

Retrofitting Thermal Mass into New Zealand Houses: What are the potential benefits?

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This article reports on a study undertaken to investigate the effectiveness of thermal mass to moderate indoor air temperatures and to reduce heating energy when it is introduced into existing timber frame residential buildings. The research investigated characteristics of the existing New Zealand housing stock and how energy is used in those dwellings. Six different house typologies were defined and computer models created. Different combinations of thermal mass retrofits were assigned to each house type with variations also involving heat pumps. In all, the investigation produced 72 different scenarios, each of which was modelled for thermal performance using IES VE software.

General trends indicate that thermal mass retrofits are more effective in older houses, with more recent dwellings generating little improvement on average annual indoor temperatures. This is most likely a consequence of the higher insulation levels required in the newer houses as well as improved construction techniques that lead to lower infiltration rates. The research concludes that, while thermal mass is an integral part of passive solar design, insulation is much more important, particularly in houses where smaller areas of glazing limit the extent to which the sun can charge the mass. Retrofitting thermal mass into an existing lightweight dwelling, while it can lead to improved thermal performance, should always be undertaken as part of a strategy that includes making insulation improvements, draft-stopping and employing efficient methods of heating. A useful outcome of the project is a set of cases that can help inform residential owners about different passive retrofit options and the associated costs / benefits.

Key Words: thermal mass; retrofit solutions; solar energy; New Zealand houses; thermal simulation

Introduction

Lightweight timber framing has been used for residential construction in New Zealand since the first Maori settlers arrived due in large part to the plentiful supply of trees and to its performance in earthquakes (Broeke, 1970; Zhang, 2010). Early colonial settlers saw timber as a way of building short term shelter (Salmond, 1986) yet it has remained a permanent part of the built environment with the vast majority of the 1.4 million existing houses constructed using stick framing methods. It is now evident that up to 900,000 of these houses were built with little or no thermal insulation and this is a major factor in the generally poor thermal performance of the residential building stock (Storey et al., 2004). As a consequence it is challenging and increasingly expensive to create healthy indoor temperatures in these houses when appliances encouraging zone heating are utilised. A number of studies have found that internal temperatures sit below World Health Organisation (WHO) standards for healthy environments, particularly during the New Zealand winter. In 1971-72 the Household Electricity Survey found that indoor temperatures during winter over the whole country averaged 15.8 °C in the living room and 14.4°C in the main bedroom. Moreover, in the south of the South Island average temperatures of 13.6°C for living rooms and 12.6°C for bedrooms were found (Lloyd et al., 2008; Isaacs, 1998). A 1989 study of units for elderly people found that over one third of minimum living room temperatures were below 16°C (Isaacs, 1998). More recently the Household Energy End-use Project (HEEP) studied 397 homes throughout New Zealand and found a mean range of evening living room temperatures in winter of between 10°C and 23.8°C (BRANZ, 2010). The problem of low temperatures endured in New Zealanders in their dwellings is not new. These are not only uncomfortable but increasingly we are becoming aware of the associated risks to people's health and wellbeing.

The average household in New Zealand uses 11,410kWh per year with around 34% of that total or 3,879kWh required to condition indoor temperatures (Isaacs et al, 2010, p. 473). Considerable research has been undertaken to improve the methods used to construct new dwellings in order to achieve better thermal performance. Improving the performance of existing houses is an area of huge potential when we consider their numbers in relation to the number of new houses built each year. The NZ Government appears to understand this and in 2009 it set up the *Warm Up New Zealand: Heat Smart* programme. Up to NZ$347 million has been set aside to subsidise insulation and heating improvements to existing houses. The HEEP study found that insulated houses are on average 1°C warmer in the winter (18.6°C compared to 17.6°C) than those without insulation and that overnight temperatures in bedrooms are 1.3°C warmer (BRANZ, 2010). On drilling deeper, it was also noted that houses built prior to insulation requirements that have subsequently been retrofitted with insulation are on average only 0.4°C – 0.6°C warmer than they were before making the change. These houses enjoy an estimated 5% annual saving in energy consumption (Hindley and Pringle, 2009). Based solely on these comparisons, expectations for the *Heat Smart* programme are not high. However, there are other benefits that accrue with living more warmly and these include increased productivity and reduced health costs. When considering these and other direct benefits against the relatively low cost of making improvements, the benefit to cost comparison is quite favourable (Grimes A and T Denne et al, 2011). The benefits to be gained by insulating external walls, ceilings and floors are well established.

