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The energy consumption of a house can be affected simultaneously by many building design factors related to its main architectural features, building elements and materials. The relationship between the building design data and energy consumption data of houses can still be identified. This study focuses on the impact of building design factors on the extra winter energy consumption of houses. This information can be used to estimate the approximate saving in extra winter energy consumption, which would result from a changed design datum for future house development, and to identify the major design problems for energy efficiency. The quantitative relationships between building design data and extra winter energy consumption data are also valuable for developing passive design guides for housing energy efficiency. There is a focus on the effects of the passive features used in the architecture.

Keywords: Building design factor; building energy efficiency; building passive design; house; house design; house energy consumption

INTRODUCTION

This study suggests that better design of new buildings could result in a 40–70% reduction in their energy consumption relative to 2000 levels (Clarke, 2001). A number of recent research studies related to housing thermal performance and energy efficiency have focused on the upgrading of insulation and new façade design to improve indoor thermal comfort and energy efficiency (Milne and Boardman, 2000; Merebeech and Hens, 2005; Lloyd *et al*., 2008; Hong *et al*., 2009; Ochoa and Capeluto, 2009; Pulselli *et al*., 2009) and to improve indoor health conditions (Su, 2002, 2006; Howden-Chapman *et al*., 2005; Gilbertson *et al*., 2006; Bullen *et al*., 2008). Others have developed an international database of low-energy homes and the low-energy techniques applied to them (Hamada *et al*., 2003). For energy-efficient house design, computer simulations are becoming available as design tools (Caldas, 2006; Karlsson and Moshfegh, 2006; Smeds and Wall, 2008), and some studies combine computer simulations with field study data for energy-efficient house design or improved housing thermal performance (Simonson, 2005; Wall, 2006; Schuler *et al*., 2007; Tommerup *et al*., 2007). Auckland has a temperate climate with comfortable warm, dry summers and mild, wet winters. Auckland has about 1150 heating degree days (New Zealand Meteorological Service, 1978). The winter temperatures are lower than the comfort zone (18–28°C) but rarely below 5°C. An Auckland house normally does not need air conditioning for cooling during summer and it only needs temporary heating during the winter.

METHODOLOGY

This study uses the actual energy consumption data of 200 sample houses, which had been using electricity as their only energy source, to calculate extra winter energy consumption. The *R*-values of the wall and roof of the sample houses are 1.9m^2 °C/W and 2.9m^2 °C/W, respectively (Standards New Zealand, 2004). For this study, the difference between mean daily electricity usage in the winter months (June, July and August) and that in the other months of the year represents the extra winter energy consumption, which mainly comprises space heating, extra energy for hot water and all appliances, which are impacted by the winter indoor thermal conditions of a house. The smaller difference between mean daily usage in winter months and that in the other months roughly represents the response of better indoor space thermal conditions to winter climate conditions.

A previous study has demonstrated the relationship between the increase in extra winter energy consumption and the trend of a design datum's variation (such as the ratio of window to wall variation), when different design data related to the main architectural features, building

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elements and building materials affect the extra energy consumption related to winter indoor thermal conditions differently and simultaneously (Su, 2008). This study focuses on the impact of a number of major design features on extra winter energy consumption. This study uses the gradient of the trend line of the design datum's variation to evaluate the impact on extra energy consumption and estimate its increase or decrease both when a design datum is changed within a range and when the other design data also impact the extra energy consumption differently and simultaneously.

The study uses the mean daily electricity usage per unit volume of house indoor space (kWh/m^3 day) as the basic energy consumption unit because extra winter energy consumption is mainly related to indoor thermal conditions. Table 1 shows energy consumption data of sample houses.

