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The role of occupant behavior in low carbon oriented residential community planning: A case study in Qingdao

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ABSTRACT

When planning a residential community, an important factor–occupant behavior–is often omitted. Previous research suggested that the age of occupants may significantly affect the dwelling time and use of air conditioners, thus should be considered during low carbon oriented residential community planning. In this study, an energy related occupant behavior survey recently conducted in Qingdao city is presented. Through this survey, the thermal preference, dwelling time, and air conditioners usage behavior of three different family structures (young couple family, old couple family, and couple with parents family) are analyzed. These information, together with urban planning parameters (floor area ratio, building coverage ratio, aspect ratio, etc.) are then fed into energy simulation models, to investigate the role of occupant behavior in low carbon oriented residential community planning. The results show that the energy demand of old couple family is more affected by community planning. Aspect ratio is more important than height in terms of space cooling and heating demand. The optimal aspect ratio strongly depends on the type of occupants and HVAC system. In general, aged occupants need more heating energy, thus are better located in buildings with lower aspect ratio. Communities with district heating system and decentralized cooling system need lower aspect ratio than that with other types of HVAC systems. The results have important implications to low carbon oriented residential community planning.

1. Introduction

Residential buildings occupy a significant portion of global energy usage. An efficient way to alleviate global warming and improve environmental sustainability is to enhance the residential building energy efficiency.

In general, it is believed that building energy consumption is affected by four factors: occupant behaviour, building geometry and envelope properties, urban planning, and building energy systems [1]. During the past, while the role building geometry, envelope properties, and energy systems in energy consumption have been heavily studied [2–5], the impact of occupant behaviour and urban geometry were studied with much less rigor. Nevertheless, as the impacts of urban geometry parameters are of interest to urban planners, some studied have already been undertaken.

Ko recently conducted a literature review to identify key planning parameters related with the energy performance of residential communities, and concluded that building density, exposed building surface area, and tree planting are the three most important parameters [6]. Besides, the effect of mutual shading due to the layout arrangement of buildings was emphasized in the study of Pisello [7]. Stromann-Andersen & Sattrup showed that the geometry of an urban canyon can increase the energy consumption of office buildings by 30% and that of residential buildings by 19% [8]. Along this line, Taleghani et al. compared three types of block typologies (single, linear, courtyard) in the Netherlands, and concluded that courtyard block is the most energy efficient form [9]. It is summarized by Sanaieian that, urban geometry affects building energy consumption mainly through three mechanisms: (1) change the solar accessibility of buildings; (2) change the thermal environment and ventilation around buildings; and (3) change the heat transfer process between buildings and its surrounding climate [10].

The above studies have undoubtedly shown that, building layout and geometry affect the space cooling and heating demands, thus should be taken care when designing residential communities with high energy performance. However, what is missing in these studies is the interrelationship between urban geometry and occupant behaviour, which could significantly change the optimal urban geometry. A study of the US residential energy use by Steemers et al. found that occupant behavior affects the energy consumption significantly in summertime, and occupant behavior can accounts for

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Table 1
Information of the surveyed estates.

Names	Real Estate Typology	Construction year	Floor Area Ratio	Green Area ratio	Average monthly family income (RMB/m)	Neighborhood
Lushang	Super Block	2013	5.2	30%	7870	Zhuhai Rd.
Hai'er	Super Block	2006	1.6	40%	8704	Fushan hou
Lihai	Small grid	2003	1.15	45%	6972	Fushan hou
Haiqing	Small grid	1999	3	35%	8093	Zhuhai Rd.

Fig. 1. Location of the surveyed real estates.

47% of the variation in cooling energy while building explains less than 10% [11].

Recently, with the increasing demand to fill the gap between buildings simulation and actual building energy consumption, understanding how occupants act at various conditions (time, temperature, solar radiation, etc.) is urgently needed [12]. For this purpose, onsite measurement is becoming a popular approach. Methods such as CO_2 density, camera, motion detectors have been developed to monitor occupancy presence and behavior [13]. For example, to understand how occupants use AC units in summer and winter, Schweiker & Shukuya monitored 39 single occupant rooms in a foreign student dormitory in Tokyo. While the temperature, humidity, and window opening are detected using wireless sensors, the usage of AC units is determined by comparing indoor and outdoor absolute humidity [14]. Their research suggested that both outdoor temperature and individual background significantly affect the usage of AC units.