Thermal mass has a stabilising effect on indoor temperatures as the high thermal inertia requires more heating energy to significantly heat up or cool down when compared with lightweight structures (BRANZ, 2010; Donn & Thomas, 2010; Pollard & Stoecklein, 1998). This means more comfortable temperatures can be achieved in houses built around thermal mass as less time is experienced at the very hot or very cold ends of the temperature scale. This can in turn reduce energy use (BRANZ, 2010). The proviso on achieving these benefits is that the mass must be insulated against outside conditions. A house that constantly fluctuates in temperature is not comfortable and houses with effective thermal mass can provide better conditions for thermal comfort. While considerable research has been undertaken to demonstrate potential benefits of including thermal mass in new construction (Donn & Thomas, 2010), not a lot is known about how thermal mass might be incorporated into existing houses to improve thermal conditions. This research addresses that knowledge gap. Of particular interest is the relative cost required to make such improvements and whether, seen alongside the potential benefits, this creates sufficient financial incentive for homeowners to make changes. What are the potential benefits of introducing thermal mass into existing lightweight dwellings in New Zealand and are the costs of such changes tenable in light of the identified benefits? The research addresses this question and presents the findings as financial analyses of six different thermal mass retrofit scenarios in a manner that will inform owners of lightweight timber houses of the potential benefits and relative costs associated with retrofitting their house.

Research methodology

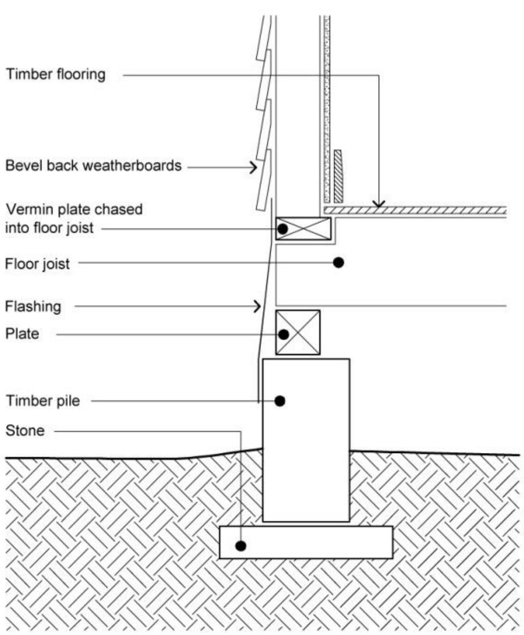
When considering the wide variety of dwellings in this country it becomes clear that there is no such thing as the typical Kiwi house. Given that a principal aim of the research is to provide owners with different examples of how thermal mass can be added to houses it was decided early on that interventions should target real houses. Typology is a term used to describe the characteristics that assist in distinguishing one example of a population from another. Beacon Pathway has produced several reports (Page & Fung, 2008; Ryan, et al., 2008; Beacon Pathway, 2008) that define New Zealand housing typologies in terms specific to their construction. This research adapts Beacon Pathway's earlier work and rationalises the ten typologies they define into six, firstly by concentrating on detached dwellings and then by grouping classifications where the characteristics were considered similar. The six typologies, representing 80% of the country's housing stock, are: the Villa (pre-1900–1920), the Bungalow (1920-1935), State Housing (1935-1960), Pre-Insulation Housing (1960-1978), Post-Insulation Housing (1978-1990) and Recent Housing (1990-Present). Each typology is described in relation to general and structural characteristics, orientation, fenestration and space heating equipment. To enhance the relevance of the description, actual built examples of each typology were researched through the Wellington City Archives. Each example was then drawn in CAD software to enhance understanding of the characteristics and as a basis for designing the interventions of thermal mass.

