Thermal performance and modelling: selected housing case studies in New Zealand

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ABSTRACT: This paper presents a joint research project between Victoria University of Wellington's School of Architecture and Design and the Wellington-based architectural practice Studio Pacific Architecture. The computer-aided thermal modelling of residential buildings currently remains outside the bounds of conventional architectural practice, leaving architectural practitioners to rely on traditional 'rules of thumb' for evaluating the thermal performance of their designs. This paper presents preliminary research into the application of thermal modelling software as a tool for the designer to better evaluate the complexities of thermal performance than through conventional means. Using the modelling software AccuRate NZ, eight recent residential projects of Studio Pacific Architecture were modelled and analysed in terms of their thermal insulation, construction materials and glazing to wall ratio to determine the efficacy and relationship of each component and to better understand how each measure can be employed to respond to the specific conditions of each architectural project.

Conference theme: Sustainability issues
Keywords: residential architecture, thermal performance modelling

INTRODUCTION

Alongside public and commercial architectural projects, the Wellington architectural firm Studio Pacific Architecture (SPA) designed 141 new and renovated houses between 2001 and 2011. The houses varied in scale from $66m^2$ to $400m^2$, with five houses receiving New Zealand Institute of the Architects design awards (SPA 2011). Although these recent houses were designed with knowledge of climate, site and sustainable ‘rule of thumb’ building design principles, SPA director Evzen Novak considered that, in order to reduce the energy consumption and operating costs of SPA-designed houses, a higher degree of understanding of the thermal performance of recent houses would be beneficial. Another main driver behind the research was the need for empirical evidence to guide future design decisions towards improved performance. Novak proposed to analyse eight (8) of the firm’s recent designs using the software AccuRate NZ. Funded by SPA and the Victoria University of Wellington (VUW) Summer Scholarship Scheme 2010/11, research assistant and MArch(prof) student Stuart Taylor undertook the modelling and analysis of the eight houses between November 2010 and March 2011. For VUW, the research project was supervised by Christina Mackay, Senior Lecturer at the School of Architecture.

Firstly, this paper presents the background to the study and the application of principles of sustainable design in architectural practice in New Zealand. The methodology of the study is explained and the case study houses briefly introduced and presented. The findings of the AccuRate NZ analysis are then presented and discussed. The paper finishes with conclusions of this study and considerations for further research.

1. BACKGROUND

While considerable thermal performance modelling analysis has been undertaken with the aim of upgrading New Zealand’s poorly performing existing housing stock, detailed modelling and analysis of high end architecturally designed houses has not been published. The key New Zealand text on sustainable housing design, *Designing Comfortable Homes* (Donn & Thomas 2010), was revised and republished in 2010. A Cement and Concrete Association of New Zealand (CCANZ) publication, this guide focuses specifically on the impact of thermal mass in building thermal performance. However, the guide corrects the misconception that compliance with the energy efficiency requirements of the New Zealand Building Code is best practice and confirms that good insulation is the most important strategy in creating high-performing building envelopes. The guide recommends three key rule-of-thumb strategies of using insulation (to slow the flow of heat in and out of the house to maintain more constant internal temperatures), using glazing (to bring heat from the sun into the house) and adding thermal mass (to soak up heat from the sun and release it slowly into the house when temperatures drop), but advises that ‘the interactions between these elements are complex, making it difficult to generalise about how much thermal mass to put into a house - more is not always better’ (Donn & Thomas 2010:22). The following factors are also cited as having considerable impact: air tightness (affected by footprint size, complexity and actual construction), shading, ventilation and orientation (although orientation to north can be plus or minus 20 degrees without having a major impact on solar gain). Other influences are the climate zone, site location, building placement, construction materials and the topography. Finally, energy consumption can be greatly affected by behaviour of the occupants and the cost and efficiency of heating systems. The form of the house also plays a role; ‘the ‘best’ building thermally is one that has the smallest external surface area’ (Donn & 2010:35). The more compact two-storey house requires around 20% less heating energy than the single-storey house when both are insulated to Building Code minimum for Climate Zone Three (when adjusted so that the floor areas are identical).