Compared with onsite measurement, questionnaire survey approach has the advantage of fastness and low cost. By asking the respondents to fill out a survey form, information of interest can be quickly collected. With this approach, Fan surveyed 3446 households in the greater Sydney region in Australia, and found that the number of occupants has the largest impact on household energy consumption [15]. Chen et al. surveyed a number of families in Hangzhou city (642 families in winter, and 838 families in summer), and showed that occupant age is a strong influential factor to energy consumption, and the household characteristics and occupant behaviour together could explain up to 28.8% of the energy use variation [16]. Furthermore, Lin & Deng surveyed the AC unit usage behavior of 554 Hong Kong residents, and found that more than 80% residents kept AC units on for more than 5 h at night [17].

Apparently, both urban geometry and occupant behavior affect building energy consumption to some extent. However, by far the contribution of these two factors to energy consumption in real settings has been studied by few. Therefore, the research presented in this paper intends to: (1) understand how residents in Qingdao city use AC units in summer; (2) evaluate the implication of occupant behavior on optimal community layout planning. To achieve these, a systematic research methodology is designed as following. First, the dwelling time and thermal preferences of various family structures (young couple, old couple, young couple with parents) are collected with questionnaire survey approach, due to its fastness, low cost, as well as to avoid privacy issues; second, simulation models are established for all of the surveyed real estates, which are then calibrated based on monthly electricity consumption data; third, parametric analysis based on the developed models is then conducted to identify the optimal community planning parameters; finally, the influence of family structure on energy consumption and optimal planning parameters is analyzed.

The content of this paper is as follows. First, the procedure and results of the questionnaire survey are introduced; second, the energy modelling method and model validation process is presented; third, the parametric analysis framework as well as the results are described; finally, conclusion remarks are given.

2. Occupant Behavior (OB) Survey

2.1. Survey procedures

To collect information regarding household characteristics and energy related occupant behavior in residential buildings, a one-week long survey was conducted in Qingdao city, Shandong Province (from July 1st to July 7th, 2015).

The first step was to choose the survey samples. To allow the variable of urban geometry to be compared, four housing estates were selected: Lushang, Hai'er Eastern Town, Lihai Garden, and Haiqing Garden. These estates are mainly distributed in two neighborhoods: Zhuhai Rd. neighbourhood and Fushan Hou neighbourhood (Fig. 1). A detailed information of these estates is shown in Table 1. While Lushang and Hai'er are high rise apartments constructed within 10 years, Lihai and Haiqing are middle rise apartments constructed 10 years ago. An exterior view of the four real estates is shown in Fig. 2.

Secondly, in each estate, around 100 survey questionnaires were distributed to its residents through the local residential committee, which were then collected again by the residential committee and sent back. The questionnaire includes mainly three types of questions: household characteristics, occupant preferences, and energy

Table 2
List of survey questions in the questionnaire.

Household characteristics	Q1: Number of residents in the family Q2: Type of family structure (couple, single, couple with kids, etc.) Q3: Family income Q4: House area Q5: Number of air conditioner and nominal power
Occupant behaviour in space cooling	Q6: Type of summer cooling (air conditioner or fan) Q7: Air conditioner usage behavior (always on, turn off when away, turn off at night, etc.) Q8: Summer indoor temperature setpoint (below 26 °C, between 26 °C and 28 °C, above 28 °C)
Energy usage	Q9: Electricity utility in spring/autumn, summer, and winter Q10: Natural gas utility

Fig. 2. Exterior view of the chosen real estates.

usage. A list of questions in each category is shown in Table 2. The survey results are presented in the following section.

Furthermore, for each housing unit, bimonthly electricity utility bill was retrieved from local electricity bureau from March to August, 2015. As shown by the average electricity consumption of the survey samples in Fig. 3, the electricity consumption in Mar-Apr is close to that in May-Jun, and obviously smaller than that in Jul-Aug. Thus, the period from March to June can be regarded as the transition season. Therefore, if denoting the monthly electricity usage in transition season as E_t, in summer season as E_s, and that for air conditioning service as E_a, then E_t, E_s, and E_a can be calculated using Eqs. (1)–(3).

$$E_t = \frac{E_{mar-apr} + E_{may-june}}{4} \quad (1)$$

$$E_s = \frac{E_{jul-aug}}{2} \quad (2)$$

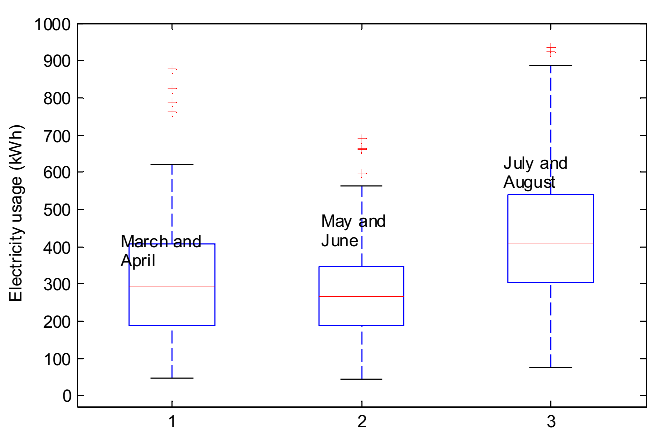

Fig. 3. Average electricity usage of survey samples in three charging periods.

