Thermal performance modelling: design strategies for improved thermal performance in selected NZ houses

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ABSTRACT: This study was a joint research project between Victoria University of Wellington's School of Architecture and Design and the Wellington-based architectural practice Studio Pacific Architecture. It is a continuation of a previous study. The aim of the study was to determine the best methods of improving the thermal performance of new houses and to provide empirical evidence to back up the selection of any particular strategy. The thermal performance of nine Studio Pacific designed case study houses was modelled for three differing New Zealand locations. A range of construction and design variations were systematically assessed. Twenty combinations of insulation, glazing, and mass were modelled, as well as a number of variable design changes including orientation, level of glazing, shading, ventilation and more. This allowed the identification of the most effective options. Comparison of the houses enabled a better understanding of how different situations affect the effectiveness of design decisions. Options were evaluated not only on their effect on heating energy use, but also on their effect on passive performance. A series of recommendations for significantly improving the thermal performance of new house designs is made.

Conference theme: Buildings and energy
Keywords: residential architecture, thermal performance, architectural research

INTRODUCTION

In the past decade, Studio Pacific Architecture (SPA) has designed over 140 houses, many of which received New Zealand Institute of Architecture awards. The studio has long been committed to Environmentally Sustainable Design (ESD), and has received multiple ESD awards (Studio Pacific Architecture, 2012). In this vein, their house designs were constructed with an understanding of the climate, site, and general ESD principles. However, 'rules of thumb' only go so far, and so in order to allow SPA to get a better understanding of how to improve the performance of their design work director Evzen Novak engaged with Victoria University of Wellington (VUW) to analyse the thermal performance of a selection of their recent house designs.

The overall aim of this study was to discover the best methods of improving the thermal performance of new houses designed by Studio Pacific Architecture, and to provide empirical evidence to show to their clients.

To accomplish this, the study focused on several key objectives, as follows:

1) To determine the most effective options for upgrading construction – comparing insulation, improved glazing, and the use of mass.
2) To find out how effective combinations of construction options can be – for example: upgrading insulation and adding mass.
3) To determine what aspects of design have significant effects on performance and how they do so. This involved looking at a range of aspects including orientation, level and placement of glazing, the use of shading, the importance of ventilation and more.

In this paper, we will first briefly cover the background of the study before outlining the methodology and the limitations of the thermal simulations. The case study houses are then briefly described. Then, the results and key lessons learned about the most effective ways of improving the thermal performance of these case studies are discussed. The paper concludes with a set of simple recommendations for improving thermal performance.

1 BACKGROUND

This study is the continuation of a study carried out in summer 2011, and which was presented at ANAZScA that year (Novak, Taylor, & Mackay, 2011). As discussed in the previous paper, the study attempts to fill a gap in New Zealand's housing performance research by providing detailed analysis of high-end architecturally designed houses (in contrast to the general focus on upgrading the existing housing stock) (Novak et al., 2011). The primary text on sustainable housing design in New Zealand is *Designing Comfortable Homes* (Donn & Thomas, 2010). While a very good primer on the principles of thermal performance in houses, it is nevertheless limited by its scope – it only analysed 2 generic house designs. The 2011 study attempted to broaden knowledge about the thermal performance of houses with a larger, and more varied selection of case studies, comparing the effects of increasing insulation, upgrading the glazing, adding mass, and reducing the amount of glazing. Ultimately however, with only a limited number of design variations modelled, and with the houses sited in different locations in New Zealand, the study was inconclusive, and could not find any clear guidelines as to when one upgrade might be preferred over another (Novak et al., 2011).

However, the study did suggest a number of areas where further study could be carried out such as looking at the effectiveness of the combination of upgrades, or the effects of orientation. Additionally, it was felt that clearer relationships between the designs and the effectiveness of the upgrades may be able to be seen if the houses were all normalised to the same location and if more elements were studied. For that purpose, the current study was started with the intent of analysing the effects of a broader range of design and construction changes on performance, and in greater detail.

2 METHODOLOGY

The case study houses were modelled using AccuRate NZ (*AccuRateNZ*, 2008). The software was selected because at the time, the Energy Efficiency and Consevation Authority (EECA) was intending to employ throughout New Zealand (Novak et al., 2011). An important change from the previous study however is the use of AccuBatch to run the simulations. AccuBatch is an external program that can be used to batch run multiple simulations. Most importantly however it allows one to change the heating schedules from AccuRate's defaults, as well as allowing one to extract the hourly temperature data for more detailed analysis of the houses' passive performance.