The rule-of thumb approach may be appropriate for lay-persons and simple house forms, but architecturally designed houses, designed to give a high degree of aesthetic pleasure, are more varied and complex. When designing with sustainability and energy performance in mind, architect Evzen Novak of SPA sought an empirical means to justify pursuing one particular design pathway over another. For example, in what scenarios, might it be prudent to introduce additional mass over increasing insulation? Is there a hierarchy of effectiveness between different strategies? SPA's residential projects were designed with cognizance of energy efficient design principles only. A recognized computer thermal performance software was required to assess the designs. By selecting eight designs, modelling and analysing their existing thermal performance, then undertaking sensitivity analysis of possible strategies of improvement, inter-relationships and/or hierarchies between the various strategies might (or might not) become apparent. At least, the investigations could allow SPA architects to more fully understand the complexity of thermal performance in their residential designs and identify areas that required more research.

2. METHODOLOGY

The research project involved the following stages: selection of modelling and analysis software, selection of case study house designs, modelling process and analysis design.

Following consultation with the Energy Efficiency and Conservation Authority (EECA), Beca engineering consultancy and E-cubed, the software AccuRate NZ (AccuRate 2011) was selected for this research project because EECA had intended to use it on a wider scale. The software is specifically designed for detached houses. It uses New Zealand climate data from 18 climate zones adjusted for latitude and longitude. Data on the building components are entered into spreadsheets. The software does not have BIM or 3D capability.

The case study houses were selected on the basis that they were designed by SPA between January 2008 and November 2010; some remain yet to be built. The selection included a variety in size, complexity of the thermal envelope, materials and location within New Zealand.

For each case study house, the most recent proposed drawings or as-built drawings as at November 2010 were selected for modelling. Floor plans were divided into various thermal zones as specified by AccuRate. Construction 'sandwiches' were modelled for the various building elements (external walls, internal walls, floors/ceilings, roof, windows/doors). The thermal envelope was then modelled by inputting the constituent building elements and designating their size and orientation, their material composition and their relationship to other building elements (e.g. whether a wall section had a wing wall projection or was obscured by an external screen and/or shaded by an overhang, or a floor/ceiling's relationship to an adjacent zone). Ventilation input included data on the building site area and urban and/or natural context. The analysis used climate data from the suburb or regional district.

To allow a benchmark for comparing potential upgrades in thermal design, each house specification design was adjusted to match the minimum requirements New Zealand Standard NZS 4218 H1 for energy efficiency. In Climate Zone 2 (the Wellington area) insulation is required at R1.9 to walls, R1.3 to floors and R2.9 to roofs. Glazing is required to be double-glazing with a maximum area on 30% of the external wall area. This is referred to in the study as the NZS 4218 Reference design.

To allow assessment of the relative effectiveness of a range of thermal performance upgrade strategies, a sensitivity analysis was proposed. A range of upgrade scenarios were applied to the NZS 4218 Reference building design and tested for their efficacy. Modelling and analysis of the scenarios was undertaken and findings are presented in the sensitivity analysis in this paper. The following seven scenarios were modelled:

2.1. As-documented

The as-documented design was modelled as per the most recent set of proposed or as-built construction drawings.

2.2. NZS 4218 Reference design

The documented design was adjusted to match the insulation value of the walls, floors and roofs to the minimum required insulation as set out by New Zealand Building Code (NZBC) H1. The window area was reduced to 30% of the total wall area (as required by the code).

2.3 NZS 4218 insulation and glazing as documented

Insulation as per the NZS 4218 Reference design. The window area remained as per the as-documented design.

2.4 Reduced Glazing (15% external surface area)

Insulation as per the NZS 4218 Reference design. The window area is reduced to 15% of the total wall area.

2.5 Increased Mass (concrete construction)

The as-documented design was adjusted to 'heavy type' construction by replacing wall and floor construction material with concrete of same dimensions and thickness. The floors and walls were insulated on the exterior to achieve H1 compliant R values.

2.6 Improved Insulation (R5 to walls, floor and roof)

The documented design was adjusted by increasing the combined construction R-value of the floors, walls and roof to equal R5 (in all cases).