$$E_a = E_s - E_t \quad (3)$$

2.2. Survey results

The household characteristics of the surveyed real estates are shown in Table 3. Among the four estates, Hai'er and Lihai are occupied with relatively young residents, with average adult age of 43 and 45 respectively. Lushang and Haiqing have older residents, with an average age above 55. As the official retirement age is 60 for men and 55 form women, it is likely that most of the residents in these two estates are already retired.

Regarding the family structure, three types are differentiated: young couple (average age below 60, including single), old couple (average age above 60, including single), and young couple with parents. From Table 3, it can be seen that while Lushang and Haiqing estate are primarily occupied by old couple, Hai'er and Lihai are occupied mainly by younger people.

As listed in Table 2, three questions related with space cooling behaviour are included in the questionnaire: type of summer cooling (fan or AC), AC usage behaviour (always on, or turn off when away or sleep), and indoor temperature setpoint. The responses to these questions are presented as below, with part of the information shown in Table 4.

In general, AC is the dominant way of space cooling. Among all respondents, 93.8% choose AC rather than fan. The percentages of occupants using fan for space cooling in Lushang, Hai'er, Lihai, and Haiqing are 10.8%, 1.8%, 2.0%, and 5.5%, respectively. Considering the difference of occupant age among the five estates (Table 3), it is suspected that older people are more likely to use fan than young occupants.

Regarding the AC usage behaviour, 50% of the respondents turn off AC if they feel cool, leave home, or go to sleep. The rest of the respondents keep their AC on more frequently. On average, occupants with energy saving attitude are 12 years older than those less motivated to save energy, again suggesting that old people are more energy conscious.

Table 3
Household statistics of surveyed samples.

Real estate	Number of survey samples	Avg. house area (m2)	Avg. adult age	Avg. family members	Avg. installed AC	Family structure		
						Young couple	Old couple (>60)	Young couple with parents
Lushang	83	103	64	2.4	1.5	19%	54%	27%
Hai'er	217	101	43	2.1	1.2	79%	7%	14%
Lihai	124	89	45	2.4	1.3	63%	10%	27%
Haiqing	102	104	56	2.0	1.7	46%	45%	9%

Table 4
Occupant behaviour in space cooling.

Occupant behaviour		Average age of adults in a family	House Area (m^2)	Number of members	Average Family income (RMB/m)
use fan/AC	fan	56	100.8	2.5	7196
	AC	53	99.3	2.6	8094
AC turn on/off behavior	turn off when leave or sleep	57	102.0	2.4	7602
	kept on more frequently	45	100.4	2.4	7108
summer indoor setpoint	less than 26 °C	50	100.4	2.4	7478
	equals to or above 26 °C	55	102	2.6	7314

Table 5
Correlation between electricity consumption for summer cooling and various influencing factors.

		p value	partial correlation	partial R^2
Household characteristics	age	0.265	−0.201	0.040
	2 occupant vs 1 occupant	0.218	−0.049	0.002
	3 occupant vs 1 occupant	0.037	−0.017	0.000
	4 occupant vs 1 occupant	0.059	−0.030	0.001
	5 occupant vs 1 occupant	0.072	0.031	0.001
	income	0.032	0.087	0.007
	household area	0.432	0.029	0.001
	1 AC vs 0 AC	0.986	0.150	0.023
	2 AC vs 0 AC	0.328	0.138	0.019
	3 AC vs 0 AC	0.361	0.038	0.001
Occupant behavior	AC vs Fan	0.025	0.456	0.208
	setpoint above 26 vs below 26	0.160	−0.221	0.049
	energy saving vs less energy saving	0.053	−0.271	0.073
Urban geometry	construction year	0.219	0.017	0.000
	floor Area Ratio	0.417	−0.015	0.000
	green Area Ratio	0.076	−0.083	0.007
	proximity to sea	0.040	0.193	0.037

Two categories are set for the summer indoor temperature set points: below 26 °C, equals to or above 26 °C. Among the respondents, 38% set their summer indoor temperature below 26 °C, and the rest 62% set above 26 °C. It is found that while there is a significant difference in occupant ages in these two groups, the income per capital is almost the same. This agrees with the general conception that older people prefer warmer environment than young people.