AccuRate has been validated by BESTEST, which compares its results to those of eight reference programs in order to check its accuracy. It can thus be considered to provide reasonably accurate models of the thermal performance that will be agreed with if the models were run in other programs (Delsante, 2005). It should however be stressed that the predictions of the energy use of the buildings are based upon a certain set of assumptions, and so should not be considered to be precise predictions of how the house would perform in reality, which can be greatly altered by how people use the buildings. Rather, the focus should be on the comparisons of the relative performance of the various models, and the general trends.

2.1 Assumptions

The most important assumption that has to be made in any thermal modelling operation is what the heating and cooling set-points and schedules are. In this study, the houses were modelled as being heated during waking hours, from 7am to 11pm. The bedrooms are assumed to be heated to 16°C, and the living areas are heated to 20°C. Other areas such as bathrooms are left unheated. Windows are opened to provide ventilation when the temperature reaches 23°C, while air-conditioning is turned on at 25°C.

Another important factor is that the location for the houses was normalised to Wellington, in order to allow clear comparison of the design factors in the different houses. The climate data used is derived from measurements made by the National Institute of Water and Atmospheric Research (NIWA), and is based on measurements of the Wellington climate made over 30 years. It is assumed to represent an 'average' year in Wellington, and it should be noted that real years may differ significantly.

The internal occupancy gains and schedules are the defaults set by AccuRate.

2.2 Model limitations

Cannot model permanent openings
The current version of AccuRate NZ cannot model permanent openings between rooms. This means that a number of zones that are permanently open to each other in reality are modelled as being separate if they are rooms with different functions. While this does mean that the models do not represent the real design as accurately, for the purposes of this research, this could in some cases be a good thing, as it removes one variable from the comparisons between the houses.

No curtains
Curtains have not been modelled as they are décor, and dependant on the occupant. This means that the windows will lose more heat at night, and the mornings will be colder than they would be if there were curtains.

Edge losses not modelled
The current version of AccuRate NZ does not model the effects of edge insulation in concrete floor slabs. If heat losses through the edges are not properly accounted for, then this could make concrete floor slabs appear to have better performance than they would have in reality.

2.3 Design changes

Construction changes
Following from the previous study, the effectiveness of a variety of construction upgrades were tested. This included 2 levels of insulation and glazing upgrades, the addition of high mass concrete floors, and the combinations thereof. To establish a common baseline between the different houses, their construction was normalised, with insulation levels set to a level defined as 'code-compliant' by NZS4218:

Roof: R-3.4	Walls: R-1.9	Floor: R-1.4	Window: Double glazing in aluminum frame

Table 1: Baseline model insulation levels

The ‘baseline’ models are not able to be used to assess compliance with the New Zealand Building Code as most of the houses have more than the 30% glazing that it allows.

The various construction upgrades are defined below. The medium insulation was conceptualised as being basically the limit of a ‘normal’ well-insulated house, with fully insulated 140mm thick walls, R-5.0 batts in the roof, and the basic floor insulation doubled. The high insulation was intended to see how effective it could be to essentially double that, by using a double frame design with offset studs to minimise thermal bridging.

Medium insulation	Roof: R 4.5	Walls: R 3.4	Floor: R 2.5
High insulation	Roof: R 9.4	Walls: R 6.4	Floor: R 4.9
Improved window frames	Window frames changed to timber		
Improved glazing	Timber window frames, double glazing with low-e coating and argon fill		
Mass floors	100mm of exposed concrete mass added to the floors		

Table 2: Summary of studied changes to construction

These upgrades were then combined in order to see how effective they could be when added together.

Design changes

To investigate their effect on the performance of the houses, a large number of different design changes were modelled for the different houses. This included changing the level of shading, changing the orientation, changing the level of glazing, removing double height spaces, separating zones, estimating the effect of not being able to close the door between rooms, changing the level of ventilation, replacing south glazing with skylights and more. This paper focuses on those design factors that were found to be generally the most important: specifically, glazing level and orientation.