2.7 Improved Window Construction (Wood IGU, low-e and argon filled)
The documented design was adjusted by changing window construction to IGU (double-glazing) in wooden frames with one low emissivity surface and an argon fill.

The four thermal 'upgrade scenarios' were then modelled using AccuRate NZ software by adjusting the base design modelled from the documented design drawings. Simulations were run for each of the scenarios in each case study and were then compared to the reference building (code minimum) to analyse the efficiency of each upgrade option.

3. CASE STUDY HOUSES

The houses chosen for the study included eight proposed or recently constructed designs from the office of Studio Pacific Architecture in Wellington. The first four houses modelled were located in various suburbs of Wellington, and the remaining projects in the Wairarapa, Malborough Sounds, and Rawhiti (Northland) respectively. In Wellington there can be a considerable variation in microclimate that impacts on the comfort and energy efficiency of a house. For example, a Wellington site near the sea will experience maximum temperatures that are 1-2 degrees lower than elsewhere in Wellington, and minimum temperatures that are 3-6 degrees higher (Donn, Thomas 2010). Wellington has a temperate maritime climate with an average temperature of 12.8 degrees C, with temperatures generally in the range between 4 degrees C and 25 degrees C, 2000 sunshine hours per year 1250mm of annual rainfall and a high predominance of windy days each year. Average relative humidity sits between 67% in January and 78% in June.

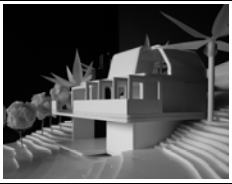
			
W1 (2008) Wadestown, Wellington 118 m^2 37% glazing 10 internal zones	**W2** (2011) Wadestown, Wellington 142 m^2 29% glazing 12 internal zones	**W3** (2011) Mt Victoria, Wellington 210 m^2 32% glazing 15 internal zones	**W4 (**2010) Seatoun, Wellington 259 m^2 34% glazing 9 internal zones
			
W5 (2011) Wairarapa, Wellington 235m^2 36% glazing 11 internal zones	**M1** (2011) Marlborough 164 m^2 41% glazing 5 internal zones	**N1** (2012) Northland 168 m^2 33% glazing 8 internal zones	**N2** (2011) Northland 94 m^2 39% glazing 7 internal zones

Figure 1: Case study house base information

House W1 is a two-storey detached dwelling located on a steep, north facing slope in an inner city suburb of Wellington, New Zealand (Latitude 41.26 south; Longitude 174.79 east). The house is mainly timber-framed, although the lower story has some concrete walls and floors. **House W2** is located on the northern hills of Wellington, New Zealand, close to the inner city (Latitude 41.26 south; Longitude 174.79 east). It is a simple two-storey timber-framed detached dwelling on a slightly south sloping hill. **House W3** has a westerly aspect and sits just above the central city in an inner city suburb of Wellington, New Zealand (Latitude 41.29 south; Longitude 174.78 east). It is a timber-framed and timber-clad compact detached house on two levels, with a relatively high level of internal subdivision. **House W4** is situated near the seaside in an outer residential suburb of Wellington, New Zealand (Latitude 41.31 south; Longitude 174.83 east). It has a central double-height internal space and is almost entirely timber-framed and timber-clad. **House W5** is located in the Wellington region near the town of Featherston in a rural part of the Wairarapa (Latitude 41.33 south; Longitude 175.50 east). In contrast to the other Wellington region houses, it is to be constructed entirely of insulated concrete sandwich panels. It has a relatively complex plan shape but is single storey.

House M1 is a simple rectangular-shaped 'bach' or holiday house located in the Marlborough Sounds, to the south of Wellington, New Zealand (Latitude 41 south; Longitude 174 east). It is entirely timber-framed and is situated at the seaside in a climate broadly similar to Wellington's.

House N1 is located in the Bay of Islands, New Zealand (Latitude 35.23 south; Longitude 174.26 east) and is a substantial 'bach' located close to the sea. It is two storeyed with a composite timber and concrete ground floor but is substantially of timber-framed construction. **House N2** is located alongside House N1 in the Bay of Islands. It is almost entirely of concrete construction, with the exception of a heavily glazed north façade, and has a full 'green' roof with extensive landscaping. The Bay of Islands sits in a sub-tropical climate zone with warm humid summers and mild winters. Temperatures fall generally into the range between 12 to 26 degrees C. Annual sunshine is circa 2000 hours with high relative humidity.