To help fulfil the aims of the project the thermal mass interventions for each typology were designed to be practical to achieve and relevant to the characteristics of the house. It was also determined that the designs should be developed according to different change strategies in order to provide a range of examples for homeowners to refer to. While concrete is widely recognised as the most cost effective method of incorporating thermal mass into dwellings the research also explored other materials capable of storing heat. The use of Phase Change Materials (PCM) as thermal energy storage in buildings has been investigated for some time as they have the ability to store 5-14 times more heat per volumetric unit than other materials, making them highly important as a thermal mass retrofit option (Romero-Sánchez et al., 2010). The PCM used in the thermal simulations was selected due to its availability in plasterboard and melting point within the desired temperature range. Knauf PCM Smartboard uses BASF solid-liquid microencapsulated Micronal DS 5008 PCM, which is a type of special wax and has a melting point of 23°C.

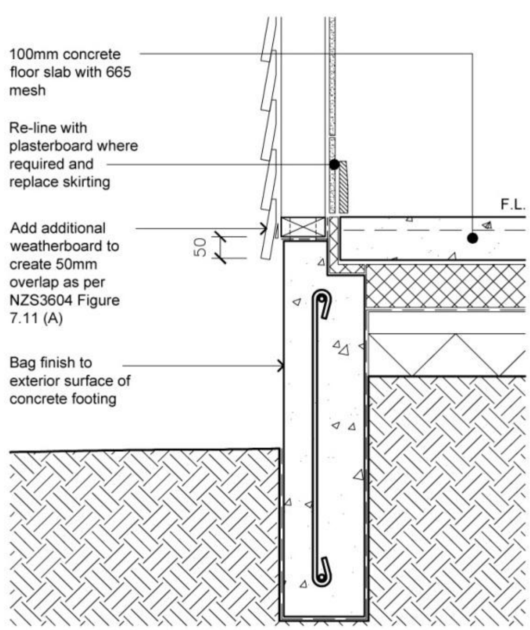
Four different thermal mass intervention types were developed and assigned to the house typologies in combinations that might reflect the motivations of a homeowner. For example, many owners of old villas face having to replace at least the piles under the timber floors of these buildings as they reach the end of their useful life. This research speculates that rather than replacing the piles alone, which can be expensive and still leave a draughty uninsulated timber floor, replacement of the floor with an insulated concrete slab might be an alternative deserving of consideration. Details of such a slab are shown in Fig 1. A summary of the different thermal mass retrofit options explored in this research is shown in Table 1:

Table 1: Summary of interventions designed into each house typology

Villa	Bungalow	State House	Pre-Insulation	Post-Insulation	Recent Housing
Full concrete floor Concrete masonry wall PCM plasterboard Insulation to all walls	Partial concrete floor Concrete masonry wall PCM plasterboard to external walls Insulation to external walls	Partial concrete floor Concrete masonry wall	Partial concrete floor PCM plasterboard to external walls Insulation to external walls.	Partial concrete floor Waterwall at north facing window	Carpet removal Concrete masonry wall



1. Existing villa foundation detail



6. Pour concrete floor slab. Add H3.1 timber wedges under bottom plate as required. Remove temporary supporting structure and replace plasterboard, skirting and add extra weatherboard. Finish footing surface.

Figure 1: Details showing the change from the original timber construction to insulated concrete slab at the floor of the Villa house typology. These two details are accompanied in the research by another four that illustrate the sequence of construction needed to implement the change. This change is made to enhance the thermal storage capacity within the house and eliminate draughtiness that often comes with older timber floors.

Heat pumps were then added to the base models and to the houses as altered to give results with and without heating. It was decided that placing materials with a high thermal mass in furniture, bench tops and hearths would not provide enough thermal inertia to affect the temperature of the room. In all 72 unique scenarios were developed and modelled in order to discover temperature and energy use differences between them.