3 CASE STUDY HOUSES

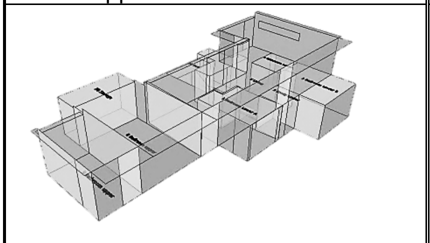
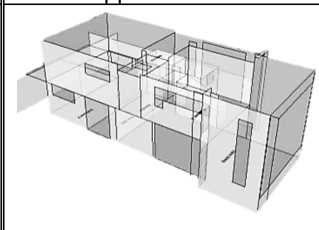
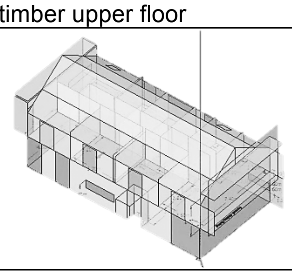
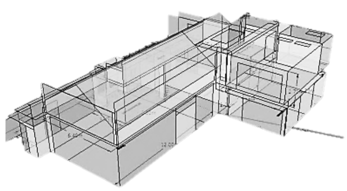
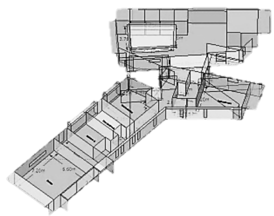
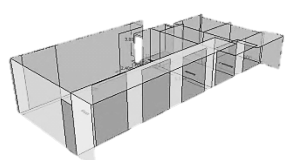
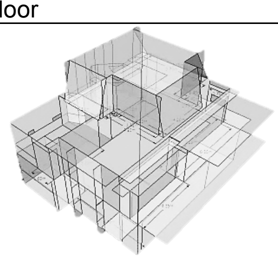
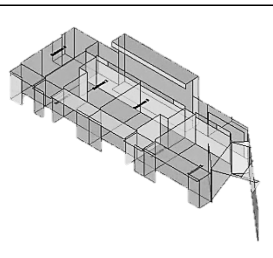
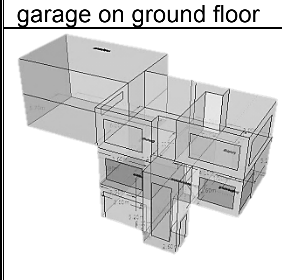
W1 (2008) 116m^2, 2 storeys 38% glazing to external wall area Timber frame, some floor slab, timber upper floor	**W2** (2011) 143m^2, 2 storeys 32% glazing to external wall area Timber frame, concrete floor slab, timber upper floor	**W3** (2011) 210m^2, 2 storeys 41% glazing to external wall area Timber frame, concrete floor slab, timber upper floor
		
W4 (2010) 263m^2, 2 storeys 36% glazing to external wall area Timber frame, some floor slab	**W5** (2011) 235m^2, 1 storey 45% glazing to external wall area Exposed concrete walls and floor	**M1** (2011) 121m^2, 1 storey 41% glazing to external wall area Timber frame
		
N1 (2012) 161m^2, 3 storeys 49% glazing to external wall area Timber frame, basement on ground floor	**N2** (2011) 94m^2, 1 storey 39% glazing to external wall area Exposed concrete walls and floor	**W6** (2012) 97m^2, 3 storeys 17% glazing to external wall area Timber frame, some floor slab, garage on ground floor
		

Table 3: Summary details and 3d models of the case study models.

The nine case study houses are a selection of proposed or recently constructed designs by Studio Pacific Architecture. They include the eight houses used in the previous study (Novak, Taylor, & Mackay, 2011) as well as the addition of a ninth house that is still in the design phase. They cover a range of typologies, orientations, and glazing levels, and are a mix of light timber frame and concrete constructions.

