluation needs to be provided to the owner, etc. – as occupants and operators – which will enable them to set up appropriate time and access to the facility and them as respondents. Prior to the carrying out of site visits, surveys and indoor monitoring is the gathering of background information and data on the facility to be evaluated. The background information of the facility sets up the context of the project. For the purpose of comparison of building performance, it is most effective that a baseline for performance analysis is established. Depending upon the purpose of the POE, comparisons of building performance can be carried out between buildings of similar type, size, geographical location, etc. or against planned performance for the project or both. For comparison of building performance during operations versus during planning and design stage, the comparison may be the building's actual energy and water use during operations against goals that were set during design. Besides energy and water usage data, other measurements that can be included in the comparison are temperatures and humidity levels related to thermal conditions, CO₂ levels related to IAQ and carbon footprint, acoustic quality related to noise levels, and thermal fitness (Gupta & Chandilawa, 2010; TSB, 2013, as cited in Chiu, Lowe, Raslan, Altamirano-Medina & Wingfield, 2014; Christoffersen, Feifer, Foldbjerg, Hannibal & Olesen, 2014; Lee et al, 2012; NASFA, 2010; Silva et al., 2017; Sodagar & Starkey, 2016; Teasdale-St-Hilaire, 2013). Setting the purpose and scope of the POE, gathering background information, establishing baseline data and after all preparation in advance is key to a smooth and productive on-site POE visit.

As noted above, various types of data can be collected during POE site visits, depending upon the scope and goals of the POE. A 'green' building's operational performance is closely correlated with its environmental performance, which is widely represented in terms of the amount of energy and water consumed in the building. A building's technical performance can also be represented in terms of

IEQ, which affects the comfort and health of occupants. The measurements of IEQ are made with the use of monitoring instruments. Other type of data collected during POE studies is experiential data – i.e. data that shows what is being experienced in the building from the perspective of the occupants. Experiential data can be obtained through surveys or through direct communication with occupants in a form of interviews. In the context of study that employs survey approach to obtain the perceptions of occupants, it is best to adopt an existing survey that has been tested, is simple and easy to apply, and allows for comparison of results (NASFA, 2010).

A large number of questionnaires had been used for assessing the indoor environment – summarizing and benchmarking their results in different ways. A literature search was carried out to compile the different methods of assessing IEQ from the occupants’ perspective. The search was limited to questionnaire-based methodologies that were for residential settings. The BUS and CBE questionnaires are the most extensively used and have a strong presence in the academic literature. Table II-6 below summarises the two sample questionnaires and the questionnaire details.

Table II-6: Questionnaire-based POE survey examples.

Survey Name	Country	Year	Building Type	Physical Measurement	Form		Type of Scale used	Application
					Paper	Web		
BUS Occupant Survey	UK	Since 1985	Offices, Residential	No	X	X	Semantic Differential Scale	Over 400 buildings
CBE Survey	USA	Since 1996	Workplaces, residential, educational	Optional		X	Semantic Differential Scale	More than 600 buildings with 60000 respondents

POE studies involving residential buildings often have a significant issue to do with privacy. Such investigations, especially where installation of monitoring equipment is involved, can potentially be perceived as intrusive (Taylor et al., 2010). Invasion of privacy can happen as a result of continuous 24/7 monitoring (Bitterman & Shach-Pinsly, 2015). It remains unresolved how the issue of privacy in housing studies can be addressed. Further research is required to address this issue.

Subsequent to the process of data gathering is data analysis and reporting. Depending upon the goals of the POE, there are multiple ways in which this should be undertaken. If the purpose of the POE is to improve the facility being evaluated, the

report should be structured to focus on providing specific examples with recommended actions for that particular facility. If the POE is carried out to feed forward information to future facilities, the report may focus on information that can be put forward in a generalized way with conclusions and recommendations that are applicable to a particular building type. POE which purpose is to improve the facility being evaluated and to inform the decision-making process for future facilities should be reported in ways that serve both purposes. In either case, it is vital that the information on facility performance is presented in an objective and diplomatic manner (NASFA, 2010).

2.5 Post-Occupancy performance of ‘green’ homes

2.5.1 Successful case studies

Extensive studies have been carried out to find out whether IEQ experienced in ‘green’ homes is better than in conventional homes. Many POE studies focused on emphasizing the differences in occupants’ perceptions before and after a move to a ‘green’ home. Results from a number of user evaluation studies have suggested that green homes’ IEQ are highly satisfying and occupants have better health and well-being. In the following, examples of studies carried out on occupants’ perceptions of ‘green’ homes are presented.

A POE study in five demonstration carbon-neutral homes across Europe was carried out, involving five families who were living for one year in these houses. Questionnaire surveys were distributed four times on a seasonal basis to each of these families during the test year to gain their insights about the houses performance in terms of energy consumption and production, indoor climate and air quality, daylight and electric lighting, house automation, and sustainability. The study concluded that the families reported high satisfaction with the indoor environment and that their well-beings have improved compared with when living in their former homes (Christoffersen et al., 2014).

Another POE survey was performed involving 235 LEED-certified homes in the Midwest, United States, with the intent to identify LEED-homes’ actual performance under occupation. The findings of this study showed that most residents were highly

satisfied with their home and the IEQ. They also reported improved health and quality of life since moving into these homes (Lee, Kim & Phillips, 2012).

2.5.2 The ‘performance gap’

A vast array of studies has indicated that significant discrepancies can exist between design expectations and the actual as-built performance of new housing. The phenomenon has been described as the ‘credibility gap’ – also called the ‘performance gap’, referring to the loss of credibility when actual performance does not meet the expected outcomes of a designed built (Bordass, Cohen & Field, 2004; Bordass, Cohen, Standeven & Leaman, 2001; Menezes et al., 2011). Although the expectation is that, being designed to an energy-efficient performance standard will essentially produce minimum – or zero – emissions, consume less energy and perform better environmentally than regular buildings, studies have found that it has not always been the case. In the actual operation of a building, not all things will perform as expected – even so for buildings that are certified ‘green’ (Agha-Hossein et al., 2013; Bordass et al., 2004; Demanuele, Tweddell & Davies, 2010; Hinge, Taneja & Bobker, 2008, as cited in Hauge et al., 2011). For example, a study performed at newly-constructed and low-energy homes in the UK found that the overall energy use and carbon emission were higher than predicted by design calculations. In the case of thermal performance, the discrepancies were much higher (Wingfield, Bell, Miles-Shenton, South & Lowe, 2008).

There exist various causes that might lead to the occurrence of the ‘credibility gap’. It remains a question however as to who in the process of the life cycle – either the designers, constructors, or the occupants – is most responsible for the slippage; but, certainly the centre of the problems can be any of them. Slippage can occur, during initial estimation, design development, construction and commissioning, and at construction completion (Bordass et al., 2004). The designers, constructors, and the occupiers are respectively involved in at least one of these processes.

Slippage that occurs during the initial estimation stage is often due to defective estimation of energy use. Designers may often only consider the energy use of typical spaces – such as the indoor spaces in a residential building – and not of other spaces in the building – such as, parking spaces, gardens, and so on. Moreover,

estimation has often been made solely based on energy use when the building is operating during the daytime and on weekdays, and left out the scenario when the building is empty at night when most systems are off – though they are not in the actual case. Simplifying estimation, in effect, leaves the designers predicting rather ‘favourable’ than ‘actual’ energy use (Bordass et al., 2004).

Slippage during the process of design development mostly occurs when the intended construction works differ to the initial design assumptions. Changes occur during the design development stage. In this case, re-estimating energy demand would be essential; however, that is seldom the case. Re-calculation on the predicted energy use might have meant having to spend extra, for people who does the work to come back and have another look (Bordass et al., 2004).

Slippage can as well occur during construction and commissioning stage. The construction of a building does not always end up perfectly in accordance with the initial design. The building may not be constructed as intended due to many factors. Cost-cuts, for instance, will affect the quality of construction especially of build details that can influence the overall performance of the building, e.g. with degraded insulation, thermal characteristics, and airtightness. Moreover, alterations are often made during construction stage, opposite to what have been specified in the original design. This may eventually affect the construction quality of the building. Poor commissioning and monitoring are seen as the main cause to the slippage occurring during construction work (Bordass et al., 2004; Taylor, 2014).

Once construction is completed, there is still room for slippage to arise. In the housing context, most of the issues are associated with unsustainable operation by the occupants. It is widely believed that the performance of a building depends on the users (Hauge et al., 2011). There were studies done to investigate how occupants’ behaviour affects green buildings operational performance. A study was done by Bond (2011) during 2009 and 2010 in Australia – following earlier surveys conducted by Connection Research in 2008 – to identify the barriers to energy efficiency in households. Bond concluded that people’s natural tendencies to being ‘lazy’- or not wanting to do extra effort – and to do only when they are told to, are the most common causes why they are not acting more environmentally responsible. Even, a building that is designed to perform optimally cannot perform as so without

the active support and involvement from the occupants. As claimed by Deuble & de Dear (2012), “green buildings work best with ‘green’ occupants” (p. 26). With building occupants consistently and actively applying sustainable behaviours – by, for instance; practice recycling in the building; avoid paper waste; turn individual electronic appliances off while not in use and etc. – the building has better likelihood to perform sustainably.

2.6 Conclusion

The review of literature highlighted some important issues:

- People spend a total of 69.7% of time at home indoors. The IEQ has been shown to have widely applicable effects on their comfort, health, and hence their overall well-being.
- The development of indoor contaminants can originate from within the building or be drawn in from outdoors.
- New Zealand house is warmest in the evening due to elevated use of heating. In addition, during this time of the day, internal heat gains are high because of increased presence of occupants and their interactions with the building.
- Heating is common in New Zealand living rooms but less common in the bedrooms.
- A minimum indoor air temperature of 18°C and a minimum of 20°C – for houses occupied by vulnerable populations, e.g., young children, elderly people or ill people – are recommended to maintain a comfortable and healthy indoor environment.
- There has been no monitoring study of relative humidity on a statistically representative sampling of New Zealand homes. A humidity level between 30% and 50% is recommended. 50% and greater RH can start and proliferate the growth of mould especially where ventilation is insufficient.
- CO₂ levels are relatively higher during winter than in summer. The concentration of CO₂ is frequently used an indicator of airtightness. Through CO₂ measurements, effectiveness of the ventilation system can be determined. Concentrations of CO₂ within the indoor space should not exceed 1000 ppm.
- Despite growing research interest in non-auditory effects associated with noise, there is almost no research studying noise levels in New Zealand homes.
- Indoor noise levels should be kept below 35 dB LAeq during the day and 30 dB LAeq at night to avoid sleep disturbance.

- Electricity is the main source of energy used for space heating in New Zealand homes. New Zealand dwellings with a size between 151-200m² and with 2 to 3 household members have an average annual energy use of 12,220 kWh per year.
- New Zealand's reputation is poor when it comes to housing condition. A large portion of them is ineffectively insulated, heated and ventilated and consequently prone to damp, cold, mould and rot. Two-thirds of the New Zealand housing stock was built before 1978 when requirements for thermal insulation were made mandatory. New Zealand homes are cold during winter. They are exposed to temperature below the WHO recommendations. Designs of most older houses were leaky, having inevitable construction gaps or defects, resulting in higher air infiltration rates; but, the airtightness of New Zealand homes has increased over time, from an average of 19 ACH@50 Pa in pre-1960s homes to 4.5 ACH@50 Pa in houses built since 2000.
- With sufficient insulation, warmer temperatures, lower humidity levels and reduction in energy consumption can be achieved
- A minimum ventilation rate of 0.35 to 0.5 ach is considered to be sufficient to maintain healthy IAQ. New Zealand Standard 4303:1990 for housing ventilation requires a ventilation rate with an approximate complete air change of at least once every three hours, to be distributed throughout the building.
- Post occupancy evaluation is a method of evaluation of building under occupied conditions. A combination of physical building performance evaluation – through energy consumption analysis and IEQ monitoring – and qualitative assessment of occupant perception – through questionnaire survey – has become the more common practice of POE.
- Past housing POEs showed high occupant satisfaction with 'green' homes; however, significant discrepancies can exist between design expectations and real operational performance of new buildings.

Chapter 3: Methodology

3.1 Introduction

The previous chapter has outlined the literature review on the subject matter. This chapter continues with the research methodology, which includes the research process participants selection, the research instrument, ethical consideration issues, data collection and processing approach, data analysis method as well as limitations and potential problems of the chosen research approach. The justification for choosing the methodological approach is also addressed.

3.2 Methodology overview

3.2.1 Research process

Figure 3.1 illustrates a flowchart of the steps of the research process.

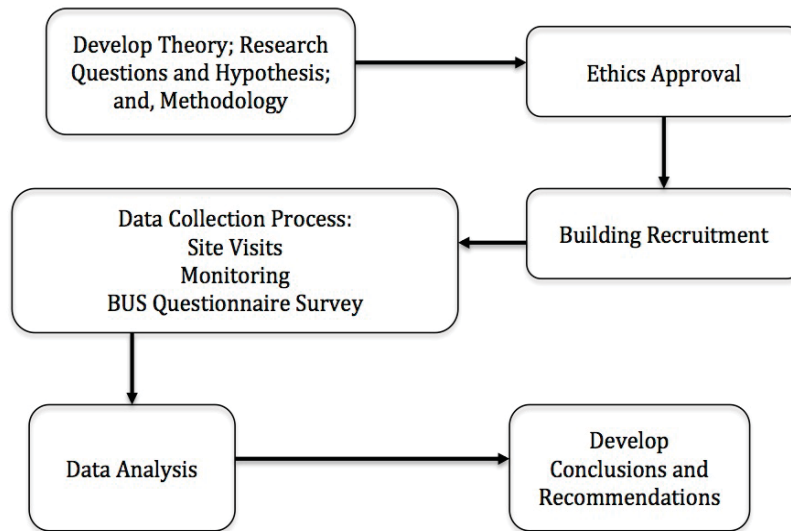


Figure 3.1: Flowchart of Steps of Research Process.

The first step of the study was performing literature review of past studies related to IEQ, New Zealand housing condition and post-occupancy evaluation in residential settings. The literature review was undertaken to review what past studies have and have not discovered. Based on the review of the literature, the research questions and hypothesis were defined, including the research methodology. Once the research methodology had been specified, the case study building was identified, contacted and recruited. Prior to that, ethical approval for the carrying out of the study had

been obtained. Data was then collected from the study building. The data collection process included preparation and carrying out of energy performance analysis, IEQ monitoring and a questionnaire survey. The data was then interpreted and analysed to answer the research questions and test the hypothesis.

3.2.2 Step 1 – Research problems

As established in Section 1.1, there is a lack of – or, no – research that thoroughly conducts monitoring of New Zealand ‘green’ homes in occupied conditions. Based on the problem statement, three research question(s) were developed as highlighted in Section 1.2. This research, as highlighted in Section 1.2, was developed based upon the interest to study the post-occupancy performance and winter IEQ of a ‘green’ residential property in New Zealand, specifically a SHM exemplar home in Christchurch. This research relied on a case study method to be able to thoroughly demonstrate the complexity and the applicability of suggested theories regarding ‘green’ building post-occupancy performance and IEQ in the literature. Data collection was carried out through a field study using a number of instruments as highlighted in Section 3.2.7.

3.2.3 Step 2 – Literature review

Prior to the collection of data, a literature review was performed to look into relevant research methods to adopt. IEQ, New Zealand housing and POE studies represent major components of the literature review. The literature review on IEQ offers an overview on the importance of IEQ in residential settings and why they are an integral performance indicator. The literature review on New Zealand housing presents the trends of New Zealand housing condition in regards to insulation, heating and ventilation – three major determinant factors of IEQ. A large part of the literature review on POE focuses on discussing how to’ perform post-occupancy evaluation at residential buildings including past POE findings in residential settings.

3.2.4 Step 3 – Identifying performance parameters

This study incorporated the analysis of energy use, monitoring of IEQ, and the surveying of building occupants. The analysis of electricity consumption was focused on the winter months. A 6-week monitoring was performed involving the

use and installation of monitoring instruments to monitor shower efficiency, air and surface temperatures, relative humidity, CO₂ levels, noise transmission levels, and building envelope thermal fitness. The monitoring was undertaken during winter of 2017. The BUS Methodology questionnaire survey was used and distributed to the occupiers – including owners – of the building in order to gain their insights about the building performance.

3.2.5 Step 4 – Ethics

Ethics in research refers to the code of behaviour to ensure that no one is harmed by the investigation (Bailey et al., 1995). The data collection process for this study involves human participants. The researcher is aware of the ethical dilemmas that may arise during the process of the data collection. Ethical approval for this research to be carried out was obtained from the Massey University Human Ethics Committee on the 16th of June 2017 before any data collection took place (Appendix 1). *This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.*

Approval to access the study buildings and occupants was obtained from the owner of the property. A project information sheet and consent form were issued to the owner (Appendix 2). Approval for participating in the questionnaire survey was obtained from the occupants of the study building. Participation information sheets and consent forms for the BUS surveys were issued to the study participants (Appendix 3). A license to carry out the BUS survey has also been obtained from BUS Methodology Ltd prior to the survey being conducted. Upon completion of this research project, all raw data and the signed consent forms will be kept for a period of six years in a secure designated lockbox cabinet on the university premises following Massey Human Ethics Code of Ethical Conduct (Massey University, 2015). After this period, the data will be suitably destroyed in a confidential manner. Participants were made aware of all relevant ethical issues via the information sheet.

3.2.6 Step 5 – Building recruitment

This study involved the monitoring of a SHM exemplar building. The study building was selected primarily on account of representing SUPERHOMES in New Zealand. Located close to the heart of Christchurch City, the study building is situated on a 904 square metres plot at 14 Jane Deans Close, Riccarton. The 174.64 square metres dwelling is two-storeyed and has three bedrooms, two bathrooms and a separate toilet. Its thermally efficient design uses rusticated weatherboards fixed to a timber frame on heavily insulated concrete floor slabs to reduce heat dissipation. The roof is super-insulated with CLT panels and the floors are equipped with a hydronic underfloor heating system. Complementing these are numerous ‘green’ features including, solar PV panels, EV car charger, water efficient fittings, and energy efficient lighting and appliances. Floor plans of the study home are presented in Figure 3.2.

The study home has been occupied since June 2017 by a family of three. Information as to who owns the building was acquired from the building architect. Through the architect, the researcher managed to gain information for background details of the building’s features, which help the researcher to get familiarized with the building conditions in general. Besides that, this study could not go ahead without access and cooperation from the builder. The builder played an instrumental support role facilitating the following activities: facilitating access to the building for study including building access permit and informing building occupants of the presence of the researcher.

3.2.7 Step 6 – Data collection and processing

There are two methods of data collection – quantitative and qualitative methods. The differences between qualitative and quantitative research are presented in Table III-1. Qualitative research collects information through for instance individual interviews focus groups and observations that allow for deeper, open-ended responses to be obtained. Quantitative research, on the other hand, obtains information that is quantifiable or can be interpreted into measurable variables; therefore responses are focused or limited. This is done most typically through various forms of surveys, and/or close-ended interviews (Latu & Everett, 2000).

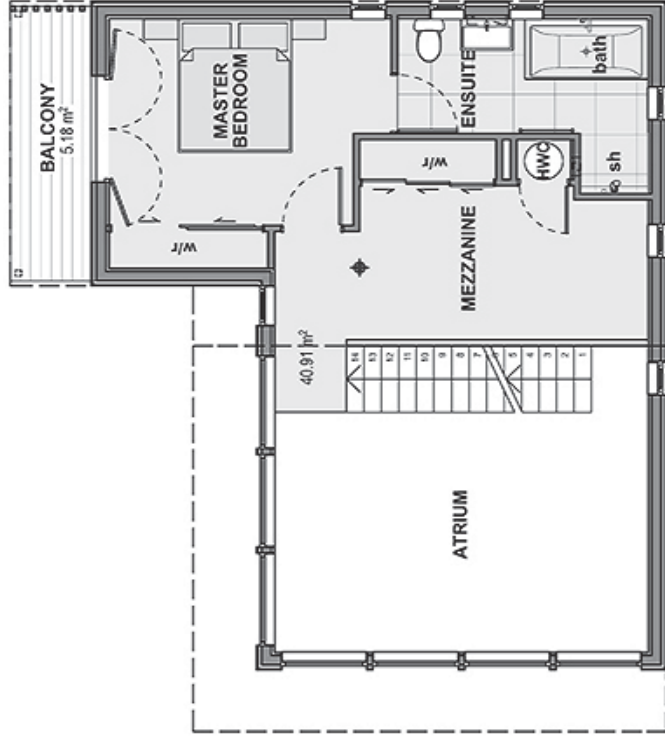
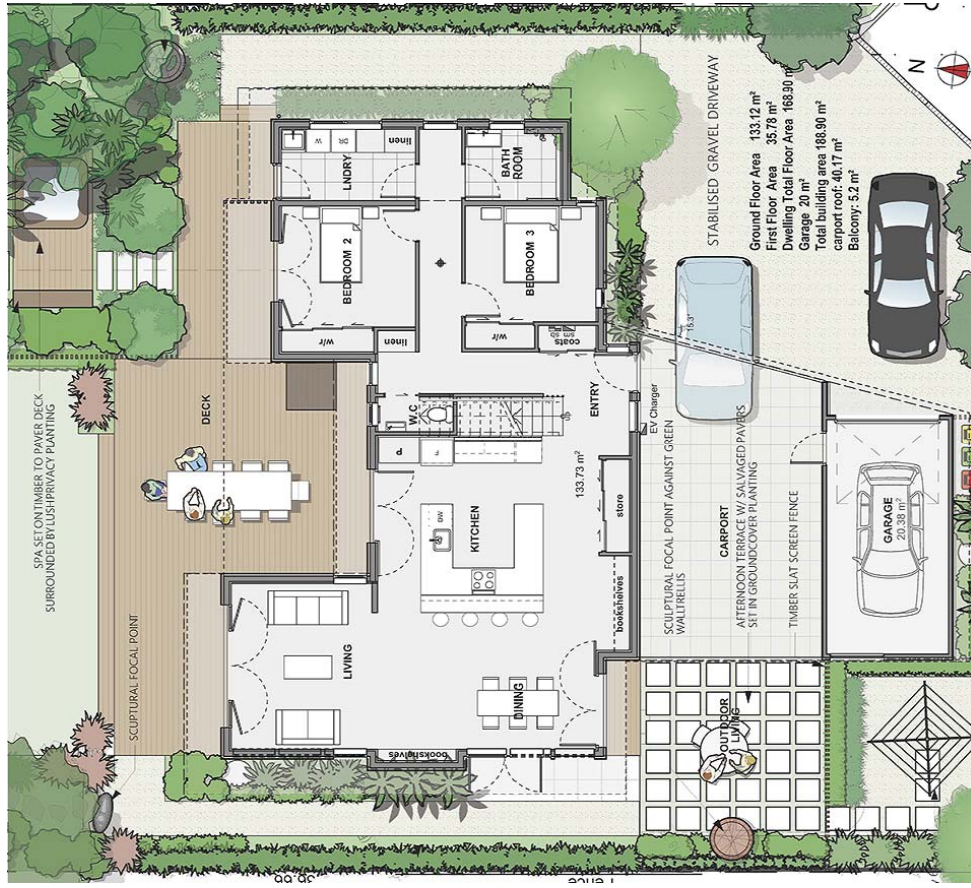


Figure 3.2: Floor plans of the study home - Ground Floor (left) & First Floor (right). Source: Bob Burnett Architecture, 2017

Table III-1: Differences between qualitative and quantitative research methods (Dutka, 1995, as cited in Latu & Everett, 2000).

	Qualitative	Quantitative
Type of Research	Exploratory	Descriptive/statistical
Type of Question	Open-ended (probing)	Closed (fixed options)
Number of respondents	Few	Many
Analysis	Subjective	Statistical
Interviewer qualifications	Special skills required	Less need for special skills
Generalization of results	Very Limited	Reasonable

In order to draw conclusions about the questions being tested, a quantitative data collection technique was adopted. This decision is based on the fact that the research questions are best answered and represented using quantitative approach.

The approach used in this research project consisted of three elements:

- Thermal Modelling using ALF
- Energy Consumption Analysis;
- IEQ Monitoring; and,
- Occupant satisfaction survey.

In total, three site visits at the study building were performed throughout a six-week monitoring period from the 20th of June to 31st of July 2017. The monitoring involved in situ measurements of shower efficiency, air temperature and RH, surface temperature, CO₂ levels, noise transmission, thermal resistance through thermography, and airtightness. The first site visit was on the 20th of June, the second site visit was on the 10th of July, and the final visit took place on the 31st of July.

3.2.7.1 Thermal modelling

The theoretical effect on energy use as a result of energy efficient, highly-insulated design can be predicted. A simulation programme – ALF 3.2 – was run for modelling the study building. The ALF (Annual Loss Factor) is a steady state model of heat gain and loss, which calculation is based on the building’s location and construction details, and a selected heating schedule (Isaacs et al., 2010). The house physical dimensions archived from the architect were entered into the

programme together with information on the construction materials of the building in order to simulate the thermal performance.

The assumptions made by the ALF calculation affect the validity of the calculation outcomes. The two most important assumptions concern the maintained indoor temperatures and the R-values of the building envelopes. For instance, the house was modelled so that the living area temperature is kept at a constant 20°C the whole day (24-hour). In reality, it is unlikely for living area temperatures to be kept constant throughout the day. Two heating levels were tested with the 24-hour heating schedule – e.g. 18°C and 20°C.

The wall features combined provide an R-value of 3.99, and it was kept as such for the ALF calculation. The R-value for the window is 0.84. However, the window R-value used for the ALF calculation was 0.53. Therefore, the actual heat loss from the windows would be lower than what had been calculated with ALF 3.2. The roofing and flooring systems combined give total R-values of 5.495 and 3.92 respectively, and they were kept as such for the ALF calculation.

3.2.7.2 Energy consumption analysis

Monitoring energy consumption – not only determines, but also – may help to improve building energy performance.

Records of electricity consumption were obtained from Contact Energy, who supplied half-hourly meter readings from the home, with authorization from the account holder – i.e. the building owner. Meter readings offer much higher-resolution electricity consumption data than monthly bills do. Solar inverter had not been installed throughout the monitoring period; therefore, the data retrieved from Contact Energy has not accounted for solar produced by PVs on the roofs.

A metering system was installed to measure the amount of electrical energy generated from the PVs on site and electricity imported from the grid. Data collection of electricity generation and load is done 24/7 at a 5-minute data-logging interval. Approximately two months of data from 22/6/17 @14:20 to 23/8/17 @14:57 is used in this study.

3.2.7.3 Shower Efficiency

A flow rate test was carried out to measure water flow rate of the showers. A 45L bucket, a 1L-measuring jug, and a timer were used for this exercise. The measurement was performed at both bathrooms and three times at each to allow a mean to be calculated. Shower was turned on full-blast. The showerhead was held facing towards the 40L bucket to catch all falling water. Using the timer, the bucket was filled for exactly 1 minute. The amount of water in the bucket was then measured with the jug.

3.2.7.4 Room temperatures, relative humidity & CO₂

Two Q-Trak IAQ Monitors (model 7575-X) were employed to monitor air temperatures, RH and CO₂ concentrations in the study building. The loggers were placed in the living area and in the master bedroom (see Figures 3.3 & 3.4). Q-Trak IAQ Monitor 7575 comes with a temperature range from 0°C to 60°C, with accuracy of $\pm 0.5^\circ\text{C}$. The relative humidity accuracy is $\pm 3\%$ in the range of 5 to 95%. CO₂ levels can be measured within a range from 0 to 5000 ppm with accuracy of $\pm 3\%$ of reading or ± 50 ppm. This instrument was chosen because of its memory capacity and its ability to measure temperature, RH, and CO₂ level at the same time. At logging intervals of one-minute, this model can store up to 39 days of data. The indoor temperatures, RH, and CO₂ levels were measured at 10 minutes interval during the monitoring period.