The mean extra winter energy is 28.4% of the mean winter energy of the sample houses. The mean total winter energy consumption is 32.3% of the mean total annual energy consumption of all the sample houses. The real mean daily electricity usages of each house for a 1-year period are from the bar chart of 12 months of mean daily electricity consumption on the monthly invoice from local electricity suppliers. Occupancy and monthly electricity invoices of sample houses were collected by a number of second-year architectural students of Unitec for their technology course studies from 2007 to 2008. For minimizing the influence of differences in climates and types of energy, the sample houses for this study are in Auckland residential area, which had been using electricity as their only energy resource. Design data of sample houses were derived from the calculation and measurement of copies of building plans of sample houses provided by Auckland City Councils. The 200 sample houses include 90 one-storey houses, 104 two-storey houses and 6 three-storey houses. The range of floor areas is 31–446m^2 with a mean floor area of 182m^2. The range of occupancy per dwelling is 1–7 persons with a mean number of occupants per dwelling of 3.4 persons. The range of floor area per occupant is 20–180m^2 with a mean floor area per occupant of 65m^2. There are 69 houses with metal roofs (15 houses with brick walls and 54 houses with weatherboard and other walls), 116 houses with concrete tile roofs (78 houses with brick veneer walls and 38 houses with weatherboard and other walls) and 15 houses with cedar shingle roofs or other roofing materials. There are 158 houses with internal garages and 42 houses without them. The study uses the following design data and extra winter energy consumption data from the sample houses to identify their quantitative relationships:

- ratio of building surface to building volume
- ratio of total window area to total wall area
- ratio of total window area to indoor space volume
- ratio of total window area to total floor area
- ratio of north window area to north wall area
- ratio of north wall area to indoor space volume
- ratio of north wall area to total wall area
- ratio of roof area to indoor space volume
- ratio of roof space volume to indoor space volume.

Table 1 | Energy consumption data (kWh/m^3 day) of sample houses

Energy consumption	Range	Mean
A. Annual energy	0.016–0.140	0.059
B. Winter energy	0.021–0.163	0.075
C. Energy for other months	0.017–0.132	0.054
D. Extra winter energy	0.002–0.045	0.021

DATA ANALYSIS

Impact of the ratio of building surface to volume

The ratios of building surface to volume of the sample houses are 0.45–0.99 with a mean ratio of 0.63. A house with a high ratio of building surface to volume has a large external surface area per unit of indoor space from which to lose heat to the outdoors, and uses more energy for space heating, hot water and other appliances that can be affected by indoor thermal conditions during the winter. An increase in extra winter energy consumption is associated with an upward trend in the ratios of building surface to volume of the sample houses (see Figure 1). The gradient of the trend line of ratios of building surface to volume is 0.35. The extra winter energy consumption is related to and impacted by not only a particular design datum (such as the ratio of building surface to volume) but also other design data, both differently and simultaneously. The positions of these real data points are also impacted by other design factors. The gradient of the trend line of a design datum's variation could appropriately be used to measure the strength of that design datum's impact.

For the sample houses under local climate conditions and under the impact of other design factors, Equation (1) shows the quantitative relationship between the increase or decrease

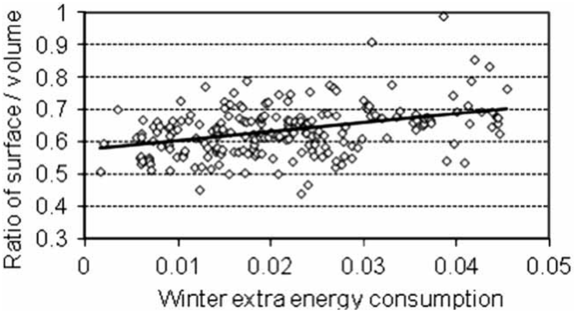

Figure 1 | Extra winter energy consumption and ratio of building surface and volume

in extra winter energy consumption and the increase or decrease in the ratio of building surface to volume, and the impact strength of the ratio of building surface to volume on extra winter energy usage. Equation (1) could be used to estimate the approximate saving in extra winter energy consumption of the future house development of Auckland associated with a decrease in the ratio of building surface under the local climate and local housing style:

$$\Delta E_{\mathrm{WE}} = 0.35\Delta R_{\mathrm{SV}} \quad (1)$$

where ΔE_{WE} denotes the increase or decrease in extra winter energy consumption, kWh/m^3 day; and ΔR_{SV} denotes the increase or decrease in the ratio of building surface to volume.