4 RESULTS: ORIENTATION

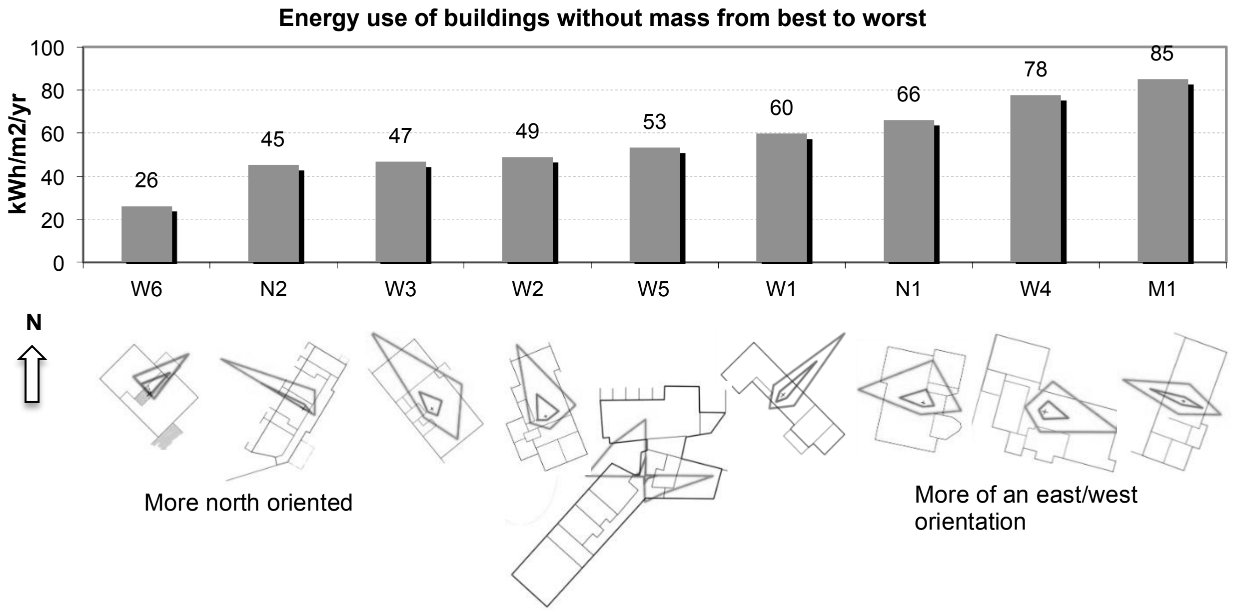


Figure 1: Comparison of the energy use of the houses with plans showing their orientations. Note: the houses here have all had their construction normalised to simple light timber frame with R-values compliant with the minimum levels specified by NZS 4218. This removes the variable of construction, and allows us to focus on the effect of design and layout. Underneath the graphs are plans of the houses with graphic overlays indicating the level and distribution of glazing. For example, on W6 we can see that the glazing is mainly on the NE wall, with the rest on the NW.

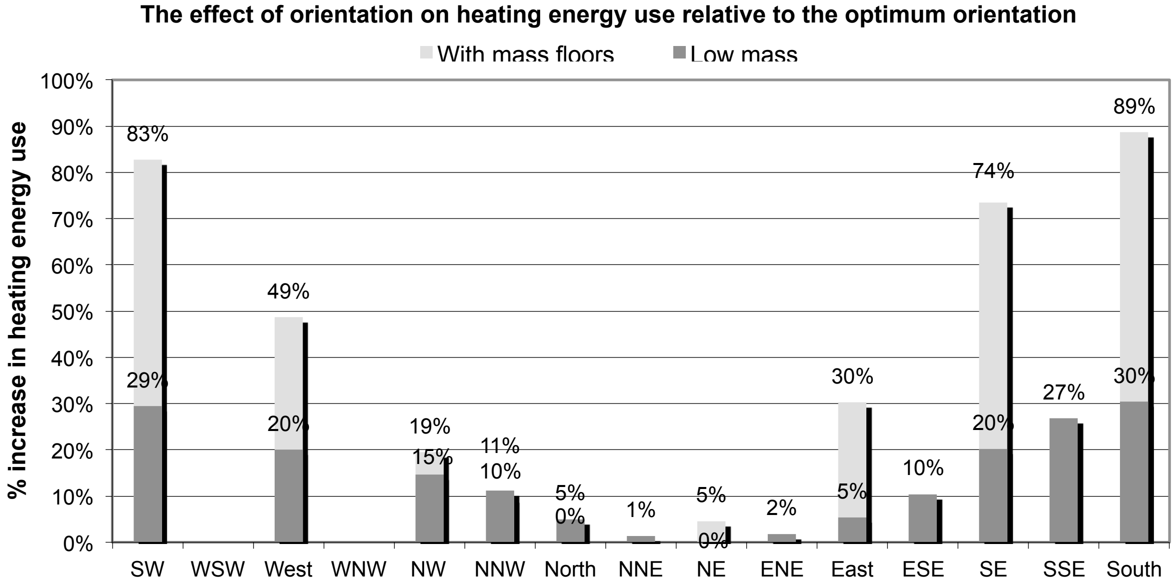


Figure 2: The effect of orientation on heating energy use with and without mass using W6 as an example. Note that the optimum orientation is different depending on whether or not there is mass. For mass, the optimum orientation is north. For low mass, the optimum orientation is north-east.