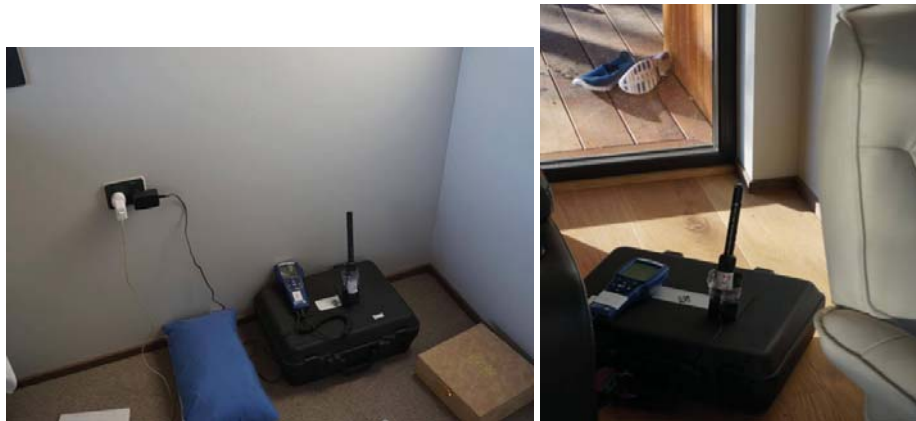


Figure 3.3: Q-Trak Loggers on site – left: master bedroom; right: living area.

The temperature and relative humidity of the outdoors are obtained from the nearest weather station – i.e. the Kyle St, Christchurch automatic weather station.

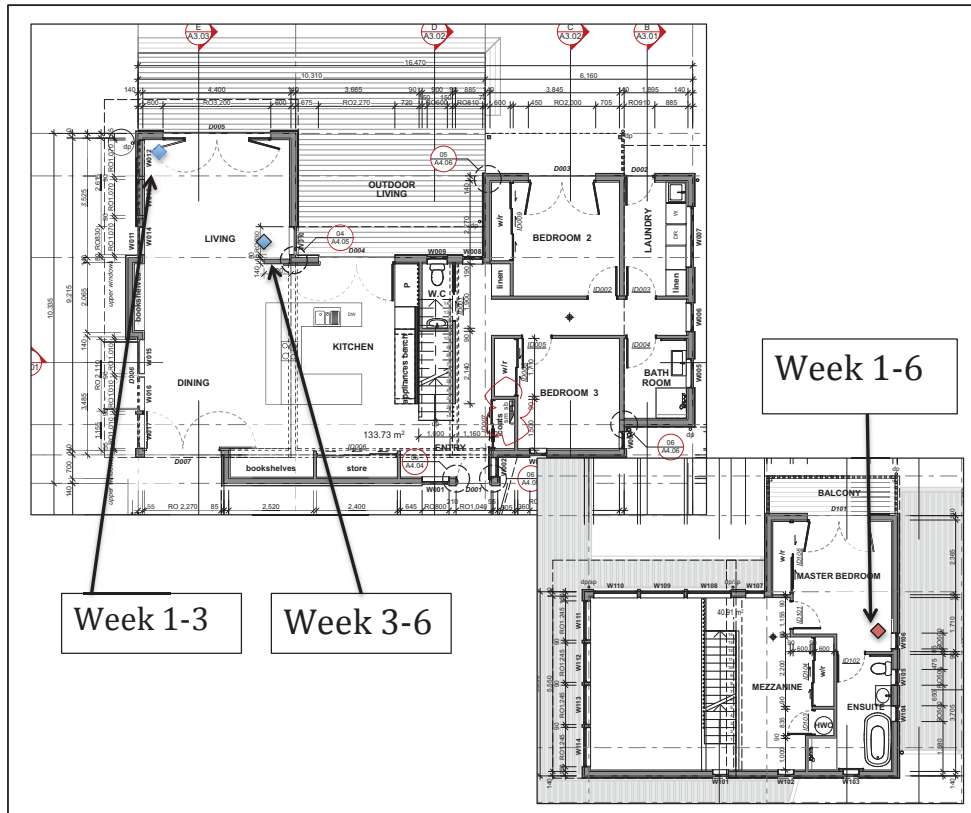


Figure 3.4: Locations of installed Q-Trak loggers – Blue: Living Room QTraks; Red: Master Bedroom QTrak.

3.2.7.5 Surface temperatures

Condensation will appear on a cold surface when the temperature of the surface drops to below the dew point temperature of the indoor air. A surface temperature measurement was undertaken. Sixteen iButton loggers (model DS1921G) were deployed and attached to the inside surfaces of wall, floor, window and window frame, in the living area, master bedroom, bathroom, and kitchen (Appendix 5). iButton is a button-sized chip encased in a stainless steel housing and is 17mm in diameter, 6mm thick and weighting approximately 3g (Figure 3.5). The Thermochron iButton device measures temperature at accuracy of $\pm 1^{\circ}\text{C}$ in the range of -30°C to $+70^{\circ}\text{C}$. The sensors attached to the walls, windows, and window frames were at 1.7 metre above the floor level. The sensors were programmed to monitor the surface temperature every 30 minutes up to 41 days (full memory capacity).

The iButton loggers were not deployed on the ceiling due to height. While the 'walls', 'floors', 'windows' and window frames' temperatures were measured, it

would have been interesting to measure the ceilings' to allow for a three-dimensional assessment of the building internal surfaces.

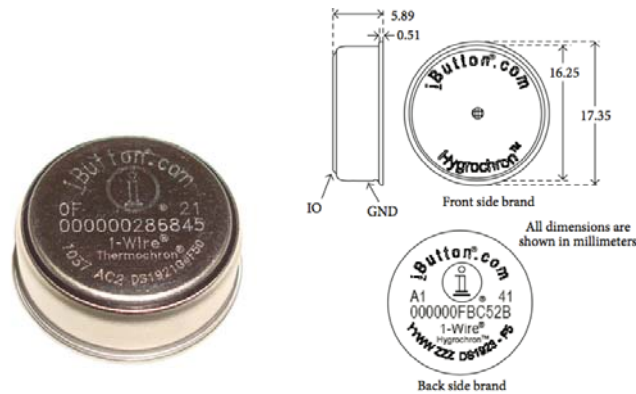


Figure 3.5: Description and photographs of iButton sensor (Fuchs, 2017).

3.2.7.6 Sound transmission measurement

Attenuation performance testing of the façade with speaker generated noise was undertaken. The noise transmission measurements were undertaken indoors and outdoors using Pulsar Nova Model 46 Class 2 sound level meter (SLM). The measurements were designed to be undertaken under unoccupied conditions and with all mechanical openings – e.g. windows and doors – closed.

The measurements were performed on the 31st of July 2017. The sound source and SLM were positioned so that the following separating distances were achieved:

- (a) 3.5 m between the sound source and building surfaces
- (b) 1.5 m between the SLM and building surfaces
- (c) 7 m between the sound source and the SLM (while indoors).

The noise was produced by a speaker generating a white noise located at a distance of at least 3.5m at a 45° angle from the building facades tested. Outdoor noise level was recorded for a period of time that were representative of an $L_{Aeq,1min}$. This is an average noise level over 1 minute. Once that was done, indoor noise levels were recorded at three different locations – i.e. in living area, dining area, and kitchen – for the same duration at each location. This exercise was applied with the loudspeaker facing the following facades: entrance door; dining-area door; and, kitchen-door in the backyard. The positions of the source

loudspeaker and the SLM are shown in Appendix 6.

3.2.7.7 Thermal resistance – thermography

Building thermography – or thermal imaging – is a technique for visualizing heat radiating from the surface of a building envelope using infrared technology. This technique is used to help pinpoint areas where heat losses and air leakage in building envelopes are high. In addition to locating thermal differences, thermal imaging can also be used to determine surface temperature. Thermal cameras are sensitive to radiation that has longer wavelengths than the human eyes can perceive – i.e. they detect radiation that our eyes cannot. Thus, it is a useful means of monitoring the performance of a building envelope (BS EN 13187, 1999; Dall, Sarto & Panza, 2013; Jaques et al., 2017; Overton, 2010; Taylor, 2014).

The general conditions for testing are a prerequisite for the effective use of thermography. The thermographic test was conducted in accordance with the simplified testing requirements of BS EN 13187:1999, under which the specific prescriptive conditions are laid out. Those conditions are as follows:

- For at least the 24h before the start of the exercise and during its execution the indoor-outdoor temperature difference has to be at least 10°C
- For at least the 12h before the start of the exercise and during its execution the building surfaces should not be exposed to direct solar radiation
- During the exercise, the outdoor and indoor temperatures must not vary by more than $\pm 5^{\circ}\text{C}$ and $\pm 2^{\circ}\text{C}$, respectively

A series of thermographic images were taken of various sections of the study building with a FLUKE TiR1 9Hz thermal imaging camera. The thermal imager has a 640 x 480 image resolution and a sensitivity of 70mK, with a thermal wavelength range of 7.5 μm to 14 μm . An aluminium baking pan was used for the measurement of the reflected apparent temperature (Figure 3.6).

The initial thermal images were taken on 31/7/2017 during the final site visit by Pavol Csiba, a certified infrared thermographer – i.e. Level 1 ITC (infrared training center) certification N 2017NZ19N004 –, to ensure competent usage (see

Figure 3.7). The environmental conditions during which the thermography exercise was carried out (9-11 am) was close to ideal for thermographic examination and did comply with the recommendation in BS EN 13187:1999 (Appendix 13). The external and internal air temperature during the test was recorded as 6°C and 22°C respectively. The auditor went through all the installations and examined all the building elements, in order to obtain sufficient data.



Figure 3.6: Visible image and thermogram of the aluminium baking pan.



Figure 3.7: Pavol Csiba operating the FLUKE TiR1.

3.2.7.8 Airtightness

Airtightness of a building significantly affects IEQ. To quantify airtightness, a blower door test to EN 13829:2001 Standard was completed on the study building post-construction on 30/05/17. The specific device used was a Model

4/230V Blower Door System manufactured by The Energy Conservatory.

The blower door was mounted into the frame of one of the exterior doors. The device then pressurized (blow into) and depressurized (blow out of) the house; typically forcing a 50 Pascals pressure difference. Prior to the testing, all openings (such as passive vents) were sealed. The blower door test allowed measurements of air leakage through the building envelope to be made. From the blower door measurement, an airtightness value was obtained.

3.2.7.9 Occupant satisfaction survey

An occupant survey is an effective and practical method for measuring environmental conditions of a facility. A questionnaire survey involving occupants at the study building was conducted to demonstrate occupants' perspectives on the building's post-occupancy performance. The Building in Use Studies (BUS) questionnaire was selected as the tool the researcher used to collect the data needed to accomplish this objective. The use of the BUS questionnaire was primarily for capturing overall occupants' evaluation in regards to the IEQ of the study home. A license to download and use the BUS questionnaire was gained for the purpose of conducting the survey. The questionnaires were delivered to the occupants on 25/7/17 via post and collected on the final site visit.

The BUS questionnaire is applied internationally and has been used extensively in POE research worldwide (Leaman, 2012, as cited in Onyeizu, 2014). The questionnaire contains questions which are concerned with building environmental performance and operational matters. It uses a structured Likert scale of 1-7 – where a '7' would represent the best score –, over 45 key variables evaluated in the questionnaire, covering aspects such as thermal comfort, lighting, personal control, noise, space, design, health, needs, lifestyle and utilities costs. The questionnaire also allows for qualitative feedback to be obtained. While respondents can rate the various variables of building performance, they can also provide comments. In this research only variables addressing IEQ were considered in the evaluation. Table III-2 highlights the

variables concerned and investigated in the survey that are relevant to this research. A sample of the BUS questionnaire is in Appendix 7.

Table III-2: BUS Questionnaire Variables Evaluated.

Questionnaire Variables	Description
Background	The age and sex of respondents. It is relevant to occupants' needs in a living space. It also has an impact on the occupants' behavioural response to an environment.
Residence Overall	Occupants' opinions in regards to location, space provision, layout, storage, and appearance.
Needs	Things in the facility that work well and poorly
Comfort	Temperature and air conditions during winter and summer. This describes the actual conditions during the winter and summer seasons of the year.
Noise	The noise in living space. The variables that were investigated are noise overall, noise from people between rooms, noise from neighbours, other noise from outside.
Health (Perceived)	The health of occupants in the building. It aims to identify if occupants feel more or less healthy.
Design overall	Occupants' satisfaction towards the design
Personal control over IEQ	Occupants' level of personal control over heating, cooling, ventilation, lighting and noise.

3.2.8 Step 7 – Data analysis

There is considerable amount of data collected during monitoring of the SUPERHOME. Therefore, it has been important that the collected data are put in place in a manner that is manageable.

To ensure measurements from the analysis have context, the study homes certification protocols initially, benchmarks set by the current building code and international guidelines, have been used to provide targets against which to assess the study homes.

3.2.8.1 Energy consumption analysis

Electricity use

Data analysis of energy consumption for the study building was conducted by examining the household electricity consumption to get the household means on a daily and hourly basis, which were then used to give estimates of consumption during winter months. Furthermore, a comparison was drawn between the

estimated energy use and the heating energy requirement as calculated by the ALF 3.2.

The data retrieved from the metering system measuring solar-generated and grid-import electricity was accounted for in the analysis. This data was used to give an estimate of potential buybacks thus savings to be made once a solar inverter is installed. For ease of comparison, energy data is reported in units of kilowatt-hours (kWh).

Water use

Analysis for the shower flow rate test was done by comparing the results to the recommended standard of less than 9 LPM for Homestar™ 6-10 equivalent homes.

3.2.8.2 IEQ monitoring analysis

Room temperatures, relative humidity & CO₂

The Q-Trak data loggers were used to monitor the IAQ in living area and master bedroom. The monitoring data was used for each location separately and combined to give an estimate of the average indoor air temperatures, relative humidity, and CO₂ levels. This separation provides more detail on how internal conditions vary across different areas within the building. Subsequently, the data was divided to cover four different time periods, i.e., morning (7am-9am), day (9am-5pm), evening (5pm-11pm), and night (11pm-7am). This provides more detail on variations in internal conditions across the day.

The monitoring data was used to determine the length of sub-standard indoor conditions by recording the time the indoor temperature, relative humidity and CO₂ concentrations were outside recommended ranges. This study refers to a range of standards in defining limits or criteria for comfort (Table III-3).

Table III-3: temperature, relative humidity & CO₂ thresholds.

	Temperature (WHO, 1987)	Relative Humidity (WHO, 1990)	CO₂ levels (NZS 4303:1990)
Comfortable	18°C/20°C -24°C	30-50%	<1,000 ppm
Posing health risks	<18°C, <i>high blood pressure</i> <16°C, <i>respiratory infections</i> <12°C, <i>stress on the cardiovascular system</i>	<30%, <i>dryness and irritation symptoms</i> >50%, <i>respiratory infections</i>	N/A

Surface temperatures

In order to monitor the variation in indoor surface temperatures, iButton data loggers were attached to the wall, floor, window and window frame surfaces across different areas in the building. Comparisons were made between the surfaces temperatures and air dew-point temperatures to see if condensation occurred on the surfaces. Calculations of dew-point were performed using the following formula (Wanielista, Kersten & Eaglin, 1997):

$$T_d = ((RH/100)^{(1/8)} * (112 + 0.9 * AT)) + (0.1 * AT) - 112$$

Where:

T_d: dew point temperature expressed in °C

AT: air temperature expressed in °C

RH: relative humidity expressed in %

Noise transmission

The noise transmission measurement was undertaken to estimate the indoor/outdoor noise level ratio. Using the TL values obtained, the OITC was obtained using the method discussed in section 2.2.5. Result from the test was then compared against the minimum requirement for noise transmission level set by the NZBC of no lower than 50dB.

Airtightness – blower door test

A blower door test to EN 13829 (2001) standard was carried out on the study building. The airtightness measurement were used to give an estimate of the mean infiltration through the envelope using the /20 rule of thumb described in section 2.3.2.4. The results were compared to the airtightness requirement of 3 ACH@50 Pa set out by the 2015 IECC.

Thermal resistance – thermography

The end result of thermography is a visual display called a thermograph. The resultant thermal images can be interpreted by the colouring on the subjects. Colours in the images indicate the amount of infrared radiation coming from a surface. The cooler temperatures (usually indicating high conductivity) are blue, then green, while the warmer temperature usually indicating low conductivity are orange, then red. Window surfaces would appear to be cooler than they are because glass reflects the cold temperature radiation coming from outside. This applies to other highly reflective surfaces as well.

As recommended in BS EN 13187:1999, the results of thermography “have to be interpreted and assessed by persons who are specifically trained for this purpose” (p. 3). The interpreter – who is also the camera operator – completed thermal imaging training to ensure competent interpretation.

The thermal images were processed through the use of specific software called Fluke Connect™. The software takes into account parameters that affect the accuracy of the measurements such as the environmental conditions recorded at the time of the survey, the target distance, and reflected temperature.

3.2.8.3 Survey analysis

The completed questionnaires were processed by BUS Ltd. The mean performance score of the building was compared against a database of scores of the most recent 47 buildings surveyed using this questionnaire in the UK. The surveyed building is compared to the benchmark mean and graded as being ‘Better’, ‘Similar’, or ‘Worse’. The building performance for each variable evaluated is considered ‘Better’ or ‘Worse’ if achieving a mean score outside the

95% confidence intervals of the benchmark and 'Similar' if within the confidence intervals range (Dykes, 2012).

Under the assessment methodology of the BUS, there are three ways of portraying the performance of buildings. One is a bar graph showing the percentage of respondents with different levels of satisfaction for individual questions of the questionnaire. Two is a slider, designed to display the mean score relative to the mean and confidence intervals for the benchmark. Three is a percentile graph, visualizing the position of the building in relation to the other buildings making up the benchmark (Dykes, 2012).

3.2.9 Step 8 – Results reporting

Specific results from the investigation carried out on the case study building are presented and discussed. Indeed, having only investigated one case study, the findings of this research cannot be generalized. But, that allowed an in-depth investigation about the post-occupancy performance of a 'green' home to be realized. Upon completion of the research work, findings were documented and submitted as a Master's Thesis as part of the completion of the programme of Master of Environmental Management, Massey University.

In addition, a three-page report summarising the results of the study building's evaluation along with key conclusions and recommendations was provided to the SHM.

Chapter 4: Results & Data Analysis

4.1 Introduction

The objective of this chapter is to report the energy performance, shower efficiency, IEQ, airtightness, thermal fitness and occupant satisfaction levels of the SUPERHOME.

4.2 ALF modelling

Results using ALF modelling to predict annual heating energy requirements are presented in Table IV-1. Using the ALF method to calculate the required heat output, to maintain 20°C in the living area with an ambient temperature of around 6°C, a minimum of 24.66 kWh heat output will be needed daily. With the same ambient temperature, a daily minimum of 19.02 kWh heat output will be required for the living area temperature to be maintained at 18°C.

Table IV-1: Heat Loss & Gain Summary.

	Heating Level	
	20°C	18°C
Heat Loss (kWh/Year)		
Slab Floor	1477.17	1207.66
Wall	2161.29	1766.97
Window	5458.97	4462.99
Roof	1053.78	861.52
Air Leakage	1798.41	1470.29
Total	11949.62	9769.43
Heat Gain (kWh/Year)		
Internal Gain	3539.81	3539.81
Usefulness of Gains	83.27%	79.91%
Useful Gains	2947.49	2828.73
Required Heating Energy	9002.12	6940.7

4.3 Electricity consumption

Results on purchased electricity came from two sources of information: meter readings from Contact Energy and from the installed metering system. Figure 4.1 shows the mean daily purchased energy (which was electricity) consumption in the study building. As this study refers to electricity data during winter, annual consumption rate cannot be determined. The highest daily consumption recorded was 82.27 kWh, and the lowest was 16.15 kWh. Overall, the estimated daily energy consumption is at 47.96-50.58 kWh per day, giving a monthly consumption of 1478.1-1527.4 kWh during winter or an

electricity performance indicator ($EnPI_{elec}$) of 8.46-8.75 kWh/m²/month. With the number of occupants taken into account, this is equivalent to around 492.7-509.12 kWh/occupant/month. These figures suggest an estimate of total consumption of 4412.01-4653.35 kWh over 92 winter days.

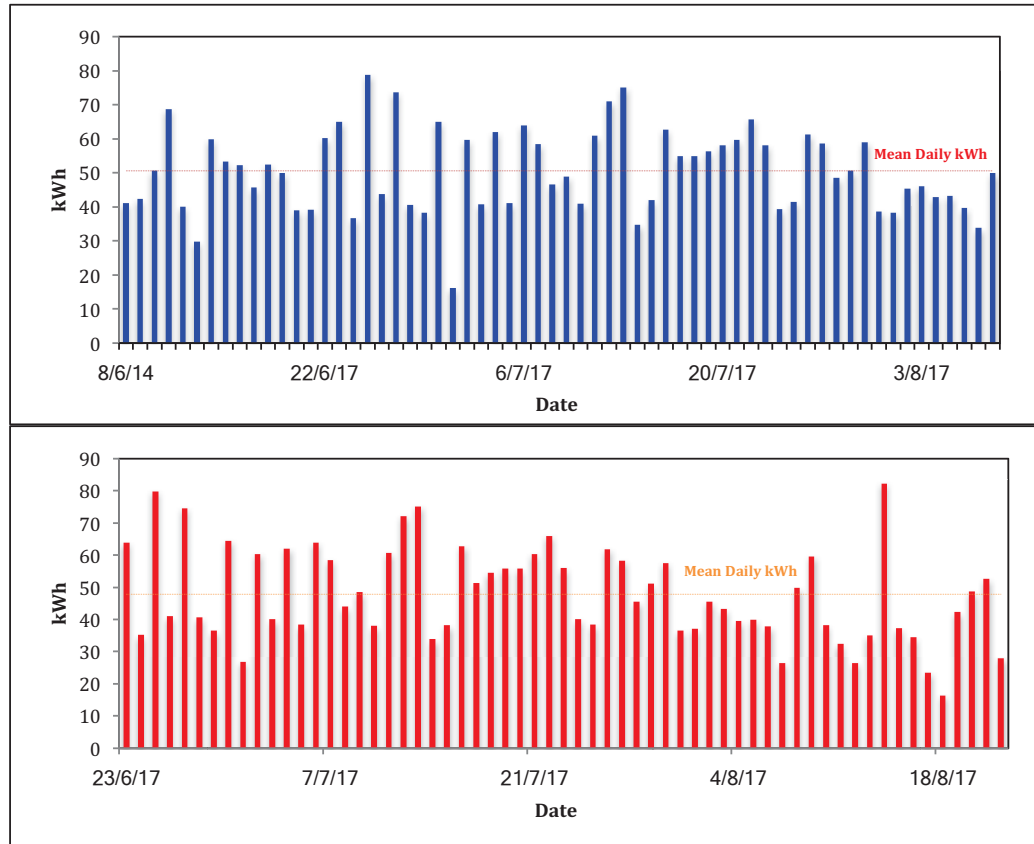


Figure 4.1: Winter mean daily purchased electricity use - Top: Contact Energy data; Bottom: Metering data.

The measured 24-hour mean electricity consumption patterns for the case study building are shown in Figure 4.2. ‘High daily consumption’ represents the 24-hour profile when the daily consumptions were above the daily average, whereas ‘Low daily consumption’ represents the 24-hour profile when the daily consumptions were below the daily average. Electricity use peaked in the morning around 8:00-9:00 am and again in the evening at 8:00 pm. Consumption dropped during the daytime, most likely due to low level of occupancy of the space. At night, when the electricity use was at its lowest point, the readings went down to approximately 1.24-1.31 kWh/hour.

A comparison was made of electricity use patterns during weekdays and weekends, as presented in Figure 4.3. On average, there was no notable difference of daily consumption between the weekends and weekdays. There were however discrepancies

in electricity use from 17:00 to 20:00, giving an indication that more household activities might be occurring during early evenings in weekends than in weekdays.



Figure 4.2: Winter 24h electricity use profiles – Top: Contact Energy Data; Bottom: Metering Data.

An estimate of winter electricity charges for the study home can be calculated by multiplying the expected energy use by the corresponding tariff, plus GST (Table IV-2). This rate is likely to drop in the summer months. Contact Energy offers a prompt payment discount and the costs presented here are without the prompt payment discount. Since the solar inverter had not been installed the total estimated costs of electricity are high, with estimated charges of \$1366.82 - \$1436.92 throughout the 92 days of winter.

An analysis has been performed for electricity consumption with with-solar-inverter-installed scenario using data from the wattage readings by the metering system installed. The analysis was done on an hourly basis to see the amount of wattage that would have been covered by generation from the PVs for every hour that electricity is used. The study home has a 3.42kW system in place generating an average of 6.87kWh/day (Table

IV-3). The electricity generated by the panels is used to power the house first and the excess, if any, gets exported to the grid for buyback – at a rate of 8¢/kWh, excl. GST.

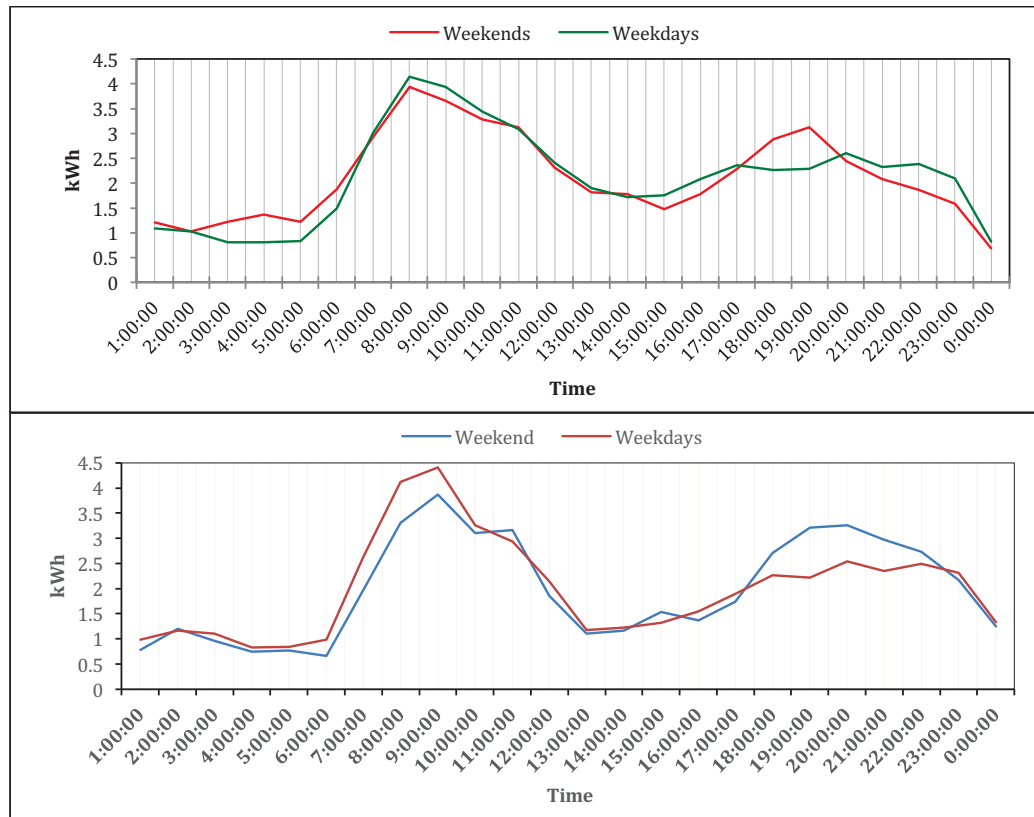


Figure 4.3: Average winter 24h electricity use profile – weekends & weekdays – Top: Contact Energy Data; Bottom: Metering Data.

Table IV-2: Estimate of purchased electricity charges without PV - winter.

Fixed daily charges

<i>Daily Charge</i>	92 days @ 80.500 cents per day	\$74.06	
<i>Fixed charges total</i>		\$74.06	
<i>Variable charges</i>		4412.01 kWh	4653.35 kWh
<i>All Day Economy</i>	@ 25.100 cents per kWh	\$1107.42	\$1167.99
<i>Electricity Authority Levy</i>	@ 0.16 cents per kWh	\$7.06	\$7.45
<i>Variable charges total</i>		\$1114.48	\$1175.44
<i>Fixed & variable charges</i>		\$1188.54	\$1249.50
<i>GST (15%)</i>		\$178.28	\$187.42
<i>Total charges</i>		\$1366.82	\$1436.92

As can be seen from Figure 4.4, the solar system could not cover the electricity needs in the building on a daily basis. On average, energy generated by the solar panels would only cover around 18% of daily energy use in the building. From 22/6/17 to 23/8/17,

433.76 kWh was generated via the photovoltaic panels. During the same period, 2,972.64 kWh of electricity was used for consumption. The number of hours where consumption would have been fully covered by generation from the PVs was 82 hours with total consumption of 48.84 kWh and solar excess of 52.75 kWh. There were times when solar energy was not used – thus, would have been exported straight to the grid – due to zero need for electricity in the building. These surpluses summed up to 141.61 kWh. The total excess of solar-generated electricity was therefore 194.36 kWh.

