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Impacts of Building Design Factors on Auckland School Energy Consumptions

Bin Su

Abstract**—**This study focuses on the impact of school building design factors on winter extra energy consumption which mainly includes space heating, water heating and other appliances related to winter indoor thermal conditions. A number of Auckland schools were randomly selected for the study which introduces a method of using real monthly energy consumption data for a year to calculate winter extra energy data of school buildings. The study seeks to identify the relationships between winter extra energy data related to school building design data related to the main architectural features, building envelope and elements of the sample schools. The relationships can be used to estimate the approximate saving in winter extra energy consumption which would result from a changed design datum for future school development, and identify any major energy-efficient design problems. The relationships are also valuable for developing passive design guides for school energy efficiency.

Keywords**—**Building energy efficiency, Building thermal design, Building thermal performance, School building design.

I. INTRODUCTION

AN Auckland school normally does not need air conditioning for cooling during the summer and only needs heating during the winter. The World Health Organisation recommends a minimum indoor temperature for houses of 18°C; and 20-21ºC for more vulnerable occupants, such as older people and young children [1], [2]. The current New Zealand Building Code does not have a general requirement for the minimum indoor air temperature, although it has a requirement of 16ºC for more vulnerable occupants, such as older people and young children [3], [4]. There are a number of previous studies on the impact of different building design factors on energy efficiency. These design factors are mainly related to building orientation, geometry and envelope. Some studies focus on building orientation, which is one of most important design factors for building energy efficiency, impacting on solar radiation received [5], [6] and shading [7]. Other studies focus on the impact of building shape [8]–[11] with different orientations [9]–[12]; or on energy consumptions under different climates [13]. All heat exchanges between indoor space and outdoor space are through the building envelope, which has the greatest impact on building energy consumption [14], [15]. Those studies based on mathematical models and computer simulations can be used to compare different building designs for energy efficiency. It is difficult to establish universal building passive design guides to achieve energy efficiency for different local buildings and climates. As different building design factors related to architectural features, envelope, elements and materials can affect energy consumption differently and simultaneously, successful passive design for energy efficiency should take different design factors into consideration as a whole under local climate conditions. Ignoring one design factor could damage the entire building passive design in terms of energy efficiency. Changing an item of design data can result in a 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 [16], [17].

In Auckland, there are 425 schools including primary, intermediate and high schools (New Zealand Ministry of Education). Building design data and energy consumption data for 57 sample schools (13.4% of the total number of Auckland schools) were collected for this study. Auckland's schools comprise 4221 buildings at an average of 9.9 per school. There are 9500 classrooms at an average of 2.3 per building. The 57 sample schools comprise 533 buildings (12.6% of the total number of Auckland school buildings) at an average of 9.4 per school. The sample includes 1740 classrooms (18.3% of the total number of Auckland school classrooms) at an average of 3.3 per school building. Table I shows general information of the sample schools. Table II shows energy consumption data for the sample schools. The sample schools use significantly more energy during the winter than summer. The thermal design of Auckland school buildings should focus on winter thermal performance and winter indoor thermal comfort for energy efficiency.

TABLE I
GENERAL INFORMATION OF SAMPLE SCHOOLS

General information	Mean	Range
Number of students	626	109 - 2600
Number of isolated buildings	9.4	1 - 38
Building height (stories)	1.4	1 – 3
Number of classrooms	30.5	5 - 135
Student number per classroom	22	12 - 33
School floor area (m^2)	5257	905 – 22680
Classroom / building floor area	48%	19% - 80%
Floor area per classroom	77m^2	51 – 141m^2

Bin Su is Professor of Architectural Science, at the School of Architecture, Unitec Institute of Technology, Auckland, New Zealand and Visiting Professor, School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan, China (phone: 0064-9-8154321 ext 7847; fax: 0064-9-8154343; e-mail: bsu@unitec.ac.nz).