This variety of climatic conditions allowed the study to test the variability and effect of different climate zones from the microclimatic differences in the various suburbs. The selection of houses also included a diverse range of designs.

4. RESULTS

The following findings document the results of the modelling process. Firstly, differences between the modelled performance of the as-documented house design and NZS 4218 Reference design for each house are presented, followed by the results of various thermal upgrades for each of the case study NZS 4218 reference designs.

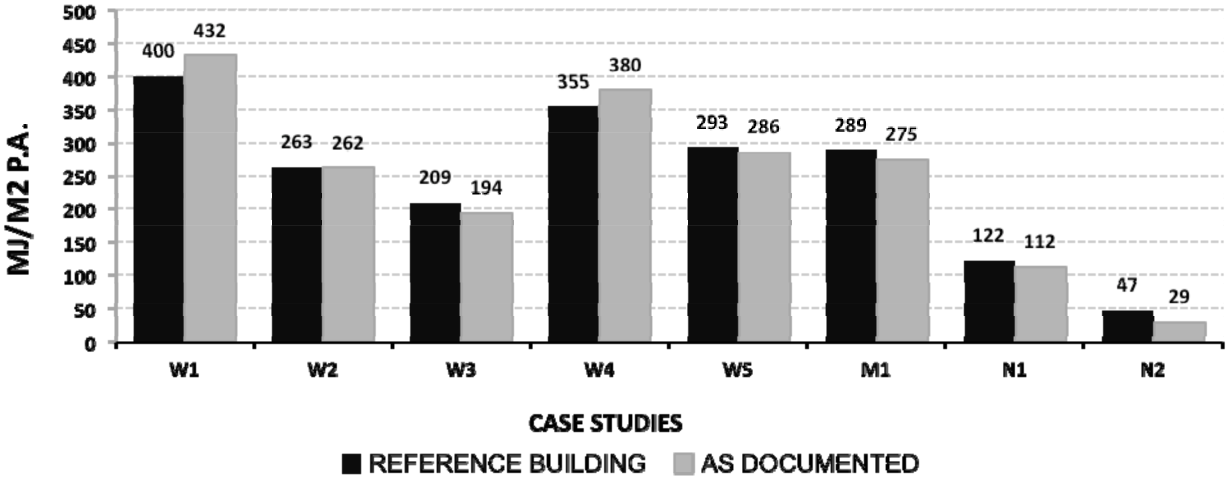


Figure 2: Comparison of the total annual energy required for space heating and cooling for the NZS 4218 reference design and as-documented design of case study houses

4.1 Performance of as-documented design compared to NZS 4218 Reference design

The figure above shows a comparative analysis between the expected performance of the building as documented, against that of the reference design. A considerable degree of variability can be seen between the individual case studies, reflecting the diversity in their design and location. The results of the documented designs reflect a marginal increase in thermal performance from the reference buildings, which suggests that the designed outcomes are consistent with the minimum thermal requirements of the NZSBC. In spite of achieving H1 code-compliance through the calculation method, the results of houses W1 and W4 demonstrate a reverse effect, where the reference building performs better than the documented design. This suggests an inconsistency between the calculation and simulation methods of code compliance.

	2.1	2.2	2.3	2.4	2.5	2.6	2.7
	AS DOCUMENTED	NZS 4218 (REFERENCE DESIGN)	NZS4218 INSULATION & GLAZING AS DOCUMENTED	REDUCED GLAZING (15%)	HIGH MASS	'BETTER' INSULATION*	IMPROVED WINDOW CONSTRUCTION
W1	432 (-7.8%)	400	469 (-17%)	250 (37.6%)	267 (33.3%)	311 (22.3%)	257 (35.8%)
W2	262 (0.2%)	263	263 (0.0%)	201 (23.5%)	223 (15.1%)	200 (23.9%)	148 (43.8%)
W3	194 (7.1%)	209	228 (-9.2%)	161 (22.9%)	178 (14.8%)	159 (23.8%)	116 (44.6%)
W4	380 (-7.0%)	355	387 (-9.0%)	284 (20.1%)	279 (21.5%)	318 (10.5%)	237 (33.2%)
W5	286 (2.4%)	293	314 (-7.0)	264 (9.9%)	-	214 (27.1%)	204 (30.5%)
M1	275 (13.8%)	289	321 (-11.1%)	248 (41.4%)	176 (39.3%)	233 (19.4%)	227 (21.5%)
N1	112 (8.2%)	122	131 (-7.4%)	92 (24.8%)	67 (55.7%)	94 (22.9%)	92 (24.6%)
N2	29 (37.1%)	47	40 (15.2%)	68 (45.3%)	-	27 (42.3%)	29 (37.3%)