Table IV-3: Daily energy usage and energy generated during winter.

		Mean Daily (kWh/day)
Grid-drawn electricity	Source: Contact Energy	50.58
	Source: Metering system installed	47.96
Solar-generated electricity		6.87

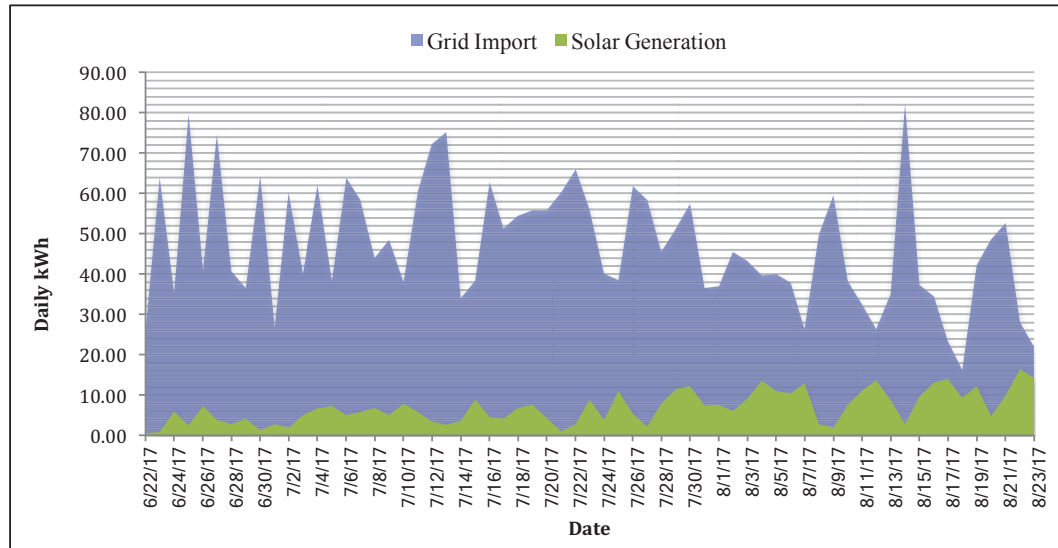


Figure 4.4: Purchased versus generated electricity – winter (22/6/17-23/8/17).

The solar PVs generated most electricity during daytime hours as would be expected – as this aligns with peak solar radiation (Figure 4.5). But, at most – especially, during hours of high demand or low solar radiation – the solar system did not meet the electricity needs in the building and the house imported some electricity from the grid.

More electricity was generated by the PVs on typical sunny days than on overcast days. Figure 4.6 demonstrates the 24-hour profile of electricity used and generated on typical sunny winter days (the 16/8/17 and 22/8/17 data are used for the demonstration). At least, 13.18 kWh and 16.42 kWh of electricity were produced on 16/8/17 and 22/8/17 respectively – higher than the 6.87 kWh daily generation average. The minus (-) figures

represent the wattage (kW) that was exported back to the grid as the load (home) did not need the electricity. Surpluses of electricity of 7.15 kWh and 10.53 kWh would have been produced during daytime hours on 16/8/17 and 22/8/17 respectively.

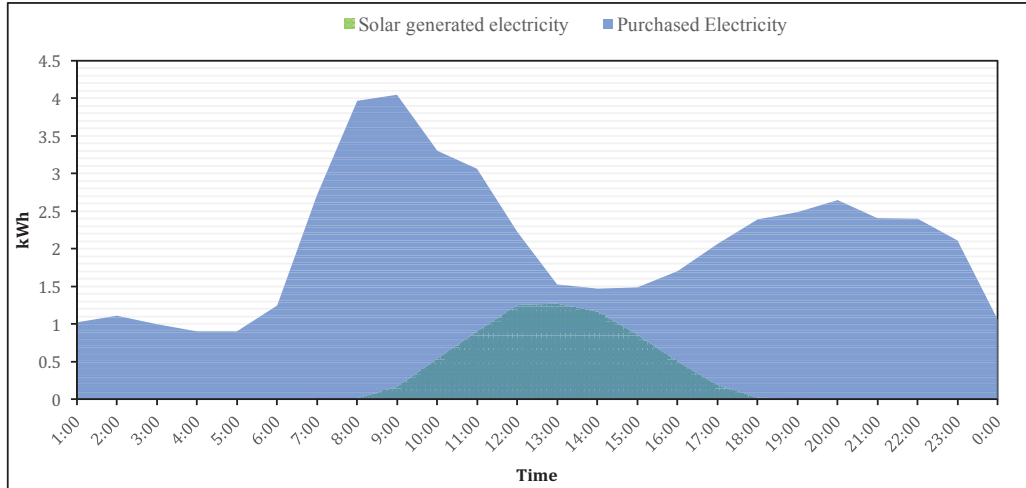


Figure 4.5: 24h profile of purchased versus generated electricity – winter daily average (22/6/17-23/8/17).

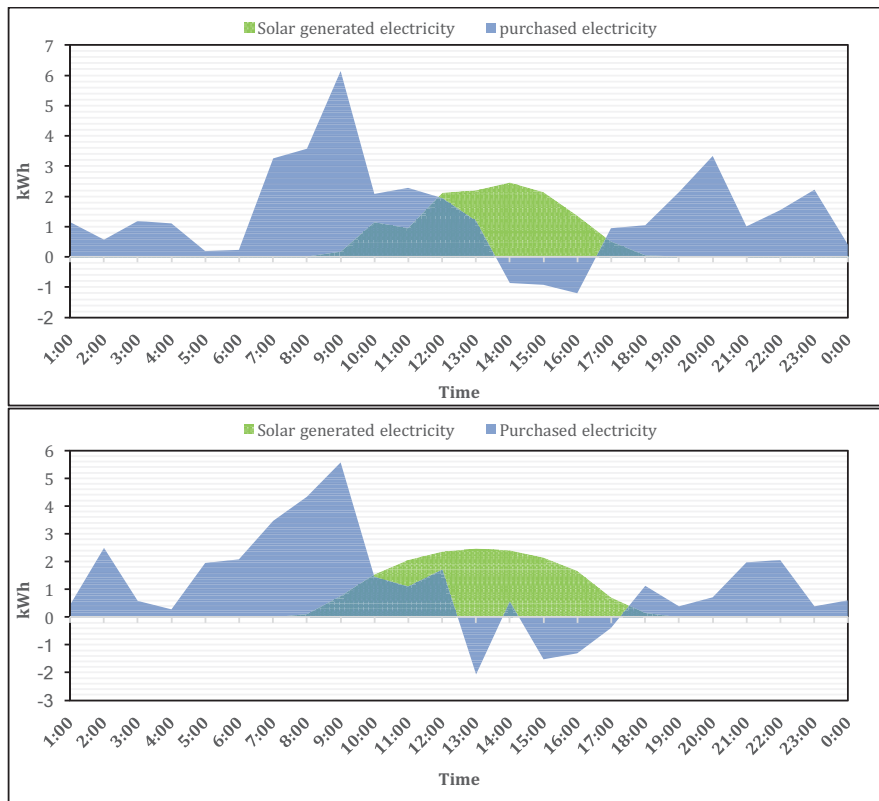


Figure 4.6: 24hr profile of purchased versus generated electricity on typical sunny winter days – Top: 16/8/17 Data; Bottom: 22/8/17.

Figure 4.7 demonstrates the 24-hour profile of electricity used and generated on typical overcast winter days (the 21/7/17 and 9/8/17 data are used for the demonstration). 1.08

kWh and 1.89 kWh of electricity were produced on 21/7/17 and 9/8/17 respectively. On the same days, 60.31 kWh and 59.51 kWh of electricity were purchased on 21/7/17 and 9/8/17 respectively for consumption. Electricity generated by the PVs would have only covered 1.8% and 3.18% of the total consumption on these days.

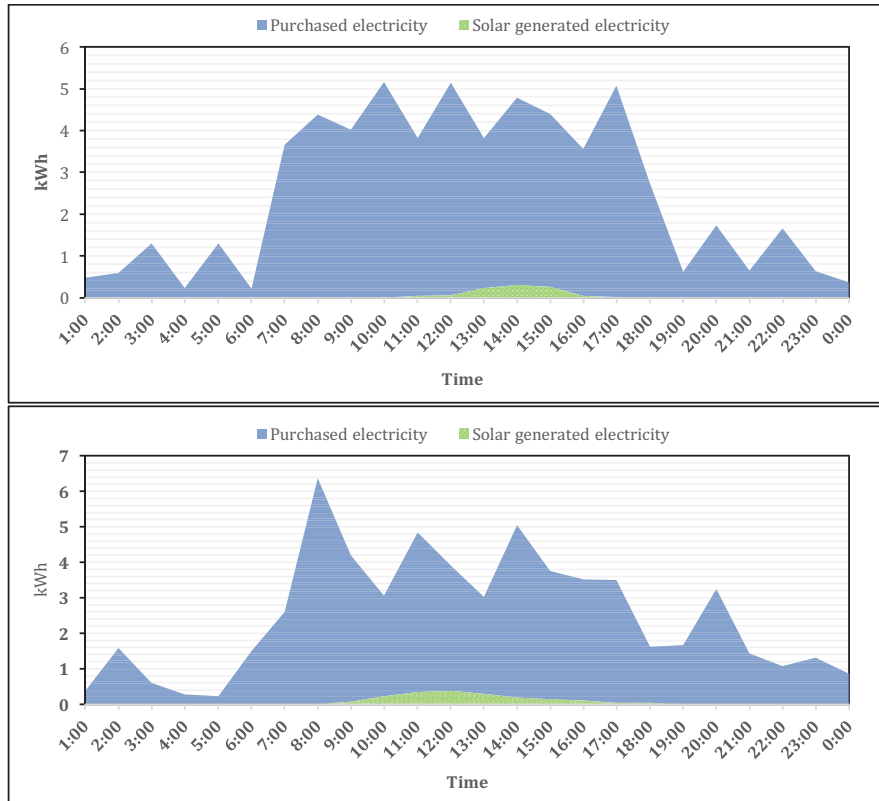


Figure 4.7: 24 hr profile of purchased versus generated electricity on typical overcast winter days – Top: 21/7/17 Data; Bottom: 9/8/17.

Figure 4.8 demonstrates the 24-hour profile of electricity used and generated on the days when consumptions were high (the 27/6/17 and 14/8/17 data are used for the demonstration). The PVs generated 3.92 kWh and 2.81 kWh of electricity on 27/6/17 and 14/8/17 respectively, which would have only covered 5.25% and 3.41% of the total consumption on these days.

Figure 4.9 demonstrates the 24-hour profile of electricity used and generated on the days when consumptions were low. The 1/7/17 and 18/8/17 data are used for the demonstration). 26.77 kWh and 16.31 kWh of electricity were purchased for consumption on 1/7/17 and 18/8/17 respectively. Surpluses of electricity of 1.23 kWh and 8.48 kWh would have been produced during daytime hours on 1/7/17 and 18/8/17 respectively.

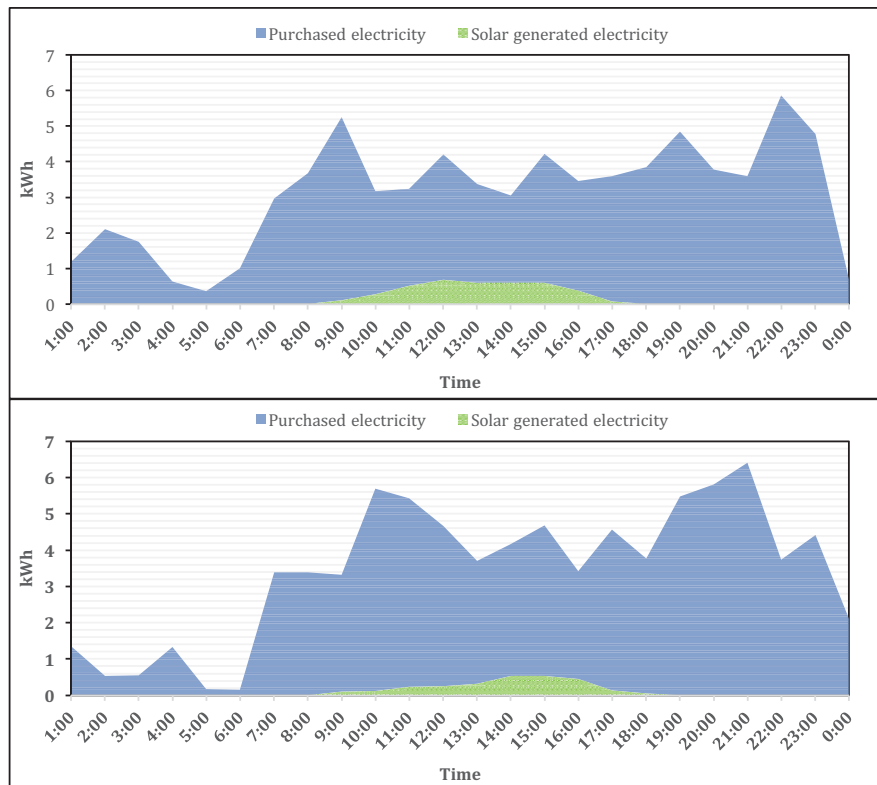


Figure 4.8: 24 hr profile of purchased versus generated electricity on typical winter days with high electricity use – Top: 27/6/17 Data; Bottom: 14/8/17.

The financial result is calculated by adding the savings made on electricity bills and income made from selling surplus energy. Without the PVs, 2,972.63 kWh of electricity used would have cost \$920.92 in electricity bills. With import of electricity from the PVs, only 2,782.11 kWh of grid-import electricity would be needed. The savings on electricity bills achieved by using solar are estimated as $\$920.92 - \$865.56 = \$55.36$ (Table IV-4). The income to be earned from selling 194.36 kWh excess solar-generated energy would be \$15.55. For two months of winter data, the solar system valued at $\$55.36 + \$15.55 = \$70.9$. Note that this value is only estimation based on data recorded by the solar metering system installed, since the solar inverter had not been installed.

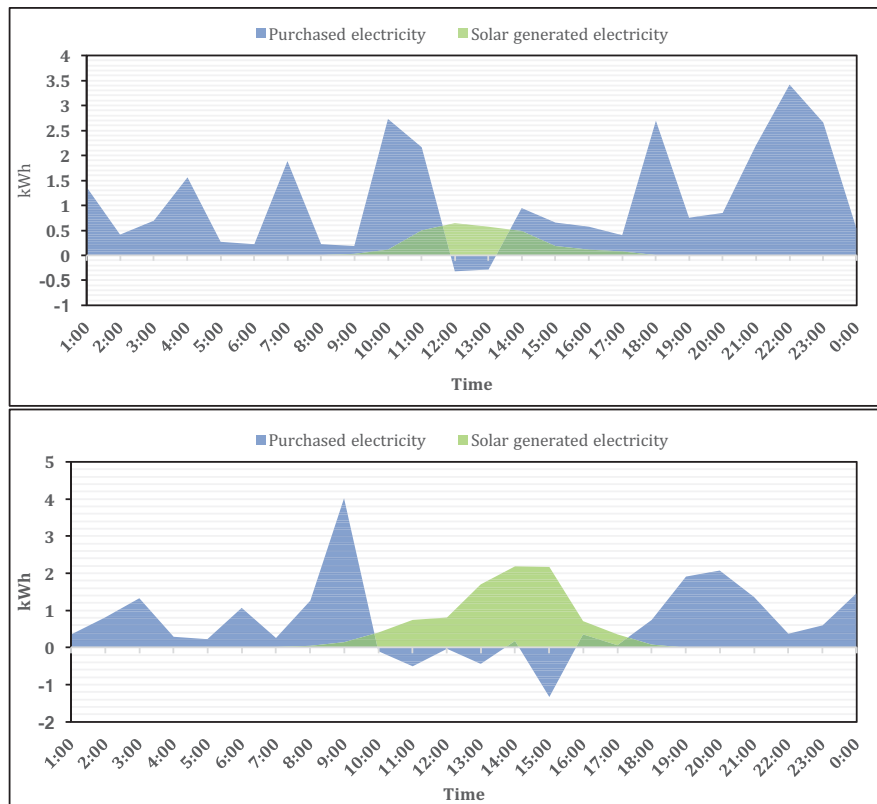


Figure 4.9: 24 hr profile of purchased versus generated electricity on typical winter days with low electricity use – Top: 1/7/17 Data; Bottom: 18/8/17.

Table IV-4: Costs estimate with and without solar - 62 days during winter.

Fixed daily charges			
Daily Charge	62 days @ 80.500 cents per day		\$49.91
	Fixed charges total		\$49.91
Variable charges		2,972.63 kWh	2,782.11 kWh
All Day Economy	@ 25.100 cents per kWh	\$746.13	\$698.30
Electricity Authority Levy	@ 0.16 cents per kWh	\$4.76	\$4.45
	Variable charges total	\$750.89	\$702.75
	Fixed & variable charges	\$800.80	\$752.66
	GST (15%)	\$178.28	\$120.12
	Total charges	\$920.92	\$865.56

4.4 Shower efficiency

In total, three measurements were taken (Table IV-5). An average flow-rate of 7.84 litres per minute was achieved. This complies with Homestar™ 6-10 Star requirement for shower efficiency of less than 9 litres per minute. Assuming an average time spent on shower of 7.8 minutes per person each day throughout the year (Heinrich, 2007), the average daily use for shower would be 183.5 litres.

Table IV-5: Shower flow rate test results.

Sample	1	2	3
Shower 1 (L/m) <i>Ensuite</i>	8.00	7.84	8.10
Shower 2 (L/m) <i>Ground Floor Bathroom</i>	7.75	7.75	7.60

4.5 IEQ

The following section demonstrates the acoustics, air temperatures, indoor surfaces temperatures, relative humidity and CO₂ levels experienced in the SUPERHOME studied.

4.5.1 Noise transmission level

A summary of the sound transmission test results is given in Table IV-6. The values quoted are for the performance with mechanical openings closed.

The living area, dining area and kitchen had an even distribution of noise levels. None of these areas was significantly more exposed to the outdoor noise than the other. Sound transmission loss of 28dB, 33.3dB, and 37.8dB in living area, kitchen and dining area respectively were achieved with the loudspeaker placed 5.66m facing the entrance door (D001). When the loudspeaker was placed 5.66m facing the dining area door (D007), sound transmission loss of 33.9dB, 33dB, and 33.7dB were achieved in living area, kitchen and dining area respectively. Furthermore, reduction of 36.8dB, 31.1dB, and 36.1dB were recorded with the loudspeaker located backyard, 4.95m facing door D004. Positioning of the loudspeaker are illustrated in Appendix 6.

Details of the outdoor indoor transmission class (OITC) calculation are provided in Appendix 8. The OITC of the building outdoor-indoor partitions is 27.57 db(A). This is below the required minimum of 50 dB (Mahn, Davy & Pearse, 2011; Walther & Beattie, 2013).

Table IV-6: Noise transmission loss test results.

With Loudspeaker				
	Outside (1)	Living Area	Kitchen	Dining Area
Duration	00:01:16	00:01:03	00:01:32	00:01:03
SPL	78.8 dB	67.5 dB	58.1 dB	45.6 dB
	(LAFmax)	(LAFmax)	(LAFmax)	(LAFmax)
	58.92 dB	45.94 dB	41.07 dB	38.5 dB
	(LAFmin)	(LAFmin)	(LAFmin)	(LAFmin)
LAeq	77.6 dB	49.6 dB	44.3 dB	39.8 dB
LCPeak	92.5 dB	92.4 dB	79.7 dB	75.3 dB
	Outside (2)	Living Area	Kitchen	Dining Area
Duration	00:01:04	00:01:07	00:01:05	00:01:03
SPL	76.8 dB	60.5 dB	49.0 dB	54.6 dB
	(LAFmax)	(LAFmax)	(LAFmax)	(LAFmax)
	74.59 dB	36.07 dB	41.45 dB	40.07 dB
	(LAFmin)	(LAFmin)	(LAFmin)	(LAFmin)
LAeq	75.6 dB	41.7 dB	42.6 dB	41.9 dB
LCPeak	91.2 dB	83.7 dB	73.0 dB	81.3 dB
	Outside (3)	Living Area	Kitchen	Dining Room
Duration	00:01:16	00:01:05	00:01:10	00:01:03
SPL	77.3 dB	49.0 dB	56.0 dB	57.7 dB
	(LAFmax)	(LAFmax)	(LAFmax)	(LAFmax)
	74.29 dB	36.86 dB	41.7 dB	36.31 dB
	(LAFmin)	(LAFmin)	(LAFmin)	(LAFmin)
LAeq	75.8 dB	39.0 dB	44.7	39.7 dB
LCPeak	90.9 dB	75.8 dB	74.1	74.2 dB

4.5.2 Room temperatures

Temperatures have been examined over the winter periods. Winter temperatures were measured from mid-June through to the end of July. This data is presented in the following section.

During the second site visit it was discovered that the two loggers installed had stopped logging data at sample unit 295, which is equivalent to 49 hours and 10 minutes of data. During the third site visit the logger set up in the living area was found off and had stopped logging data at sample unit 279, recording 46 hours and 30 minutes of data. In total the logger recorded a total of 99 hours and 59.6 minutes of data in the living area, compared to 550 hours and 40 minutes of data recorded in the master bedroom. The issues around monitoring and data collection experienced are discussed in Appendix 4.

Table IV-7: Winter room and ambient temperatures for the period of 20/6/17 to 31/7/17.

Area	Mean °C	Median °C	Minimum °C	Maximum °C
Living Area	21.2	20.7	17.9	33.4
Master Bedroom	19.8	19.5	15.6	34.5
Ambient	6.7	7.0	-3.4	16.5

Table IV-7 presents the mean, median, minimum and maximum temperatures for each of the areas examined in the study home and the ambient temperature. The temperatures inside the house were much warmer than outside. The living area was on average warmer than the master bedroom (21.2°C vs. 19.7°C), which is consistent with the floor heating being located on the ground floor. The living area and master bedroom reached the coldest room temperatures of 17.9°C and 15.6°C each – which are below the required minimum for healthy temperature of 18°C (WHO, 1987). A maximum of 33.4°C was reached in the living area which was slightly less than the maximum reached in the master bedroom of 34.5°C. Figure 4.10 shows the temperature profiles when the areas were exposed to these maximum temperatures. Both are relatively unusual temperatures to reach during winter. One probable cause could be that the loggers were exposed to excessive sunlight at the time these maximums were reached.

Figure 4.11 demonstrates the average, maximum and minimum winter temperature 24-hour profiles. The temperature profiles show the indoor temperature patterns during a day for the 6-week monitoring period and are compared with the 24-hour average ambient temperature profiles for the same period. The 24-hour ambient temperature profiles were calculated by averaging the measured hourly profiles for each day throughout the monitoring period – i.e. 20/6/2017–31/7/2017. The internal temperatures can be seen to rise and fall at the same time as the external temperature. The highest and lowest temperatures recorded in the living area were 33.4°C at 10 am and 17.9°C at 9 am. The highest and lowest temperatures recorded in the master bedroom were 34.5°C at 3 pm and 15.6°C at 6 am.

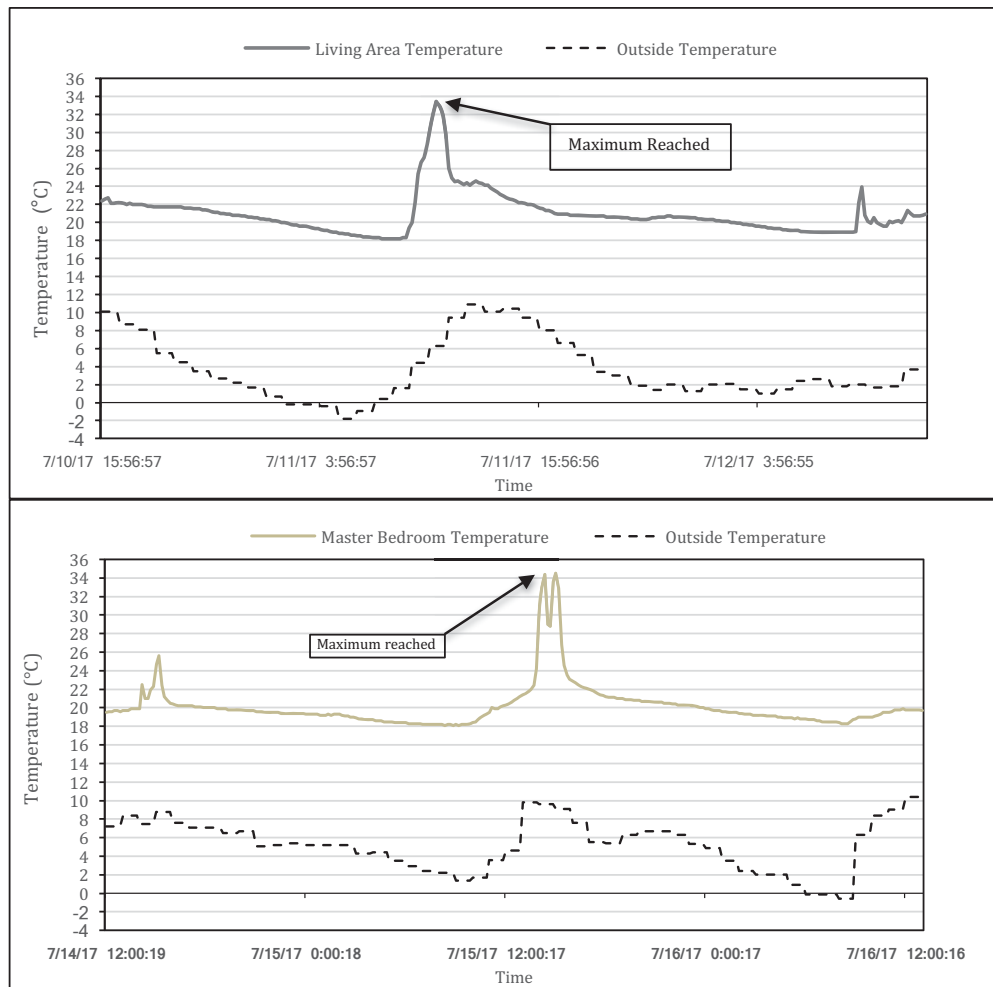


Figure 4.10: Temperature profiles when maximum temperatures were reached.

Table IV-8 gives the mean, median, minimum and maximum temperatures for the four different periods during the day for the areas examined within the study building and ambient temperature. The time periods are morning (7 am – 9 am); day (9 am – 5 pm); evening (5 pm – 11 pm); and night (midnight – 7 am). The study home, with an average winter evening temperature of 20.8°C, was warmest during the day - peaking around 3 pm - and least warm during morning hours. The difference between ambient and internal temperature appeared to be greatest during night-time – for both rooms it was a difference of over 13.9°C. The smallest difference between ambient and internal temperature occurred during daytime hours – for both rooms, the difference was less than 14.0°C. The bedroom was less warm than the living area – at most a difference of 2.1°C occurred during daytime. The mean living area and bedroom temperatures increased during the morning period, but dropped between day and evening, in the evening, and again overnight. The temperature increase

between morning and daytime was most likely due to increase in solar radiation and internal gains.