The mean extra winter energy is a large portion (28.4%) of the mean winter energy and the mean total winter energy consumption is also a large portion (32.3%) of the mean total annual energy consumption of the sample houses. Saving the extra winter energy consumption will significantly reduce winter energy consumption and annual energy consumption (Su, 2009). An increase in winter energy consumption and annual energy consumption is also associated with an upward trend in the ratios of building surface to volume of the sample houses (see Figures 2 and 3). An Auckland house does not normally need air conditioning or a ceiling fan for cooling during the summer and it only needs temporary heating during the winter. In Auckland, the design of a house should therefore focus more on its indoor thermal conditions and thermal performance related to winter conditions for energy efficiency.

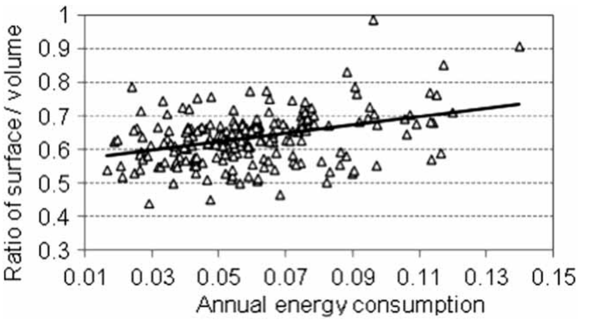

Figure 3 | Annual energy consumption and ratio of building surface and volume

Impact of ratio of window to wall area

The ratios of window area to wall area in the sample houses range from 0.07 to 0.42 and the mean ratio is 0.21. Windows are commonly weak elements of building thermal performance. The windows of all sample houses of this study and of the majority of local houses are single glazed. The thermal resistance (*R*-value) of a single-glazed window (0.26m^2 °C/W) is very low when compared with walls (1.9m^2 °C/W) and roofs (2.9m^2 °C/W) insulated in accordance with the current standard. With single-glazed windows, and an increase in the ratio of window area to wall area, the ratios of window area to indoor space volume and the ratios of window area to floor area of an Auckland house can negatively impact the winter internal space thermal conditions (see Figures 4–6) and significantly increase extra winter energy consumption. The trend line gradients of ratios of window area to wall area, window area to indoor space volume and window area to floor area are 2, 2 and 0.9, respectively. Equations (2)–(4) could be used to estimate the approximate increase or decrease in extra winter energy consumption of the future house development of Auckland associated with an increase or decrease in the ratios related to window design under the local climate and local housing style:

$$\Delta E_{\mathrm{WE}} = 2\Delta R_{\mathrm{WW}} \quad (2)$$

$$\Delta E_{\mathrm{WE}} = 2\Delta R_{\mathrm{WI}} \quad (3)$$

$$\Delta E_{\mathrm{WE}} = 0.9\Delta R_{\mathrm{WF}} \quad (4)$$

where ΔE_{WE} denotes the increase or decrease in extra winter energy consumption, kWh/m^3 day; ΔR_{WW} denotes the increase or decrease in the ratio of window area to wall area; ΔR_{WI} denotes the increase or decrease in the ratio of window area to indoor space volume; and ΔR_{WF} denotes

