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Cost benefit analysis of simulated thermal energy improvements made to existing older South Australian houses

David M Whaley[a*], Timothy O'Leary[b], Bashar Al-Saedi[a]

[a]*School of Engineering (ENE), Barbara Hardy Institute, University of South Australia, Adelaide, Australia*
[b]*School of Natural and Built Environment (NBE), Barbara Hardy Institute, University of South Australia, Adelaide, Australia*

Abstract

Since 2010/2011 changes to the national construction code require newly constructed houses to perform at a minimum Nationwide House Energy Rating Scheme (NatHERS) energy rating of 6 stars (or BASIX equivalent in NSW), which determines the predicted thermal energy a house requires to maintain thermal comfort, given its location. This initiative aims to improve the energy performance of new housing stock in the residential sector, however, many existing houses were built before the introduction of these regulations. These houses account for the vast bulk of the nation's housing stock and are shown by studies to achieve low star ratings and can require significantly higher amounts of thermal energy to maintain occupant thermal comfort.

This paper investigates the likely impact of various renovations for six existing houses in South Australia mainly within the Adelaide climate zone representing a range of typical housing stock constructed before the adoption of NatHERS based energy regulations. These houses were built between the 1930's to 1990's, are sited on individual allotments, and are modelled in NatHERS rating software from an existing base case and then for a variety of both minor and more significant building shell and fabric upgrades; extensions to floor areas or major structural modifications are not considered. The costs associated with the upgrades is presented together with the thermal energy improvements, which bring older houses up from star ratings of 1-3 to the current minimum performance of 6, which reduces the demand for and greenhouse gas emissions of heating and cooling devices, for material and labour costs of $15-25k. Further analysis identifies the types of renovations that are the most cost effective.

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Keywords: NatHERS; retrofitting existing houses; FirstRate5; thermal energy requirements; star rating; energy performance.

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* Corresponding author. Tel.: +61-8-8302-5669; fax: +61-8-8302-3380.
E-mail address: david.whaley@unisa.edu.au

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1. Introduction

The energy demand for air conditioning of residential buildings has been escalating in many developed and developing countries in the last two decades. In Australia, space heating and cooling represents 41% of the energy demand of dwellings. Residential buildings currently make up about 20% of Australia's greenhouse gas emissions, with 30-40% of this being directly attributed to heating and cooling [1, 2]. As the number of dwellings and their size continue to increase, the demand on the electricity infrastructure will increase, which is anticipated to further exacerbate the peak summer electrical demand, which is already largely caused by residential buildings [3, 4, 5].

Nomenclature

DG	Double-glazed
NatHERS	Nationwide House Energy Rating Scheme
MJ/m^2	Mega Joules per square metre
Rx	Thermal Resistance of value x
SG	Single-glazed
SHGC	Solar Heat Gain Coefficient
SS	Single-sided
U_w	Heat transfer through window

1.1. Recent Trends of Cooling Appliances and Demand in Australia

The proportion of households with cooling systems and their demand has increased recently [6]. Data from the Australian Bureau of Statistics for 2008 [7] shows that about 65% of dwellings have either refrigeration-based or evaporate-based cooling systems. Comparison with data from 2005 shows there has been an increase of 2.1% of cooling equipment installed. This growth is expected to increase in the future, given that the number of days where cooling is used is expected to also increase, as it is predicted that many Australian climate zones will become cooling dominant by 2050 [6].

1.2. Nationwide House Energy Rating Scheme

The Australian Building Codes Board introduced energy efficiency measures for houses into the Building Code of Australia now known as the National Construction Code on 1 January 2003. It has been adopted by all Australian states and territories which did not already have an equivalent system in place. Victoria and South Australia enacted a more stringent 5-star rating in 2004 with other states following later in 2006/2007. As of 2011 all states and territories except the Northern Territory have adopted the more stringent 6 star standard, although notably in Queensland compliance can be achieved by a lower 5 star level with concessions for outdoor living areas and solar PV installation.

The NatHERS scheme uses a set of assumptions as to how buildings are constructed and operated [8, 9]. NatHERS predicts a thermal heating and cooling (sensible and latent) load, based on building material thermal properties, climate zone typical meteorological year data, and assumed occupancy profiles. The development of a set of software simulation tools began several decades ago using the Cheetah/Cheenath building thermal simulation software engine developed at the CSIRO. The engine is a transient numerical simulation of the heat transfer and ventilation flow through the building, calculating the thermal load needed to achieve the set point each hour [10].