To understand the contribution of each influencing factor on electricity consumption for summer cooling, the cooling energy is correlated with Occupant Behavior (OB), Household Characteristics (HC), and Urban Geometry (UG), and the results are shown in Table 5. Based on the value of partial R^2, it can be seen that, OB is the strongest influencing factor, followed by HC and UG. Among various OB factors, the choice of AC vs. fan is the most significant factor, with partial R^2 as high as 0.21. Besides the choice of AC vs. fan, the energy saving motivation, preference of cooling set point, and occupant age are also important, with R^2 value of 0.07, 0.05, and 0.04, respectively.

In sum, occupant behavior is found to be the most important factor in energy use for summer cooling. Due to the strong correlation between occupant age and occupant behavior, household structure and occupant age are considered in the following analysis.

3. Building energy modelling and validation

To understand how energy is consumed in the surveyed estates, dynamic building energy simulation approach is taken. In this section, both the modelling method and the validation process are introduced.

3.1. Building energy modelling

The building energy modeling tool used in this study is CitySim 1.0, developed by EPFL specifically for urban energy planning purpose [18]. It is a successor to SunTool (sustainable urban neighbourhood modelling tool), a project initially launched by EU to address urban modeling complexity [19]. Similar with other detailed building energy simulation tools (such as EnergyPlus), CitySim simulates hourly building heating and cooling energy demands, based on the theory of heat transfer and thermal dynamics. However, to suit the purpose of simulating energy flow at urban level, Citysim is designed with quicker algorithms. There are four core models in CitySim: a RC network based thermal model for building heat transfer analysis; a Simplified Radiosity Algorithm (SRA) based radiation model for solar accessibility analysis; an occupant behavior model for energy related activity analysis; and

Table 6
Parameters of buildings in the surveyed real estates.

Indicator	Lushang	Haiqing	Hai'er	Lihai
Height	99.8	57.6	72.6	19.5
Average street width(east-west oriented)	80	50	20	18
Average window-to-wall ratio	0.31	0.52	0.63	0.32
External wall U value (W/m^{2}K)	1.61	1.84	1.18	1.52
glazing U value(W/m^{2}K)	2.75	2.14	2.88	2.36

a category of various energy systems. Walter and Kampf compared the simulation accuracy of CitySim with some already validated and widely applied programs (such as Esp-r, DOE2.1, Blast 3.0, etc.) on a set of BESTEST cases, and found that while the annual heating demand is relatively small, the annual cooling demand is relatively large. However, for all test cases, the results of Citysim fall within the acceptable range [20].

3.2. Building energy model validation

To verify the validity of the simulation model, all four estates (Lushang, Hai'er, Lihai, and Haiqing) are modelled with CitySim, with parameters shown in Table 6. The assumptions regarding occupant behavior can be found in Section 4.2.1. Average electricity consumption for cooling in July and August is used as the actual energy consumption data. Both the calculated and actual monthly electricity consumption for summer cooling are shown in Fig. 4 (assuming the COPs of all air conditioners are 4.0).

It can be seen from Fig. 4 that, Lihai garden has the highest simulated cooling demand, due to its large surface area to volume ratio. Hai'er and Haiqing have higher cooling demand than Lushang estate, due to their relatively high window to wall ratio. However, there is a large discrepancy between simulated and actual electricity consumption. The latter is only about 16%, 13%, 3.9%, and 13% of the former in Lushang, Hai'er, Lihai, and Haiqing respectively. This discrepancy is caused mainly by two reasons: (1) instead of cooling down the whole apartment, in reality only part of the space (where occupants are located) is cooled; (2) instead of keeping air conditioners on all the time, some occupants tend to turn off air conditioners as soon as they feel comfortable. Therefore, the simulated electricity usage for cooling needs to be corrected.

Through questionnaire survey, it has been found that the usage of air conditioners is highly correlated with the average age of the occupants. In general, old people are more energy saving than young people. Therefore, the simulation model is calibrated with the following approach. First, the actual electricity consumption for cooling is decomposed to each type of family structure, (as shown in Eq. (4)). Second, a correction coefficient for each family structure is calculated, by dividing the actual electricity usage by the simulated one for each family structure.

$$E_c = k_y P_y E_{s,y} + k_o P_o E_{s,o} + k_a P_a E_{s,a} \tag{4}$$

where k denotes the correction coefficient, P denotes the percentage of each family structure in the estate, E denotes the monthly electricity consumption for cooling. The subscript c, s, y, o, a denotes actual energy consumption, simulated energy consumption, young couple family, old couple family, young couple with parents family, respectively. It is observed that the electricity usage of Lihai estate is especially low, this might be caused by reasons other than family structure, such as family income. Thus, Lihai is excluded in the regression analysis.