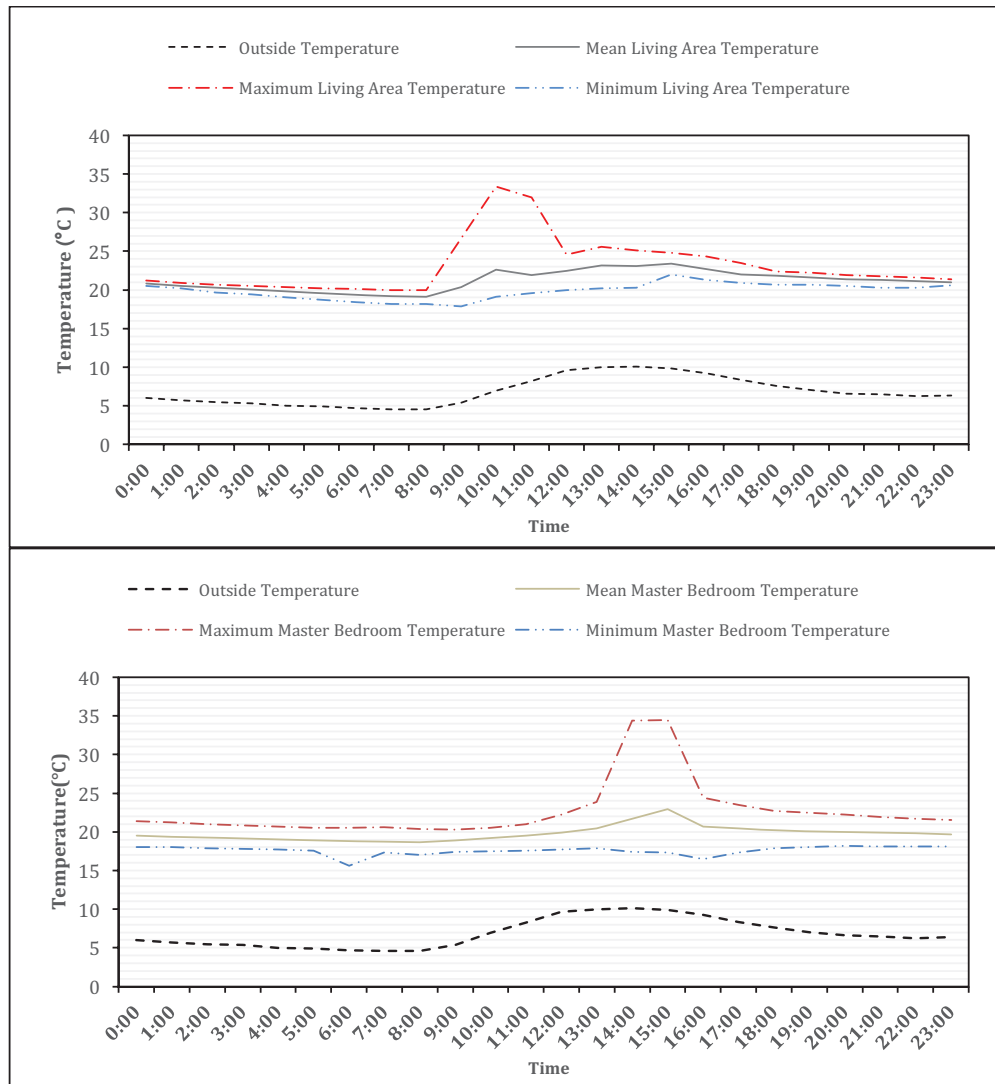


Figure 4.11: Average 24-hour temperature profiles for the period of the monitoring.

Table IV-8: Mean temperatures at different times of the day for the period of the monitoring.

Area	Morning	Day	Evening	Night
Mean temperatures (°C)				
Living Area	19.1	22.6	21.4	20.1
Master Bedroom	18.7	20.5	20.0	19.2
Ambient	4.9	8.7	6.7	5.3
Median temperatures (°C)				
Living Area	19.1	22.5	21.5	20.2
Master Bedroom	18.7	19.9	19.9	19.1
Ambient	5.5	9.6	6.7	5.8
Minimum temperatures (°C)				
Living Area	18.2	17.9	20.3	18.3
Master Bedroom	17	16.5	17.7	15.6
Ambient	-2.2	0.9	-1.6	-3.4
Maximum temperatures (°C)				
Living Area	20	33.4	22.4	21.3
Master Bedroom	20.5	34.5	23.1	21.5
Ambient	10.7	16.5	12.6	12.6

4.5.2.1 Healthy temperatures

As noted earlier, a healthy range for indoor temperatures has been established as 18°C-24°C, and 20-24°C, for vulnerable population (WHO, 1987).

Table IV-9 shows the proportion of time the study home was in and out of this range for each of the areas examined in the study home. In the master bedroom, 20°C was more difficult to reach than 18°C. The living area temperature data had a different pattern, with only 23.5% of data recorded temperatures of less than 20°C. However, both living area and master bedroom temperatures were maintained within the WHO's recommended healthy range for 89.5% and 92.6% of the time that the areas were monitored respectively. 10.3% of data recorded temperatures of more than the allowed maximum of 24°C in the living area. The proportion of time that the master bedroom temperatures were above 24°C was 2.1%.

Table IV-9: Proportion of time in each temperature range over 24 hrs for the period of the monitoring.

Area	<18°C (%)	18-24°C (%)	< 20°C (%)	20-24°C (%)	>24°C (%)	Hours Measured
Living Area	0.2	89.5	23.5	66.2	10.3	99.99
Master Bedroom	5.4	92.6	66.4	31.5	2.1	550.67

Table IV-10 shows the proportion of time spent within and outside temperature range – i.e. below 16°C, between 16°C and 18°C and above 24°C – for each of the areas during occupied periods. Although nearly 30% of outside-range temperatures occurred during daytime, the case study building presented healthy living area temperatures during the evening, with the occupants never being exposed to temperatures outside the range. The master bedroom had fairly healthy night-time temperatures, maintaining the room within the comfort range for 94.75% of the time. The bedroom got colder than 18°C for 5.25% of the total monitoring period at night. This is equivalent to at least half an hour each night.

Table IV-10: Proportion of time in each temperature range during occupied time periods for the period of the monitoring.

Area	Temperature range °C						Hours Measured	Time Period
	<16	16-18	18-24	< 20	20-24	>24		
Living Area	0	0.46	70.83	13.43	57.86	28.71	35.99	day
	0	0	100	0	100	0	24	evening
Master Bedroom	0.09	5.16	94.75	85.24	14.76	0	184	night

4.5.3 Surface temperatures

Temperatures of the indoor surfaces, including walls, floors, windows and window frames, within the house had been recorded. There were also few issues found around monitoring using the iButton sensors – these are discussed in Appendix 4.

Table IV-11 presents the mean, median, minimum and maximum temperatures during winter for each of the areas examined. The surface temperatures of the windows and window frames in the living area, kitchen and master bedroom could reach very high temperatures (34-39°C max on window surfaces; 37.5-47.5°C max on frames) during the day. This is thought to be due to influence of solar radiation to these areas. Interestingly, the highest temperatures recorded on the window and

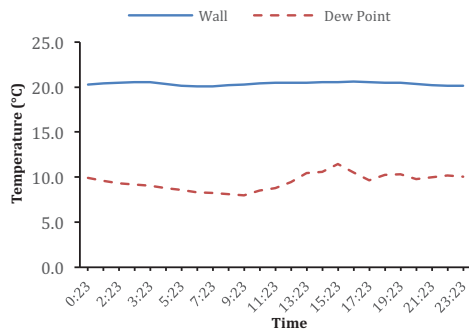
window frame in the ensuite bathroom were not as high. Frosting of the ensuite windows is thought to have helped reduce solar heat transmission.

Table IV-11: Internal surface temperatures.

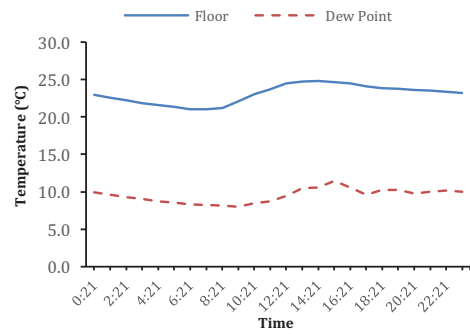
Area		Mean °C	Median °C	Minimum °C	Maximum °C
Living Area	Wall	20.4	20.5	16.5	26.0
	Floor	23.0	23.0	15.0	28.0
	Window	19.2	18.5	14.0	39.0
	Window Frame	19.1	18.0	13.0	41.5
Kitchen	Wall	20.5	20.5	16.5	25.0
	Floor	21.9	22.0	17.5	23.5
	Window	18.7	18.0	14.0	34.0
	Window Frame	18.3	17.5	13.5	37.5
Master Bedroom	Wall	19.1	19.0	16.0	25.0
	Floor	19.5	19.5	16.5	24.0
	Window	18.8	17.5	14.5	35.5
	Window Frame	18.6	17.0	14.0	47.5
Ensuite	Wall	19.6	19.5	17.0	22.5
	Floor	18.9	19.0	17.5	21.0
	Window	17.2	17.0	13.5	22.0
	Window Frame	16.0	16.0	12.0	21.0

Comparisons between the surfaces temperatures and the air dew point are given in Figure 4.12. It appeared that the walls, floors, windows and window frames were warm enough to prevent condensation from occurring on the surfaces. The floors had the warmest temperatures, followed by the walls, then windows and window frames. The windows and window frames surface temperatures peaked around mid-day at approximately 25.7°C in the living area, 24.9°C in the master bedroom, 23.8°C in the kitchen, and 18.3°C in the ensuite.

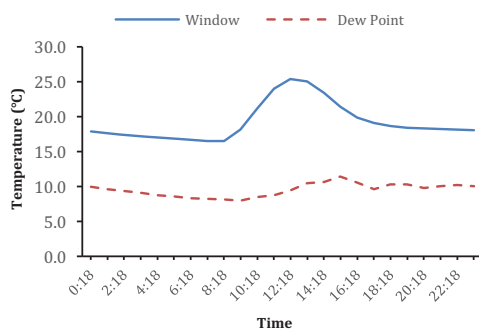
Living Area Wall Surface Temperature



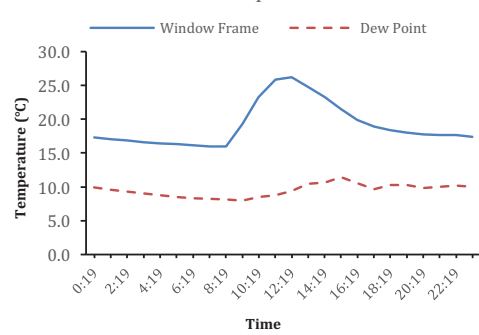
Living Area Floor Surface Temperature



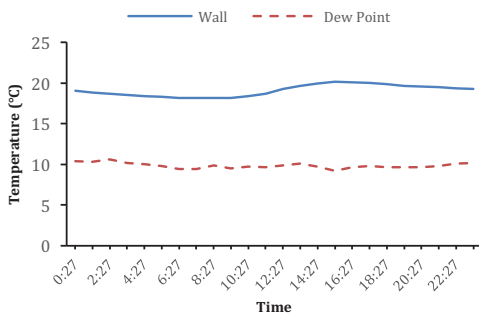
Living Area Window Surface Temperature



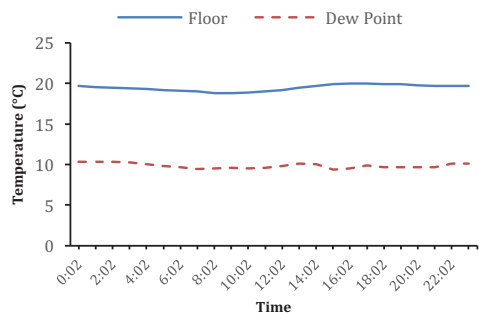
Living Area Window Frame Surface Temperature



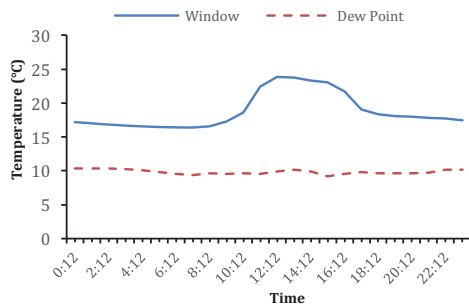
Master Bedroom Wall Surface Temperature



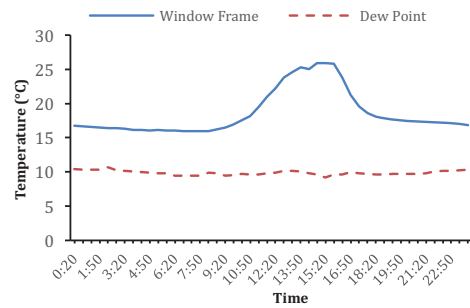
Master Bedroom Floor Surface Temperature



Master Bedroom Window Surface Temperature



Master Bedroom Window Frame Surface Temperature



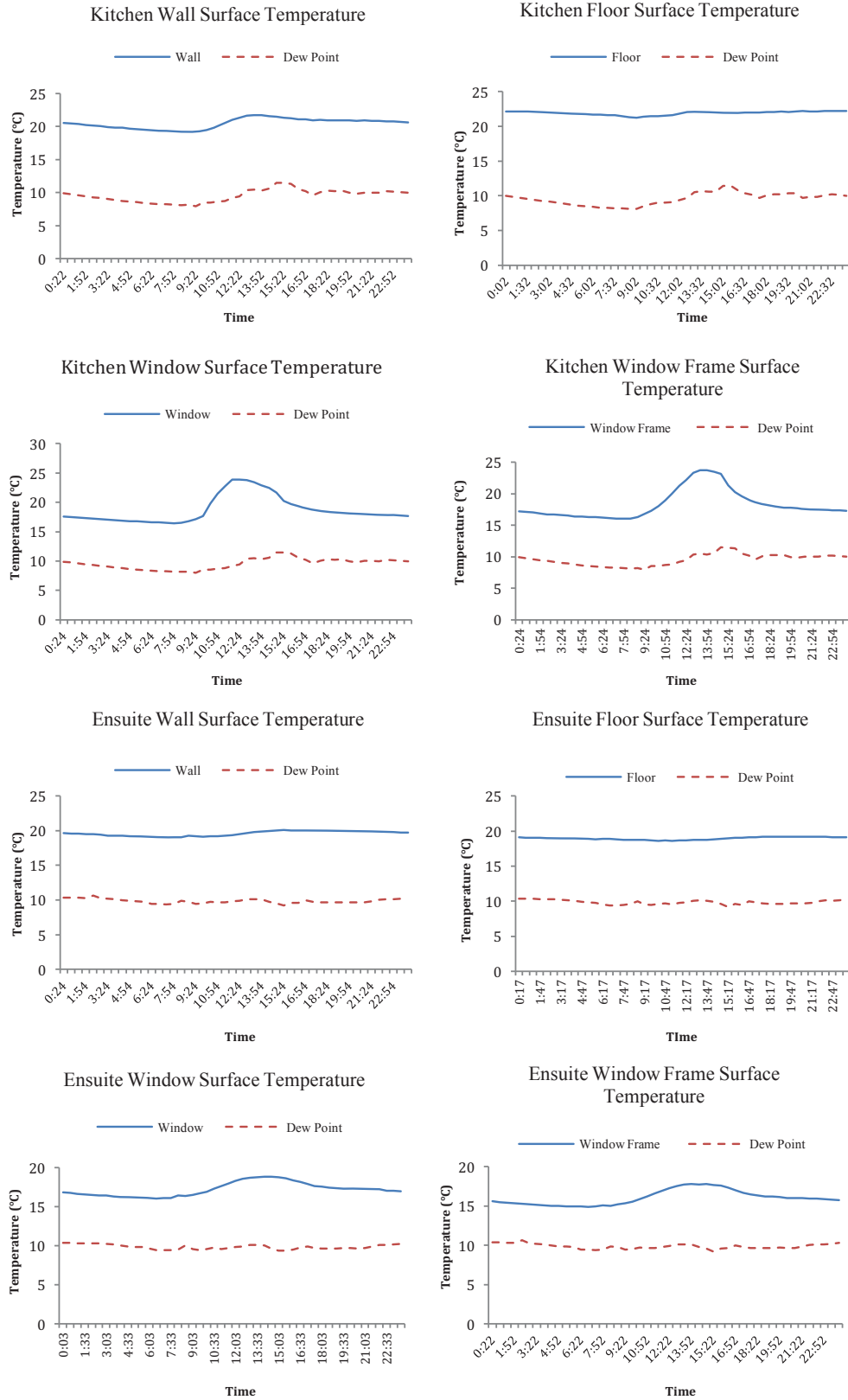


Figure 4.12: Indoor temperatures on surfaces during winter.

4.5.4 Relative humidity

RH was measured throughout the 6-week monitoring period. As the humidity data was recorded on the same instrument as the temperature data, the problems with the loggers discussed in section 4.5.2 also affected the humidity data; thus, there was a significant gap in the total hours measured between loggers in the living area and the master bedroom.

The mean RH level was higher in the bedroom than in the living area (53.26% vs. 47.67%), as can be seen in Figure 4.13. This result is consistent with the finding that the bedroom temperature (19.8°C) was lower than the living area temperature (21.2°C). Compared to the mean RH outdoors, there was an indoor to outdoor RH difference of 36.1%.

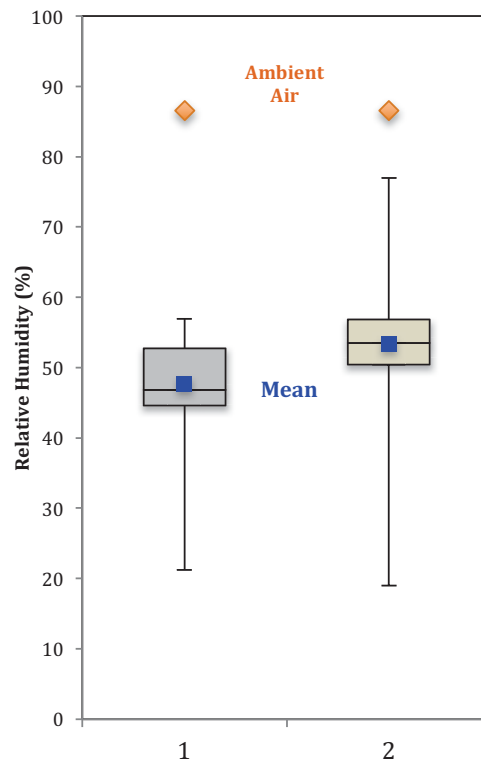


Figure 4.13: Winter RH – 1: living area; 2: master bedroom.

4.5.4.1 Humidity profiles

The humidity profiles, as presented in Figure 4.14, show the average internal RH during 24 hours, compared with the 24-hour average ambient RH profiles throughout the monitoring period. Both rooms measured had a profile of RH

between 40-60% consistently. Typically, new construction will have a higher level of internal moisture as excess water in the framing timber, concrete floor slabs and other building materials require time and conditions to dry out and stabilize. The internal RH can be seen to follow the changes in ambient RH outdoors. The indoor and outdoor RH dropped and reached their lowest during daytime (9am-5pm) and then increased in the evening.

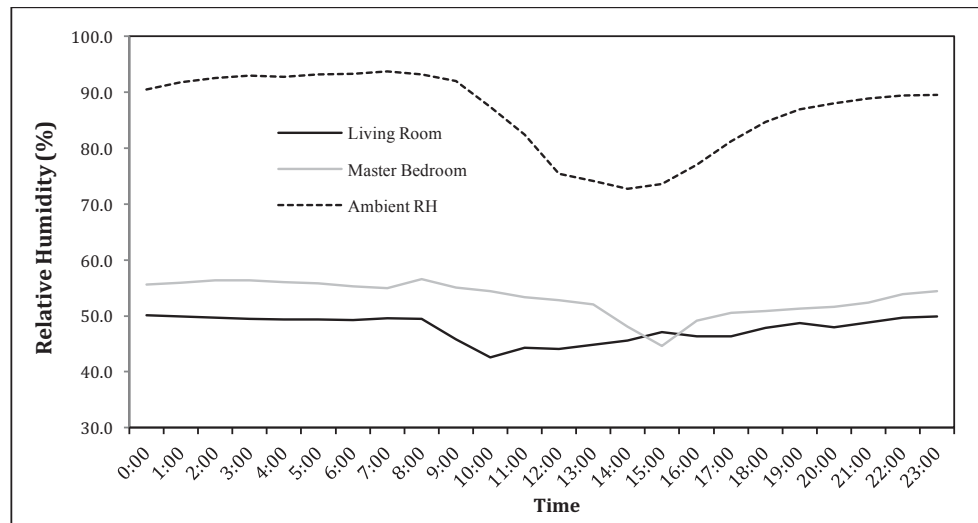


Figure 4.14: Average 24-hour indoor & outdoor RH profiles for the period of the monitoring.

Both rooms monitored had higher RH at night than at other times (Table IV-12). Colder temperature appears to be the reason for the increased relative humidity at night. A reduction in RH indoors occurred in the morning – i.e. by 1.3% in the living area and 0.2% in the bedroom – and continued throughout daytime.

Table IV-12: RH means for the period of the monitoring.

Area	Relative Humidity (%)			
	Morning	Day	Evening	Night
Living area	48.3	45.2	48.5	49.6
Master Bedroom	55.5	51.1	52.2	55.7
Ambient	93	79.5	86.9	92.2

4.5.4.2 Acceptable RH levels

Acceptable levels of humidity vary by the room temperature. WHO recommends a RH between 30% and 50% for indoor temperatures between 18-24°C (WHO, 1990; WHO, 1987).

Table IV-13 shows the proportion of time RH was below 30%, between 30-50%, and above 50% during daytime, evening and night-time. The RH levels exceeded 50% for 37% over the day in the living area, and 77.6% in the master bedroom. During morning hours, the master bedroom was above 50% of RH for 88.8% that the room was monitored, but was never below RH level of 30%. The RH level indoors dropped to below 30% during daytime, but only for a small percentage of time – i.e. 4.2% in the living area and 2.6% in the bedroom. Nearly three-fourths of the time –during daytime hours – that the living area was measured recorded RH level within the 30-50% range. The bedroom, however, was exposed to this range for only 30.5%. In the evenings, both rooms measured never had a RH level below 30%, but were exposed to above-50% RH for 38.2% and 66.7% in the living area and the bedroom respectively. The master bedroom spent the least time within the acceptable range during night-time – with a proportion of 6.25%.

Table IV-13. Proportion of time at acceptable RH levels for the period of the monitoring.

		AREA	
Time	Range	Living Area (%)	Master Bedroom (%)
24 hr	<30%	1.5	0.9
	30-50%	61.5	21.5
	>50%	37.0	77.6
Morning (7am-9am)	<30%	0	0
	30-50%	50	11.2
	>50%	50	88.8
Day (9am-5pm)	<30%	4.2	2.6
	30-50%	74	30.5
	>50%	21.8	66.9
Evenings (5pm-11pm)	<30%	0	0
	30-50%	61.8	33.3
	>50%	38.2	66.7
Nights (11pm-7am)	<30%	0	0
	30-50%	50	6.25
	>50%	50	93.75

A surprisingly high RH level of 77% was recorded by the logger in the master bedroom at 9:50pm. Figure 4.15 illustrates the RH profile when this event occurred. As there was no apparent drop in the room temperature when the maximum level was reached, which suggests that the cause of the increase was unrelated to temperature changes, it is thought that transfer of moisture from the adjoining ensuite – e.g. due to use of the shower facility – was the reason.

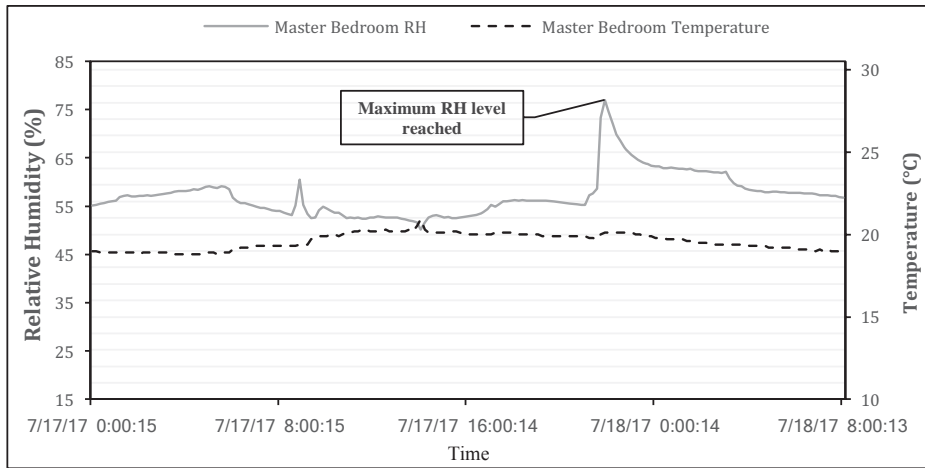


Figure 4.15: Profile when maximum RH level was reached.

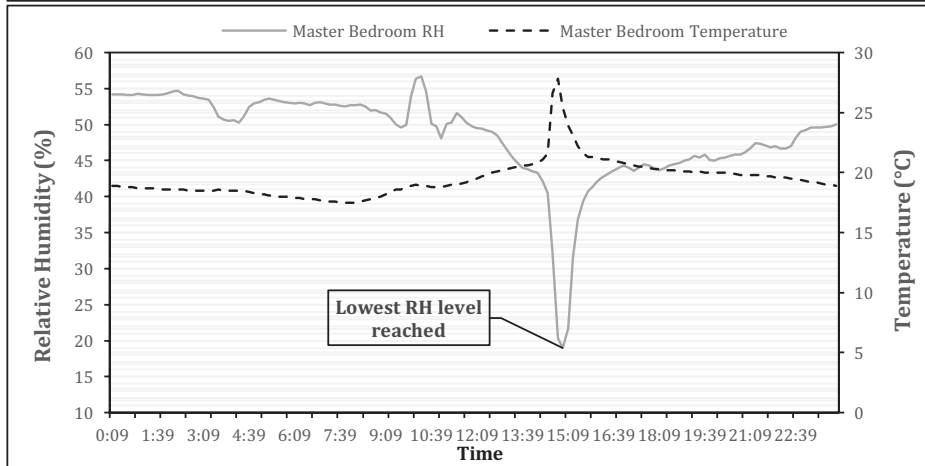
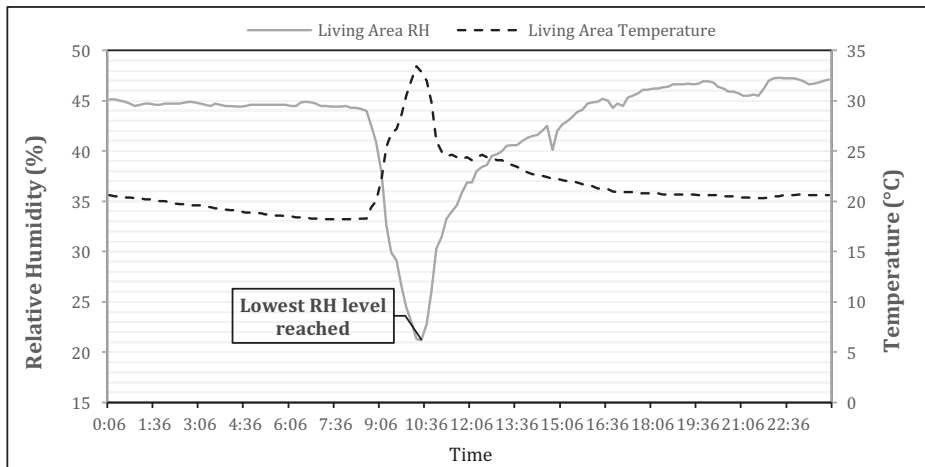


Figure 4.16: Profiles when the lowest RH levels were reached – Top: 11/7/17; Bottom: 29/7/17.

The loggers installed in both the living area and the bedroom recorded unusual drops in RH levels. In this instance, the living area and the master bedroom were exposed to RH levels of as low as 21.2% and 19% respectively. Figure 4.16 shows the RH profiles when these areas were exposed to these minimum

temperatures, compared against the room temperature profiles. It appears that that these drops in RH level corresponded to the notable increase in the room temperature.

4.5.5 Carbon dioxide levels

Measurement of CO₂ concentrations was carried out in the study home to evaluate IAQ and find out if the building is sufficiently ventilated. The CO₂ monitoring took place in the living area and master bedroom. Prior to the monitoring, the loggers' measurements were tested against each other. The testing indicated difference in CO₂ levels between the two loggers. It was concluded that one of the loggers was not recording proper measurement of CO₂ level. The 'faulty' logger was used for the first 3 weeks of the monitoring period logging temperatures and RH data in the living area. A replacement logger was installed on the second site visit, and set up in a different location in the living area. The analysis of CO₂ level in the living area therefore makes use of data collected since the second site visit and is therefore not comparable to the CO₂ level recorded in the master bedroom.