In more recent times the advent of Second Generation NatHERS compliant software tools such as Accurate®, FirstRate® and BersPro® has included modifications and improvements to the Cheenath engine utilising data from post occupancy studies and an expansion of climate zones and climate data. These three software applications are the only tools that exist to produce a NatHERS rating and compliance certificate under the code. Their use is spread relatively evenly across state jurisdictions however with a bias towards the Firstrate software in Victoria and South Australia [11], whereas BersPro is used more widely in the eastern states.

NatHERS provides a unique star band that ranges from 0.5 to 10, which vary for each clime zone yet allows comparisons between buildings across Australia. Table 1 shows the maximum thermal load for some of Australia's 69 climate zones. A comprehensive summary of each climate zones and star rating can be found in [12].

Table 1. NatHERS energy Star Bands Rating, numbers correspond to thermal load (MJ/m^2) [12].

Climate Zone	Location	Energy Rating (Stars)									
		1	2	3	4	5	6	7	8	9	10
1	Darwin	773	648	555	480	413	349	285	222	164	119
10	Brisbane	203	139	97	71	55	43	34	25	17	10
13	Perth	387	251	167	118	89	70	52	34	17	4
16	Adelaide	480	325	227	165	125	96	70	46	22	3
21	Melbourne	559	384	271	198	149	114	83	54	25	2
26	Hobart	723	498	354	262	202	155	113	71	31	0
59	Mt Lofty	987	706	518	391	301	230	166	105	48	1

1.3. Purpose of Study

There are a large number of existing dwellings in Australia that were built over the past 80 years. The ABS reported that in the period prior to 2001 there were over 7 million privately occupied individual dwellings. These were built [13] using materials and construction methods appropriate at the time and before the introduction of minimum energy performance regulations described above. These older houses typically achieve low star ratings 1-2 and hence can require significantly higher amounts of thermal energy to maintain thermal comfort compared with new houses that require a 6 star energy rating, as shown in Table 1. This study therefore examines the predicted thermal energy savings that may be achieved by retrofitting existing houses, which has the potential to significantly reduce the energy consumed, running costs and greenhouse gas emissions associated with heating and cooling devices.

1.4. Limitations of Study

This study uses FirstRate5 software, to predict the thermal energy required as a result of retrofitting houses with materials such as double-glazed (DG) windows and ceiling, roof, floor and wall insulation. It is assumed that these materials are able to be installed in these houses and that these are installed correctly, as poor installation of roof insulation for example can significantly affect its R-value, i.e. a 5% air gap can reduce the R-value by 50% [14].

2. Literature Review

A case study that investigated the cost of a moving from 5 to 6 star energy rating, for existing houses in the Northern Adelaide suburb of *Playford North*, was presented in [15]. The building envelope improved the thermal performance as measured by the house energy rating, however, the modeling was limited to adjustments in roof and wall insulation, as well as window glazing. The study showed that the average capital cost to increase from 5 to 6 stars was found to be $4.9k for an average house size of 171m^2 [15], which had payback period of about 25 years.

Another South Australian study was conducted that examined predicted energy efficiency ratings for an existing house built in the 1950s [16]. The house was modeled using FirstRate5 and improved from an initial 1.2 star rating to the now minimum requirement of 6 stars. This used an iterative approach that varied retrofit options and showed that a cost of $15.6k was required to achieve the 6 star rating. This resulted in a payback period of 6.7 years, given the improvements saved $2.3k in energy costs per year.

The fundamentals to improve energy efficiency in volume Australian housing were investigated in [17]. This showed significantly lower order costs for typical houses, i.e. $2k-6$k could achieve new star ratings of between 5 and 6 stars and that the costs were shown to increase with increasing house size. This study also mentioned that capital costs could be reduced by decreasing windows, and concluded that window glazing together with insulation are the most significant cost factors to consider when improving a dwelling's energy efficiency [17].