Orientation has a significant impact

As shown in Figure 1, if the house's heating energy use is compared with normalised construction, then we can see a rough trend where the houses that use the most energy are oriented more east/west, while the better-performing houses face more northward. While it is clearly not the only important factor, it suggests that orientation has significant effects on performance.

This supposition is confirmed by controlled tests using a version of House W6, modified so that all of the glazing is on one side. As shown in Figure 2, with standard light-weight construction, non-optimal orientation can result in heating energy use increasing 10%-20%, or even higher if one were to make the mistake of orienting it significantly south.

A note should be made however: crudely rotating house designs to try to “improve” orientation generally has little effect. This is because most house designs have their glazing distributed around the house, facing in multiple directions. This means that, for example, if one rotates the house so that its main “north-east” windows face more north, then one has also made its “north-west” windows face more south – which serves to counteract any benefits.
Thus, in designing a high-performance house, it should be well-oriented from the beginning, as it will (probably) not be able to easily, or effectively, re-oriented later on.

Good orientation is even more important for high mass construction
As shown in Figure 2, houses with high mass floors (such as a concrete floor slab) are much more sensitive to the effects of orientation than houses of purely light-weight construction. The increases in energy use from non-optimal orientation can be as much as 200% higher than with light construction, and could result in heating energy use being as much as 50% higher.
This is, of course, unsurprising, as high mass is very dependent upon solar gains for effective operation.

It is important to stay close to ‘optimal’ orientation…
Looking at Figure 2, we see that for light construction, it is best for orientation to be between north and east if significant increases in energy use are to be avoided (no more than ~5% increase), with north-east being the optimal orientation for heating. For high mass however, due to its’ greater dependence on solar gains, the orientation is more restricted, with angles outside north to north-east having significant negative effects on heating. In general, we can see that east facing tends to be better than west facing for heating (although obviously this will depend on the site). The advantage of east orientations may be explained as being due to it providing greater useful solar gains – the morning sun is very useful to warm up the house when it is cold in the morning, in contrast, by the afternoon the house will have warmed up already, and so much of the west sun is effectively wasted as once the house is warm enough, further gains are unnecessary.

… However, designers do have some freedom in distributing their glazing
Despite the significant potential costs of non-optimal orientation, designers do have some freedom to distribute their windows. Some further tests using W6 indicate that if half of the glazing is well oriented (e.g. facing north-east) then the rest can be distributed around the house without reducing performance too much (e.g. <5% reductions). Again though it should be noted high mass is much more sensitive, and greater care should be employed.

5 RESULTS: GLAZING LEVELS

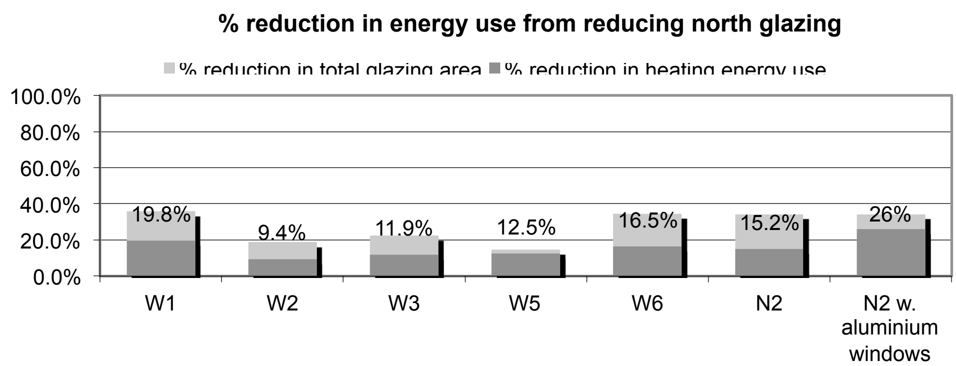


Figure 3: Reduction in heating energy use from reducing north glazing on different houses