Table IV-14: CO₂ concentrations for the period of the monitoring.

Area	CO ₂ Average	CO ₂ Median	CO ₂ Max	CO ₂ Min	Hours Measured
Living Area	701.8	694	1018	468	50.8
Master Bedroom	722.0	693	1290	323	550.7

The CO₂ concentrations indoors reflect the ambient conditions and the CO₂ exhaled through breathing. Over the monitoring period, the number of occupants was consistent so that variations in CO₂ levels were likely due to changes in ventilation and occupancy of the room. Table IV-14 shows the mean values of CO₂, followed by the average daily profiles presented in Figure 4.17. As required by the NZS 4303:1990 (Boulic et al., 2010), sufficient ventilation must be provided so that 1,000 ppm of CO₂ is not exceeded. The living area was exposed to a mean concentration of 701.8 ppm whilst the bedroom had an average concentration of 722 ppm. Both rooms measured had exceeded the established maximum for CO₂ level indoors of 1,000 ppm, maximising at 1,018 in the living area and 1,290 in the bedroom.

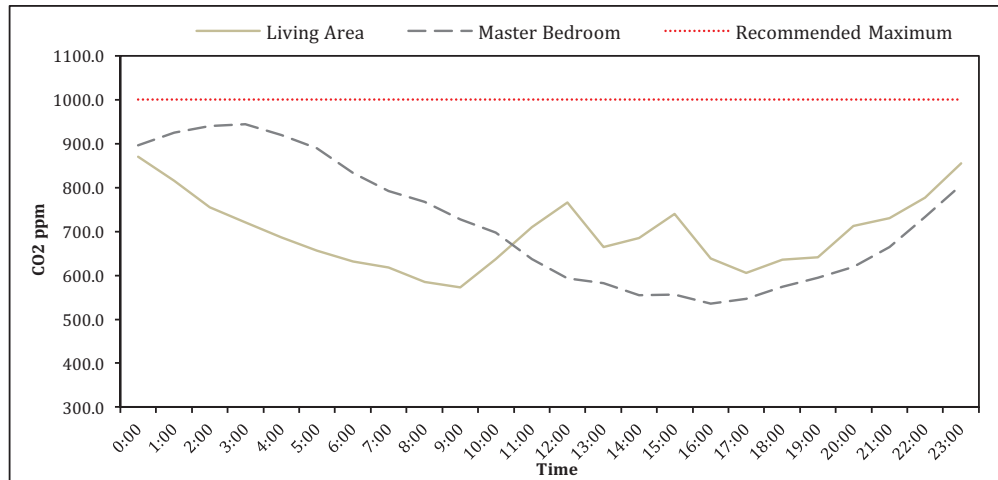


Figure 4.17: Average 24-hour CO₂ profiles for the period of the monitoring.

Table IV-15 shows the proportion of time the study home indoors was exposed to CO₂ levels within and outside the recommended range. The living area was only exposed to concentrations above 1,000 ppm during daytime hours for 30 minutes of the total of 18.8 daytime hours that the area was measured. In the master bedroom, CO₂ levels were above 1,000 ppm most often during night-time, accounting for 28.62% of the total 184 night-time hours that the room was monitored. CO₂ levels in the bedroom were kept under 1,000 ppm at most during daytime hours, accounting for 98.27% of the total hours measured.

Table IV-15: Proportion of time at acceptable indoor CO₂ level for the period of the monitoring.

Area	<1,000 ppm (%)	>=1,000 ppm (%)	Time Period	Hours Measured
Living Area	99	1	24 hr	50.8
	100	0	Morning	4
	97.33	2.67	Day	18.8
	100	0	Evening	12
	100	0	Night	16
Master Bedroom	88	12	24 hr	550.7
	86.59	13.41	Morning	46
	98.27	1.73	Day	182.7
	97.46	2.54	Evening	138
	71.38	28.62	Night	184

It appeared that the CO₂ level was affected by occupancy of the space as the levels dropped in the morning through to daytime when the occupants were away and rose again during the evening when they returned. The gain in CO₂ level in the living area was most pronounced in the late evening, whereas in the master bedroom the rise was most apparent overnight which reflects occupancy (Table IV-16).

Table IV-16: Mean CO₂ concentrations in parts per million (ppm) at different times of the day for the period of the monitoring.

Area	Mean CO ₂ levels			
	Morning	Day	Evening	Night
Living Area	591.9	668.8	708.0	734.2
Master Bedroom	762.4	603.5	648.5	883.1

4.6 Airtightness

Pre-handover blower door test was carried out by GDW Builders Limited on 30/05/2017, according to the procedures laid down in EN 13829:2001 Standard, which provides guideline for the measurement of air permeability of buildings. A detailed description of the test results is presented in Appendix 9.

Table IV-17: Test results of the environmental parameters.

Test mode	Indoor/outdoor temperature °C	Barometric pressure kPa
Depressurization	24.5/12.0	101.325
Pressurization	24.5/12.0	101.325

The environment conditions during the test are shown in Table IV-17. The measurements fulfil the corresponding requirements in EN 13829:2001 Standard which indicates that the test results are valid. The technician completed both a depressurization and a pressurization measurement, resulting in 10 tests each. The measurement data provided by the technician is shown in Figure 4.18. Based on the measurement data, calculations on the performance of building air-tightness were done, and the results are shown in Table IV-18.

Table IV-18: Test results of building airtightness.

Test mode	Flow coefficient	Flow exponent	Airflow at 50Pa m ³ /h	ACH
Depressurization	48.0 (+/-18.4%)	0.671 (+/-0.051)	668 (+/-2.4%)	1.34
Pressurization	19.2 (+/-5.9%)	0.646 (+/-0.016)	239 (+/-0.8%)	0.48

Test results showed that the air change rate of the building at the pressure difference of 50 Pa under the depressurization mode is 1.34 ACH and that under the pressurization mode is 0.48 ACH. In average, an n50 of 0.91 is reached. Converting to the mean infiltration rate provides a figure of about 0.0455 ACH. This means that about 4.55% 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 meets the 2015 IECC standards of no more than 3

ACH@50 Pa. Note that the pressurization result is much better, implying that the joinery is sealing better with the air pressure exerted from inside. In reality, the depressurization and pressurization results should be closer in gaps.

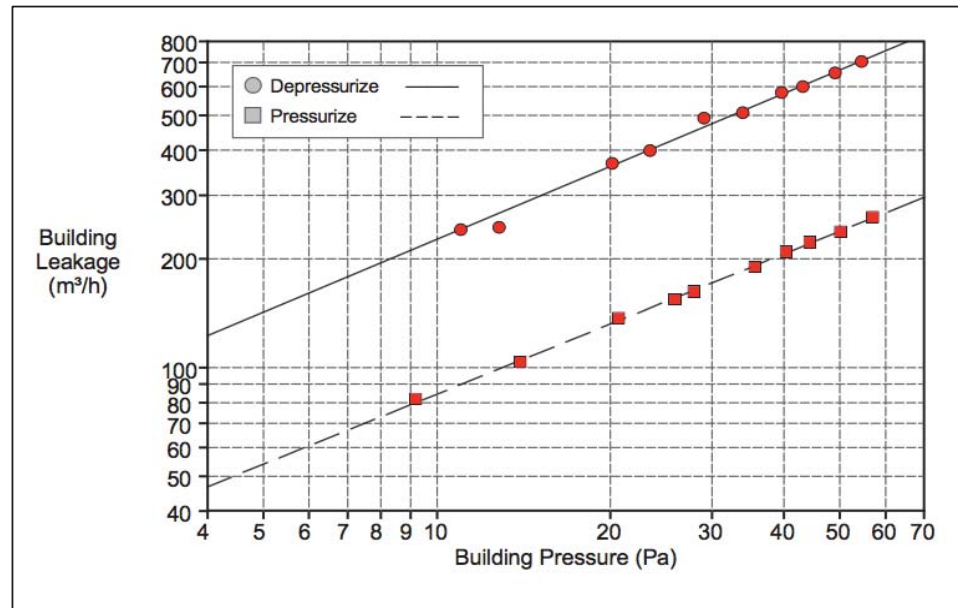


Figure 4.18: Depressurization and pressurization test results provided by GDW Builders Ltd.

Comparing with results of airtightness measurements carried out by McNeil et al. (2015) over 36 New Zealand homes, the measured infiltration rate of 0.91 ACH@50 Pa is more airtight than the survey mean n50 result of 6.7. The study home therefore has a relatively high airtightness level.

4.7 Thermography

The purpose of this work was to test the internal and external surfaces of the study building for air leakage, thermal bridging and general defects in the thermal envelope. The thermal images highlighted some weak points in the thermal envelope outlining missing, improperly installed or damaged insulation. These are presented as followed:

Finding 1: Missing/incomplete coverage of insulation

The junctions of internal surfaces – e.g. corners and joints – typically appeared colder than the adjacent surfaces in a thermal image (Taylor, 2014). Lower surface temperature was observed at the junction between wall and ceiling in the ground floor above the ‘store’ area. The shape of the observed cold area was beyond the shape of typical cold corner-effect (Figure 4.19a). Thermal variations also appeared around wall surfaces area

above the bookshelf (Figure 4.19b). It is suspected that this was due to lack of insulation – or lack of proper installation – in this area.



Figure 4.19: Thermographs illustrating lack of insulation (a) at the junction between the wall and the ceiling; and, (b) wall coverage above the bookshelf.

Finding 2: Insulation defects in the laundry room

Figure 4.20 shows the thermal-variation of the ceilings in the laundry room. There appeared to be lack of insulation – or lack of proper installation – in 75% of this area. Cold air ingress was also evident on the ceiling vent. Whether the insulation above the ceiling is present or not, it is not providing enough thermal insulation.



Figure 4.20: A thermograph showing lack of insulation of laundry room's ceilings.

Finding 3: Floor heating defects in the toilet

The shape and thermal variation of the accessed area in the toilet (Figure 4.21) may be an indication of possible fault in the floor heating. This finding requires further verification with a voltage detector.

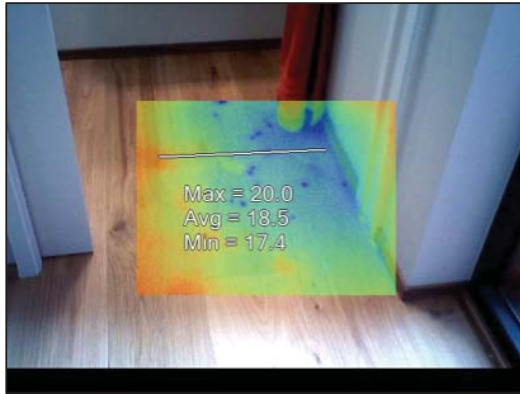


Figure 4.21: A thermograph showing possible heating defects.

Finding 4: A thermal anomaly on wall surface

The thermograph presented in Figure 4.22 illustrates a possible anomaly on the thermal properties of the wall. The thermal imaging camera operator – who also is the interpreter – had been provided with the approved City Council Plans for the property; however, no exact explanation is able to be confirmed for this finding. Further investigation is recommended in this matter.

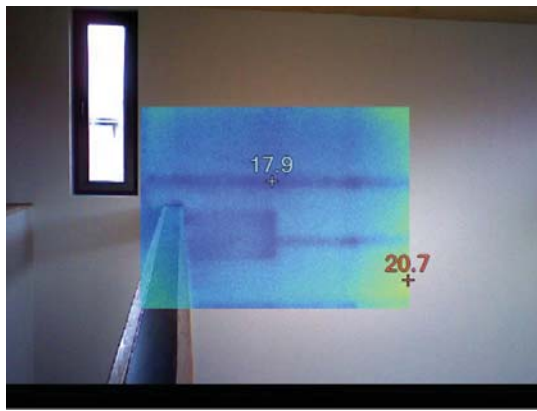


Figure 4.22: A thermograph showing a thermal anomaly.

4.8 Occupant satisfaction

The results of the BUS survey were analysed by the licensing company – BUS Ltd. The 2014 UK Housing BUS benchmark was used as a comparison. The position of the study building amongst the 47 studied buildings in the UK is represented by a building percentile. This shows how well the building has performed in comparison with other buildings that have been studied.

Three occupants responded to the survey, two of whom were male. Two of three respondents were aged under than thirty, but all of them are over 18. All occupants have lived in the building for less than a year since early June 2017.

The overall perception of occupants on the study building gives the general performance of the building by the standards of the occupants. The general performance is represented by the satisfaction, comfort, forgiveness and summary indices as calculated by BUS Ltd (Table IV-19). The occupants were comfortable with their building's performance (CI=1.1) and were satisfied with the building (SI=1.29). The occupants were also tolerant of the environmental conditions in the building (FF=1.46).

Table IV-19: Comfortable perception indices for the study home.

	Study Mean	Building Percentile
Comfort Index (CI)	1.1	92
Summary Index (S _u I)	1.19	96
Satisfaction Index (SI)	1.29	97
Forgiveness Factor (FF)	1.46	97

Table IV-20 presents the satisfaction ratings in the study building for each variable evaluated.

The respondents were asked to rate the overall building location, space availability, layout, storage availability, and appearance. All respondents perceived the location of the building to be satisfactory, scoring higher than the UK BUS benchmark. Responses were varied when they concerned the space availability of the building. Satisfaction values of 4, 5 and 7 were reported, averaging at a mean score of 5.33. Although no dissatisfaction was reported of the space availability, the building performed below the benchmark value of 5.74. Similar results were found for satisfaction towards the building layout. The responses were mixed resulting in an average score of 5.33, also below the benchmark value of 5.81. All respondents responded positively in regards to storage availability in the building, placing the building above the benchmark value of 4.48, with a mean score of 6. The outside appearance was rated differently by each respondent, resulting in a mean score of 5.33. The building sit below the benchmark with respect to this variable.

The occupants were asked whether the facilities in the building as a whole met their needs. All respondents felt that the facilities met their needs. The building had a high

percentile in the benchmark (87) with a mean of 6.66 against 5.92. Comments such as “like kitchen design, height of ceilings”, “roomy living room, ample shelf space, very warm!” were made highlighting satisfaction with the building design, storage availability and thermal comfort. Other comments like “I would prefer higher water pressure”, “shower could use a door” highlighted the inadequacy or shortcomings of the bathroom facilities. It is interesting that there were comments given on the limitations of the facilities despite of occupants’ high level of satisfaction.

Questions on comfort asked the occupants to rate the thermal conditions – specifically temperature and air quality – in the winter and summer. The occupants have not experienced summer conditions since they moved in. Benchmarking for thermal conditions in the summer was therefore not made. The temperature in winter was noted as warm and stable. Overall, the temperature in the winter was rated comfortable, achieving a perfect mean score of 7. The air in winter was regarded as dry, still, and mostly fresh and odourless. Satisfaction rating for air in winter was high, scoring a percentile of 91 with a mean of 6.66 – i.e. above the benchmark value of 5.52. In conclusion, the study building provided satisfactory perceived thermal conditions in the winter season.

The occupants were asked to describe their exposure to noise in the building. Two respondents were satisfied with the overall noise level. All respondents perceived the noise from neighbours as normal. A positive comment was included in regards to this, saying “almost unaware of neighbours. House is very quiet”. The noise from outside was perceived as normal by two respondents and low by one. This was expected considering the quite neighbourhood where the building is located. Noise from other people was regarded as normal by one respondent and high for the rest. Despite this, the building scored slightly higher than the benchmark – i.e. 5.56 against 5.29.

Questions concerning lighting condition were included in the questionnaire. The overall lighting condition was perceived to be satisfactory. The building scored higher satisfaction level than the benchmark for overall lighting condition with a mean of 6.67 against 5.52, giving it a percentile of 89. Disagreement was present when rating natural lighting condition. One respondent regarded natural lighting level as excessive, while the rest rated the level to be satisfactory.

The occupants were asked to rate the overall comfort of the house. All occupants reported high satisfaction level in terms of overall comfort. The building scored higher than the benchmark – e.g. 6.33 against 5.85 – and had a percentile of 74. One respondent termed the building as “so comfortable!”. In addition, the overall design of the house was also perceived to be satisfactory, scoring a mean of 6.33 against a benchmark value of 5.66. These results are in line with the lack of complaints and the numerous positive comments by the respondents about the building.

The occupants were asked whether they feel more or less healthy when in the building. Two respondents felt they were ‘more healthy’ in the building, while one felt neither less nor more healthy. According to one respondent, the health benefits were noticeable especially after moving in from the rental property they were in for first half of the build. This gave the building a percentile of 94 amongst houses in the UK with a mean score – of 6 – higher than the benchmark of 4.65.








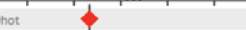


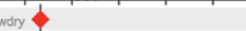

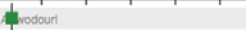


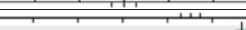
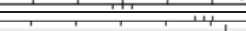
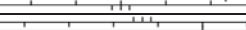
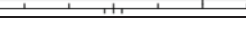



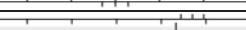

Control over the IEQ features of a building is critical to occupants’ satisfaction. Two respondents acknowledged that control over cooling were partial to minimal whilst perceived controls over heating and lighting as satisfactory. All respondents regarded control over noise as partial to minimal, scoring a mean of 3 against the benchmark value of 3.9. Differences in perception exists for control over ventilation as one respondent claimed to have almost full control over ventilation whilst the other two perceived to have only partial to minimal control. The study building scored lower than the benchmark in all aspects of control except for control over heating.

The occupants were asked to give comments about the energy and water-saving features of their home. However, only one of them responded, stating “I don’t know anything about them sorry”. When asked to give additional comments relevant to the performance of the house, one occupant responded, stating “love living here, but the length of time to complete the house is much longer than expected - and the cost is high”.

The results indicate that the study building scored worse than the benchmark in control over noise and the same as the benchmark in “Space”, “Layout”, “Appearance”, “control over heating”, “control over cooling”, “control over ventilation”, and “control over lighting”, but higher than the benchmark in rest of the factors compared (location,

storage, needs, temperature in winter, air in winter, overall noise, overall lighting, overall comfort, perceived health, and design overall). Generally, the building was perceived to perform well with respect to the UK BUS benchmark.

Table IV-20: ‘Slider’ graphs of variables evaluated and ratings relative to the 2014 UK BUS Benchmark (Amber = ‘Similar’; Green = ‘Better’; Red = ‘Worse’).

The Residence Overall		Rating
Location	Unsatisfactory :1  7: Satisfactory	Green
Space	Not enough overall :1  7: Enough overall	Amber
Layout	Poor layout :1  7: Good layout	Amber
Storage	Not enough :1  7: More than enough	Green
Appearance	Poor :1  7: Good	Amber
Needs	Unsatisfactory :1  7: Satisfactory	Green
Comfort		
Temperature in Winter	Uncomfortable :1  7: Comfortable	Green
	Too hot :1  7: Too cold	Red
	Stable :1  7: Varies during day	Green
Air in Winter	Still :1  7: Draughty	Red
	Dry :1  7: Humid	Red
	Fresh :1  7: Stuffy	Green
	Odourless :1  7: Smelly	Green
Overall Conditions in Winter	Unsatisfactory :1  7: Satisfactory	Green
Overall Noise	Unsatisfactory :1  7: Satisfactory	Green
Overall Lighting	Unsatisfactory :1  7: Satisfactory	Green
Overall Comfort	Unsatisfactory :1  7: Satisfactory	Green
Perceived Health	Less healthy :1  7: More healthy	Green
Personal Control		
Control over heating	No control :1  7: Full control	Amber
Control over cooling	No control :1  7: Full control	Amber
Control over ventilation	No control :1  7: Full control	Amber
Control over lighting	No control :1  7: Full control	Amber
Control over noise	No control :1  7: Full control	Red
Design Overall	Unsatisfactory :1  7: Satisfactory	Green

4.9 Chapter summary

The results of the assessments performed are presented and summarized as followed:

- The study home had a winter daily energy consumption of 47.96-50.58 kWh on average – i.e. a maximum daily wattage of 82.27 kWh was consumed and the lowest daily consumption recorded was 16.31 kWh. Electricity use was highest in the morning followed by the evening. There was no significant difference found between consumption during weekdays and weekends.
- The PVs were not generating sufficient wattage of electricity to cover consumption during winter – i.e. the electricity produced by the PVs would have only covered 18% of total use in the building.
- The showers' flow rate was measured with an average rate of 7.84 L/m – i.e. less than the recommended maximum of 9 L/m.
- Findings from the noise transmission measurements showed that the building is vulnerable to outside noise even with doors and windows closed.
- The winter temperatures in the study home are warm. The mean winter evening temperature in the living area was 21.4°C. The highest and lowest temperatures were recorded in the master bedroom at 34.5°C and 15.6°C respectively. The difference between the ambient and the indoor temperatures was at its highest during the night-time period – with an indoor-outdoor temperatures gap of 13.9°C, compared to a gap of 11.8°C during daytime.
- The mean winter RH in the living area was approximately 47.7% and 53.3% in the main bedroom. The RH in the master bedroom was above the recommended maximum of 50% for 77.6% of the time that the room was monitored. The indoor RH level was expected to be at its highest in the first year following construction completion.
- The mean CO₂ level in the master bedroom was higher than in the living area. The indoor CO₂ levels are expected to decrease with time.
- The study home has an airtightness level of 0.91 ACH@50 Pa which implies a high level of airtightness.
- The results of the thermography test revealed a few areas including walls, ceilings and floors with possible thermal defects.
- It was observed that the occupants of the study building reported being comfortable and satisfied with the building's performance.

Chapter 5: Discussion of Results

5.1 Energy-efficiency: electricity and water use

5.1.1 Electricity use for heating

This section compares the estimated energy use with energy used calculated by ALF 3.2. Assuming that daily heating requirement is the same throughout the year, calculations using the ALF method showed that a minimum of 19.02 kWh heat output will be required daily to maintain a minimum living area temperature of 18°C and a minimum of 24.66 kWh to maintain 20°C with outside temperature of 6°C. Based on the power company records, the winter mean for electricity use in the study home is 50.58 kWh per day. It can be assumed therefore that two-fifths to half of the building's total electricity use per day is allocated for heating.

The generation inverter for solar PV had not been installed. The current meter does not record the solar energy exported to the grid nor the electricity consumed in the building. Inverter is required for the conversion of the PV-generated direct current (DC) electricity to the building grid safe alternating current (AC) electricity. It is therefore recommended that the inverter be installed soon so that the electricity generated by the solar PV panels can be used within the home.

During the period that monitoring of solar generation was undertaken, more energy was consumed than would have been generated in the building for all days. The solar generation would have not supplied enough electricity to cover for all electric loads under winter conditions. This figure is expected to change during summer because of higher solar radiation – thus, more generation – and lower consumption.

It is understood that the data used for the electricity consumption analysis is insufficient and that more data are required to conclude the energy-efficiency of the building. In order to improve analysis of the energy use in the building, end-use breakdown of the electricity in the study home should be measured. End-use monitoring will give an estimation of each appliance's contribution to the electricity use.

5.1.2 Water consumption

The showers meet Homestar™ 6-10 Star standard of less than 9 litres per minute, hence perform a high level of efficiency.

This data only covers the efficiency of the showers. The total water volume used is unknown, as the shower is not the only water fixture in the building. Besides being used for showering, water is also being used for indoor uses – e.g. the washing machine, dishwasher, toilets and taps – and outdoor uses. Monitoring of water use at an end-use level will allow for a more comprehensive analysis of water use efficiency in the building. By obtaining end-use information, areas in which water efficiency can be improved are able to be identified. Hence, further research on water consumption in the building is recommended.

Water supply and wastewater discharge are free-of-charge services in Christchurch. Consequently, the incentive to save water might be weak, since there are no direct costs involved from water consumption. Despite this, the environmental impacts associated with water consumption should not be underestimated. The amount of CO₂ released into the atmosphere increases by an increasing water demand. The reduction in water use translates to energy savings, thus a reduction in GHGs, which contribute to global warming.

As had been discussed previously, a green building should maintain sustainable performance at operational stage. Maintaining efficient use of water is important to ensure sustainability. Using rainwater for the supply of water for toilet use, washing machine and outdoor uses can be an option. Although the average annual rainfall in Christchurch is lower than the New Zealand average, the use of rainwater can reduce the use of mains water in the study home and thus the energy required for wastewater removal. As demand for mains water and the amount of wastewater produced are reduced, CO₂ reductions can be achieved. It is recommended that a water use metering be installed so that the occupants can keep track on – hence, be more well aware of – their consumption. As well, these represent an opportunity for future study of the home.

5.2 IEQ achieved: technical and occupants' perspectives

5.2.1 Thermal conditions

The internal temperatures were affected by the variations in external temperature. Results showed that the indoor temperatures were much warmer than the outside and that the occupants were exposed to winter living area temperature that meets the WHO recommended minimum for comfort of 18°C most of the time. Living area temperatures were found to go above the recommended maximum of 24°C at times during the day. A major cause to the increase in temperatures could be solar heat gain and transmission through windows. The window and window frame surfaces experienced significant elevation in temperatures at times when the air temperature was higher than 24°C. Occupancy of the area could also be a contributing factor.

The occupants perceived the study home's warm indoor environment positively even-though indoor temperatures were found to surpass outside the recommended comfort range occasionally. This perception may result from a number of reasons, either that the occupants judged their perceptions in comparison with their previous house or that they were influenced by the 'thermally-comfortable' image of the building, or both.

The building was at its warmest during the day. The argument that indoor temperatures are warmest in the evening during winter due to heating (French et al., 2006) is not applicable in this instance.

5.2.2 Level of internal moisture & condensation on indoor surfaces

The mean living area relative humidity of the study home fell within the WHO recommended range of 30-50% – unlike the humidity levels reported at NOW Homes® in Auckland and Rotorua, which failed to meet the WHO standard in their first two years of operation. However, RH levels in the living area and the master bedroom were reported to exceed the recommended maximum of 50% for almost two-fifths and more than three-fourths of the time respectively that the areas were monitored. Interestingly, these findings contradict the occupants' perception of the building's level of indoor humidity, judging the winter indoor air as slightly dry. The common understanding of dry air is air that has a low RH. In addition, despite the indoor RH fell outside the recommended range at times, the occupants were extremely pleased with the overall winter air quality of the house. These are interesting findings that should be investigated further.

50% and greater RH can trigger the proliferation of mould. It is common for new homes to suffer from high level of internal moisture. Many materials used during construction contain moisture that needs time to cure. This moisture evaporates into the indoor air – adding to the moisture generated by day-to-day household activities –, which eventually increases the humidity indoors. Besides the fact that the study home would need some time after recent construction completion for its materials to dry out and stabilize, the high level of moisture in the master bedroom could be due to transfer of moisture from the adjoining ensuite. A large contributor to this problem is thought to be due to user behaviour of not venting the ensuite bathroom properly, drying towels inside the bathroom, and keeping the window vents in the master bedroom closed most of the time.

No condensation on indoor surfaces was observed during the monitoring. The results suggested that the surface temperatures were unsuitable for condensation to occur indicating adequate thermal performance of the building surfaces including the walls, floors, windows and window frames.

5.2.3 IAQ

Using CO₂ as a surrogate to estimate the ventilation rate, the study building was exposed to CO₂ levels, which were low enough to meet the current NZ Standard (4303:1990) for acceptable IAQ. This finding suggests that, overall, the ventilation in the study home was sufficient to expel the CO₂ generated from a combination of unvented combustion and occupants' respiration. CO₂ concentrations in the bedroom, however, were found to exceed the established maximum at times, mostly during night-time. Given the relatively high airtightness level, active ventilation may be needed to provide adequate air and dilute moisture and other indoor contaminants. This finding somehow suggests that window opening behaviour should be increased to keep the indoor CO₂ level within the recommended range. Occupants' positive responses to overall winter air quality of the house support the claim that generally, the IAQ of the building was satisfactory from both technical and occupants' point of views. Occupants also reported improved health since moving in. These findings are similar to that of Christoffersen et al. (2014) and Lee et al. (2012), who reported high satisfaction and improved perceived health of occupants of 'green' houses.