A study on Victorian houses built between 1945 and 1965 was conducted and presented in [18]. These typical post-war style houses are single-storey, face North, have a relatively small floor area of 100m^2, and were constructed from weatherboard and obtained a star rating of 2, using FirstRate5. The study examined improving three quarters of the house while demolished the last quarter to improve comfort and livability while reducing running costs. These retrofits focused on minimizing thermal energy consumption, and maximizing sunlight, and showed that houses could improve from 2 to 7.7 stars [18].

A pilot project conducted on-ground research on 15 typical Victorian dwellings that were constructed pre-1990 to measure the energy efficiency [19]. FirstRate5 was used to model these houses to determine the improvement in energy rating and to estimate the financial saving that could be achieved, by applying a range of envelope closure upgrades, such as, floor, wall, and ceiling insulation, double glazing and draught sealing [19]. The average initial star rating was 1.3, with 4 ranging between 0 and 1, whilst 2 houses exceeded 2 stars. The predicted results showed that a significant improvement could be made after enhancing the house envelopes, where 10 houses achieved ratings of 4+ stars, whilst the highest was 5.3. The average new rating was 4.3 stars, which saved an average of $600 and 3.2 tonnes of greenhouse gas emissions, per year; the latter representing an 80% reduction. The results of this study have the potential to better inform government policies, such as the regulation of residential building energy performance as well as incentives to increase housing upgrades.

An Australia-wide study modelled and assessed 20 house designs, including single and double-storey detached, semi-detached houses and apartments, using builder supplier specifications across all 8 Australian capital cities, which aimed to achieve 6 stars in Adelaide and Canberra, whilst all other capital cities aimed for 5 stars [20]. The orientation of each dwelling was adjusted to reflect the best, worst and intermediate thermal performance and then thermal design principles were introduced using an automated tool known as Roborater that was developed by Sustainability House. Roborater allows a rapid simulation across a wide range of variables that includes all the parts of the envelope closure, such as, insulation and glazing. This was used to thoroughly understand climate and thermal principles and to identify building specifications that achieves the lowest cost energy efficiency improvements [20].

3. Methodology

This study performed house energy assessments on six typical houses located within the Adelaide and Adelaide Hills climate zones. Details of the houses, simulation tool, assumptions made to create base case (as built) models and the cost of retrofitting are discussed in the following sections, together with base case NatHERS star ratings.

3.1. Selection of Houses

This study selected six houses that were constructed between the 1930s and mid 1990s. These were deemed typical of the 1930s, 1950s, 1960s, 1970s, 1980s and 1990s eras as determined by both real estate and house energy rating experts. Five of the houses examined were built in the Adelaide climate zone, whilst one (1930s) was built in the Mt Lofty (Adelaide Hills) climate zone, to demonstrate the difference in thermal energy required and star rating. Note that each house is single-storey and relatively small compared with more modern houses, in terms of floor area.

3.2. Simulation Tool and Scenarios Modelled

FirstRate5 v5.2.2 was selected to predict the energy performance of the six houses. The simulations compared the 'as built' base case scenarios, to those that were retrofitted with a various options. Note that a very large (thousands) of retrofitting options are possible, however this study only focused on 25-30 simulations per house, given the time required to adjust the models and perform the simulations. The options investigated were based on those identified in [21] which performed a parametric study on one of the six houses to gauge the retrofit options that are most likely to improve the thermal performance of older existing houses.

Fig. 1 shows a screenshot of the ‘*Plan*’ tab of the FirstRate5 software tool, for the 1970s house. This gives an overview of the house floor plans and the eaves associated with the dwelling. Various zones, e.g. living, bed and others are indicated by the various colours.

Note: Data has been entered via the Zoning tables. This may affect the rating.

Name
Level 1

☑ Background ☑ Lines ☐ Edit areas

Connections: ☑ Screens ☑ Eaves

Properties Level

Name	Value
Name	Level 1

North offset (degrees) 0.0

Fig.1: Screenshot of FirstRate5 simulation tool, showing the model of the 1970s house.

3.3. House Assumptions and Base Case Performance

Each house was simulated using FirstRate5, and each base model was built from scratch based on information obtained from floor plans, such as size and height of windows and doors, eave projection etc., and Google Maps, such as house orientation. All other details required to complete the house models were assumed, as listed below. Table 2 summarises the FirstRate5 input parameters, including the climate zone, and the predicted output, i.e. the normalized thermal energy required to maintain thermal comfort and the corresponding NatHERS star rating.