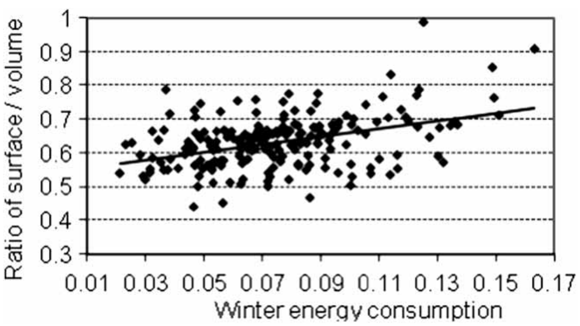

Figure 2 | Winter energy consumption and ratio of building surface and volume

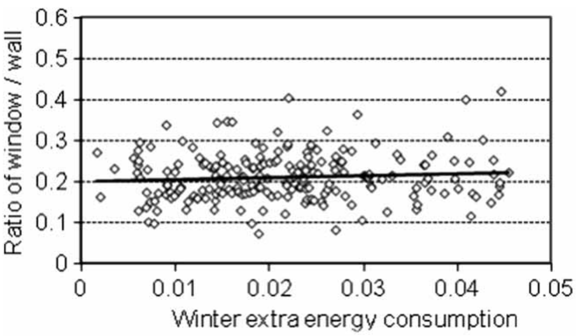

Figure 4 | Extra winter energy consumption and ratio of window area to wall area

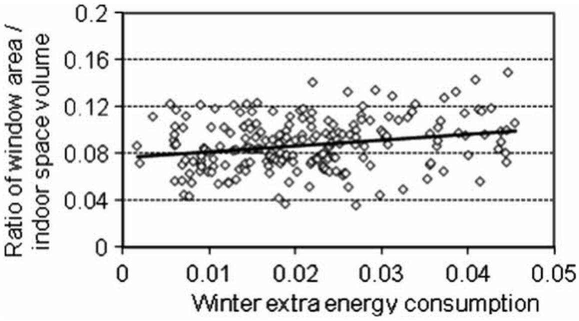

Figure 5 | Extra winter energy consumption and ratio of window area to indoor space volume

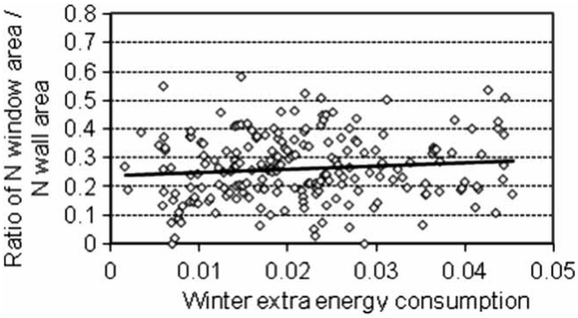

Figure 7 | Extra winter energy consumption and ratio of north window area to north wall area

the increase or decrease in the ratio of window area to floor area.

Impact of the ratio of north window area to north wall area

The ratios of north window area to north wall area of the sample houses range from 0 to 0.58 and the mean ratio is 0.26. Large single-glazed windows on north walls are simply a traditional local design convention based on older houses constructed without insulation materials for daytime passive solar heating. For an old house without insulation, when the *R*-values of both the walls and the single-glazed windows are low, the more the radiant solar heat that comes into the indoor space, the greater may be the positive impact on indoor thermal conditions and the reduction of energy consumption for space heating (Su, 2008). For the sample houses with sufficient insulation within their walls and roofs, a large area of single-glazed windows on a north wall does not impact extra winter energy positively (see Figure 7). The gradient of the trend line of the ratios of north window area to north wall area is 0.7. Normally, the ratio of north window area to north wall area is higher than the ratios of window area to other walls. For the sample houses, the mean ratios of north window area to north wall area, south wall area, east wall area and west wall area are 26, 17, 21 and 20%, respectively. The single-glazed windows on north walls create a large portion of wall area with very low thermal resistance (*R*-value) compared with insulated walls and roofs. A house with good insulation loses a lot of heat through these 'cold holes', which can damage the entire passive house design in terms of energy efficiency and indoor thermal comfort. The occupants in a sample house with large north windows may enjoy passive solar heating during the short winter days, but during the longer winter nights, the large single-glazed north windows can negatively impact indoor thermal comfort. As a result, the occupants often use temporary heating during the night. If the thermal resistance of north windows could match or come close to the insulation level of walls, the high ratio of north window area to north wall area could truly and positively impact on energy efficiency and winter indoor thermal comfort for future house development. Equation (5) shows the negative impact of increasing ratios of north window to north wall area on extra winter energy consumption under the local climate and in local housing style. Successful passive building design for energy efficiency should combine local design traditions with new building materials and new design concepts for building energy efficiency. Some local design traditions, however, based on old building design concepts and materials, should be reviewed in the light of new design concepts and materials:

$$\Delta E_{\mathrm{WE}} = 0.7\Delta R_{\mathrm{NW}} \tag{5}$$

where ΔE_{WE} denotes the increase or decrease in extra winter energy consumption, kWh/m^3 day; and ΔR_{NW} denotes the increase or decrease in the ratio of north window area to north wall area.