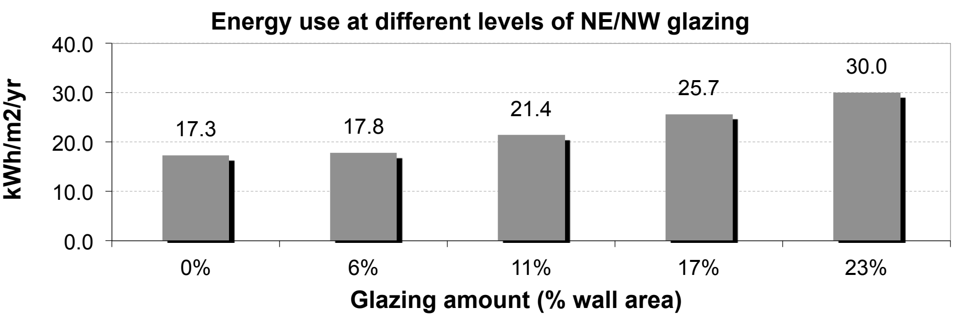


Figure 4: Heating energy use for W6 at different levels of glazing

Glazing is bad for performance
In every case modelled, reducing the level of glazing resulted in reduced heating energy use (example of north glazing in Figure 3) to a degree related to the magnitude of the change in glazing area. This effect is even more starkly demonstrated in Figure 4, above. To investigate further the effects of glazing level on performance, controlled tests were done using house W6. In it, the glazing level of the case study was systematically reduced. As can be seen, with each reduction the heating energy was significantly reduced – by about 16% each time until the final step where the glazing was entirely removed. It should also be noted here that the passive performance also improved most of the time – reducing the glazing made the house less cold and at less risk of overheating. The exception here was removing the glazing entirely – the resulting lack of solar gains did mean that the house was colder than it was with windows – suggesting that having *some* windows may be advisable. Notable is that W6 is the best performing case study – it is well oriented, with its windows nearly all facing NE/NW, and it has significantly less glazing than the others. Yet it still, consistently, got significant benefits from reducing its glazing.

Reducing glazing also serves to reduce the risk of overheating, as windows are the primary source of solar gains. Furthermore, windows are around 10 times as expensive as walls, on a square meter basis (Rawlinson & Co., 2011). Thus, designing larger windows means that you are spending more money in order to have a less comfortable and more expensive-to-run house.

Obviously, however, there is a clear desire for windows in houses, and the very low 'optimal' level of glazing suggested by Figure 4 is probably much lower than people would accept. In this light, it should be suggested that while windows of some size are necessary and important, their size should be kept to a minimum, and if they are interested in providing good thermal performance then designers should be advised to try to do more with less, and avoid things like excessively large floor to ceiling glazing.

The damage can be mitigated with good orientation, mass, and thermal resistance
The negative effects of glazing can, however, be reduced. If the glazing is well oriented for heating (facing north/north-east) then it will not be as bad. Additionally, thermal mass can also make north glazing significantly less bad by allowing the house to make better use of the solar gains. And, of course, the losses through the glazing can be significantly reduced by using windows with higher thermal resistance.