TABLE II
ENERGY CONSUMPTION DATA OF SAMPLE SCHOOLS

Energy (kWh)	Mean	Range
Annual	242633	16376 – 1498621
Winter	92951	5662 – 570679
Winter/annual	38%	29% - 49%
Summer	33199	2783 – 164123
Winter/summer	2.8	2.0–3.5
Heating months	144892	8699 – 900417
Heating months/annual	58%	48%-76%

II. METHOD

The study uses the difference between mean daily energy usage in the winter months (June, July and August) and the other months of the year to represent the extra energy usage related to winter indoor thermal conditions of the sample schools. Extra winter energy consumption mainly comprises space heating, water heating and other appliances, which is impacted by the winter indoor thermal conditions of a school. Smaller extra winter energy consumption indicates better indoor space thermal conditions in response to winter climate. This study uses the mean daily energy usage per unit volume of school building indoor space (kWh/m^3/day) as the basic energy consumption unit. It is difficult to purely identify the clear relationship between a single design datum and the winter extra winter energy consumption for different school buildings when other building design factors also affect the extra winter energy consumption simultaneously in different strengths. The previous study shows that the relationship between the increase in the design datum's variation (such as the ratio of building surface to volume) and the trend of extra energy consumption can still be identified [18]. This study uses the gradient of the trend line to evaluate the impact strength of a design datum on winter extra energy consumption, and estimate the decrease of winter extra energy consumption when a design datum is changed within a range when other design data also impact the winter extra energy consumption differently and simultaneously. This study is to identify major design problems and explore possible energy efficiency design guides for future school developments. The study takes account of the following design data:

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

III. BUILDING DESIGN FACTORS

A. Ratio of Building Surface to Volume

A school building 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 and other appliances which can be affected by indoor thermal conditions during the winter months. An increase in the ratios of building surface to volume of the sample schools is associated with an upward trend in winter extra energy consumption (see Fig. 1). Decreasing the mean ratio of building surface to volume in future Auckland school developments can reduce the mean winter extra energy consumption. For the sample school buildings the gradient of the trend line of winter extra energy consumption related to ratios of building surface to volume is 0.023 and the mean winter extra energy consumption is 0.0234kWh/m^3/day. Based on the sample schools' design and energy data, if the mean ratio of future Auckland school buildings is 0.3, future development with a mean ratio of 0.3 could potentially be reduced by 0.0041 kWh/m^3/day of the mean winter extra energy consumption (0.023 × (0.48 - 0.3) = 0.0041) and save 17.5% of mean winter extra energy consumption (0.0041÷0.0234 = 17.5%). The future winter extra energy consumption of Auckland schools could potentially be 0.0193 kWh/m^3/day (0.0234 - 0.0041 = 0.0193). Fig. 2 shows savings in mean winter extra energy with the decrease of the mean ratio of building surface to volume for future school development in Auckland.

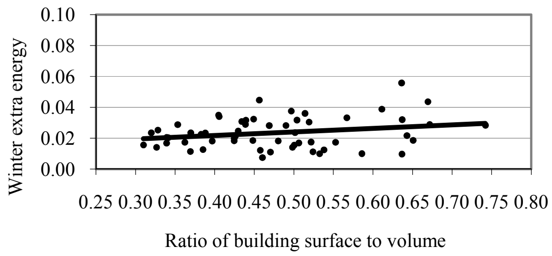

Fig. 1 Winter extra energy consumptions and ratios of building surface to volume of sample schools

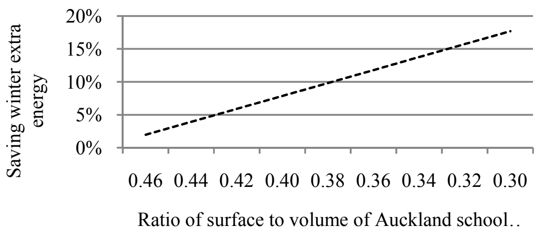

Fig. 2 Savings in mean winter extra energy with decreasing mean ratio of building surface to volume of Auckland school buildings

As the mean extra winter energy is a large portion (44%) of the mean winter energy and the mean total winter energy consumption is also a large portion (38%) of the mean total annual energy consumption of the sample schools, an increase in the ratios of building surface to volume of the sample schools is also associated with an upward trend in winter energy consumption and annual energy consumption (see Figs. 3, 4). An increase in the ratios of building surface to volume is also associated with an upward trend in the ratio of winter extra energy to winter energy and the ratio of winter energy to annual energy of the sample school buildings (see

Figs. 5, 6). Decreasing the ratio of building surface to volume of school buildings can reduce winter extra energy, and also reduce winter energy and annual energy consumption.