The hypothesis tested in this study is that thermal mass retrofits can reduce the number of days low temperatures (<16°C) are experienced; reduce the number of days overheating (>25°C) is experienced and can reduce space heating energy use. Dynamic thermal simulation of the six housing typologies was used to assess the impact of different thermal mass retrofit options. While several modelling packages could be used to simulate and analyse the thermal environment of a building, it was decided to make use of IES VE, as a method of simulating the effects of PCMs had recently been developed using that software by other researchers. The construction of each typology was modelled to correspond with the period of the original construction, based on original plans. The only change for the older typologies was the addition of ceiling insulation throughout, as the 2005 New Zealand House Condition Survey found that this was one retrofit that most owners of older houses were likely to have made by now. The base models had no opening windows at any time and no heating devices but all internal doors were modelled to be open, allowing free air movement between rooms. Each house was placed on a flat site with no neighbouring buildings and the house was oriented with the Living Room facing north. This would ensure optimal thermal performance of the added areas of mass, notwithstanding differences in the areas of windows in those rooms.

Costs of the alterations were calculated by the cost consulting firm Rawlinson's. This analysis also included the cost of financing alterations using Kiwibank's variable interest rate of 5.65% on home loans over a seven year period. Seven years was selected as a payback period of seven years provides a good indication that the alteration will be financially attractive when considering cost-benefit analyses. A 12 year payback period is considered the maximum tenable period over which an improvement such as adding thermal mass would be paid off. This reflects the average length of ownership for all houses in New Zealand (Amitrano et al., 2006). The study also quantifies gains in comfort that derive with the retrofit.

Findings

Key findings of the thermal simulations are discussed in the first part of the following section before the measured thermal performance benefits are compared with the estimated costs. The first comparison is between the average temperatures in the living room of each house with no heating other than that available from the sun and due to the body heat of the room's occupants. Table 2 below describes the net effect of adding the thermal mass, with a positive number indicating that the mass has acted to increase the average indoor temperature by the amount indicated. A general finding is that thermal mass retrofits are more effective in older houses, with more recent dwellings enjoying smaller improvements in average temperatures, when no heating is utilised.

Table 2: Average annual living room temperatures without heating

	Villa	Bungalow	State House	Pre-Insulation	Post-Insulation	Recent Housing
AKLD	1.5°C	1.5°C	0.9°C	0.9°C	0.3°C	-0.3°C
WGTN	1.6°C	1.5°C	0.9°C	2.1°C	0.2°C	-0.3°C
CHCH	1.5°C	1.5°C	0.9°C	2.1°C	0.3°C	-0.3°C

This is most likely caused by the greater insulation values imposed by NZS4218 for recent houses and improvement in construction techniques in these newer dwellings that led to lower air infiltration rates. Furthermore, the decision to replace wall linings in the Villa and Bungalow typologies enabled insulation to be added to the external walls of those houses. This had the effect of diminishing heat loss while the thermal mass stores heat made available from the sun. Although the average annual temperatures in the Recent Housing typology are lower once the mass is added, as with each of the other typologies the variations throughout the year in these houses are not as extreme.

This phenomenon, evidence of the so-called *flywheel effect* is illustrated in Table 3, which sets out the net increase in minimum indoor temperatures that can be enjoyed with the addition of thermal mass.

Table 3: Increase in minimum temperatures in the living room without any heating input.

	Villa	Bungalow	State House	Pre-Insulation	Post-Insulation	Recent Housing
AKLD	4.8°C	4.7°C	4.3°C	6.0°C	3.6°C	2.0°C
WGTN	4.2°C	4.0°C	3.3°C	5.4°C	3.8°C	1.7°C
CHCH	5.8°C	5.7°C	5.0°C	7.2°C	4.6°C	2.3°C

This shows that the thermal mass stabilises internal air temperatures a benefit that should not be underestimated as it helps lift temperatures toward the healthy comfort range. The addition of heating is required to bring the temperatures into the recognised comfort band at times, but these results indicate that the thermal mass allows such heating to start from a higher set point.