5.2.4 Exposure to noise

The study home provided A-weighted noise reduction in the 28-37.8 dB(A) range, with an OITC rating of 27.57 dB(A), which is a relatively low OITC rating to achieve for a highly-insulated building.

Disregarding all limitations described and despite the under-performance of the acoustic quality from the technical standpoint, overall satisfaction towards noise level was high. The occupants' perception towards acoustic comfort in general was positive. Excessive noise production outdoors is a very unlikely event in the neighbourhood where the house is sited. On the day-to-day basis, occupants would more likely be exposed to noise that originates indoors from household activities such as cooking, watching television, using computer, etc. It is therefore recommended that noise monitoring be done with longer coverage for a more representative period – i.e a year – to allow for more accurate analysis of the building acoustics.

5.2.5 Lighting

Lighting level is a contributing factor to occupants' satisfaction towards a building (Sakellaris et al., 2016). Technical measurement of indoor daylight levels was not carried out due to assumingly minimal occupancy of the building during daytime. In the questionnaire, however, lighting-related questions were included. Although satisfaction towards overall lighting condition was high, one occupant felt exposed to too much day-lighting within the space. Closing curtains of windows during daylight hours can be the daylight protection measure taken by the occupant.

5.3 Thermal fitness

Thermography is an effective tool to reveal defects in the thermal resistance of a building, which would otherwise go undetected. The thermographic test at the study building indicated a problem with the wall-ceiling junction above the 'store' area, indicating possibly higher levels of heat loss at the eaves. Lower surface temperatures were also observed around the ceiling in the laundry room. As discussed in the literature review chapter, past research acknowledges the potential for occurrence of slippage during construction phase of building and that construction of a building does not

always end up perfectly in accordance with the initial design (Bordass et al., 2004; Taylor, 2014). Results from the thermographic test imply that insulation was not properly installed in the areas where thermal defects were detected. Reinstallation of insulation is therefore recommended for these areas.

Chapter 6: Conclusion

6.1 Introduction

A home had been monitored to study the post-occupancy performance of a ‘green’ residential building. A SUPERHOME Movement exemplar home was chosen as a case study. The monitoring was carried out to study the building’s electricity consumption, showers’ flow rate, room temperature and relative humidity, indoor surfaces temperatures, IAQ, and acoustic quality. In addition, a survey was carried out using the BUS questionnaire to understand how occupants perceive the overall performance of the house since occupation.

At the beginning of this thesis, the claim that a ‘green’ home is a home with a third-party certification – or Homestar™ – in this instance, was challenged. It was hypothesized that a SUPERHOME can have satisfactory operational energy and thermal performance. The outcome of this research shows that this claim is valid. The ‘green’ status of a build should not be limited to ratings by third-party certification

6.2 Findings arising from the study objectives

The three objectives of this study were: (1) to report on the building’s energy performance; (2) to measure the winter IEQ (air temperature, relative humidity, IAQ, thermal performance of indoor surfaces, and acoustic quality); and (3) to investigate occupants’ comfort, satisfaction and tolerance levels towards the building winter performance. Overall, it could be concluded that the investigation has successfully met the objectives set in the beginning of the research process.

6.1.1 Findings to Objective 1

The building’s electricity use data was obtained and analysed. The study home had a daily electricity consumption of 50.6 kWh during winter, half of which might be allocated for heating purposes. The solar inverter had not been installed in the study home; as a result, the actual generated kWh of solar energy has not been accounted for in the analysis. A metering system has been installed to measure solar generation and electricity use in the building. Analysis on solar energy was based on data derived from the meter readings. Results suggest that electricity generated from the

rooftop solar system was insufficient to cover all electric needs in the building during winter. On average, only around 18% of daily energy use in the building would come from the solar panels.

The electricity consumption performance of the building can only be determined only if end-use data has been considered in the evaluation. The data collected is insufficient to make a statement regarding the energy performance of the study home.

6.1.2 Findings to Objective 2

From a technical standpoint, a gap does not exist between the design assumptions and the reality of the IEQ achieved in the study building. All in all, the home provides a healthy, stable, and thermally efficient living environment.

Data on the temperature and relative humidity reached in the living area and master bedroom of the study home were obtained. Results showed that these areas of the study home were exposed to winter air temperatures between 18-24°C for most of the time. No health risk is associated with temperatures falling within this range. It can be concluded that the building maintains healthy indoor temperatures in winter. The mean winter RHs in the study building were approximately 48% in the living area and 53% in the master bedroom. These values are expected to decrease in the following winter. Overall, the building was thermally healthy and comfortable to stay during the first winter.

The indoor surfaces of walls, floors, windows and window frames, were exposed to temperatures insufficient for condensation, thus for the proliferation of mould. The surfaces climate was too warm for condensation to occur. To conclude, these results suggest that the insulation features installed on the building surfaces has a positive impact on the room and the surfaces climate, by increasing the temperature, which in turn reduce the water availability for mould growth.

The air quality of the building was represented by the concentration level of CO₂ within the indoor space. The results showed that CO₂ concentrations in the building during winter were well below the recommended maximum of 1,000 ppm – i.e. the NZ Standard (4303:1990) for acceptable indoor air quality – for most of the time.

Exposure to CO₂ indoors is not of concern for the occupants' health. This result showed that, without a major source of pollution, ventilation is sufficient to maintain an acceptable IAQ in the study home.

A sound transmission measurement was undertaken to examine the outdoor-indoor noise transmission level. The study home provided A-weighted noise reduction in the 28-37.8 dB(A) range, with an OITC rating of 27.57 dB(A), which is a relatively low OITC rating to achieve for a highly-insulated building. This is a surprising finding but given the limitations that arise during the measurements, the quality of data gained is not satisfactory enough to determine the acoustic quality of the study home. Further validation is required for a conclusion to be made.

6.1.3 Findings to Objective 3

POE was undertaken using the BUS questionnaire. The occupants reported high comfort, satisfaction and tolerance levels with the building's performance over winter.

6.3 Overall Conclusion

Upon the completion of the research project, a number of conclusions have been drawn based on the findings of the research questions. As there is insufficiency of data for determining the energy efficiency of the study building, it is difficult to conclude with one brief answer what the winter energy consumption performance of the SUPERHOME is. However, there are several trends that can be drawn from the findings in regards to this first research question. There are two sources of energy that power the house – i.e. electricity supplied by a power company and solar generated from roof-mounted photovoltaic panels. About half of total electricity used is allocated for heating in winter. Solar energy is unable to be used, as inverter is not yet installed. However efficient and effective the energy generated by the PVs may be, it is impossible to optimally use them without having an inverter installed in order to export and import the PV-generated energy to and from the grid. On the whole, it can be concluded that the study building has not achieved its design potential with regards to electricity use. The second research question, “What is the operational winter indoor environment quality of a SUPERHOME?” demonstrated two major trends. The results prove that a SUPERHOME achieves a high level of thermal performance and provides adequate

IAQ in winter conditions. Given these circumstances, there should be no plausible health risks from living in the property. However, results revealed poor acoustical quality of the home, which implies poor sound insulation by the building envelopes. In regards to the last question, this study concludes that occupants' overall perceptions towards the post-occupancy and winter performance of a SUPERHOME are positive. The results showed that the occupants rated the building highly. An exception however was found for satisfaction towards personal control over the internal environment which tended to score rather less well than some other aspects including needs, thermal, air quality, acoustic, lighting, and perceived health. In conclusion, a SUPERHOME provides a healthy and satisfactory indoor environment for occupants.

6.4 Limitations of the study

This study has several major limitations:

- (1) This study is only a representative of one SUPERHOME. The study could have involved more than one SUPERHOME to gain a more representative sample of SUPERHOME Movement projects. Unfortunately, this was not possible mainly due to time constraints and the lack of availability of monitoring instruments to use for this project.
- (2) Data on electricity consumption is limited to the length of time that the house has been occupied. The estimates made on consumption rate are limited to winter months.
- (3) The study home is brand new and has only been occupied for about three weeks at the start of the monitoring. The house was still not fully furnished and some furnishing works had been carried out during the monitoring period. Furnishing works might have affected the stability of thermal conditions and air quality in the building, thus affecting the data recorded by the monitoring loggers.
- (4) The number of samples collected for indoor room temperature, RH and CO₂ level were insufficient due to data collection issues that arose during the monitoring. Some of the issues that came up were due to the inexperience of the researcher and thus could have been prevented by better planning. The minimum presence of the researcher in the study building is thought to be a contributing factor. For instance, unwanted events can occur which may stop the recording of data by the loggers. With full presence of the researcher – who understands how the loggers should

operate – such technical problem could have been minimized. Given that full presence of the researcher may interrupt the privacy of occupants, future research could consider incorporating full participation of the occupants to watch over the monitoring instrument(s) installed to ensure that they are operating properly.

- (5) All respondents have only recently moved in – at the start of winter 2017. The length of time that an occupant has lived in a building is of significant importance. Adaptation time has not been accounted for in the analysis.

6.5 Recommendations

It is recommended that the monitoring of the home – i.e. temperatures, relative humidity and CO₂ levels – continue until at least gaining two years of data. It would be interesting to see the changes, if any, in terms of performance over time. In addition, it is recommended that monitoring for the following elements are performed:

- **Direct physical measurements for electricity use**

Fixed appliances – such as lights, dishwasher, fridge, washing machine, water pumps for rainwater tank, etc – would be the high contributors to energy use and therefore it would be of high interests to examine the breakdown of energy use for these end-users of energy.

- **Direct physical measurements for water use**

Monitoring of water use at appliances and fixtures level – toilets, showers, taps, outdoor uses, washing machine, dishwasher – will allow for a more comprehensive analysis of water use efficiency in the building. It would be of great interests to have water use metering systems installed so that the occupants – or, at least the owner – can keep track on water use in the building. By obtaining end-use information, areas in which water efficiency can be improved can be identified.

- **In-home noise measurements**

Noise has the potential to cause annoyance to comfort and adverse effects to health. One-off, outdoor exposure measurements cannot accurately account for noise added by

activities inside the home. Long-term in-home monitoring of noise levels is essential to understand the relationship between noise and indoor comfort.

- **Household waste management**

The management of household waste – although not common – is an important element to look at in order to determine the operational sustainability of a home. An estimate of the quantity of waste generation in a home is a very important indicator for environmental performance. Thus, it would be of major importance to determine the amount and types of waste generated on the day-to-day basis.

6.6 Future Research

This work has indicated areas that require more research. There are several suggestions if future research was to be conducted. These suggestions are discussed below.

6.6.1 Green Lifestyle in ‘Green’ Homes

The focus of ‘green’ building POEs has been limited to building performance based on energy-efficiency, IEQ, and occupants’ comfort. The literature review carried out in Chapter 2 on performance gap has shown the importance of occupants’ behaviour on the operational sustainability of residential building. Occupants’ unsustainable lifestyle can hugely deteriorate the sustainability potential of a design. Future POE research on ‘green’ home should have this question in mind:

“To what extent do green homes influence the implementation of green behaviour or change the lifestyle of occupants to become more sustainable?”

6.6.2 Cost Benefit Analysis of a SUPERHOME

This study is small step in evaluating the performance of SUPERHOMES based on technical and social aspects. Future studies on SUPERHOMES could go further by encompassing the economic aspects of the building performance. This would offer an even broader view of how SUPERHOMES perform.

“What does it cost to build a SUPERHOME and what financial return can be expected from savings in energy?”

6.6.3 Comparisons between Homestar™ homes and SUPERHOMEs

The outcomes of this study showed that a home with no third-party certification could perform as well as a rated home would. Future research should look at how the performance of SUPERHOMEs is compared to Homestar™ homes with the following question in mind:

“Which one is more affordable, environmentally-friendly, energy-efficient, and comfortable to live in?”

6.6.4 Addressing privacy issues in home monitoring research

Another area for further research is the issue of privacy in housing studies, and how this can be addressed. It was shown in the literature review section on POE that housing POEs often have a significant issue to do with invasion of privacy. There is a need for further research to get solutions on how to deal with this problem.

“How can the issue of privacy in housing studies be tackled?”

6.6.5 Sample Population

This research involved a case study of only one SUPERHOME. Future studies could be carried out on more SUPERHOMEs.

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APPENDIX 1



Date: 14 March 2017

Dear Bramantino Armiento

Re: Ethics Notification - 4000017390 - 10 Star Homestar™ Homes in Christchurch Under Winter Conditions: Real Performance Through Post-Occupancy Evaluation

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

If situations subsequently occur which cause you to reconsider your ethical analysis, please go to <http://rims.massey.ac.nz> and register the changes in order that they be assessed as safe to proceed.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research."

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director - Ethics, telephone 06 3569099 ext 86015, email humanethics@massey.ac.nz.

Please note, if a sponsoring organisation, funding authority or a journal in which you wish to publish requires evidence of committee approval (with an approval number), you will have to complete the application form again, answering "yes" to the publication question to provide more information for one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

Yours sincerely

Research Ethics Office, Research and Enterprise

Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand T 06 350 5573; 06 350 5575 F 06 355 7973
E humanethics@massey.ac.nz W <http://humanethics.massey.ac.nz>

APPENDIX 2



PROJECT INFORMATION SHEET

The Property Owner, 14 Jane Deans Close.

Project Title: A SUPERHOME in Christchurch Under Winter Conditions: Real Performance Through Post-Occupancy Evaluation

Name of Researcher: Bramantino Armiento

Supervisor: Prof Robyn Phipps & Dr Eziaku Onyeizu Rasheed

Researcher introduction

I am a Masters candidate of the Department of Ecology, Massey University.

This project aims to investigate the post-occupancy performance and indoor environment quality of a Superhome Movement Exemplar building, in Christchurch, New Zealand. Your building is a suitable candidate for this exercise. As the owner of this building, I am requesting your permission to access the building and its occupants to participate in this exercise.

Project Procedures

The procedure for this exercise is simple and requires little time of the occupants. It is outlined as follows:

- A 6-week indoor environment quality and on-site energy generation and energy usage monitoring will be carried out. Monitoring instruments will be installed in the building and this requires the researcher's presence inside the building. The instrumentation will take 3-4 hours to set up, and will be undertaken at a time that is convenient to the occupants. All instruments are small and handheld instruments that are silent and non-polluting. During the 6-week monitoring period, the researcher will need to check the monitoring instruments between the 3rd and 4th week of the monitoring period and will again visit the building to remove the instruments at week 6.
- An invitation for participating in a questionnaire survey will be delivered to the occupants. It is solely the choice of the occupants whether or not to participate. The questionnaire is an internationally recognized questionnaire, i.e. BUS Methodology two-page occupant questionnaire 2011 used for Building in Use Occupant Survey – with license from Building Use Studies (BUS) Ltd 2011¹. The questions are easy to answer without any ambiguities. The questionnaire requires approximately 5-10 minutes of the participants' time and will be undertaken at anytime during the data collection period with further notice. The questionnaires will be delivered to the occupants prior to the final site visit and I will be available to collect them during my last visit in the envelope to be delivered along with the questionnaires. This is to avoid compromising anonymity if I collect it from the occupants.

¹ More details of this approach can be found at www.usablebuildings.co.uk/WebGuideOSM/index.html.

Data storage/retention/destruction/future use

Data collected during this exercise will be stored with the University for a Period of 6 years² in its original format in a locket cabinet on the university premises. This is to enable the researcher use the data when required after which the data will be destroyed. The results of this exercise will be used for academic purposes only and any intended publication to external sources outside the university will be with your approval. Outside these terms, the data has no future use.

Right to Withdraw from Participation

As the manager of the building, you have the right to accept or deny this permission at any time of this study.

Anonymity and Confidentiality

In any publication the occupants will be anonymous and the address of the property will not be included. The questionnaire is a licensed document and cannot be altered. However, it is solely the choice of the occupant whether or not to give their names and department. Should they choose to give their identity, it will be kept anonymous and confidential. It will not be used in any publication.

Contact Details and Approval Wording

Mr Bramantino Armiento –

Department of Ecology
Massey University
bram_antino@yahoo.com
021 053 1978

Prof Robyn Phipps (Supervisor) -

Department of Construction
Massey University
r.a.phipps@massey.ac.nz

Dr Eziaku Onyeizu Rasheed (co- Supervisor) -

Department of Construction
Massey University
e.o.rasheed@massey.ac.nz
Phone: +64 9 4140800 ext 43796

² The period data is to be kept will be commensurate to the scale of its research. For peer reviewed publication that might be further developed, the university expects six (6) years.

A SUPERHOME in Christchurch Under Winter Conditions: Real Performance Through Post-Occupancy Evaluation

PROJECT CONSENT FORM

Researcher: Bramantino Armiento

Supervisors: Prof Robyn Phipps & Dr Eziaku Onyeizu Rasheed

I have read the Project Information Sheet and have understood the nature of the research and why my building has been selected. All my questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I understand that:

- A 6-week indoor environment quality and on-site energy generation and energy usage monitoring will be carried out;
- Monitoring instruments will be installed in the building and this requires the researcher's presence inside the building;
- the researcher will need to check the monitoring instruments between the 3rd and 4th week of the monitoring period and will again visit the building to remove the instruments at week 6;
- An invitation for participating in a questionnaire survey will be delivered to the occupants. The questionnaire is a licensed document and cannot be altered. However, it is solely the choice of the occupants whether or not to give his/her identities;
- Should the participant choose to give his/her identity, it will be kept confidential to the researcher and not be used in any report or publication;
- The questionnaires are to be dropped off in the envelope provided along with the questionnaires and this will be done to avoid compromising anonymity of the participants;
- this exercise will be used for academic purposes only and any intended publication to external sources outside the university will be with your approval;
- I am free to withdraw the participation of the building and the occupants (and/or any information I provide) from the project up to 1st of August 2017; and,
- Data obtained will be placed in an official archive for 6 years in its original format and in an electronic format in a locket cabinet on the university premises.

I accept your request for access to the building and the occupants under the conditions set out.

Signature: _____ **Date:** _____

Full Name - printed _____

APPENDIX 3



PARTICIPANT INFORMATION SHEET – BUS QUESTIONNAIRE

The Occupant, 14 Jane Deans Close.

Project Title: A SUPERHOME in Christchurch Under Winter Conditions: Real Performance Through Post-Occupancy Evaluation

Name of Researcher: Bramantino Armiento

Supervisor: Prof Robyn Phipps & Dr Eziaku Onyeizu Rasheed

Researcher introduction

I am a Masters candidate of the Department of Ecology, Massey University.

This project aims to investigate the post-occupancy performance and indoor environment quality of a Superhome Movement Exemplar building, in Christchurch, New Zealand. Your building is a suitable candidate for this exercise. A part of what is being examined in my study is your satisfaction towards the building. As the occupant of this building, I am requesting your participation in this exercise.

I have obtained permission from the owner of the building to conduct this study in the building.

Project Procedures

The procedure for this exercise is simple and requires little of your time. It is outlined as follows:

A questionnaire survey will be delivered to you. It is solely your choice whether or not to participate. The questionnaire is an internationally recognized questionnaire, i.e. BUS Methodology two-page occupant questionnaire 2011 used for Building in Use Occupant Survey – with license from Building Use Studies (BUS) Ltd 2011¹. The questions are easy to answer without any ambiguities. The questionnaire requires approximately 5-10 minutes of your time. The questionnaires will be delivered to you along with an envelope which will be made available, wherein you can drop your answered questionnaires. This is to avoid compromising anonymity if I collect it from you directly.

Data storage/retention/destruction/future use

Data collected during this exercise will be stored with the University for a Period of 6 years² in its original format in a lockert cabinet on the university premises. This is to enable the researcher

¹ More details of this approach can be found at www.usablebuildings.co.uk/WebGuideOSM/index.html.

use the data when required after which the data will be destroyed. The results of this exercise will be used for academic purposes only and any intended publication to external sources outside the university will be with your approval. Outside these terms, the data has no future use.

Right to Withdraw from Participation

As the occupant of the building, you have the right to accept or deny this permission at any time of this study up to the 1st of August 2017.

Anonymity and Confidentiality

The questionnaire is a licensed document and cannot be altered. However, it is solely your choice whether or not to give your identities. Should you choose to give your identity, it will be kept anonymous and confidential and not be used in any publication.

Contact Details and Approval Wording

Mr Bramantino Armiento –

Department of Ecology
Massey University
bram_antino@yahoo.com

021 053 1978

Prof Robyn Phipps (Supervisor) -

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² The period data is to be kept will be commensurate to the scale of its research. For peer reviewed publication that might be further developed, the university expects six (6) years.

A SUPERHOME in Christchurch Under Winter Conditions: Real Performance Through Post-Occupancy Evaluation

PARTICIPANT CONSENT FORM – INDIVIDUAL

Researcher: Bramantino Armiento

Supervisors: Prof Robyn Phipps & Dr Eziaku Onyeizu Rasheed

I have read the Participant Information Sheet and have understood the nature of the research and why I have been selected. All my questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I understand that:

- My participation in the project is entirely voluntary;
- The questionnaire is a licensed document and cannot be altered. However, it is solely your choice whether or not to give your identities;
- Should you choose to give your identity, it will be kept confidential to the researcher and not be used in any report or publication;
- The questionnaires are to be dropped off in the envelope delivered along with the questionnaires and this will be done to avoid compromising anonymity of the participants;
- this exercise will be used for academic purposes only and any intended publication to external sources outside the university will be with your approval;
- I am free to withdraw myself (and/or any information I provide) from the project up to 1st of August 2017; and,
- Data obtained will be placed in an official archive for 6 years in its original format and in an electronic format in a locket cabinet on the university premises.

I accept your request for access to the building and the occupants under the conditions set out.

Signature: _____ **Date:** _____

Full Name - printed _____

APPENDIX 4

Data Collection Issues

QTRAK

1. Site Visit 1

There were two QTrak loggers brought in for the monitoring of the study home. The Q-Trak loggers were installed for logging data in the living area and the master bedroom. A side-to-side testing of the loggers was carried out prior to the site visit to see any irregularities in the data measured. The testing indicated significant difference in CO₂ levels measured by the two loggers. A conclusion was made that one of the two loggers' CO₂ sensor was faulty. Due to time constraints, a replacement for the faulty logger was not available at the time, and the logger was still used to record room temperature and relative humidity data in the living area.

2. Site Visit 2

A replacement logger was brought in to replace the faulty logger in the living room. The researcher discovered that both loggers had stopped recording data at sample unit 295, which is equivalent to 49 hours and 10 minutes of data. An investigation was carried out to find the cause of the failure. It was discovered that a solar metering system was being installed on the day that the loggers stopped logging data, which may have involved the shutting down of power. It was therefore assumed that the loggers stopped working as they ran out of batteries. New batteries were installed before the loggers were set to launch again.

3. Site Visit 3

The logger set up in the living area was found plugged off from the electricity outlet and had stopped logging data at sample unit 279, which is equivalent to 46 hours and 30 minutes of data. The logger in the living room was re-launched to record data for 4 hours while the researcher was in the study building undertaking thermography and sound transmission test. The logger set up in the master bedroom was found working fine.

IButton

On the second site visit:

1. the sensor on the master bedroom's floor – underneath the wardrobe – was found upside down. It was discovered that on the 6/7/17, a refurbishing took place at the master bedroom on the wardrobe. This refurbishing is assumed to have been the cause that the sensor was found upside down.
2. the window sensor, also placed in the bedroom, was found unattached from the window surface. The tape used to stick the sensor on the surface was replaced with a new one, and the sensor got deployed back onto the same spot on the window.
3. a relocation of the wall sensor at the kitchen was made 10 cm lower than the previous spot due to placement of a new painting on the 9/7/17.