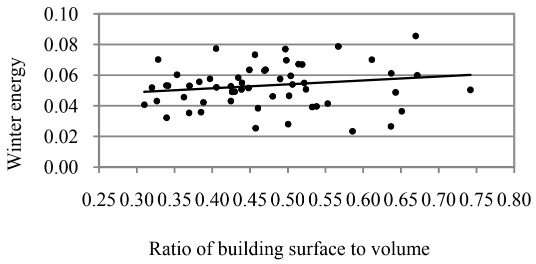

Fig. 3 Winter energy and ratio of building surface to volume of sample schools

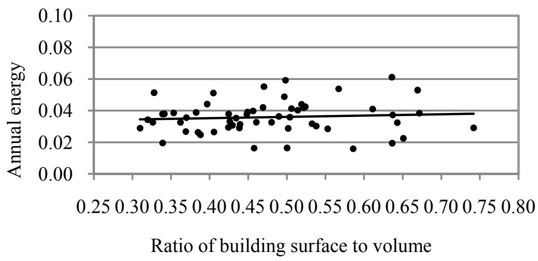

Fig. 4 Annual energy and ratio of building surface to volume of sample schools

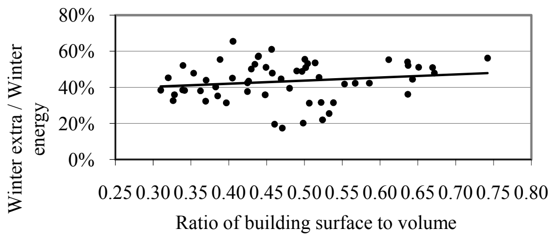

Fig. 5 Ratio of winter extra to winter energy and ratio of building surface to volume of sample schools

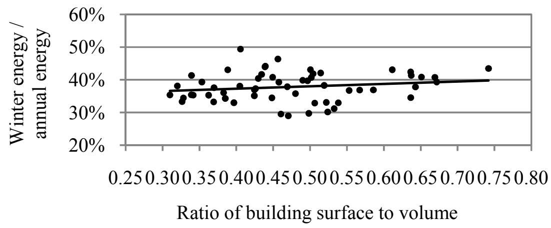

Fig. 6 Ratio of winter energy to annual energy and ratio of building surface to volume of sample schools

Isolated buildings of the sample schools are in the range of 1 to 38 with a mean of 9.4 in number. Building heights of the sample schools are in the range of 1 to 3 stories with a mean of 1.4 stories in number. The mean (0.48) and range (0.31 to 0.74) of ratios of building surface to volume of the sample schools are close to and only slightly lower than the mean (0.63) and range (0.45 to 0.99) of Auckland houses [17] and much higher than the mean (0.17) and range (0.09 to 0.24) of Auckland large hotel buildings [18]. The mean and range of annual and winter daily energy consumption per m^3indoor space of sample school buildings are quite close to the local houses (see Table III). Generally, an Auckland school building is more like a 'big house' than a multi-stories building and its thermal performance is also more close to those of the local houses.

TABLE III
ENERGY CONSUMPTIONS (KWH/M^3/DAY) OF LOCAL HOUSES AND SCHOOLS

Energy	Building	Mean	Range
Annual energy	School	0.036	0.016 - 0.061
Annual energy	House	0.059	0.016 - 0.140
Winter energy	School	0.053	0.023 - 0.103
Winter energy	House	0.075	0.021 - 0.163

An Auckland school commonly includes a number many low-rise isolated buildings spread over a large site. Over 20% of Auckland schools have at least 13 isolated buildings, over 50% Auckland schools have at least 9 isolated buildings, about 80% Auckland schools have at least 7 isolated buildings and over 90% Auckland schools have at least 4 isolated buildings (see Fig. 7). Conventional school design in Auckland, with many low-rise isolated buildings spread over a large site area, is not energy efficient for using a central heating system under the local climate. About 50% of Auckland schools have one or two classrooms in each isolated school building, over 80% of Auckland schools have three or less classrooms in each isolated school building, and over 90% of Auckland schools have four or less classrooms in each isolated school building (see Fig. 8). Most Auckland schools have a number of isolated buildings with only one or two classrooms, or and three or four classrooms, in rows. Most classrooms have a large external surface area including two sides or three sides of external walls and roof surface areas. A classroom with a large external surface area will lose more heat and use more energy for space heating during the winter. Current Auckland school buildings with a high ratio of building surface to volume are not energy efficiency under the local climate. For improving energy efficiency of new school developments, designers should change the current school design convention. Reducing or minimizing the number of isolated buildings in a school campus and increasing the height and volume of a school building can significantly reduce the ratio of building surface to volume of a school, not only saving energy but also saving land. For improving the energy efficiency of new school developments, designers should change the current school design convention from low-rise 'big house' to multi-stories building.