Of particular interest here is the effect in Christchurch. Although the ambient outdoor temperatures can be quite low, often falling below freezing during a winter's night, the dependable effects of the sun on a typical Canterbury day help charge the thermal mass. Although each of the older house typologies provide evidence of this, the pre-insulation house with larger windows that enable more of the sun's energy to reach the mass gives the greatest increase in minimum temperature over the year.

We now turn to consider the annual reduction, as a consequence of adding thermal mass, in time that temperatures in the living room fall below 18°C. These results are based on the models run without heating and so can be considered to wholly reflect the influence of the mass.

Table 4: Reduction in the number of hours (excluding the periods 8AM to 5PM, Monday to Friday) where temperatures below 18°C are experienced in the living room.

	Villa	Bungalow	State House	Pre-Insulation	Post-Insulation	Recent Housing
AKLD	762hrs **11.9%**	902hrs **14.0%**	456hrs **7.1%**	1288hrs **20.1%**	359hrs **5.6%**	-8hrs **0.1%**
WGTN	736hrs **11.5%**	824hrs **12.8%**	412hrs **6.4%**	1191hrs **18.6%**	272hrs **4.2%**	88hrs **1.4%**
CHCH	613hrs **9.5%**	683hrs **10.6%**	359hrs **5.6%**	1060hrs **16.5%**	228hrs **3.6%**	114hrs **1.8%**

Reductions in periods during which living areas fall to potentially unhealthy levels range from 20.1% in the Pre-Insulation house in the Auckland climate zone to virtually none at all in the Recent Housing exemplar in the same climate. These results are significant as improvements in internal temperatures can be linked directly to improvements in the health of many people. As for all modelling of thermal performance in this research, the conditions here are idealised. The way people manage their dwelling, particularly around ventilation and closing drapes can of course enhance or diminish these results.

Again we see the best results being achieved in the Pre-Insulation house, built generally between 1960 and 1978. This is the period during which New Zealand designers developed strong ideas about how national identity could be expressed architecturally. One of the key attributes of housing built during this period, and one that certainly helps distinguish it from housing of earlier periods, is the way openings were used to link the internal environment to outside space. On the basis of these results we are able to understand that the large areas of glass used to connect people with the outdoors also enables the sun to charge thermal mass more effectively. By managing heat losses through the glass areas by way of drapes during the heating season when the sun is not available to charge the mass the results will be even more positive. Recent Housing shows the least improvement, indicating that the improved insulation values and air tightness of this typology already reduces heat loss effects prior to any thermal mass retrofit. Another interesting result is that all as-modified exemplars begin to approach the same number of hours spent within the comfort range of 18°C to 24°C on an annual basis, indicating that levels of insulation and thermal mass planned for in this research are approaching optimum levels.

The paper now goes on to identify two areas where cost savings can be attributed to the interventions of thermal mass, insulation and efficient heating sources. Table 5 sets out the annual cost of keeping the living area of each house typology within the recognised comfort band without the addition of thermal mass and noted insulation. Below that, the savings that would accrue with the reduced cost of heating the space with the thermal mass in place are listed. The savings attributed to thermal mass is then expressed as a percentage. The relatively large savings gained by the Bungalow and Pre-Insulation typologies indicate that more efficient areas of mass were retrofitted into these dwellings than in the other typologies:

Table 5: The annual cost to keep living area within the comfort band with the savings that can be attributed to thermal mass and insulation retrofits indicated below

	Villa	Bungalow	State House	Pre-Insulation	Post-Insulation	Recent Housing
AKLD	$1,077.85	$1,116.45	$1,001.17	$1,071.29	$1,151.12	$682.11
savings	$315.12	$408.87	$283.61	$521.52	$148.11	$48.06
% savings	**29.2%**	**36.6%**	**28.3%**	**48.7%**	**12.9%**	**7.0%**
WGTN	$1,540.81	$1,585.46	$1,485.41	$1,537.93	$1,604.10	$1,162.14
savings	$304.09	$380.51	$255.77	$516.53	$139.70	$4.73
% savings	**19.7%**	**24.0%**	**17.2%**	**33.6%**	**8.7%**	**0.4%**
CHCH	$1,685.24	$1,709.67	$1,627.21	$1,656.62	$1,723.06	$1,377.48
savings	$273.10	$335.08	$236.60	$466.64	$126.31	$7.09
% savings	**16.2%**	**19.6%**	**14.5%**	**28.2%**	**7.3%**	**0.5%**