6 RESULTS: CONSTRUCTION

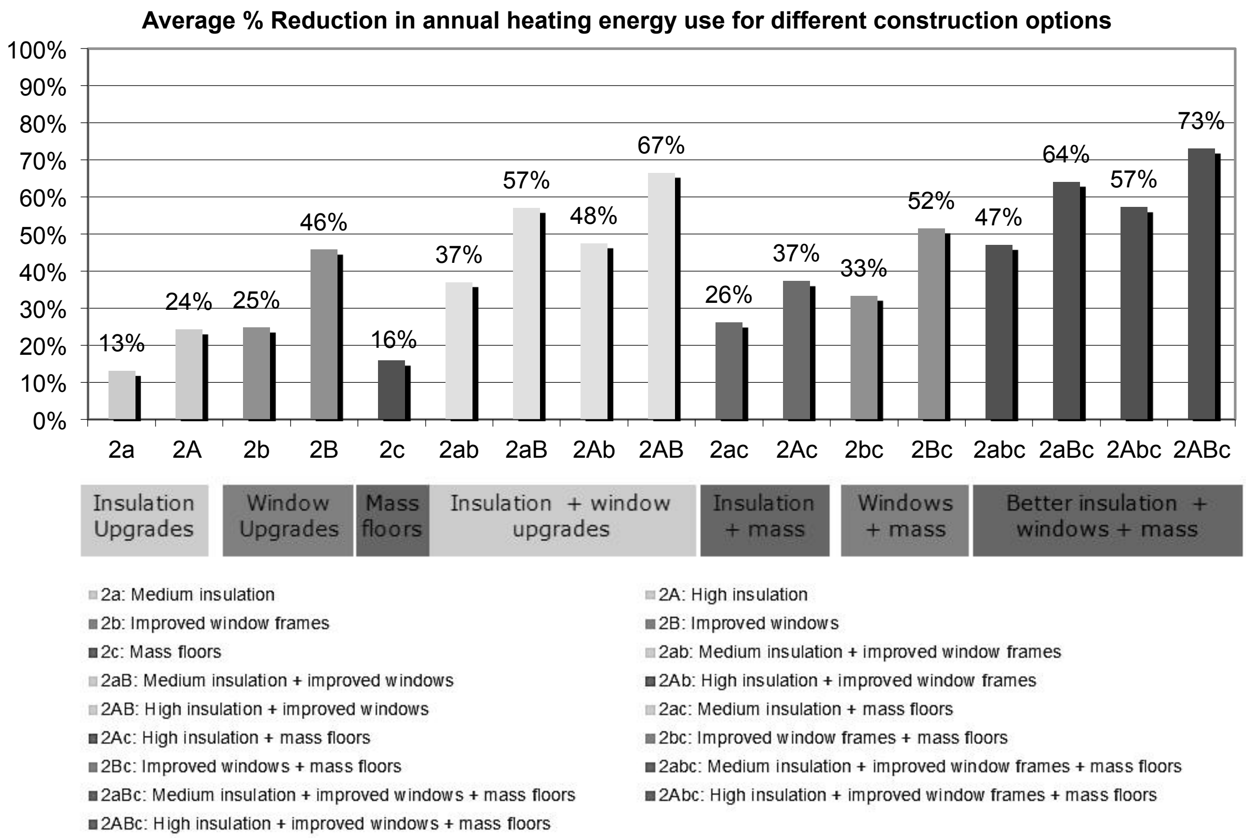


Figure 5: Average % reduction in annual heating energy use for the different construction options compared to the reference model. Note: The 'Mass floors' reduction is in comparison to the houses without mass.

Upgrading the construction can provide very large improvements

The first thing that can be seen from the above graph is that improving the construction can greatly reduce heating needs, with the potential to reduce it by as much as 75% if multiple improvements are used.

Upgrading the windows is the most effective option

For most of the case studies, the most effective option is to upgrade the windows. This is because they have large amounts of glazing – all but one of them have a window to wall ratio (WWR) of over 30%, and 4 have over 40% WWR. If the glazing is reduced, to around 20% WWR, then the effectiveness of glazing and insulation upgrades is about the same, providing about a 20% heating reduction for medium insulation, and roughly 35% for high. It is possible though that the effectiveness of upgrading the windows is being exaggerated by the lack of curtains in the models.

Mass can have significant effect

Mass can also have significant effects. This is, however, reliant upon the house being well oriented to north – if it is not, then the mass will likely provide little benefit. The average shown here arguably does not accurately represent its potential – the houses that were less optimally oriented saw lower reductions in heating energy use of only around 4% to 10%, while the better oriented houses got reductions of ~20% to 26%. Mass is also very effective at reducing overheating, making it generally good for thermal performance. Another point of interest is that, while less effective than high insulation at reducing energy use, mass floors are about as effective as high insulation or improved window suites at making the house less cold – it's very good at improving passive performance.

If a house has a concrete floor slab, then it should be used rather than covering it up with carpet.

7 DISCUSSION

7.1 Limitation of results: the effects of climate

As mentioned in Section 2, the houses were all modelled in Wellington. This does affect the general applicability of the results, as design changes may vary in effectiveness in different climates. The construction changes were all modelled again in Auckland and Christchurch to see how they changed in a hot and cold New Zealand climate. Notable is that the window upgrades do not outstrip the insulation upgrades as much in the other climates. Indeed, where in Wellington high insulation has about the same effectiveness as upgrading to timber window frames, in the other climates high insulation is better than just upgrading the window frames. Also notable is that mass is far more effective in Auckland – in some houses it is twice as effective, in the best case cutting the heating needs by half. This is good news, as mass is also good at dealing with overheating, which is a significant issue in Auckland's hotter climate. This suggests that mass is highly recommended in hotter climates as a way of significantly reducing both heating and cooling needs.