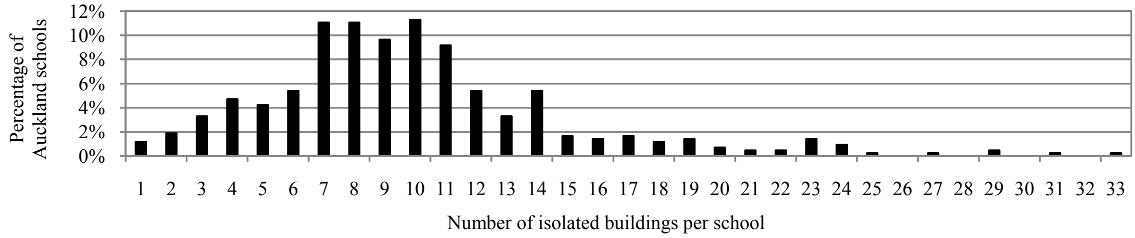

Fig. 7 Number of isolated buildings per school in Auckland

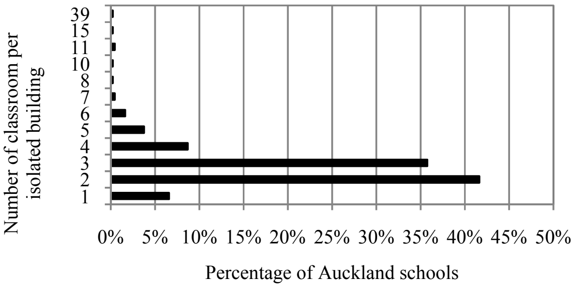

Fig. 8 Number of classrooms per school building in Auckland

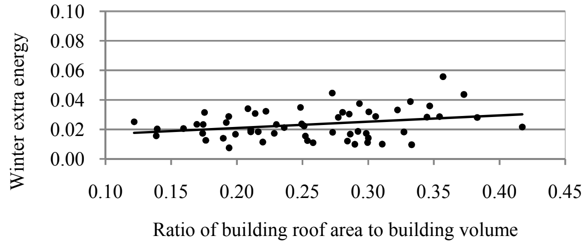

Fig. 9 Winter extra energy and ratio of building roof area to building volume

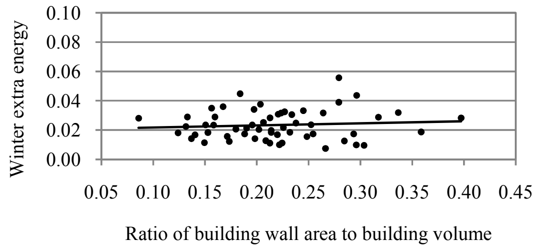

Fig. 10 Winter extra energy and ratio of building wall area to building volume

B. Ratio of Roof Surface Area to Building Volume and Ratio of Wall Surface Area to Building Volume

The ratios of roof area to building volume of the sample school buildings are 0.12 to 0.42 with a mean ratio of 0.26 and the ratios of wall area to building volume are 0.40 to 0.09 with a mean ratio of 0.22. An increase in the ratios of roof area to building volume and the ratios of wall area to building volume is associated with an upward trend in winter extra energy consumption (see Figs. 9, 10). The gradient of the trend line of roof (0.04) is higher than wall (0.01). A low rise building such as a house with one to two stories loses more heat through roof than wall. Auckland houses with one to two stories loses about 40% of its heat through ceiling and roof and about 20% of its heat through wall during the winter. The ratios of roof area to building volume of Auckland houses are 0.12 to 0.40 with a mean ratio of 0.29 [17]. The ratios of roof area to building volume of the sample school buildings are very close to the local houses. Building roofs of Auckland schools with one to three stories should be a more important building element or portion of building envelope from which to lose more heat to outdoor or the sky than the walls. Increasing the ratio of roof area to building volume can cause a more negative impact on winter extra energy of Auckland schools with low rise buildings than increasing the ratio of wall area to building volume.