Figure 3: Predicted annual energy consumption (MJ/m^2 per annum) **for heating and cooling of the as-documented case study houses and design upgrade scenarios with percentage improvement to Reference design** (shown in brackets)

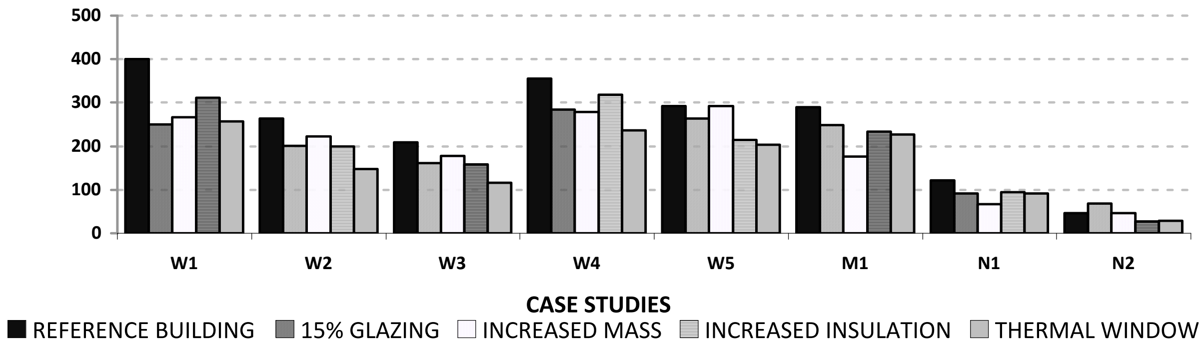


Figure 4: Sensitivity analysis documenting various upgrade options for each case study