Through calibration, the calculated correction coefficient k_y, k_o, and k_a are found to be 0.1, 0.14, and 0.24 respectively. The correction coefficient for young couple is smaller than old couple, is mainly because the household samples distribute randomly in different buildings, thus there is a mismatch between the simulated building energy consumption, which is the average value of all buildings in an estate, and actual electricity usage data. To solve this problem, an identical correlation coefficient k is used for all three types of family structures, which can be calculated with Eq. (5).

$$E_c = k\left(P_y E_{s,y} + P_o E_{s,o} + P_a E_{s,a}\right) \tag{5}$$

The uniform correction coefficient is determined to be 0.14. Based on this correction coefficient, simulated energy consumption for cooling is corrected, and shown in Fig. 4. It can be seen that after correction, the simulated energy consumption for cooling and actual electricity usage are much closer.

It should be noted that, the correction coefficient calculated above is for decentralized cooling systems. However, since the value of k indicates the energy saving behavior (more energy saving family have lower k value), the same value is also used for decentralized heating systems. For cases where centralized cooling is provided, as the heating service fee is charged based on the house area rather than the actual heating energy consumption, the correction coefficient should be much higher, in this study this value is assumed to be 1. These assumptions will be further used during the community layout planning optimization process in this paper.

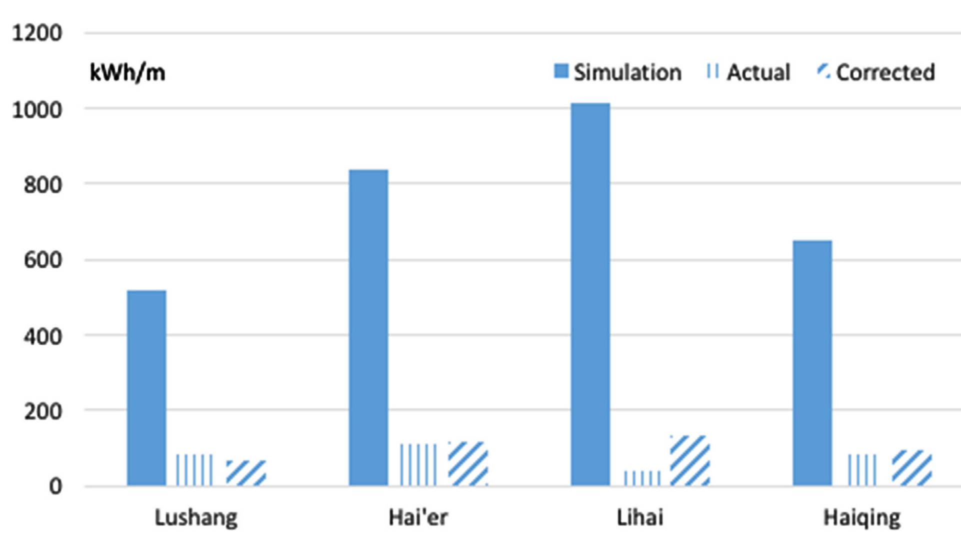

Fig. 4. Monthly cooling electricity consumption of four estates.

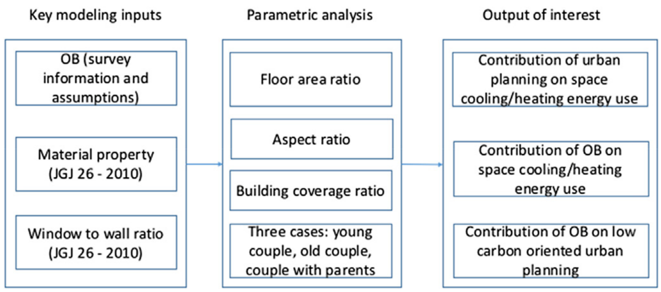

Fig. 5. Experimental analysis framework.

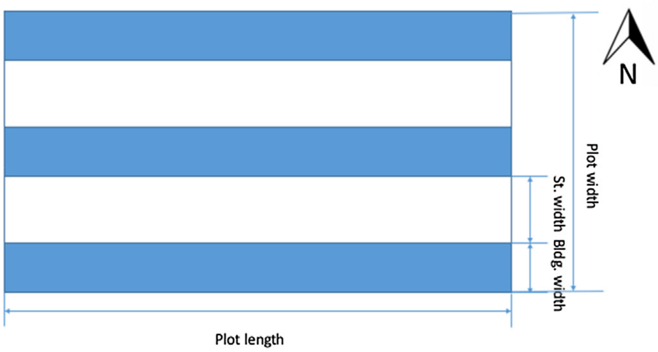

Fig. 6. Community layout with north-south orientation.