While the actual savings are relatively small it must be noted that these figures are for the main living spaces within each typology only. Depending on the orientation of the house and the extent of each retrofit these small gains could be conceivable larger over the whole of the dwelling.

A key finding is that the improved comfort conditions and potential energy savings produced by the thermal mass cannot cover the cost of the changes based on conventional payback period expectations. None of the six typologies in any of the three locations produces a simple payback period of 7 years or less. The longest payback period is noted in the Recent Housing typology in Wellington due largely to the small financial savings gained through the operation of a heat pump, even after installation of mass. Based solely on the savings in energy costs that would be generated by the interventions, the shortest payback period is 67.6 years, which occurs in the Pre-Insulation typology located in Auckland. Long payback periods require home owners to identify benefits other than just financial if they are to be convinced to undertake thermal mass enhancement projects in their dwellings. Noting the increased time internal temperatures fall within the comfort band verifies that thermal comfort will be enhanced with or without applied heating once thermal mass is increased in the dwelling. Another potential benefit can be found in relation to the health of the residents.

The expected health savings, although they cannot be guaranteed, that each project could expect is given below in Table 6:

Table 6: Potential annual health savings.

	Villa	Bungalow	State House	Pre-Insulation	Post-Insulation	Recent Housing
Potential annual savings	$2, 946.00	$744.00	$386.00	$628.00	$319.00	$0.00

These figures derive from the relationship described by McChensy et al. (2006). They found that cost savings in the area of health are similar to the initial cost of insulation. As the recent housing typology does not require any additional insulation to meet the Building Code requirements it also does not receive any savings in this comparison.

A further scenario was developed following the poor financial incentives generated by the six initial cases. The cost of replacing a smaller area of the existing floor in the Bungalow typology with a concrete slab was also investigated. This would allow more accurate suggestions concerning the thermal mass benefits associated with the partial use of concrete slabs. A full year simulation of the Bungalow with only a partial concrete slab replacement was carried out. Decreases in average temperatures, percentage of occupied hours within the comfort band and in the minimum temperature experienced occurred as a result of reducing the thermal inertia of the room when comparing the results with the previous Bungalow scenario. This in itself was a useful comparison, confirming the advantages of concrete floors in moderating internal air temperatures. In addition, a shorter payback period is required as the cost of the alteration decreased significantly ($20,971 lower than the original) while reductions in the annual energy saved decreased by only $53.76 on average across the three locations. This does not bring the payback period close to seven years but does make it the most financially viable of all the schemes, with a 55.6 year payback in Auckland. As with the other alterations, there is not sufficient incentive to make the alterations on purely financial grounds. When this scenario is compared to the original bungalow (base model), average annual temperature improvements of 1.2°C are seen with an average of a 7.1% increase in the percentage of occupied hours within the comfort band when no heating is used.

Conclusions

While thermal mass is an integral part of passive solar design, its applicability to retrofits where glazing areas have not been specifically designed to enable the sun to charge the mass does limits effectiveness. Nevertheless, thermal mass retrofits have been shown to improve internal conditions by reducing the amount of time low and high temperatures are experienced in existing timber-framed dwellings. Their efficiency varies in relation to the period during which the original dwelling was constructed. The most important factors affecting effectiveness of the interventions appear to be insulation levels and air tightness. This reinforces Donn and Thomas' (2010) view that "insulation is the most important factor in passive solar design".