C. Ratio of Roof Space Volume to Building Volume

An increase in the ratios of roof space volume to building volume is associated with a downward trend in winter extra energy consumptions of the sample school buildings (see Fig. 11). Increasing roof space volume can positively impact on saving winter extra energy consumption for the low rise school buildings. The ratios of wall to building surface area of Auckland large hotel buildings are in the range of 0.54 to 0.93 with a mean ratio of 0.77 [19]; which is significantly higher than the range of 0.34 to 0.82 with a mean ratio of 0.55 for local houses [17], and the range of 0.18 to 0.63 with a mean ratio of 0.46 for the sample school buildings. A multi-stories building loses more heat through wall than roof as the roof becomes a small portion of building surface area and multi-floors supply more protection from heat loss through the roof. Changing school building design conventions from low rise to multi-stories not only can reduce the building surface area per unit of indoor space but also significantly reduce the roof surface area per unit of indoor space, which can significantly reduce the upward heat transfer or heat loss through the roof for a school with the same floor area. The walls of a multi-stories school building can become a more important portion of building envelope for building thermal design compared with the roof.

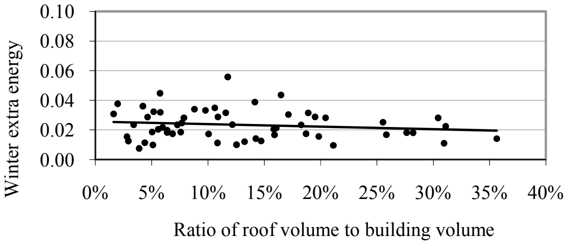

Fig. 11 Winter extra energy and ratio of roof volume to building volume

D. Ratio of Window to Wall Area

Ratios of window to wall area of the sample school buildings with a mean ratio of 0.25 in the range of 0.11 to 0.46 are higher than the local houses with a mean ratio of 0.21 in the range of 0.07 to 0.42. The ratio of east (0.21) and west (0.22) windows to east and west walls of sample school buildings are very close to east (0.21) and west (0.2) windows of local houses. The ratio of north (0.29) and south (0.24) windows to walls are higher than the north (0.26) and south (0.17) windows of local houses, especially for south windows [17]. Most windows of the sample school buildings are single glazed windows. The windows of school buildings could negatively impact on winter indoor thermal conditions and winter extra energy consumption than the local houses. An increase in the ratios of window to wall area is associated with an upward trend in winter extra energy consumption of the sample school buildings (see Fig. 12). Windows are commonly weak elements of building thermal performance. The thermal resistance (R-value) of a single glazed window (0.15 m^2 °C/W for aluminum window frame and 0.19m^2°C/W for wooden or PVC window frame) is very low compared with walls (1.9-2.0 m^2 °C/W) and roofs (2.9-3.5m^2°C/W) insulated in accordance with the current standard [20]. Increasing the ratio of window to wall area of the school buildings, which have single-glazed windows with low R-value, will significantly increase heat loss through the envelope of school buildings, and heating energy. An increase in the ratios of window to wall area is also associated with an upward trend in winter energy and annual energy consumptions of the sample school buildings (see Figs. 13, 14).