APPENDIX 5

Living Room - Window & Window Frame



Living Room - Wall



Living Room - Floor



Kitchen - Window & Window Frame



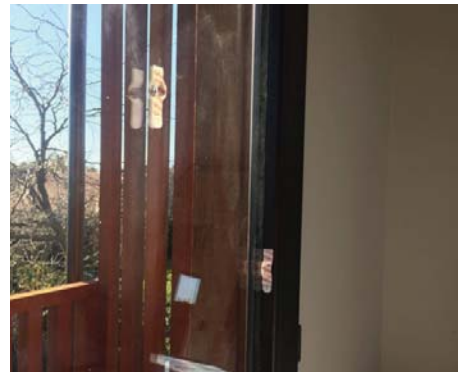
Kitchen - Wall



Kitchen - Floor



Master Bedroom - Window & Window Frame





Master Bedroom - Wall



Ensuite - Wall



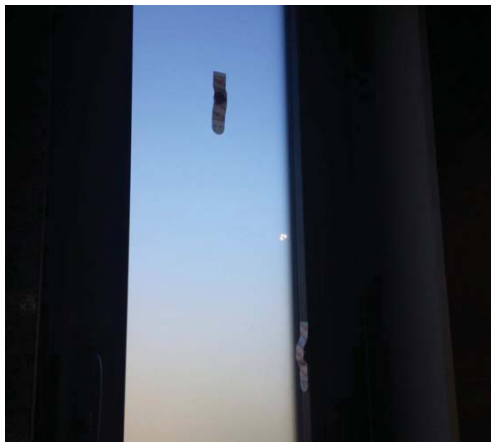
Master Bedroom - Floor



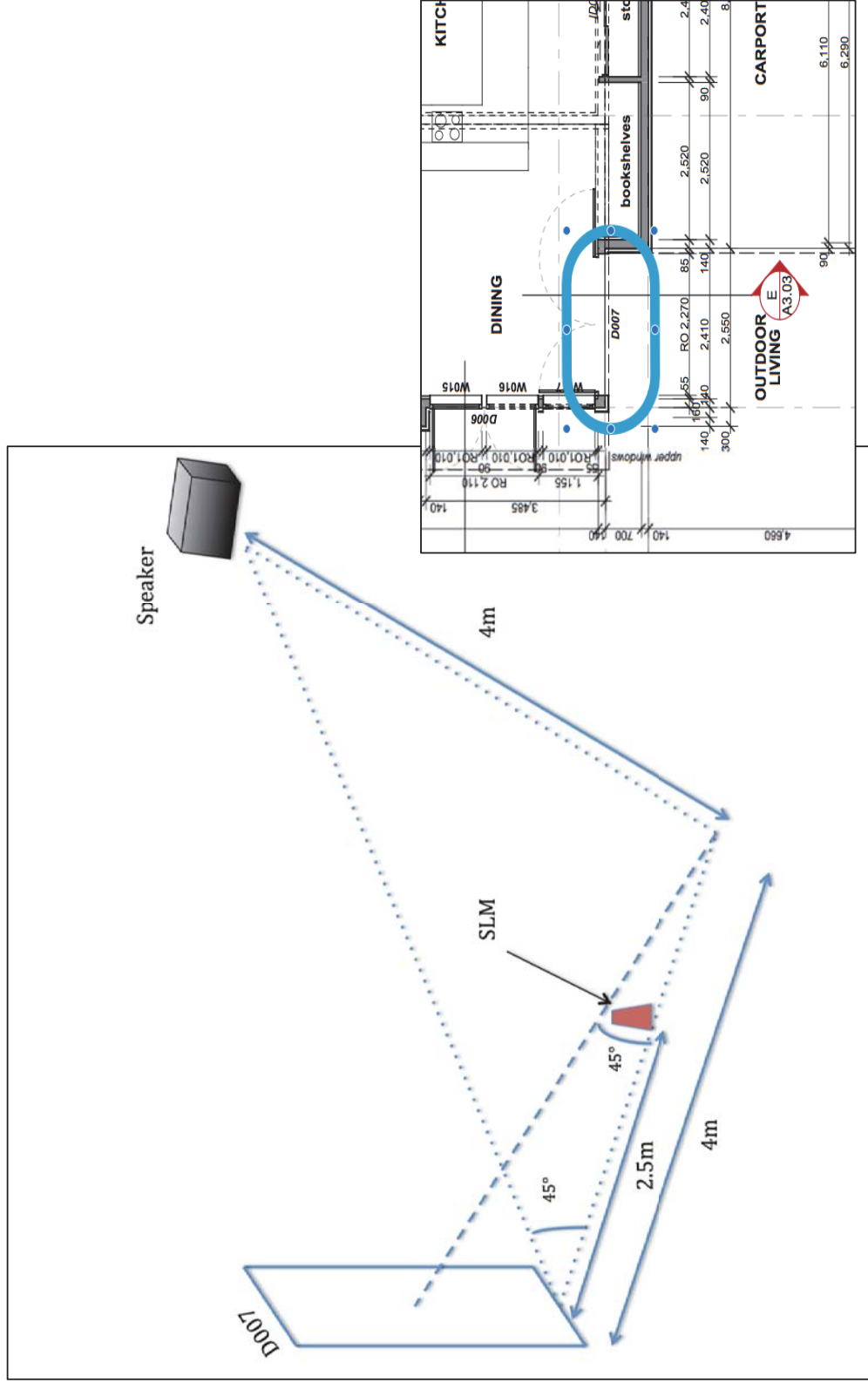
Ensuite - Floor



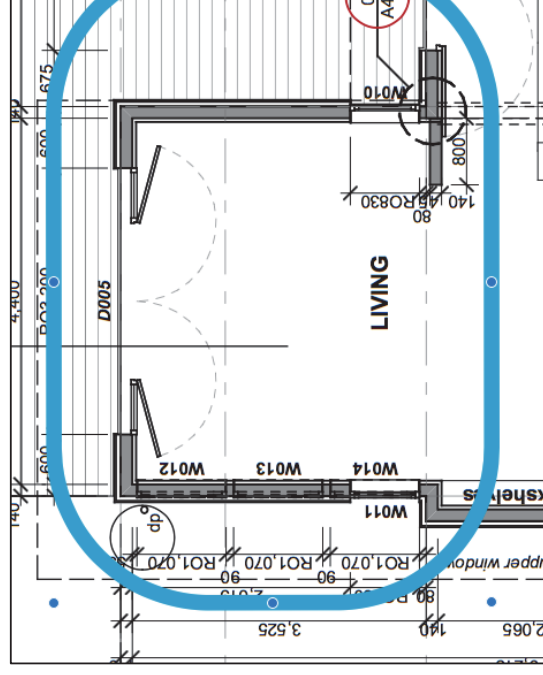
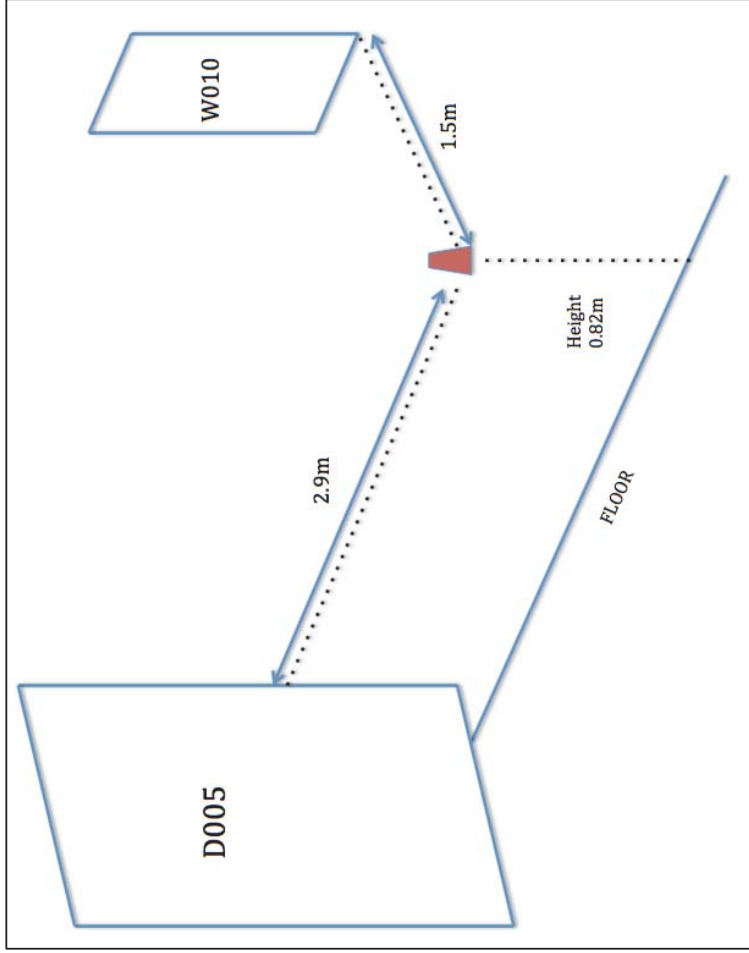
Ensuite - Window & Window Frame



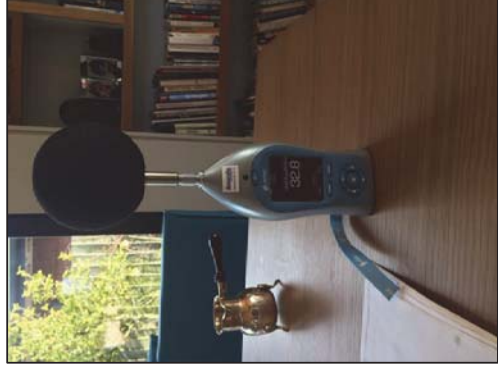
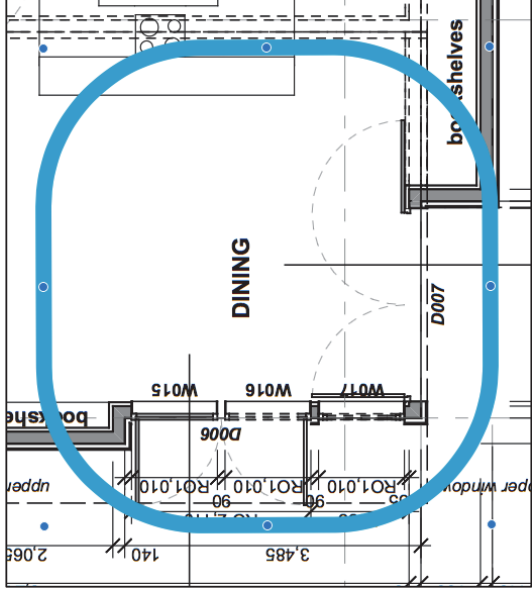
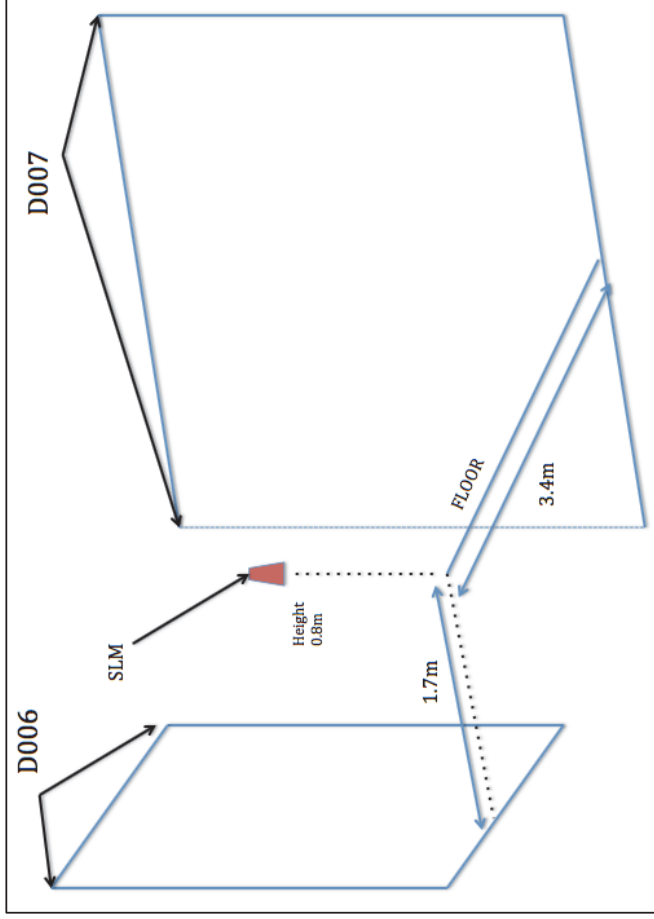
POSITION 2



Living Room



Dining Area



Comfort This section asks how comfortable you find the building in both winter and summer. Please try to evaluate this building with respect to your experience of using buildings in general.

How would you describe typical conditions in WINTER? If you have not lived here in winter then please leave these questions blank and just complete the questions on Temperature in Summer.

Temperature in winter Please tick your rating on each scale

Uncomfortable 1 2 3 4 5 6 7 Comfortable

Too hot 1 2 3 4 5 6 7 Too cold

Stable 1 2 3 4 5 6 7 Varies during day

Air in winter

Still 1 2 3 4 5 6 7 Draughty

Dry 1 2 3 4 5 6 7 Humid

Fresh 1 2 3 4 5 6 7 Stuffy

Odourless 1 2 3 4 5 6 7 Smelly

Conditions in winter

Unsatisfactory 1 2 3 4 5 6 7 Satisfactory overall

Comments about heating

Health Do you feel that the building affects your health by making you feel less healthy or more healthy? Please try to evaluate this building with respect to your experience of using buildings in general.

Less healthy 1 2 3 4 5 6 7 More healthy

Comments about health

Personal control How much control do you personally have over the following ...?

Heating No control 1 2 3 4 5 6 7 Full control

Cooling No control 1 2 3 4 5 6 7 Full control

Ventilation No control 1 2 3 4 5 6 7 Full control

Lighting No control 1 2 3 4 5 6 7 Full control

Noise No control 1 2 3 4 5 6 7 Full control

Comments about personal control

Design overall All things considered, how do you rate the design overall...?

Unsatisfactory 1 2 3 4 5 6 7 Satisfactory

Comments about design overall

Noise How would you describe the effects of noise ...? This question refers to conditions all year round

Noise overall Unsatisfactory 1 2 3 4 5 6 7 Satisfactory

Noise from people between rooms Too little 1 2 3 4 5 6 7 Too much

Noise from neighbours Too little 1 2 3 4 5 6 7 Too much

Other noise from outside Too little 1 2 3 4 5 6 7 Too much

Comments about noise and its sources

Comments about cooling and/or ventilation

Environmental design features If you have anything to add about the energy and water-saving features of your home please put them here.

Comments about energy or water-saving design features

Anything else ...? If you have anything else to add which is relevant to the topics raised please put it here.

Other comments

Lighting How would you describe the quality of the lighting ...? This question refers to conditions all year round

Lighting overall Unsatisfactory 1 2 3 4 5 6 7 Satisfactory

Natural light Too little 1 2 3 4 5 6 7 Too much

Artificial light Too little 1 2 3 4 5 6 7 Too much

Comments about lighting conditions

Overall comfort All things considered, how do you rate the comfort of the residence's environment overall ...? Please tick

Unsatisfactory 1 2 3 4 5 6 7 Satisfactory

Comments about comfort

Lifestyle

Has living here changed your lifestyle ...?

Please tick
Yes 1 2 No

If yes, please give examples of lifestyle changes ...

Work

Leisure

Diet

Travel

Anything else?

Utilities costs

How do your utilities costs (for heating, electricity and water) compare with your previous accommodation...?

Please tick

Heating Much lower 1 2 3 4 5 6 7 Much higher

Electricity Much lower 1 2 3 4 5 6 7 Much higher

Water Much lower 1 2 3 4 5 6 7 Much higher

Please give examples of how you have changed your use of heating/cooling, lighting, appliances and water since coming here ...

Heating/cooling

Lighting

Appliances

Water

Anything else?

Thank you for your help If you have any more comments on the topics raised, please add them on a separate sheet.

Please return the filled-in questionnaire to Bramantino Armiento, or as otherwise requested.

APPENDIX 8

OITC (Position 1 ⇔ Living Area)				
Frequency	AWRS	Transmission Loss	A-weighted correction	
(Hz)	(dB)	(dB)	(dB)	
80	80.5	16.5	64	
100	82.9	18	64.9	
125	84.9	18	66.9	
160	84.6	18	66.6	
200	86.1	25	61.1	
250	86.4	25	61.4	
315	87.4	25	62.4	
400	88.2	29	59.2	
500	89.8	29	60.8	
630	89.1	29	60.1	
800	89.2	29.5	59.7	
1000	89	29.5	59.5	
1250	89.6	29.5	60.1	
1600	89	27.5	61.5	
2000	89.2	27.5	61.7	
2500	88.3	27.5	60.8	
3150	86.2	27	59.2	
4000	85	27	58	
OITC:				25.2

OITC (Position 1 ⇔ Kitchen)				
Frequency	AWRS	Transmission Loss	A-weighted correction	
(Hz)	(dB)	(dB)	(dB)	
80	80.5	26.5	54	
100	82.9	20.75	62.15	
125	84.9	20.75	64.15	
160	84.6	20.75	63.85	
200	86.1	23.75	62.35	
250	86.4	23.75	62.65	
315	87.4	23.75	63.65	

400	88.2	27.75	60.45
500	89.8	27.75	62.05
630	89.1	27.75	61.35
800	89.2	33.75	55.45
1000	89	33.75	55.25
1250	89.6	33.75	55.85
1600	89	36	53
2000	89.2	36	53.2
2500	88.3	36	52.3
3150	86.2	32.75	53.45
4000	85	32.75	52.25
OITC:			
27.4			

OITC (Position 1 ⇔ Dining Area)				
Frequency	AWRS	Transmission Loss	A-weighted correction	
(Hz)	(dB)	(dB)	(dB)	
80	80.5	26	54.5	
100	82.9	24.5	58.4	
125	84.9	24.5	60.4	
160	84.6	24.5	60.1	
200	86.1	30	56.1	
250	86.4	30	56.4	
315	87.4	30	57.4	
400	88.2	34.2	54	
500	89.8	34.2	55.6	
630	89.1	34.2	54.9	
800	89.2	37	52.2	
1000	89	37	52	
1250	89.6	37	52.6	
1600	89	40.5	48.5	
2000	89.2	40.5	48.7	
2500	88.3	40.5	47.8	
3150	86.2	37.75	48.45	
4000	85	37.75	47.25	
OITC:				32.2

OITC (Position 2 ⇔ Living Area)				
Frequency	AWRS	Transmission Loss	A-weighted correction	
(Hz)	(dB)	(dB)	(dB)	
80	80.5	7.5	73	
100	82.9	23.45	59.45	
125	84.9	23.45	61.45	
160	84.6	23.45	61.15	
200	86.1	27.75	58.35	
250	86.4	27.75	58.65	
315	87.4	27.75	59.65	
400	88.2	34.45	53.75	
500	89.8	34.45	55.35	
630	89.1	34.45	54.65	
800	89.2	34.0625	55.1375	
1000	89	34.0625	54.9375	
1250	89.6	34.0625	55.5375	
1600	89	35.3125	53.6875	
2000	89.2	35.3125	53.8875	
2500	88.3	35.3125	52.9875	
3150	86.2	32.9375	53.2625	
4000	85	32.9375	52.0625	
OITC:				25.5

(Position 2 ⇔ Kitchen)				
Frequency	AWRS	Transmission Loss	A-weighted correction	
(Hz)	(dB)	(dB)	(dB)	
80	80.5	18	62.5	
100	82.9	28.75	54.15	
125	84.9	28.75	56.15	
160	84.6	28.75	55.85	
200	86.1	27.125	58.975	
250	86.4	27.125	59.275	
315	87.4	27.125	60.275	

400	88.2	32.5	55.7
500	89.8	32.5	57.3
630	89.1	32.5	56.6
800	89.2	32.25	56.95
1000	89	32.25	56.75
1250	89.6	32.25	57.35
1600	89	33.75	55.25
2000	89.2	33.75	55.45
2500	88.3	33.75	54.55
3150	86.2	34.5	51.7
4000	85	34.5	50.5
OITC:			30.3

OITC (Position 2 ⇔ Dining Area)

Frequency (Hz)	AWRS (dB)	Transmission Loss (dB)	A-weighted correction (dB)
80	80.5	13.75	66.75
100	82.9	26.25	56.65
125	84.9	26.25	58.65
160	84.6	26.25	58.35
200	86.1	26	60.1
250	86.4	26	60.4
315	87.4	26	61.4
400	88.2	32.875	55.325
500	89.8	32.875	56.925
630	89.1	32.875	56.225
800	89.2	33.3	55.9
1000	89	33.3	55.7
1250	89.6	33.3	56.3
1600	89	36.25	52.75
2000	89.2	36.25	52.95
2500	88.3	36.25	52.05
3150	86.2	34.5	51.7
4000	85	34.5	50.5
OITC:			28.9

OITC (Position 3 ⇔ Living Area)

Frequency	AWRS	Transmission Loss	A-weighted correction
-----------	------	-------------------	-----------------------

Frequency (Hz)	AWRS (dB)	Transmission Loss (dB)	A-weighted correction (dB)
80	80.5	17.5	63
100	82.9	19.625	63.275
125	84.9	19.625	65.275
160	84.6	19.625	64.975
200	86.1	22.5	63.6
250	86.4	22.5	63.9
315	87.4	22.5	64.9
400	88.2	31.875	56.325
500	89.8	31.875	57.925
630	89.1	31.875	57.225
800	89.2	40.4375	48.7625
1000	89	40.4375	48.5625
1250	89.6	40.4375	49.1625
1600	89	37.8125	51.1875
2000	89.2	37.8125	51.3875
2500	88.3	37.8125	50.4875
3150	86.2	36.6875	49.5125
4000	85	36.6875	48.3125
OITC:			27.0

OITC (Position 3 ⇔ Kitchen)

Frequency (Hz)	AWRS (dB)	Transmission Loss (dB)	A-weighted correction (dB(A))
80	80.5	19.75	60.75
100	82.9	19.6875	63.2125
125	84.9	19.6875	65.2125
160	84.6	19.6875	64.9125
200	86.1	20	66.1
250	86.4	20	66.4
315	87.4	20	67.4
400	88.2	28.4375	59.7625
500	89.8	28.4375	61.3625
630	89.1	28.4375	60.6625
800	89.2	31.6875	57.5125

1000	89	31.6875	57.3125
1250	89.6	31.6875	57.9125
1600	89	32.375	56.625
2000	89.2	32.375	56.825
2500	88.3	32.375	55.925
3150	86.2	31.0625	55.1375
4000	85	31.0625	53.9375
OITC:			25.3

OITC (Position 3 ⇔ Dining Area)

Frequency (Hz)	AWRS (dB)	Transmission Loss (dB)	A-weighted correction (dB)
80	80.5	19.125	61.375
100	82.9	18.125	64.775
125	84.9	18.125	66.775
160	84.6	18.125	66.475
200	86.1	22.8125	63.2875
250	86.4	22.8125	63.5875
315	87.4	22.8125	64.5875
400	88.2	32.5	55.7
500	89.8	32.5	57.3
630	89.1	32.5	56.6
800	89.2	38.875	50.325
1000	89	38.875	50.125
1250	89.6	38.875	50.725
1600	89	37.6875	51.3125
2000	89.2	37.6875	51.5125
2500	88.3	37.6875	50.6125
3150	86.2	34.5	51.7
4000	85	34.5	50.5
OITC:			26.5

Mean OITC

$$(25.2 + 27.4 + 32.2 + 25.5 + 30.3 + 28.9 + 27.0 + 25.3 + 26.5) \div 9 = 27.57 \text{ dB(A)}$$

APPENDIX 9

BUILDING LEAKAGE TEST

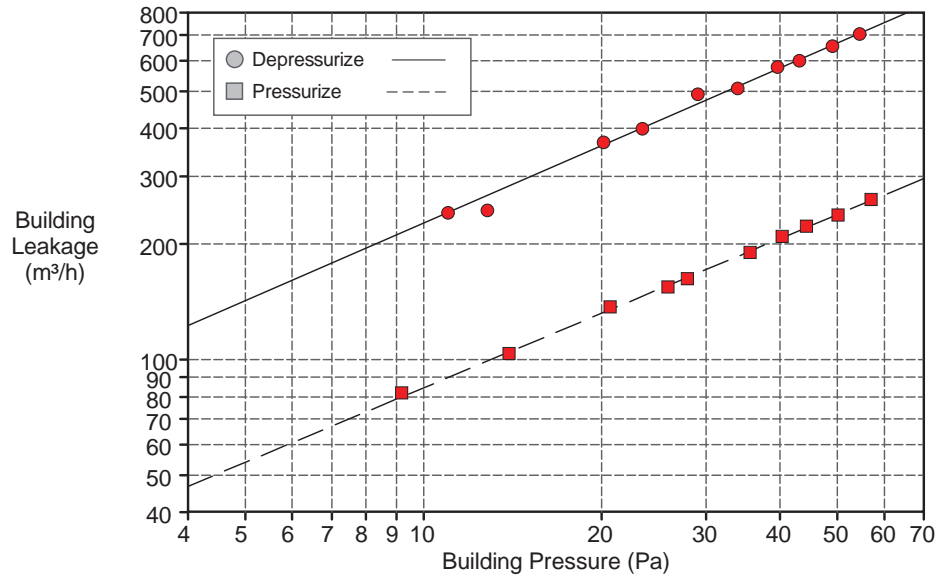
Date of Test: 30/05/2017
 Test File: Presurisation Test 2

Technician: GDW
 Project Number: BBA/ DSC 1.

Customer: Bob Burnett
 Dan Saunders
 Church Square
 Christchurch,
 Phone:
 Fax:

Building Address: Buck House
 Jane Deans Close

	<u>Depressurization</u>	<u>Pressurization</u>	<u>Average</u>
Test Results at 50 Pascals:			
V50: Airflow (m ³ /h)	668 (+/- 2.4 %)	239 (+/- 0.8 %)	453
n50: Air Changes per Hour (1/h)	1.34	0.48	0.91
w50: m ³ /h/m ² Floor Area	5.02	1.79	3.41
q50: m ³ /h/m ² Surface Area	2.08	0.74	1.41
Leakage Areas:			
Canadian EqLA @ 10 Pa (cm ²)	253.2 (+/- 6.9 %)	94.2 (+/- 2.3 %)	173.7
cm ² /m ² Surface Area	0.7887	0.2933	0.5410
LBL ELA @ 4 Pa (cm ²)	132.3 (+/- 11.5 %)	50.3 (+/- 3.7 %)	91.3
cm ² /m ² Surface Area	0.4120	0.1568	0.2844
Building Leakage Curve:			
Air Flow Coefficient (Cenv)	48.0 (+/- 18.4 %)	19.2 (+/- 5.9 %)	
Air Leakage Coefficient (CL)	48.4 (+/- 18.4 %)	19.1 (+/- 5.9 %)	
Exponent (n)	0.671 (+/- 0.051)	0.646 (+/- 0.016)	
Correlation Coefficient	0.99574	0.99953	
Test Standard:	EN 13829		
Test Mode:	Depressurization and Pressurization		
Type of Test Method:			
Regulation complied with:	Superhome		



BUILDING LEAKAGE TEST Page 2 of 4

Date of Test: 30/05/2017 Test File: Presurisation Test 2

Building Information

Volume (m ³)	499
Surface Area: (m ²)	321
Floor Area: (m ²)	133
Height (m)	4
Uncertainty of Dimensions (%)	5
Year of Construction	2017
Type of Heating	Ecomaster Underfloor
Type of Air Conditioning	
Type of Ventilation	Ecomaster
Building Wind Exposure	Partly Exposed Building
Wind Class	Fresh Breeze

Equipment Information

Type	Manufacturer	Model	Serial Number	Custom Calibration Date
Fan	Energy Conservatory	Model 4 (230V)	CE3983	
Micromanometer	Energy Conservatory	DG700	34985-7	30/05/2012

Comments

None

BUILDING LEAKAGE TEST Page 3 of 4

Date of Test: 30/05/2017 Test File: Presurisation Test 2

Depressurization Test 1:

Environmental Data

Indoor Temperature (°C)	Outdoor Temperature (°C)	Barometric Pressure (Pa)
24.5	12.0	101325.0

Pre-Test			Baseline Pressure Data			Post-Test		
$\Delta p_{0,1-}$	$\Delta p_{0,1+}$	$\Delta p_{0,1}$	$\Delta p_{0,2-}$	$\Delta p_{0,2+}$	$\Delta p_{0,2}$			
-0.6	1.0	0.4	-1.2	0.7	-0.4			

Data Points:

Nominal Building Pressure (Pa)	Baseline Building Pressure (Pa)	Adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (m ³ /h)	Adjusted Flow (m ³ /h)	% Error	Fan Configuration
0.4	n/a	n/a	n/a				
-54.6	-54.5	80.5	722	704	-0.6	Ring B	
-49.0	-49.0	69.6	672	655	-0.7	Ring B	
-43.1	-43.1	58.3	616	600	-0.9	Ring B	
-39.6	-39.6	54.2	594	578	1.2	Ring B	
-33.9	-33.9	41.8	521	508	-1.3	Ring B	
-29.1	-29.0	38.9	504	491	5.7	Ring B	
-23.4	-23.4	25.7	410	399	-0.7	Ring B	
-20.2	-20.1	320.4	378	368	1.5	Ring C	
-12.8	-12.8	145.0	251	245	-8.7	Ring C	
-11.0	-11.0	141.2	248	241	-0.2	Ring C	
-0.4	n/a	n/a					

Deviations from Standard EN 13829 - Test Parameters

None

BUILDING LEAKAGE TEST Page 4 of 4

Date of Test: 30/05/2017 Test File: Pressurisation Test 2

Pressurization Test 1:

Environmental Data

Indoor Temperature (°C)	Outdoor Temperature (°C)	Barometric Pressure (Pa)
24.5	12.0	101325.0

Pre-Test

Baseline Pressure Data

Post-Test

$\Delta p_{0,1-}$	$\Delta p_{0,1+}$	$\Delta p_{0,1}$	$\Delta p_{0,2-}$	$\Delta p_{0,2+}$	$\Delta p_{0,2}$
-0.6	0.8	0.2	-1.5	1.6	0.3

Data Points:

Nominal Building Pressure (Pa)	Baseline Adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (m ³ /h)	Adjusted Flow (m ³ /h)	% Error	Fan Configuration
0.2	n/a	n/a				
57.2	57.0	148.6	254	261	0.4	Ring C
50.4	50.1	124.5	232	238	-0.5	Ring C
44.6	44.3	108.9	217	222	0.6	Ring C
40.6	40.4	96.7	204	209	0.5	Ring C
35.9	35.7	80.7	186	190	-0.8	Ring C
28.2	27.9	59.4	159	162	-0.8	Ring C
26.1	25.9	53.8	151	154	-1.0	Ring C
20.9	20.7	42.6	134	137	1.4	Ring C
14.2	14.0	24.8	101	103	-1.2	Ring C
9.4	9.2	15.8	80	82	2.5	Ring C
0.3	n/a	n/a				

Deviations from Standard EN 13829 - Test Parameters

- The minimum (baseline adjusted) building pressure is less than 10 Pa.

APPENDIX 10

ALF Results Energy

The results in this section are calculated from the designer inputs including, occupancy, and heating temperature and schedules.

- Heating Schedules: 24 hour heating
- Heating Level: 20°C
- Calculation Date: 26/8/2017

The information in the table gives you an overview of all the heat flows in and out of the designed building, based on the heating temperatures, climate and schedule selected.