Heating appliance efficiencies should also be considered as these clearly have greater impact on internal air temperatures than thermal mass as well as on running and resource costs. If a dwelling has both adequate insulation and an efficient heating device then a thermal mass retrofit can introduce cost savings and reduce the operation of the heating device in both winter and summer. This would have beneficial effects nationwide by reducing the summer peak that has arisen due to increasing cooling demands. As has been reported by other authors, this would reduce burdens on the health system with fewer admissions for cold-related sicknesses.

Accordingly, it is clear that thermal mass retrofits should only be considered as part of a total energy efficiency retrofit, one that also includes installation of appropriate insulation and an efficient source of heating. With these combined measures, the potential energy, comfort and health benefits that can accrue with the installation of appropriately placed thermal mass in existing lightweight framed houses can be achieved.

Out of the different retrofit options, the PCM enhanced wallboard used in combination with insulation has the most promise. However, the relatively high cost of the material in New Zealand, requiring a very long payback period, is a significant barrier. In terms of current technologies, replacement of suspended timber floors with concrete slabs is appropriate, particularly in areas where large areas of glass are oriented toward the sun. If a house requires foundation work, the replacement with a concrete slab should be seriously considered. This will also reduce draughts, another factor in improving the thermal environment.

The effect of comfort creep on the expected savings gained from the thermal mass retrofit should also be discussed when promoting thermal mass retrofits. This will help limit expectations of financial gains by building owners at the same time as making them aware of the enhanced comfort levels they will be able to enjoy. The potential health benefits and savings on health bills that have not been taken into account in this research can be promoted as added incentives to retrofit houses with thermal mass.

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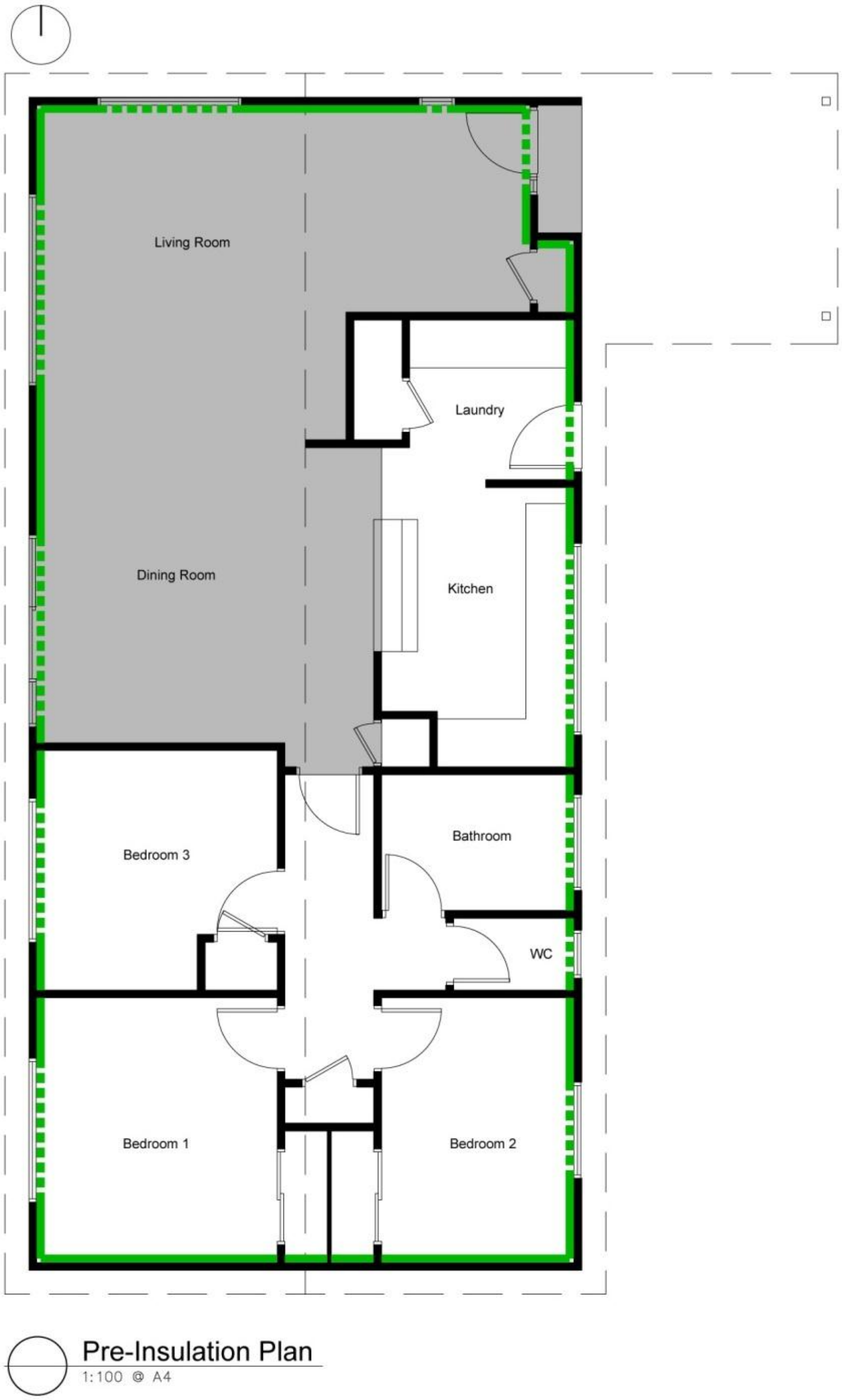
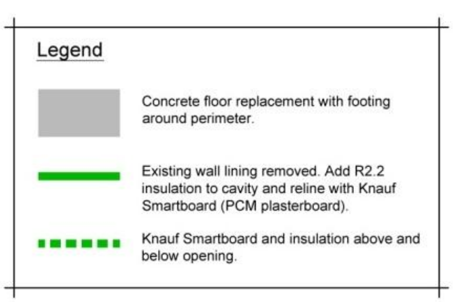
Appendix A: Example of the Proposed Modifications