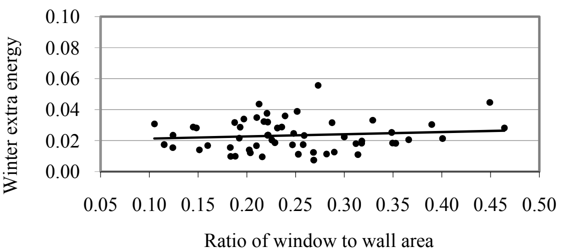

Fig. 12 Winter extra energy and ratio of window to wall area

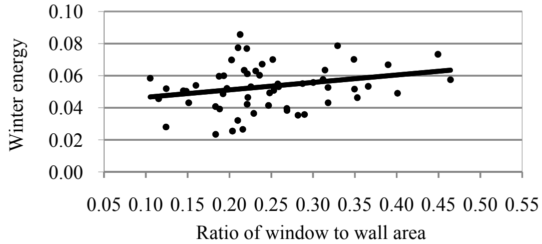

Fig. 13 Winter energy and ratio of window to wall area

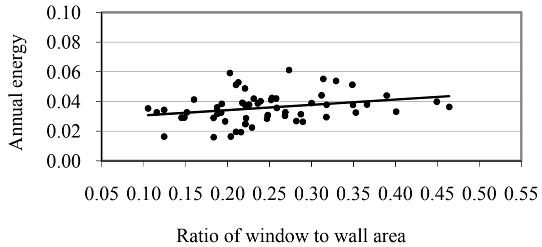

Fig. 14 Annual energy and ratio of window to wall area

E. Ratio of Window Area to Building Volume

The ratios of window to building volume of the sample school buildings are in the ranges of 0.02 to 0.1with a mean ratio of 0.05. An increase in the ratios of window area to building volume is also associated with an upward trend in winter extra energy consumption (Fig. 15). The gradient of the trend line of the ratio of window area to building volume is 0.08, which is much higher than roof (0.04) and wall (0.01). Even using double glazed windows, the R-value 0.26 is still very low compared with wall (1-1.9 m^2 °C/W) or roof (2.9-3.5 m^2 °C/W), and increasing the ratio of window area to building volume can still cause stronger negative impact on winter extra energy than increasing the ratios of roof and wall to building volume.

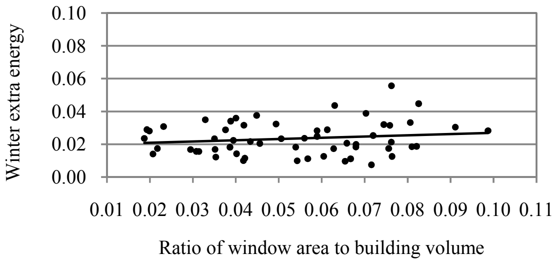

Fig. 15 Winter extra energy and ratio of window area to building volume

F. Ratio of Window to Floor Area

The ratios of window to floor area of the sample school buildings are in the range of 0.07 to 0.42 with a mean ratio of 0.21. An increase in the ratios of window to floor area is associated with an upward trend in winter extra energy consumption (see Fig. 16). The Energy Efficiency and Conservation Authority (EECA) research report shows that New Zealand schools use approximately 50% of energy for space heating, 30% of energy for lighting, 12% of energy for equipment and appliances and 8% of energy for water heating. From the energy efficiency point of view, school building envelope design should mainly focus on winter thermal performance to save space heating energy under local climate conditions. Increasing the ratio of window to floor for improving day lighting is in contradiction with decreasing the ratio of window to floor for reducing heat loss and space heating energy. The ratios of window to floor area of the sample school buildings are in a wide range of 0.07 to 0.42 (see Table IV). According to the compliance document for New Zealand building 'Code Clause G7, natural light' vertical windows in external walls of a house shall have a window area of no less than 0.1 of the floor area. This acceptable solution G7/AS1 is a minimum requirement and unlikely to meet the requirements for school classrooms. The mean ratios of window to floor area of some sample schools do not meet this minimum requirement. New Zealand building codes do not give the requirements or an acceptable solution for the ratio of window to floor area of school buildings. The mean ratios of window to floor area of 58% of sample schools meet 0.2, which other counties require a vertical window area of not less than 0.2 of the floor area. The mean ratios of window to floor area of some sample schools are over 0.3. Natural day lighting should always be the main source of lighting in schools, supplemented by electric light when the daylight fades. The window design for school buildings should not only meet the minimum requirement of day lighting but also avoid the big ratio of window to floor area which can create major heat loss during the winter, excessive solar heat gain during the summer, direct sunlight and glare.