The main message here though should be that extrapolating these findings to houses in other regions should be done with caution, as the effects can be expected to change.

7.2 Limitation of results: no cost-benefit analysis

It should be noted that all of the results here are discussed on the basis of *effectiveness*, not efficiency. Upgrading the glazing may be more effective than upgrading the insulation, but we have not checked to see which is most cost-effective.

7.3 Results are complex – modelling is recommended

The effects of the changes varied widely amongst the different houses. Every house is different, and interactions between the different elements of design are complex. The best way to ensure the best design is hour-by-hour modelling using a thermal simulation program. Rules of thumb and general recommendations, while useful as guidance, can only go so far.

7.4 Implications towards current design practice and performance standards

Comparison between the performance of the different case studies reveals, quite starkly, the limitations of the current performance standards, and its focus on insulation levels (NZS 4218). There is considerable variation in the performance of the different houses, even when their construction is normalised, or when (in the previous study) 'code-compliant' benchmark models are made (e.g. Novak et al., 2011). While such comparisons are complicated by issues such as having different sized living rooms, comparisons between houses with similar room proportions (e.g. W2 and M1) also show large disparities that can be related, at least partly, to orientation and glazing area. While NZS 4218 does limit glazing area somewhat (with reference buildings being able to have no more than 30% WWR), it pays only token attention to orientation – only saying that glazing on the East, West and South faces should have no more than 30% WWR – and this only for the schedule method. This, combined with the misleading information in the Standard that solar gains through north glazing are greater than losses, as well as *Designing Comfortable Homes* showing how crude rotation of houses generally has little effect, may serve to encourage designers not to take orientation seriously. To treat it as something that is nice to have if possible, but not really very important. The findings in this study however make it clear that it can have significant effects upon performance and greater attention should be paid to orientation.

7.5 Significance of study

The significance of this research lies in the fact that it provides analysis of a cross-section of recent designs from a leading New Zealand architectural practice. The design issues and key areas for improvement that are identified from the varied case studies can be considered to be generally applicable to all house designs from Studio Pacific, and likely for many modern houses designed by architects in New Zealand. The comparison of a range of house designs also allows the effects of design features on the effectiveness of performance upgrades such as insulation to be assessed.

This research highlights the key design features that separates the better performing architecturally designed houses from the less well performing – something which is highly relevant to future revisions to the New Zealand Building Code as well as providing an example to other architectural practices.

Most importantly, in the use of simulation to provide a self-critique of their designs, and to learn how to improve the performance of their future designs, the study has provided a series of significant benefits to Studio Pacific as an architectural practice. The empirical evidence of energy performance on their own work, rather than just that from rules of thumb and anecdotal evidence is a very useful tool in setting design direction for ourselves and in discussing design direction with, sometimes sceptical, clients. Studio Pacific has used the research as a basis for client advice, has advised changes in specification for some work currently underway and in other cases has been able to change the specification of some buildings still in the early design phases. The fundamentals of the design of each house such as orientation, level of glazing and mass are now investigated with extra care. Additionally some of the lessons are being transferred to the practice's commercial work. All of these efforts collectively make a difference within Studio Pacific and in a wider sense will do to energy use in the future.

8 CONCLUSION

The modelling of the buildings in this study has yielded a set of recommendations for improving the performance of these architecturally designed houses and others like them in New Zealand:

- Use less glazing – maybe limit it to no more than 20% of the wall area?
- Plan the house so it is mainly facing north/north-east. If at least half of the glazing is facing this direction then it may be possible to place the rest where needed, with only small losses.
- If you have a concrete floor slab – use it. It can significantly reduce both heating energy use and the risk of overheating.
- Upgrading the R-value of the glazing has the most benefits. Timber window frames with argon fills, low-e coating and double glazing was the most effective option studied.
    - However, if significantly less glazing is being used, and it is well oriented, then this may be no longer true.
- In a hot climate like Auckland, use mass. It is highly effective in warmer climates and addresses both heating and overheating.

It must be stressed however that the study found significant complexity in the interaction of the various variables and their effect on performance. For good thermal performance, the design options should be modelled in order to properly assess the individual circumstances of each house. These recommendations should be used as starting points in the concept design stage, and as guidance towards the kinds of design decisions that people should be thinking about.

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