Appendix





B: Estimated Costs of the Alterations

VUW Thermal Mass Research Project

Indicative Costings	Villa	Bungalow	State House	Pre Insulation	Post Insulation	Recent Home
Slab on Grade						
Total 1a Demolition and Propping	$10,350	$3,440	$3,988	$4,305	$2,714	
Total 1b Wall Framing Alterations	$3,084	$1,019	$597	$1,044	$521	
Total 1c Foundations	$15,096	$7,188	$8,759	$8,998	$5,843	
Total 1d Hardfill	$3,765	$875	$1,061	$1,126	$623	
Total 1e Concrete Slab, DPM and Insulation	$12,618	$3,029	$3,712	$3,864	$2,205	
Total 1f Making Good	$3,236	$932	$969	$1,116	$767	
Total	**$48,148**	**$16,482**	**$19,086**	**$20,452**	**$12,673**	
Masonry Wall						
Total 2a Demolition	$3,460	$3,112	$1,428			$1,373
Total 2ab Footing to Masonry Wall	$288	$402	$208			$134
Total 2b Masonry Wall	$4,684	$6,969	$2,852			$2,397
Total 2c Making Good	$542	$620	$183			$346
Total	**$8,973**	**$11,102**	**$4,671**			**$4,250**
Knauf Smartboard and Insulation						
Total 3a Demolition	$1,964	$615	$318	$604	$292	
Total 3b Insulation	$2,946	$744	$386	$628	$319	
Total 3c Knauf Smartboard	$26,283	$6,635	$3,447	$5,601	$2,844	
Total 3d Making Good	$6,274	$1,875	$965	$1,790	$872	
Total	**$37,468**	**$9,869**	**$5,116**	**$8,624**	**$4,327**	
Water Wall						
Total 4a Water Wall					$3,847	
Total					**$3,847**	
Carpet Removal						
Total 5a Carpet Removal						$246
Total 5b Polish and Seal Concrete Floor						$3,069
Total						**$3,314**
Total	**$94,590**	**$37,453**	**$28,873**	**$29,076**	**$20,846**	**$7,565**