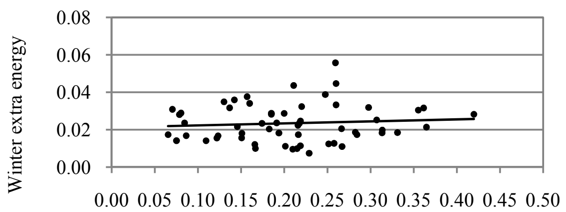

Fig. 16 Winter extra energy and ratio of window to floor area

TABLE IV
RATIO OF WINDOW TO FLOOR OF AUCKLAND SAMPLE SCHOOL BUILDINGS

Ratio of window to floor	Percentage of sample schools
≥0.1	86%
≥0.15	77%
≥0.2	58%
≥0.25	33%
≥0.3	16%
≥0.35	9%

G. Ratio of North Wall to Total Wall Area and Ratio of North Window to North Wall Area

School buildings with a better orientation normally have a higher ratio of north wall to total wall area. There is no clear and strong relationship between extra winter energy consumption data and ratios of north wall to total wall; an increase in the ratios of north wall to building volume of the sample hotels is not clearly associated with a downward trend in extra winter energy (see Fig. 17). An increase in the ratios of north window to north wall of the sample schools is associated with an upward trend in winter extra energy (see Fig. 18). A school building with large north wall area has more exposed surface area to get passive solar heat but may also experience significant heat loss as the ratio of north window to north wall is usually higher than for other walls. Direct sunlight is commonly shaded by the curtains in a classroom as it is not suitable for a learning environment. The negative impact of increasing heat loss through large north windows could weaken or override the positive impact of increasing north wall surface area to get more sun heat.

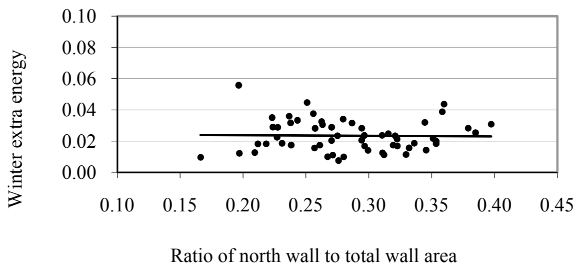

Fig. 17 Winter extra energy and ratio of north wall to total wall area

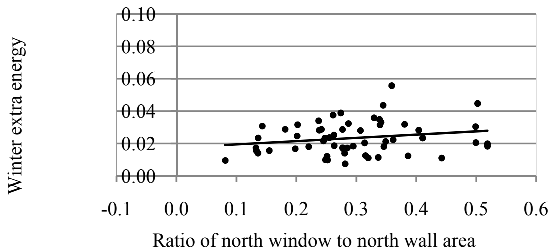

Fig. 18 Winter extra energy and ratio of north window to north wall area

IV. CONCLUSION

According to the Auckland climate, school building thermal design should focus on its winter thermal performance. According to the sample schools' design data, most Auckland schools have a number of low-rise isolated buildings on their campus and each isolated building typically has only two classrooms. School buildings with a high ratio of building surface to volume, and classrooms with large external surface areas, can significantly lose heat through the building envelope and use more energy for space heating during winter. From the energy efficiency point of view, Auckland school conventional design with a high ratio of building surface to volume is not suitable for the local climate. The mean winter extra energy consumption and ratio of building surface to volume are closer to those of the local houses. For improving energy efficiency of new school developments, designers should change the local school design convention from low-rise 'big house' to multi-storey building. School building thermal design should focus on the whole school building thermal design not only classroom thermal design, in order to achieve the best thermal performance according to local climate for energy efficiency. Minimizing the number of isolated buildings and increasing the height and volume of school buildings on a school campus can significantly reduce the ratio of building surface to volume to save winter extra energy – and also save land.

For existing school buildings in New Zealand, there are thousands of old classrooms that need to be retrofitted for improving their thermal performance and energy efficiency. Retrofitting an old school building and classrooms should focus on winter and daytime thermal performance as school buildings are public buildings and mainly used during the daytime, which is different from residential building used for 24 hours. According to envelope design data for the sample school buildings, the window area is the weakest portion of the envelope, having the lowest R-value, and more negative impact on winter extra energy than roof and wall. The first thing to do for retrofitting an old school building is to improve the thermal performance of the window area to reduce heat loss; and secondly, the roof area, which has more negative impact on winter extra energy than the wall area. The ratios of window to floor of the sample school buildings are in a wide range – the small ratios cannot meet the minimum requirement of day lighting and the big ratios can create major heat loss during the winter. The New Zealand building code should give some acceptable solutions for classroom window design related to ratio of window to floor, which can balance the minimum requirement of day lighting and prevention of excessive heat loss.

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