	Area	R-value (m ² °C/W)	Loss (kWh/year)	Gain (kWh/year)	Useful Gain (kWh/year)
Floor	133.73 m ²	3.92	1477.17		-1477.17
Roof	133.73 m ²	5.495	1053.78		-1053.78
Walls & Windows					
Wall 1	0.96 m ²	3.99	10.41		-10.41
Wall 2	14.04 m ²	3.99	69.02		-69.02
Window 2-1		0.53	627.44		-627.44
Wall 3	27.024 m ²	3.99	155.38		-155.38
Window 3-1		0.53	117.65		-117.65
Window 3-2		0.53	51.47		-51.47
Window 3-3		0.53	445.09		-445.09
Window 3-4		0.53	66.18		-66.18
Window 3-5		0.53	119.24		-119.24
Window 3-6		0.53	119.24		-119.24
Window 3-7	0.53	119.24		-119.24	
Wall 4	22.6875 m ²	3.99	142.03		-142.03
Window 4-1		0.53	392.15		-392.15
Window 4-2		0.53	392.15		-392.15
Wall 5	5.9015 m ²	3.99	40.34		-40.34
Window 5-1		0.53	178.43		-178.43
Wall 6	41.8665 m ²	3.99	396.66		-396.66
Window 6-1		0.53	90.28		-90.28
Window 6-2		0.53	90.28		-90.28
Window 6-3		0.53	88.23		-88.23
Window 6-4		0.53	55.15		-55.15
Window 6-5		0.53	55.15		-55.15
Window 6-6	0.53	55.15		-55.15	
Wall 7	5.191 m ²	3.99	56.33		-56.33
Window 7-1		0.53	53.10		-53.10
Wall 8	1.836 m ²	3.99	5.08		-5.08
Window 8-1		0.53	111.76		-111.76
Wall 9	11.728 m ²	3.99	105.66		-105.66
Window 9-1		0.53	162.74		-162.74
Wall 10	5.18925 m ²	3.99	56.31		-56.31
Wall 11		3.99	322.58		-322.58
Window 11-1	31.72 m ²	0.53	53.10		-53.10
Window 11-2		0.53	54.94		-54.94
Window 11-3		0.53	54.94		-54.94
Wall 12	25.705 m ²	3.99	249.78		-249.78
Window 12-1		0.53	164.70		-164.70
Window 12-2		0.53	54.94		-54.94
Wall 13	16.65 m ²	3.99	121.57		-121.57
Window 13-1		0.53	445.09		-445.09
Wall 14	1.002 m ²	3.99	10.87		-10.87
Wall 15	1.92 m ²	3.99	21.87		-21.87
Wall 16	20.06 m ²	3.99	136.16		-136.16
Window 16-1		0.53	413.72		-413.72
Window 16-2		0.53	61.97		-61.97
Window 16-3		0.53	66.67		-66.67
Window 16-4	0.53	71.46		-71.46	
Wall 17	7.434 m ²	3.99	35.55		-35.55
Window 17-1		0.53	74.25		-74.25
Window 17-2		0.53	81.37		-81.37
Window 17-3		0.53	88.49		-88.49
Window 17-4		0.53	95.61		-95.61
Wall 18	11.47 m ²	3.99	85.23		-85.23
Window 18-1		0.53	162.74		-162.74

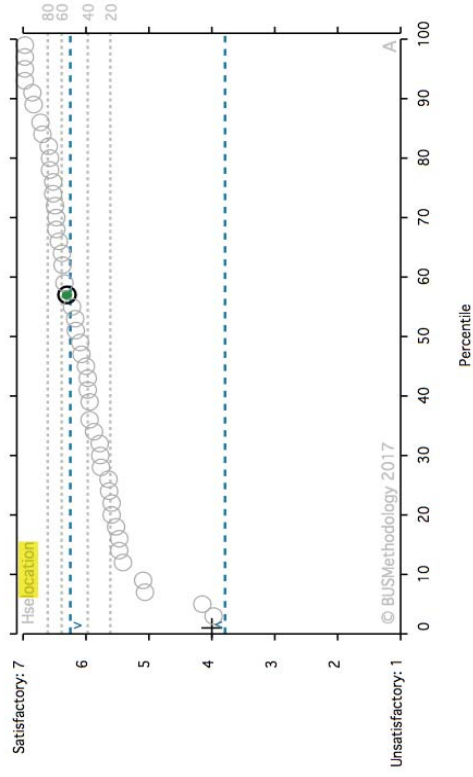
Window 18-2		0.53	38.90		-38.90
Window 18-3		0.53	44.23		-44.23
Window 18-4		0.53	49.57		-49.57
Wall 19	13.496m ²	3.99	146.46		-146.46
Air Leakage	499 m ³		1798.41	-	
Internal Gain				3539.81	
	TOTAL		11956.62	3539.81	

Total Load: 11956.62 kWh/year
 Total Gain: 3539.81 kWh/year (*this value is the net gain not the actual useful gains*)
 Gain Load Ratio: 29.61%
 Usefulness of Gains: 83.27%
 Useful Gains: 2947.49 kWh/year

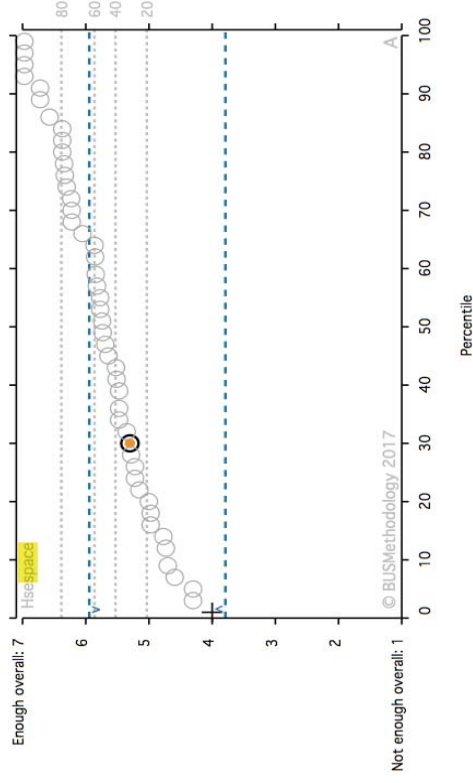
Required Heating Energy: 9002.12 kWh/year

APPENDIX 11

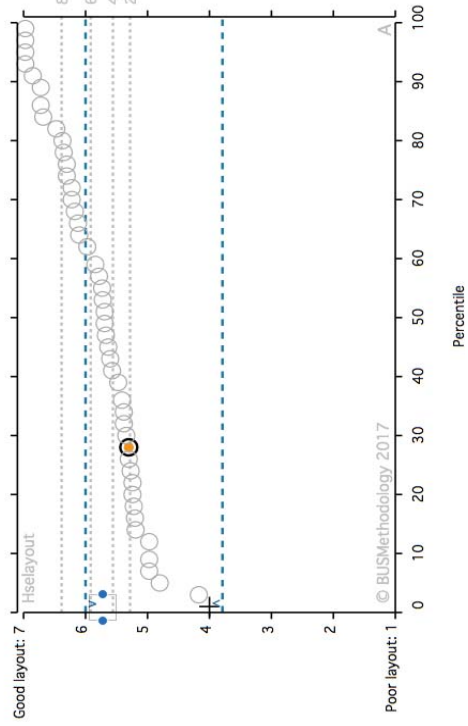
Building Location



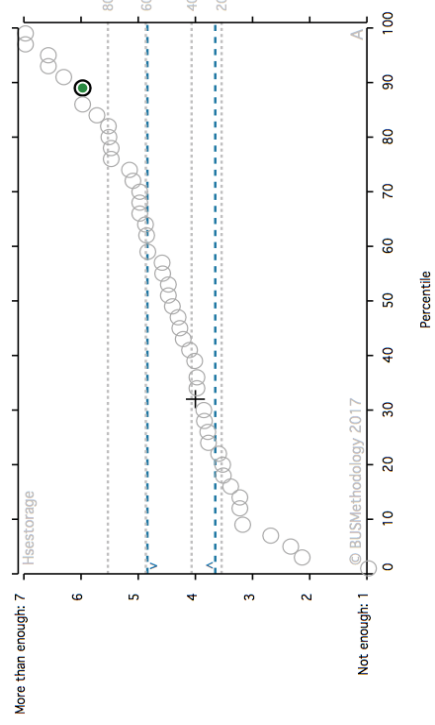
Space



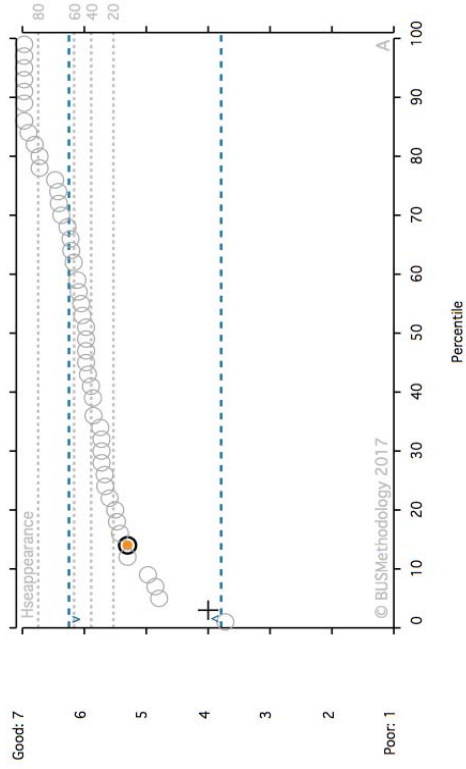
Layout



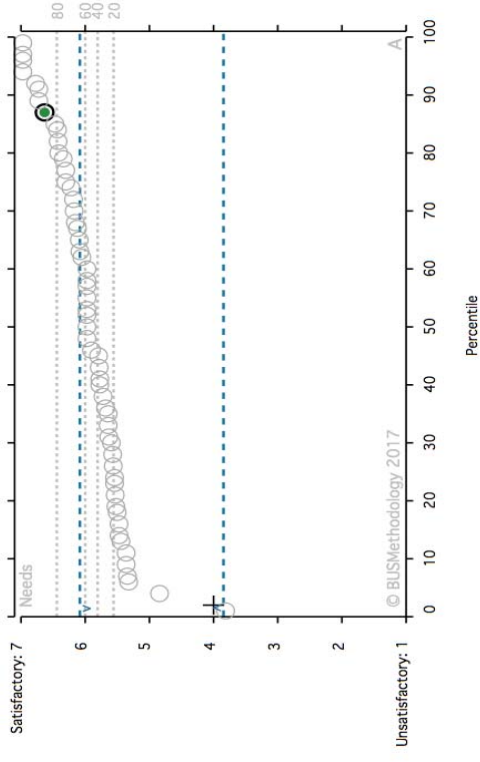
Storage Availability



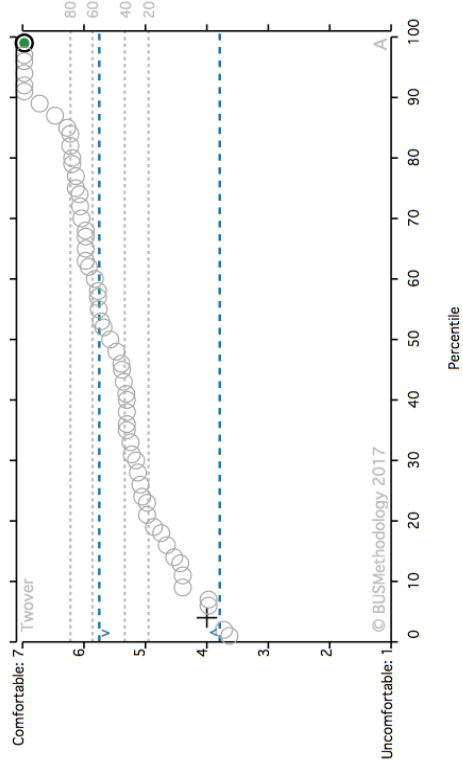
Appearance



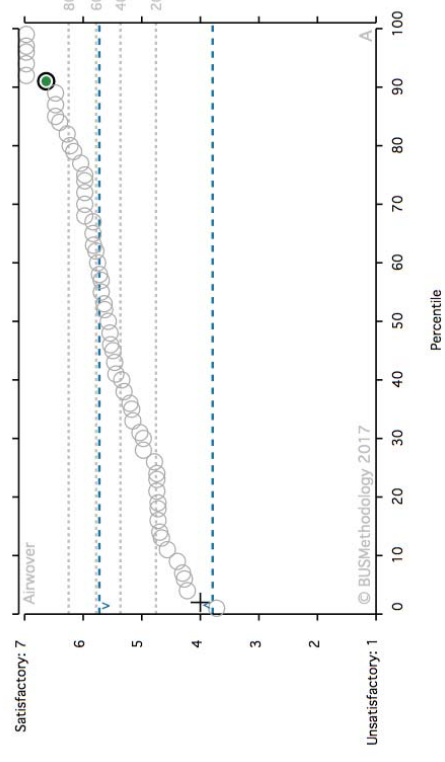
Needs



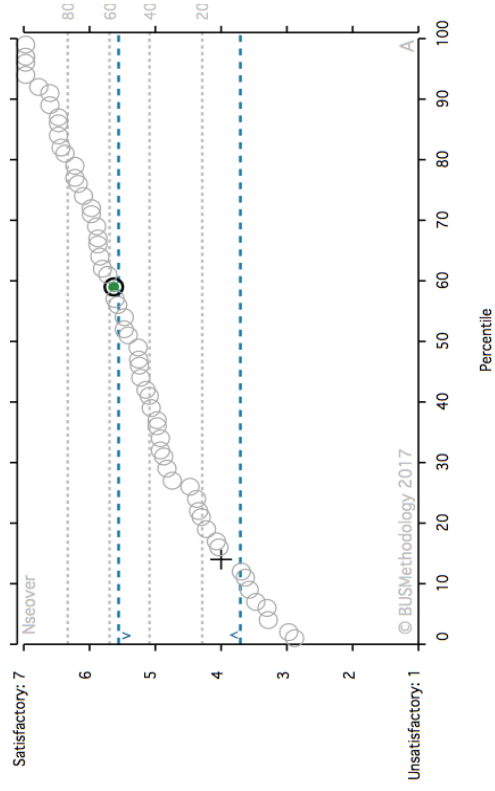
Temperature in winter



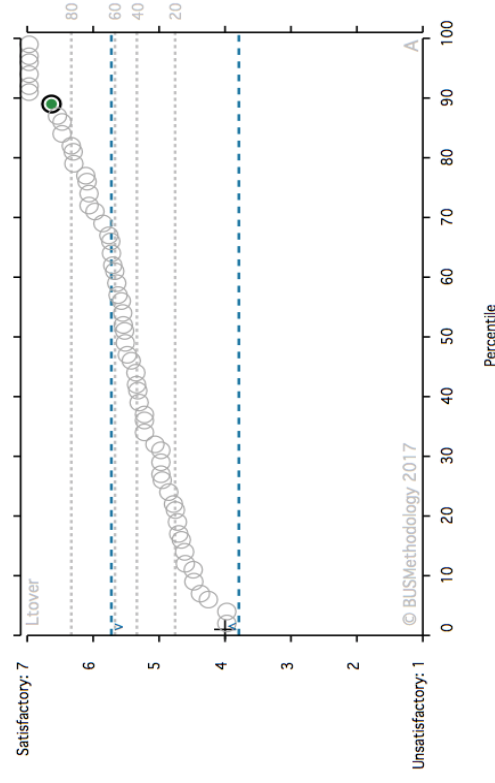
Air in winter



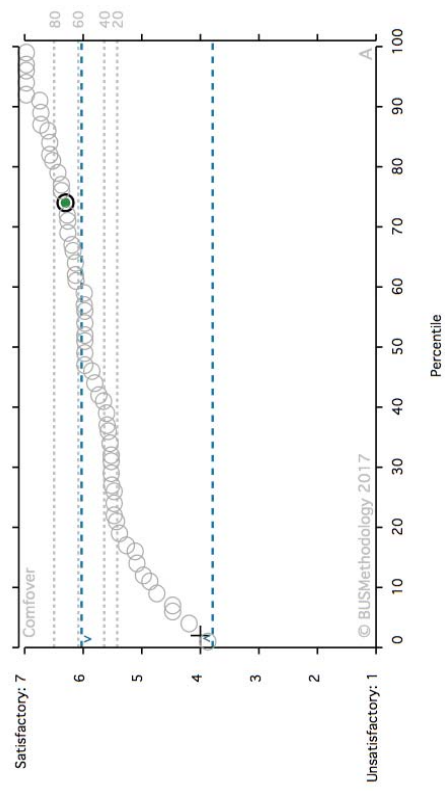
Noise



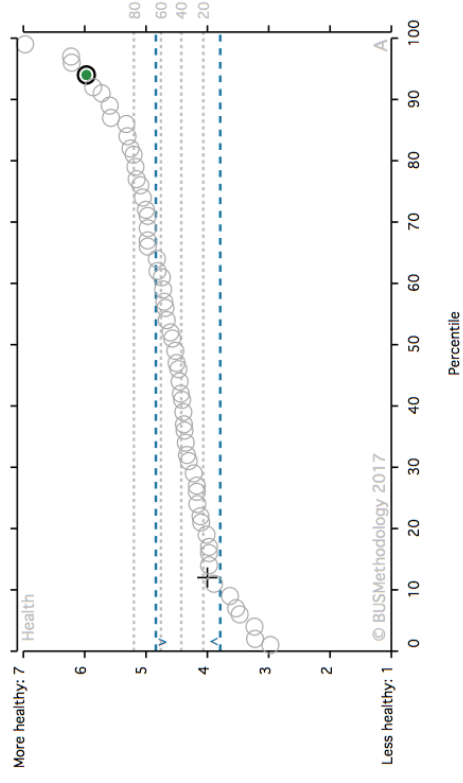
Lighting



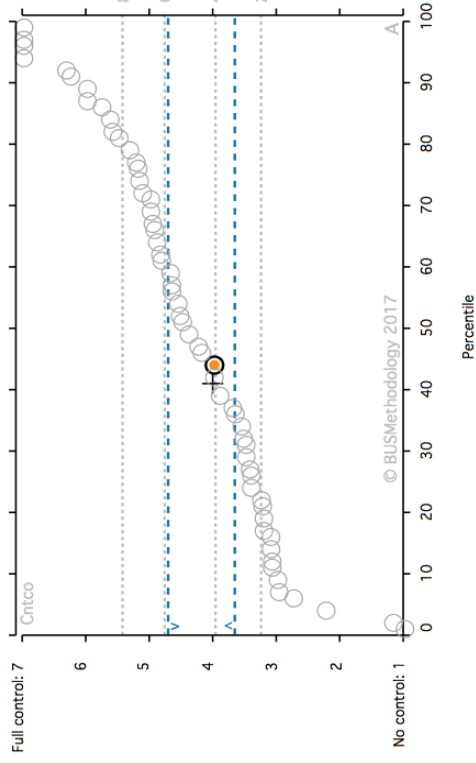
Overall Comfort



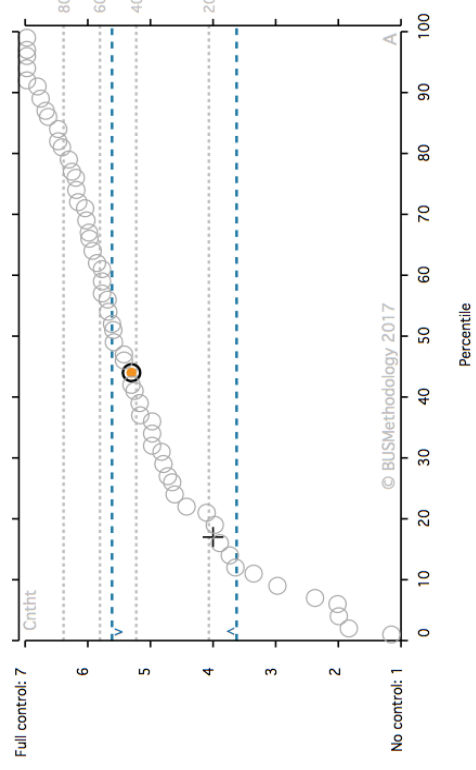
Perceived Health



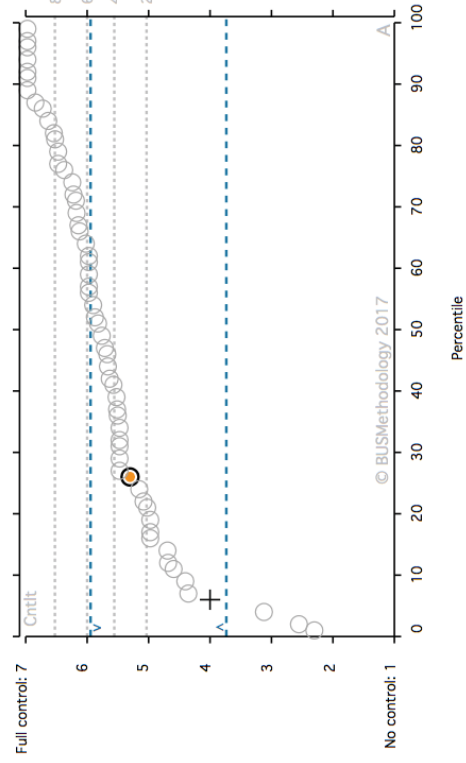
Control over cooling



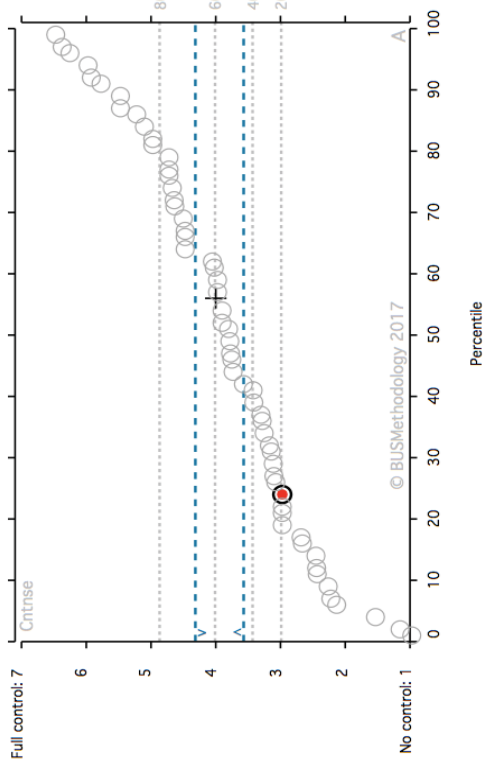
Control over heating



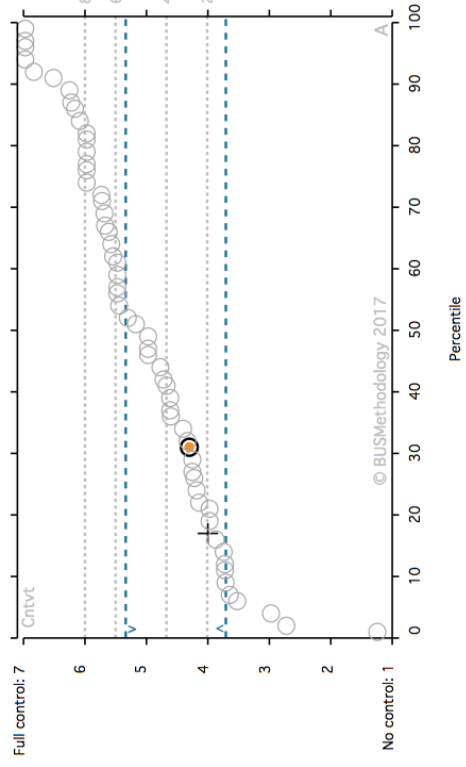
Control over lighting



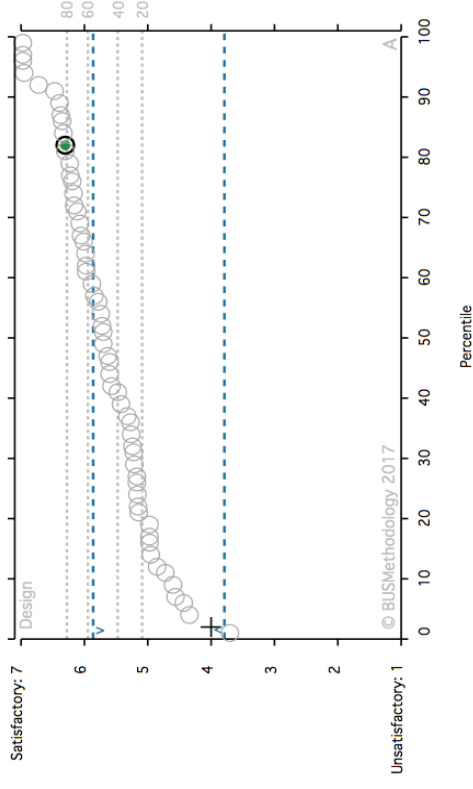
Control over noise




Control over ventilation



Design




APPENDIX 12



Contact us
Our Customer Care team are available 7 am-9 pm Monday to Friday and 8 am-5 pm Saturday.
All enquiries 0800 80 9000 or email help@contactenergy.co.nz
To find out more, visit contactenergy.co.nz

Your bill for 8 Jun 2017 to 6 Jul 2017
Tax Invoice/Statement
GST number [redacted]
Invoice number [redacted]
Statement date 10 Jul 2017
Page 1 of 3




17/07/17

Your next meter reading will be on approximately 8 August

Account number: Jane Deans Close, Riccarton, Christchurch 8011

Previous activity	Charges	Actual reading	Credits
Previous balance			\$385.22
Credit Card Payment (15 Jun 17)			\$323.18
Prompt Payment Discount			\$62.06
Balance outstanding			\$0.00
Summary of Current activity	Charges	Credits	
Fixed daily charges	\$23.32		
Variable charges	\$374.10		
GST	\$59.61		
Total current charges			\$457.03
Total amount due			\$457.03
Save \$91.40 with your prompt payment discount (Includes \$47.60 of GST on current charges)			\$365.63
If paid by 26 Jul 2017			

Check out our Fuel Reward plans at contactenergy.co.nz and earn up to \$1000 in fuel savings with AA Smartfuel.




Energy used by
to 6 Jul 17 09:28:01

Meter Number	Read Date	Previous Actual Reading	Current Actual Reading	Units used	Energy units
216699795.1	6 Jul 17	00082	00283	1,481	1,481 kWh

Fixed daily charges
Daily Charge 29 days @ 80.400 cents per day Fixed charges total \$23.32

Variable charges
All Day Economy 1,481 kWh @ 25.100 cents per kWh \$374.10
Electricity Authority Levy 1,481 kWh @ 0.160 cents per kWh \$23.77
Variable charges total \$397.87

Your electricity usage



About your energy use graph
The data for the monthly graph is calculated on a calendar month rather than billing period so your bill and monthly graph may slightly differ.

Account number [redacted]

Total amount due \$457.03
If paid by 26 Jul 17

Save \$91.40
If paid after 26 Jul 17

You can pay your bill by phone, cheque, direct debit or credit card, or in person at 82 Post or Warehouse, or by internet using our online bill payment service. For more information, go to www.contactenergy.co.nz

Please make cheques payable to **Contact Energy Limited** and send to us at **Private Bag 4709, Christchurch 8154**

#6354: #000501039065# #1500196665# #0000036563#

APPENDIX 13

Date of Test: 31/7/17

Time: (10:00) – (11:30)

Building Address: 14 Jane Deans Close, Riccarton

Camera Operator: Pavol Csiba, Infrared Thermographer Level 1 – Infrared Training Center - 9/06/17

Test Standard: BS EN 13187:1999

Outside Air temperature:

24h prior to test: Max: 9.2°C Min: 0.9°C

During test: Max: 7°C Min: 3.2°C

Outside Relative Humidity: 78.5%

Inside Air temperature: 22°C

Internal Relative Humidity: 39.6%

Precipitation, direction of the wind, and velocity of the wind during the examination:

10:00 a.m. = 4 km/h, Wind blowing 50° from Northeast to Southwest

10:30 a.m. = 11 km/h, Wind blowing 50° from Northeast to Southwest

11:00 a.m. = 9 km/h, Wind blowing 60° from East-northeast to West-southwest

11.30 a.m. = 9 km/h, Wind blowing 50° from Northeast to Southwest

The surfaces to be inspected were dry at the time of the test, and there had been no precipitation 24 hours prior to the test.

Solar Radiation conditions:

12h prior to test: 10 hours of no exposure to sun (night) + 2 hours of exposure to sun

During test: Sun is out radiating from the backyard side of the building.

Equipment Technical Specs

Type	IR Camera
Manufacturer	Fluke
Model	TiR1
Spatial Resolution	2.5 mRad
Thermal Sensitivity (at 30°C)	≤0.07°C (70 mK)
Spectral Range	7.5 - 14 µm
Image Frequency	9 Hz
Display	3.6" colour diagonal landscape VGA 640x480 LCD
Image Modes	Full infrared Picture in picture (displayed in center 320x240 pixels)
Accuracy	±2°C or ±2% of reading
Focus	Manual
Temperature range	-20°C - +150°C
Viewfinder	N/A
Emissivity Correction	Yes
Operating temperature range	-10°C - +50°C
Storage temperature range	-20°C - +50°C
Humidity, non-condensing	10-90% non-condensing