4. Urban planning parameter analysis

4.1. Analysis framework

To understand how OB may change the low carbon oriented community planning, an experimental analysis has been designed as in Fig. 5. Three urban planning parameters: Floor Area Ratio (FAR), Aspect Ratio (AR), and Building Coverage ratio (BCR) are the key parameters to be analysed. These three parameters, together with OB (based on survey information and assumptions), material property and window to wall ratio (based on JGJ 26-2010), are the fed into simulation models. The yearly energy demands for space cooling and heating energy are the output of interest (Fig. 5).

Suppose the buildings are geometrically evenly distributed, the community layout to be studied is shown in Fig. 6. Denote the plot area as S_p, the total building area as S_b, the plot width and length as W_p and L_p, the building height, width and length as H_b, W_b and L_b, the width of street is W_s, the number of buildings is N_b, and the relationship between FAR, AR, and BCR are shown in Eqs. (6)–(11).

$$S_b = \text{FAR} \times S_p \tag{6}$$

$$L_b = L_p \tag{7}$$

$$N_b = W_p \times BCR/W_b \tag{8}$$

Table 7
Levels of variables in Parametric Analysis.

Household structure	FAR	BCR	AR
young couple	1	0.1	AR_{min}
old couple	3	0.2	$2AR_{min}$
couple with parents	5	0.7	$3AR_{min}$

$$H_b = 3S_b/(N_b \times L_b \times W_b) \tag{9}$$

$$W_s = H_b/AR \tag{10}$$

It should be noted there is a minimal AR value, as defined by Eq. (6),

$$AR_{min} = \frac{(N_b - 1)H_b}{W_p(1 - BCR)} \tag{11}$$

In this analysis, a total of four variables (household structure, FAR, BCR, and AR) are analysed in terms of their contribution to space cooling and heating demand. For each variable, three levels are defined, as shown in Table 7.

4.2. Modelling assumptions

4.2.1. Occupant preference

As mentioned above, three types of family structures are studied in this paper: young couple, old couple, and young couple with parents. It is assumed that the environment is completely controlled by adults, therefore either these families have or don't have kids will not affect the results.

The presence and thermal preference of young and old couple are shown in Table 8. For young couple, it is assumed that they work from 9am to 5pm, and it takes one hour for one-way transportation, thus they stay at home from 6pm to 8am. If they are at home, they turn on the AC all the time if the indoor temperature is not comfortable. For old couple, it is assumed that they spend two hours in the morning for exercise and shopping, and one hour after dinner for exercise. Considering old people are more energy saving, AC is turned off when they are outside or at sleep.

4.2.2. Building envelope properties

Qingdao city is in the cold region (2000 < HDD18 < 3800), building envelope properties in this study are determined based on design requirement set for cold region in "The national standard for energy efficient residential buildings in severely cold and cold regions" (JGJ 26-2010) [21].

Based on JGJ 26 –2010, the parameters are determined as follows. The value for the infiltration rate is 0.5ACH. The window to wall ratio for north wall, east/west wall, and south wall are 0.3, 0.1, and 0.5, respectively. The heat transfer coefficients for roof, wall, window are 0.31 W/(m^2K), 0.38 W/(m^2K), and 2.0 W/(m^2K), respectively. The SHGC for windows in all orientations is 0.7.

Table 8
Presence and preference of various household structures.

Household structure	Presence	Thermal preference	AC control behaviour
young couple	6pm–8am (weekday) 24 h (weekend)	20 °C (winter) 24 °C (summer)	turn on all the time if needed
old couple (already retired)	10am–7pm 8pm–8am	22 °C (winter) 26 °C (summer)	turn off at 10pm–6am, 8am–10am, 7pm–8pm. turn on at other time needed
couple with parents	young couple plus old couple	follow old couple if young couple are not present, follow young couple if young couple are present	follow old couple