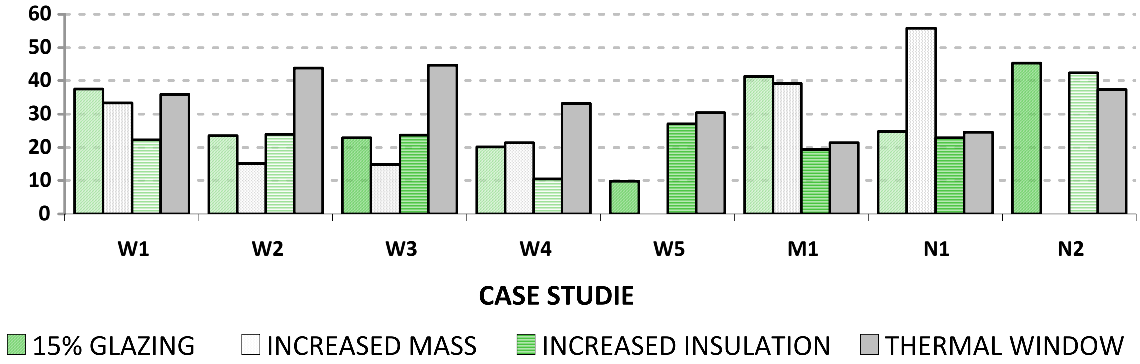


Figure 5: Percentage improvement of thermal upgrade from reference building

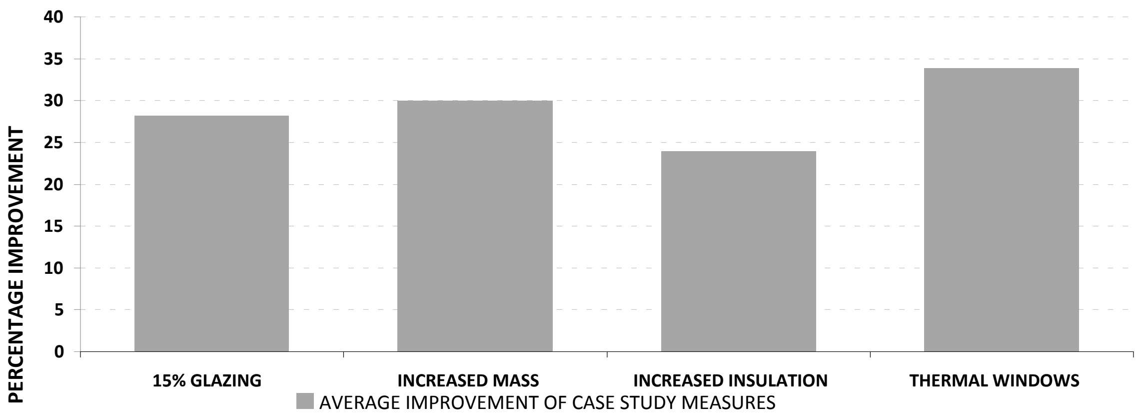


Figure 6: Average percentage improvement of thermal upgrade from reference building

4.2 Actual and relative performance of upgrade strategies compared to the performance of the NZS 4218 Reference design

Figures 3, 4 & 5 above display the predicted performance of upgrade scenarios with respect to annual energy consumption for heating and cooling, percentage improvement in relation to the NZS 4218 Reference design**.**

4.3 Average percentage improvements in thermal performance of upgrade strategies as compared to the performance of the NZS 4218 Reference designs

Figure 6 above compares the effective of different upgrade strategies across the eight house designs. While the values here show the average percentage increases between 24% and 35%, there was a large degree of variability within each of the upgrade scenarios.

	MOST EFFECTIVE MEASURE	SECOND MOST EFFECTIVE MEASURE	THIRD MOST EFFECTIVE MEASURE	FOURTH MOST EFFECTIVE MEASURE
W1	Reduced Glazing (-150MJ/m^2.annum)	Improved Window Construction (-143MJ/m^2.annum)	High Mass (-133MJ/m^2.annum)	'Better' Insulation (-89MJ/m^2.annum)
W2	Improved Window Construction (-115MJ/m^2.annum)	'Better' Insulation (-63MJ/m^2.annum)	Reduced Glazing (-62MJ/m^2.annum)	High Mass (-40MJ/m^2.annum)
W3	Improved Window Construction (-93MJ/m^2.annum)	'Better' Insulation (-50MJ/m^2.annum)	Reduced Glazing (-48MJ/m^2.annum)	High Mass (-31MJ/m^2.annum)
W4	Improved Window Construction (-118MJ/m^2.annum)	High Mass (-76MJ/m^2.annum)	Reduced Glazing (-71MJ/m^2.annum)	'Better' Insulation (-37MJ/m^2.annum)
W5	Improved Window Construction (-89MJ/m^2.annum)	'Better' Insulation (-79MJ/m^2.annum)	Reduced Glazing (-29MJ/m^2.annum)	-
M1	High Mass (-113MJ/m^2.annum)	Improved Window Construction (-62MJ/m^2.annum)	'Better' Insulation (-56MJ/m^2.annum)	Reduced Glazing (-41MJ/m^2.annum)
N1	High Mass (-55MJ/m^2.annum)	Improved Window* Construction (-30MJ/m^2.annum)	Reduced Glazing* (-30MJ/m^2.annum)	'Better' Insulation (-28MJ/m^2.annum)
N2	'Better' Insulation (-20MJ/m^2.annum)	Improved Window Construction (-18MJ/m^2.annum)	Reduced Glazing** (+21MJ/m^2.annum)	-

Figure 7: Relative effectiveness of different upgrade strategies on case study house designs and decrease in annual energy consumption (noted in brackets)

4.4 Relative effectiveness of upgrade strategies in case study house designs.

Figure 7 documents the comparative effectiveness of each upgrade measure for each of the eight case studies. Each of the four possible upgrades is ordered by their effectiveness for each of the case studies. Houses W5 and N2 do not include the upgrade measure of increased mass owing to their existing concrete construction.