- Roof insulation is ‘added bulk’ type, and did not exist in any house except 1978 and 1980, which has R1 installed,
- Roof colour is medium in solar absorbance terms, and roof pitch is 26°, with respect to the horizon,
- External walls were brick cavity,
- Wall insulation to be modeled in external walls only, and is ‘polyurethane rigid foamed aged’ and ‘foam’ types,
- Ceiling and floor insulation are single layer of single-sided (SS) foil,
- Ceiling, roof and walls are assumed accessible, for the purposes of installing insulation,
- Ceiling fans do not exist in any house; those added as retrofits are 1200mm in diameter,
- Only house 1996 had weather stripping installed when constructed,
- All external windows and sliding doors are single-glazed.

Table 2. FirstRate 5 input parameters and base case predicted thermal energy requirements and NatHERS star ratings.

Year of construction	Suburb	Floor Area (m^2)	Window Area (m^2)	Roof Insulation	NatHERS Climate Zone	Thermal Energy (MJ/m^2)	NatHERS Star Rating
1930s	Bridgewater	109.4	22.7	-	59 (Mt Lofty)	953.0	1.1
1950s	North Plympton	91.1	18.5	-	16 (Adelaide)	384.2	1.6
1967	Hackham	87.7	18.5	-	16 (Adelaide)	412.0	1.4
1978	Aberfoyle Park	99.0	17.5	R1	16 (Adelaide)	289.6	2.5*
1980	Happy Valley	106.4	26.4	R1	16 (Adelaide)	246.8	2.8*
1996	Marleston	107.0	26.0	-	16 (Adelaide)	448.7	1.2

* The higher base case star ratings for the 1978 and 1980 houses is likely attributed to the installation of R1 roof insulation, whereas the remaining houses were assumed to have no roof insulation fitted at the time of construction.

3.4. Retrofitting Cost Estimation

Dwelling upgrade cost estimates were completed by one of the authors who is an experienced *Royal Institution of Chartered Surveyors* qualified quantity surveyor and construction economist. The costs estimates, include both materials and labour (installation), and were initially prepared for Adelaide using rates benchmarked from cost data derived from similar projects, cost data sourced from Rawlinsons Australian Construction Handbook 2016 [22] and by using a retail market based approach from product suppliers. In costing the various material and technology combinations modelled to improve the star rating some suppliers and subcontractors in the South Australian home building market were willing to provide indicative prices as a cost check. The building cost data used in this and other studies by the authors is regularly reviewed and revised to reflect the current market conditions in South Australia.

3.4.1. Window Costs

A summary of the window types used in the house simulations performed in this study are shown in Table 3, along with a brief description of its construction / glazing arrangement, i.e. whether they are single-glazed (SG) or double-glazed (DG); the total window system solar heat gain coefficient (SHCG) and heat transfer through the window (U_w) value; and the estimated supply and installation cost. Note that it was assumed that aluminium framed clear SG windows were installed in all houses before any upgrades were simulated, which forms the base case*. Although these windows have an associated cost of \$310/m^2, it is assumed that there is no additional cost for these.

Table 3. Window properties and retrofit cost. * indicates assumed window type for base cases of all houses.

Window type	Description	U_w-value	SHGC	Cost (\$/m^2)
*ALM-001-01A	Aluminium A SG Clear	6.7	0.57	310*
ALM-005-03A	Aluminium A DG Argon Fill High Solar Gain low-E -Clear	4.1	0.47	570
ATB-006-03 B	Aluminium Thermally Broken B DG Argon Fill High Solar Gain Low-E-Clear	2.9	0.51	680
CMP-005-04 I	Composite A DG Argon Fill Low Solar Gain low-E-Clear	2.2	0.32	840
FIB-006-03 W	Fiberglass B DG Argon Fill High Solar Gain low-E-Clear	2.0	0.31	1,150
PVC-006-03 W	uPVC B DG Argon Fill High Solar Gain low-E-Clear	2.0	0.31	870
TIM-006-03 W	Timber B Argon Fill High Solar Gain low-E-Clear	2.0	0.31	620

3.4.2. Insulation Costs

Table 4 lists the estimated total cost of the various types of ceiling, floor, roof and wall insulation used in the modelling; these also include the cost for materials and installation. Note that the ceiling and floor insulation costs shown are for a single layer of single-sided (SS) foil, whilst that in the roof and walls is ‘added bulk insulation’ and ‘polyurethane rigid foamed aged’ types, respectively. An appropriate allowance for waste, cutting and any overlaps where required is included in these indicative rates.