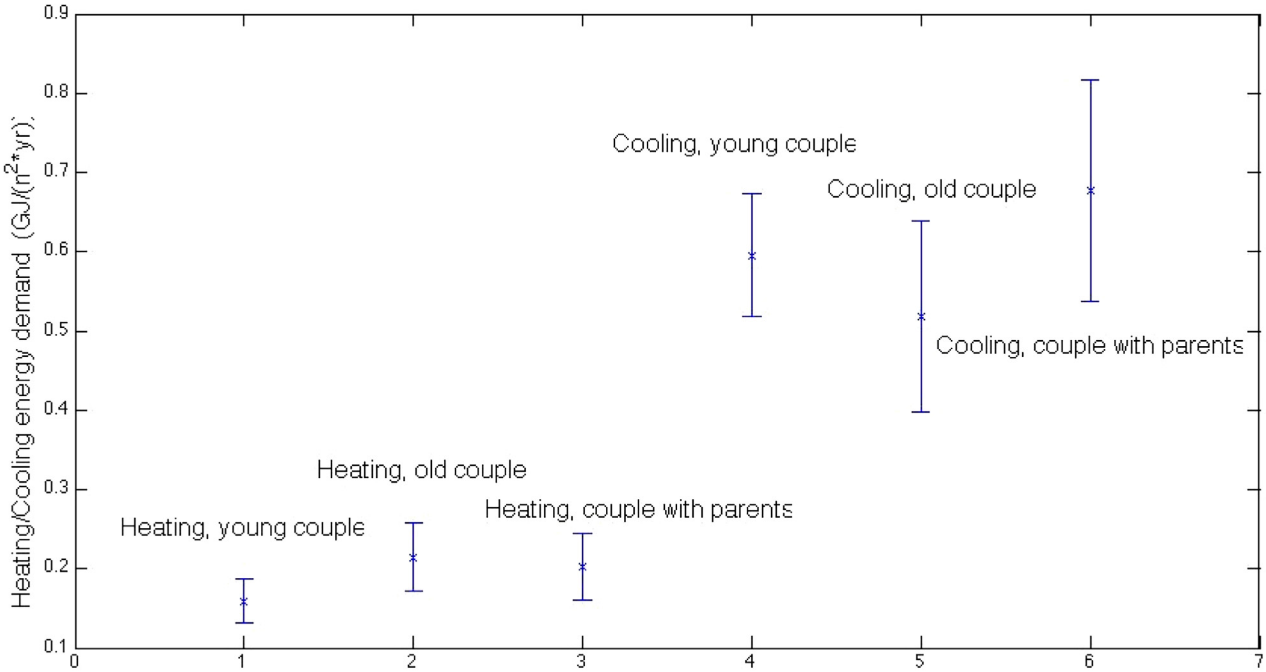

Fig. 7. Heating and cooling demand of Three Family Structures.

Table 9
Yearly average efficiency of heating and cooling system.

		Decentralized	District
heating	COP	2 (electricity)	0.9 (coal)
	demand correction coefficient	0.14	1
cooling	COP	4 (electricity)	4.5 (electricity)
	demand correction coefficient	0.14	1

4.2.3. Heating and cooling systems

To analyse optimal AR value, there needs additional assumptions regarding the type of space heating and cooling system. In general, there are two types of building cooling and heating systems: decentralized and centralized. In this study, the following assumptions are made regarding the type of HVAC systems. The decentralized heating and cooling system is heat pump, whose efficiency is assumed to be 4.0 in summer and 2.0 in winter. The centralized heating system is coal fired boiler, whose average efficiency is 0.9. The centralized cooling system is electric chillers, whose efficiency is assumed to be 4.5 (as shown in Table 9). When comparing the heating and cooling energy consumption of centralized heating system, it should be noted that the latter (electricity) is secondary energy, thus needs to be converted to primary energy before comparison. In this study, an efficiency of 30% to generate electricity from coal is assumed. During the optimization, the height is assumed to be 15m, the lower and upper bound of aspect ratio is set to be 0.2 and 5, respectively.

5. Results and discussion

5.1. Importance of input parameters

In this study, four parameters that may affect the heating and cooling demand are analysed: type of family structure, Floor Area Ratio (FAR), Building Coverage Ratio (BCR), and Aspect Ratio (AR).

The average and distribution of cooling and heating loads in all three scenarios (young couple, old couple, couple with parents) are shown in Fig. 7. It can be seen that on average, young couple family has the least heating demand, due to their short dwelling time and preference of relatively high temperature. On the contrary, old couple family has the largest heating demand, since they stay longer at home and they like warmer environment. Couple with parents family requires less heating demand than old couple family, as the presence of young people increases indoor heat source intensity, while the dwelling time is kept the same. Regarding the cooling demand, old couple family require the least cooling demand, due to their preference of warmer temperature again. Couple with parents family has the largest cooling demand, due to their longest dwelling time and most intense indoor heat source.

From Fig. 7, it can also be seen that the variations of heating and cooling demand for the young couple family are the least, suggesting that the impact of planning parameters on their heating and cooling demands is relatively insignificant. On the other hand, the variations of the other two types of families are much larger, meaning that community planning has larger influence on these two types of families.

To further understand the contribution of each parameter on the energy demand, a detailed ANOVA analysis is performed for each type of family, and the results are shown in Table 10. It should be noted that, since FAR and BCR together determine the height of the building, these two parameters are replaced by building height during the regression.