5. INTERPRETATION & ANALYSIS

5.1 Basic energy requirements prior to improvement measures

The reference design energy use figures generated by AccuRate for the eight case study houses are generally substantially higher than average New Zealand energy use. This is because AccuRate uses heating assumptions with temperatures at World Health Organisation (WHO) standards, whereas typical New Zealand practice is to leave large parts of the house (e.g. bedrooms) unheated or heated substantially below WHO standards.

In 2009, the average New Zealand home used 11,182 KWh/year from all energy sources of which, in 2007, 29% was used for heating and cooling (Hoerning 2011). Average energy use for heating and cooling can therefore be taken to be circa 3240 KW/h per annum. All the case study houses (except N2) theoretically required more energy than the New Zealand average consumption because of these modelling assumptions. Actual usage was not compared and in some cases was not yet available.

5.2 Variability of the most effective improvement measures

Figure 6 shows the average improvement from the four studied measures as being very similar: for each improvement, approximately a 30% reduction in energy consumption could on average be expected. However, with a variety of bespoke architect-designed houses of differing sizes, constructions and locations, the most effective improvement measure to reduce energy consumption is in fact dependent on the circumstances of each building. Often, the most effective measure was also substantially better than the second most effective measure; sometimes by as much as 45%. A result of this study is therefore to question whether 'rules of thumb' approaches to the design of low energy consumption housing can be effective in fine tuning building design.

5.3 Rankings for the most effective measures

Each of the improvement measures was most effective in the followed ranked order:

First:	Improved window construction	4 houses
Second:	Increased mass	2 houses
Third=:	Reduced glazing	1 house
Third=:	'Better' Insulation	1 house

Each measure is discussed below as the sample size is too small for the rankings to be significant.

5.4 Improved window construction

This strategy was numerically the most effective response, and in the three timber-framed houses W2, W3 and W4, it is around 40% more effective than the next best measure. In 3 of 4 cases, better insulation was the second most effective solution. All the houses in this group are in the Wellington region with strong climatic similarities. As glazing is a source of significant heat loss, improvement to the insulation performance of windows has significant benefits. The results also suggest that controlling the area of glazing will be beneficial and that the current New Zealand practice of using non-thermally broken aluminium framed IGUs needs to be improved upon.

5.5 Increased mass

This strategy was the most effective measure in two houses: M1 and N1. While both are in seaside locations with a warmer climate, AccuRate does not use climate data modified to account for the smaller temperature range expected in seaside locations (Hoerning, 2011) so location is unlikely to be a factor. Both houses, however, are north facing with simple forms and planning. Higher mass would therefore moderate the expected greater solar gains and losses from the design and orientation of the houses.

5.6 Reduced glazing

This strategy was the most effective response for house W1, although improved window construction and higher mass were nearly as effective as reducing the amount of glazing in this case. This dwelling is relatively small at $118m^2$, has a relatively high percentage of glazing at 37% and is located in an exposed, elevated position. The notable element of this house is its small floor area. In a small house the percentage of external wall relative to floor area can be much higher than large houses and hence the impact of a higher glazing percentage is proportionately greater, especially as glazing accounts for significantly more heat loss (or gain) than other building elements. For example, proportionately *doubling* the size of a theoretical rectangular 118 m^2 building with 3m high walls and 37% glazing increases the glazed area by only 42%, from 57 m^2 to 81 m^2. The results suggest extra care needs to be taken with area construction and placement of glazing in small houses.

5.7 Better insulation

This strategy was the most effective measure in the buildings that had already been optimized for energy performance in other respects. N2 had high mass flooring and walls and a landscaped high mass roof, and was oriented to the north. Improved window construction provided almost the same benefit as better insulation. While its energy performance appears substantially better than the other examples, it is located in the sub-tropical north of New Zealand and, as a result, can only be compared with N1. As the building is virtually only glazed to the north, one notable result is that reduced window area in this case leads to increased energy consumption.