Table 4. Various insulation retrofit costs; all costs are shown in \$/m^2.

Insulation	Ceiling (SS)	Floor (SS)	Roof	Wall
R1	3.00	4.00	5.40	10.30
R1.5	3.75	4.75	-	11.20
R2	3.82	5.40	6.15	15.60
R2.5	-	-	6.65	18.00
R3	4.40	5.80	6.95	22.50
R3.5	-	-	-	24.70
R4	5.10	6.10	7.15	30.00
R5	5.53	6.55	7.88	-
R6	6.00	7.00	8.40	-

3.4.3. Other Retrofitting Costs

In addition to window and various insulation upgrades, the simulations also examined the effect of installing ceiling fans, in living and bedrooms, and weather stripping to external doors and windows. The cost to install ceiling fans varies between \$500 and \$700 for small to large rooms, and does depend on existing wiring and suitable access to roof / ceiling spaces. In this study, it is assumed that all ceiling fans are 1200mm in diameter and that these are installed where lighting infrastructure exists. As such a cost of \$500 is assumed per ceiling fan in each house.

The cost associated with the supply and installation of weather stripping to external windows and doors also varies with the size of the house. It is assumed that this cost varies with size, i.e. the cost to retrofit small (floor area less than 120m^2), medium (120-200m^2), and large (greater than 200m^2) houses is \$500, \$750 and \$1,000, respectively. As each house is less than 120m^2, these all attract the same cost of \$500 per house. Note that only the 1996 house had weather stripping installed during its construction, whilst those constructed prior to this did not.

4. Results

4.1. Thermal Energy Improvement to Retrofitted Houses

The estimated cost vs. predicted thermal energy load required to maintain thermal comfort (MJ/m^2) is shown for 25-30 simulations for each house in Fig. 2. These scatter points cover a variety of retrofit options, including the base cases, which are shown for a retrofit cost of \$0 (along the x-axis, within the green dotted box). The figure shows that each house shows a similar trend that retrofit cost is inversely proportional to thermal energy requirement to a certain point equivalent of approximately 4 stars. The outlier is the 1930s house, which shows a similar trend, however this occurs at higher predicted thermal energy requirements, which is a reflection of the vast typical meteorological conditions experienced in these climate zones. This is highlighted by the vertical solid and dashed lines, which represent the star rating bands ranging from 1 to 8 for the Adelaide and Mt Lofty regions, respectively.

To compare each house on a level playing field, the same data is shown as a function of NatHERS star rating in Fig. 3, which normalizes the effect of varying climate zones. The figure now shows that each house, including the 1930s house, has a similar star rating improvement and that it is now possible for each house to achieve a rating of 6 stars, which corresponds to the NatHERS requirement for new houses; shown by the vertical dashed line.

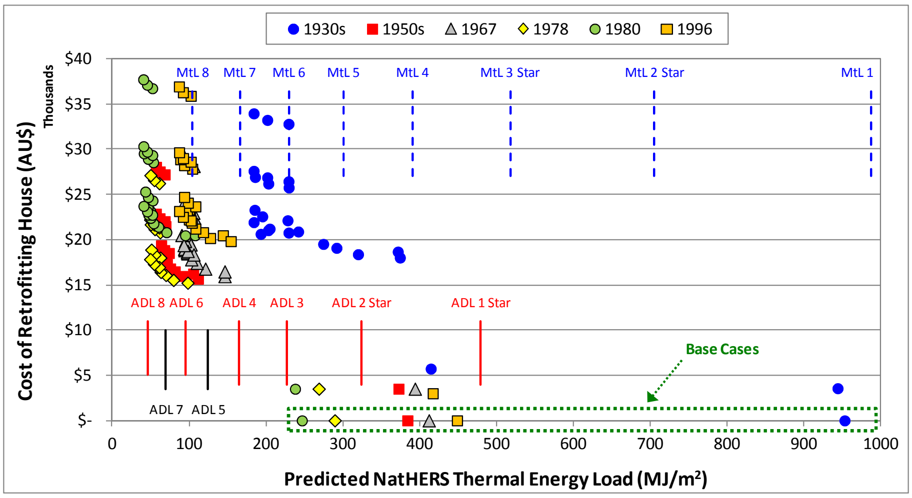

Fig.2: Retrofit cost vs. predicted thermal energy load for each house. Note that the vertical dashed and solid lines represent star rating bands (1-8) for the Mt Lofty (MtL) and Adelaide (ADL) climate zones, respectively. The dotted green box shows the base case predicted thermal energy.