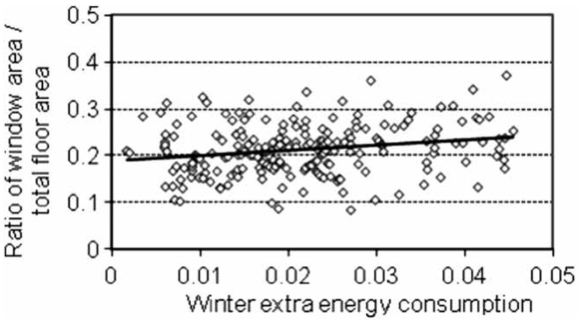

Figure 6 | Extra winter energy consumption and ratio of window area to floor area

Impact of the ratio of north wall area to total wall area

An Auckland house with good orientation will usually have high ratios of north wall area to total wall area or to indoor space volume. Good orientation should improve winter indoor thermal condition and energy efficiency, but a decrease in mean extra winter energy usage is not associated

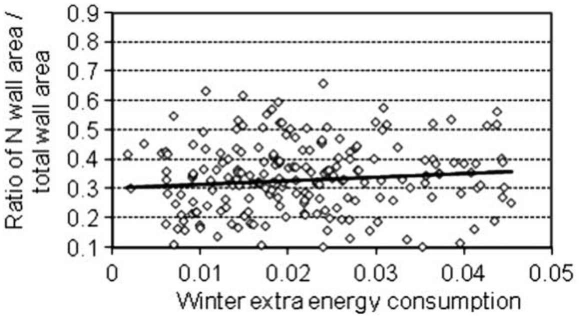

Figure 8 | Extra winter energy consumption and ratio of north wall area to total wall area

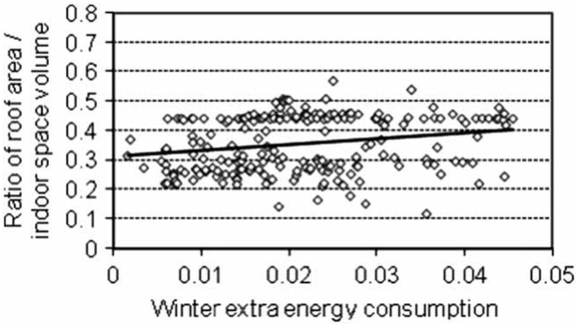

Figure 10 | Extra winter energy consumption and ratio of roof surface area to indoor space volume

with an upward trend in ratios of north wall area to total wall area or to indoor space volume for the sample houses (see Figures 8 and 9). All windows in the sample houses are single glazed and the mean ratio of north window area to north wall area in the sample houses is higher than the ratio of window area to other walls. Therefore, increasing the ratio of north wall area to total wall area also significantly increases the north-facing, single-glazed window area with a very low *R*-value compared with the insulated walls, which increases the ratio of window area to wall area. For houses with good insulation and single-glazed windows, the negative impact of increasing the ratio of north window area to north wall area and the ratio of window area to wall area could weaken or override the positive effect of good orientation, thus increasing the ratio of north wall area to total wall area.

Impact of the ratio of roof area to indoor space volume

As a New Zealand house loses a big portion of its heat through the ceiling and roof during the winter, increasing roof surface area could increase heat loss and the need for space heating energy during the winter. Figure 10 shows that an increase in extra winter energy consumption is associated with an upward trend in the ratios of roof surface area (excluding eaves) to the indoor space volume of the sample houses. The gradient of the trend line of ratios of roof surface area (excluding eaves) to the indoor space volume is 0.45. Figure 11 shows that an increase in extra winter energy consumption is associated with an upward trend in ratios of roof space volume to indoor space volume in the sample houses. For houses without insulation, air with low conductivity in a larger roof space can increase the thermal resistance of the roof when limited air movement occurs in the roof space (Su and Aynsley, 2006). For houses with insulation, the increase in *R*-value caused by increasing roof space volume is small compared with the *R*-value of good insulation materials on the upside of the ceiling in the roof spaces. The negative impact of increasing the ratio of roof surface area to indoor space volume can also simultaneously weaken the positive impact of increasing the thickness of air in the roof space. Passive house design should therefore focus more on reducing roof surface area for energy efficiency. Equation (6) could be used to estimate the approximate saving in extra winter energy consumption of the future house development of Auckland associated with a decrease in the ratio of roof surface area to indoor space volume under the local climate and local housing style:

$$\Delta E_{\mathrm{WE}} = 0.45 \Delta R_{\mathrm{RAI}} \quad (6)$$

where ΔE_{WE} denotes the increase or decrease of extra winter

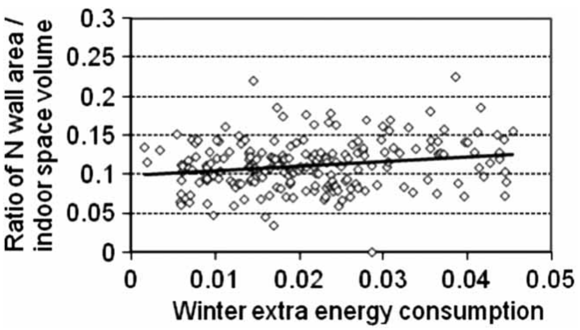

Figure 9 | Extra winter energy consumption and ratio of north wall area to indoor space volume

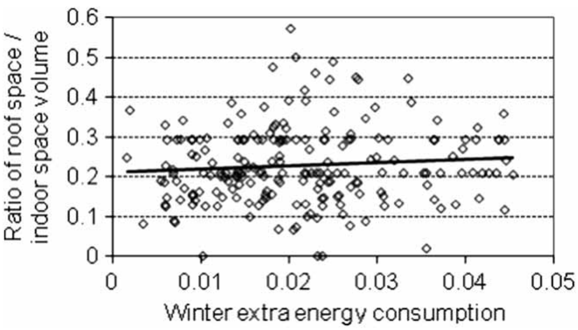

Figure 11 | Extra winter energy consumption and ratio of roof space volume to indoor space volume

energy consumption, kWh/m^3 day; and ΔR_{RAI} denotes the increase or decrease in the ratio of roof surface area to indoor space volume.

CONCLUSIONS

There are no universal passive house design guides for different locations and climates. Passive house design guidelines should be related to the major thermal problems of local climate conditions and local housing design, structure and materials. Development of passive house design guidelines could be based on the actual energy consumption data and real design data of local houses. With a large number of sample houses, this study not only identifies the impact of design factors on energy consumption data, but also estimates the quantitative relationships between energy consumption data and house design data, which are valuable benchmarks for estimating the potential energy saving associated with a change from current house design for future housing development. Equations (1)–(6) show the quantitative relationship between extra winter energy consumption and design data and the impact strength of the major house design data on extra winter energy usage in the Auckland house market. Equations (1)–(6) can also be used to estimate the approximate saving in extra winter energy consumption or be a quantitative benchmark if the future house development data and the positive variation of design data are available in Auckland.

Successful passive house design for energy efficiency should take the different design factors related to architectural features, building elements and building materials into consideration as a whole. Ignoring one design factor could damage the entire passive house design in terms of energy efficiency. For example, single-glazed windows can negatively impact the energy efficiency design of a whole house. Changing different design data can result in positive or negative impact on the energy efficiency of a house. The negative impact of changing one design datum can weaken or override the positive impact of changing another design datum. For example, the negative impact of changing the window wall ratio such as increasing the single-glazed north (equator-facing) window area can weaken or override the positive impact of increasing the north wall area of a house with good orientation (equator facing). The positive impact of one design datum could be significantly stronger than the positive impact of another. For example, there is only marginal benefit in increasing roof space volume compared with adding sufficient bulk insulation in the roof space.

This study introduces a method for using actual energy consumption data to identify the major design problems for housing energy efficiency and the impact of a particular design datum on the extra winter energy consumption data of existing local houses. It includes the impact of all the design factors of the local houses and varies with the local climate. For a hot-humid climate with a hot summer and comfortable winter, a similar study could use the summer extra energy consumption data, which are the differences in energy consumption between the summer months and the other months of the year. For a climate with extremes of summer and winter, a similar study could use both the summer and extra winter energy data, which are the differences in energy consumption between the summer months and other months and between the winter months and other months. The data could identify the major thermal design problems for building energy efficiency and the impact strength of a particular design datum on the summer or extra winter energy consumption data of existing local buildings.

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