Glass is typically not only the single greatest source of heat gain, but also the greatest contributor to heat loss in a house (Donn 2010). While demonstrably important in bringing passive solar gain into the house, the amount of glazing must strike a fine balance as both a solar collector and the place where the greatest heat loss occurs.

6. DISCUSSION

6.1 Some Limitations

The study is entirely contingent on the assumption of accuracy of the modelling software used. The AccuRate settings for control of temperature, based on WHO standards and essentially a behavioural indicator, have already been mentioned. The assumptions made within the software settings are not realistically capable of being queried. Despite its seemingly simple system of inputting data, AccuRate NZ's user interface does not allow a means of graphically checking the numerous inputs, which generate a degree of complexity, in 3D. The input of complex data sets is also dependent on consistent judgement in the interpretation of the data so that each of the eight case study houses is treated in the same way for each variable. Two check tests were conducted by another separate user on two of the case study projects.

6.2 Results compared to original aims

The researchers found that thermal modelling was more complex than had been originally anticipated. The findings demonstrated that significant improvements could be made to each case study house using the four factors in the sensitivity analysis. However, it became apparent that there was no clear hierarchy that would enable the promulgation of a coherent set of 'rules of thumb' applicable across designs that differed in size, location, design and materials. The importance of this conclusion was to confirm the complexity of thermal performance factors in practice and to identify the potential for using thermal modelling software in the design phase to improve the thermal performance of differing design strategies.

6.3 Significance of Study

The significance of this research lies in is its co-authorship between VUW and SPA, which situates it at the intersection between research and practice. Through the use of actual built examples of recent residential projects, the research is aimed at positively influencing current architectural practice by determining which strategies of thermal design are the most beneficial in terms of improving performance.

The principles developed in thermal modelling studies are often limited to reference, or typical average, dwellings. This study highlights the possibility of using thermal modelling software during design processes where the degree of complexity in building form is considerably greater, in order to more accurately evaluate the impacts of a complex and interrelated set of components that influence thermal performance.

6.4 Impacts on current practice

Following the modelling of the eight case studies, it was decided that the use of AccuRate NZ as a design tool should continue through design development of house N1. The ability to optimise window size, insulation and orientation through small fast iterations of the AccuRate NZ model has been taken advantage of to optimise the thermal performance of the building. This optimisation has taken place after the results of the study were collated and is not represented in the results published here.

6.5 Some potential future steps

This study, through the review of existing designs, suggests what might have been changed in the design had the detailed knowledge of thermal performance been available. The study itself is capable of further development to account for the following factors:
a) an increase in the size of the study sample to improve accuracy,
b) an increase in the number of factors influencing thermal performance (from glazing percentage, insulation, mass and window construction in this study) to include orientation, project location and micro-climate, shape, volume thermal bridging, window operability, and other design factors,
c) an analysis of combinations of factors to hone in on the possibility of establishing and evaluating particular efficiencies or sets of rules of thumb, and
d) cost analysis of the various measures of improving thermal performance to establish cost/benefit scenarios and refinement of the hierarchy of available measures.

A sensitivity analysis was useful in isolating the individual impacts of various factors; however the combined effect of pairs or groups of variables (due to their complex relationship) may not follow the patterns expressed in this study.

7. CONCLUSION

The thermal modelling of residential buildings in this study has not yielded any particular set or hierarchy of effective measures to reduce energy usage in residential dwellings that applies in the same way in multiple cases.

While thermal modelling is a reasonably complex exercise, the primary advantage of architects or designers using software of this type in the design stages of their projects is its ability to provide empirical reasoning for making particular design decisions. The relationship between a given design and the factors which can improve thermal performance appears to be dependent on a complex set of variables that cannot readily be simplified into universal ‘rules of thumb’ and this highlights the potential for this simulation process to aid the architect in the design of new residential buildings.

ACKNOWLEDGEMENTS

The research team would like to thank the owers of the case study houses and acknowledges the research assistance funding by Victoria University of Wellington and Studio Pacific Architecture, as well as review and advice provided by Dr Michael Donn and Assoc Prof John Storey, Victoria University of Wellington, Christian Hoerning, NZ Energy Efficiency Authority, Stefan Waldhauser, Beca Engineers and Patrick Arnold, E-cubed Wellington.

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