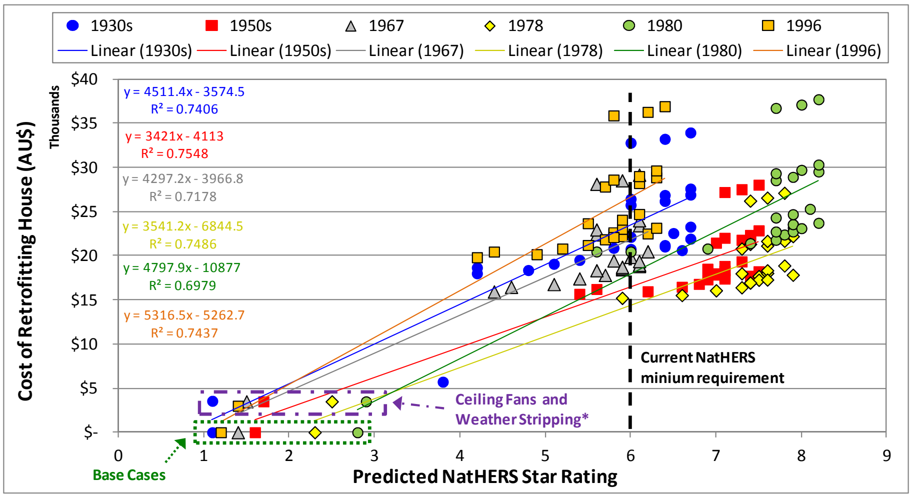

Fig.3: Retrofit cost vs. predicted star rating scatter and trendline for each house. Data corresponding to the base cases and those where ceiling fans and weather stripping were installed are shown by dotted and dash-dotted boxes, respectively. *1996: effect of ceiling fans only.

A colour-coded trendline is shown for each house that gives an indicative cost to achieve a desired star rating, with a degree of confidence, as the coefficient of determination (R^2) varies between 0.69 and 0.75 for all houses. Note that this R^2 value would likely approach 1, if some of the higher cost options were removed, given that each house suggests that the same star rating can be achieved by spending up to an additional $12k. The scatter also shows that a small increase of star rating (up to 0.7) can be attained for a relatively small cost of about $1k. These indicate that an optimized approach, or suggested path, can be taken to ensure that the highest star rating is achieved for the least cost.

4.2. Suggest Pathway to Reduce Thermal Energy Requirements

Fig. 4 (a) and (b) shows the same data as Fig. 3, however, the retrofitting costs of Fig. 4 (b) are now shown as a function of predicted thermal energy saving compared to the base case, which normalizes the results given the variation in base case thermal energy requirements and hence star ratings. The data again show that there are multiple methods to achieve the same energy saving, for vastly different costs as shown by the vertical solid boxes. This shows the effect of varying only the types of double glazed windows between composite, fiberglass, timber and PVC, whilst maintaining other parameters. This is explained by recalling Table 3, which shows that each of these window types have similar U_w-values and SHGCs, which results in the same thermal predicted energy requirement and star rating, yet the estimated cost ($/m^2) varies considerably. Overspend on expensive windows for little performance improvement is an issue, particularly the less commonly used Composite, Fiberglass and PVC types.

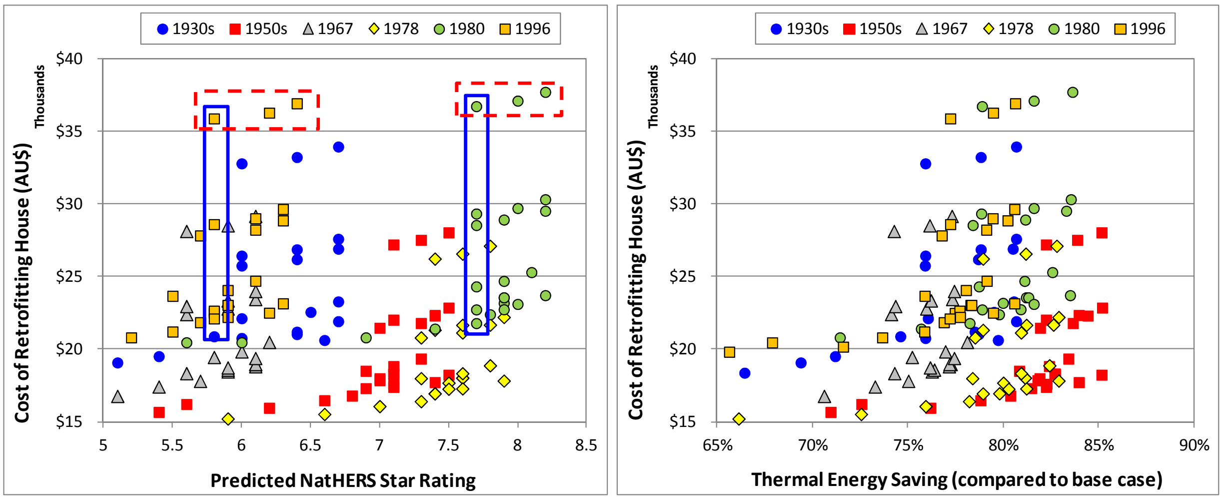

Fig. 4: Retrofit cost vs. (a) NatHERS star rating, and (b) predicted thermal energy saving scatter for each house. Note that the solid vertical boxes show the effects of installing different double-glazed window types, whilst the dashed red boxes show the effect if increasing insulation R-values.

The horizontal dashed boxes demonstrate that there are alternative options that predict a higher energy saving for only a marginal increase in cost. These show the effect of simultaneously increasing the ceiling, floor and wall insulation, whilst maintaining a certain window (Fiberglass) type. Although both the horizontal and vertical boxes of Fig. 4 (a) highlight the effects of varying various insulation and window types, respectively for the 1980 and 1996 houses, the same type of groupings can be found for each house, based on other window types.

It is therefore recommended to select a low-cost window option with low U_w-value and SHGC over higher cost windows that offer no additional thermal performance improvements, and to increase the insulation R-value in the ceiling, floor and walls. The combination of these two measures effectively maximize thermal resistance (and hence minimise the heat transfer) of the surface area of the internal spaces. It is recommended that double-glazed windows are used together with external wall, ceiling and floor insulation, to reduce the thermal and ultimately auxiliary energy (provided by space heating or conditioning devices) required to maintain thermal comfort. This concurs with the conclusions reported in [17].

5. Summary and Conclusions

This paper investigated the cost of retrofitting and improving the energy efficiency of existing small, single-storey houses in South Australian that were built before the introduction of minimum energy performance standards. Six houses were modeled in the Adelaide and Adelaide Hills climate zones and 25-30 improvements were simulated for each house significantly improved the base case star rating and improved the energy efficiency of the house's envelope. The following conclusions were made, that may be used as a guide to improve existing houses rather than extending or demolishing and rebuilding these:

- Houses built before the introduction of minimum performance standards have low star ratings ranging between 1 and 3, and houses constructed closer to the introduction of these standards did not perform any better.
- Each house was able to be brought up to the current minimum energy performance standard, for a cost between $15k and $23k; equivalent to an average cost ($/m^2) of between $150 and $230.

- In many cases the star rating of each house could be further improved beyond 6 stars, by spending additional money on higher R-value insulation in external walls, ceiling, floor and the roof.
- An indicative cost of retrofitting houses to achieve a desired star rating can be estimated, with confidence.
- There are multiple ways to improve the energy efficiency of existing houses, and a suggested path / optimised approach can be taken to reduce the cost of retrofitting, whilst maximising the star rating of each house.
- Due to the high variability in the cost of different types of double-glazed windows, the benefit of some higher cost window types is negligible or marginal, yet can result in significant overspending.
- Improvements to energy efficiency and hence star ratings require the envelope of the house to improve its thermal resistance (minimize heat transfer) surrounding the surface area of the house, which is achieved by glazing windows in conjunction with external walls, ceiling, floor and roof insulation.

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