Based on the results shown in Table 10, it can be seen that the p value of AR is below 5% in all six cases, suggesting that AR is strongly correlated with both heating and cooling demand. While the p value of height is below 5% for heating and cooling in young couple family, it is much larger than 5% for heating in old couple and couple with parents family. This suggests that while both height and AR are critical for heating demand, height is not as important as AR for cooling demand.

5.2. Effect of planning parameters

5.2.1. Building height

Generally, taller building means less Surface to Volume Ratio (SVR), therefore is preferable in cold climate. This principle also works in Qingdao city, since it is located in the cold climate in

Table 10
p values of height and aspect ratio.

	Heating (young couple)	Heating (old couple)	Heating (couple with parents)	Cooling (young couple)	Cooling (old couple)	Cooling (couple with parents)
Height	0.02	0	0.01	0.02	0.63	0.3
Aspect ratio	0.04	0	0.01	0	0.02	0.01

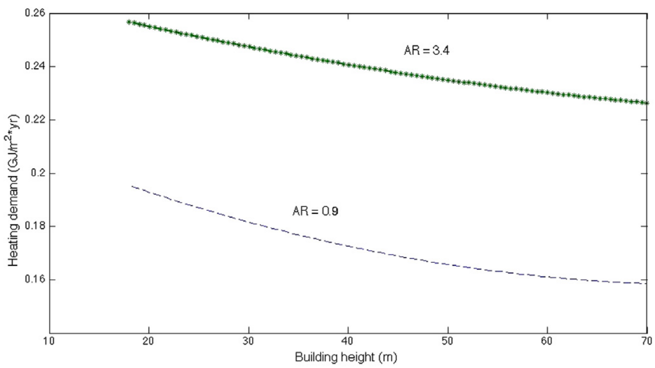

Fig. 8. Impact of height on heating demand (old couple family).

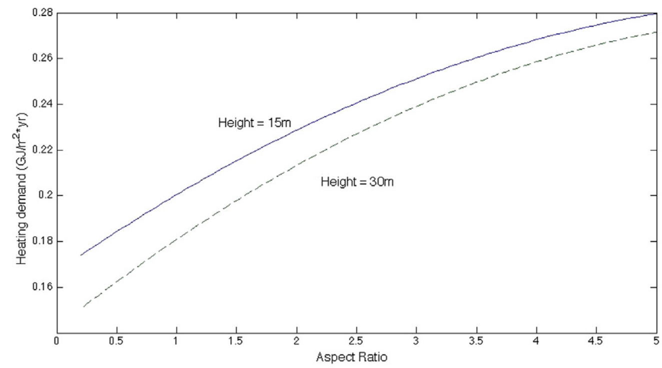

Fig. 10. Impact of aspect ratio on heating demand (old couple family).

China. As shown in Fig. 8, when AR is 0.9, increasing height from 18 m to 70 m decrease heating demand intensity by 20%, from 0.2 GJ/(m^2*yr) to 0.16 GJ/(m^2*yr). In both cases (AR = 0.9 and 3.4), increasing height helps decrease heating demand intensity.

It is also note that, after a certain amount, the effect of increasing height slowly decreases. For example, when AR is 0.9, it takes 15 m height increase (from 15 m to 30m) to decrease heating demand intensity from 0.2 GJ/(m^2*yr) to 0.18 GJ/(m^2*yr), however, it takes another 40 m height increase (from 30 m to 70m) to decrease heating demand intensity from 0.182 GJ/(m^2*yr) to 0.162 GJ/(m^2*yr).

The impact of building height on cooling demand is shown in Fig. 9. Increasing building height from 18 m to 70 m decreases building cooing demand intensity by 4% if AR is 3.4, and by 8% if AR is 0.9. This suggests that increasing building height is most effective when both aspect ratio and building height are low. Compared with the heating demand, cooling demand is less affected by building height.

5.2.2. *Aspect ratio*

The impact of aspect ratio on building heating demand is shown in Fig. 10. When building height is 30m, increasing AR from 0.5 to 5 leads to a 69% increase of heating demand intensity, from 0.16 GJ/(m^2*yr) to 0.27 GJ/(m^2*yr). Similarly, when building height is 15m, increasing AR from 0.5 to 5 leads to a 56% increase of heating demand intensity. Obviously, AR affects building heating demand significantly.

The impact of aspect ratio on cooling demand is shown in Fig. 9. When height is 15m, increase of aspect ratio from 0.5 to 5 decreases cooling demand intensity by 29%, from 0.72 GJ/(m^2*yr) to 0.51 GJ/(m^2*yr). Obviously, aspect ratio strongly affects building

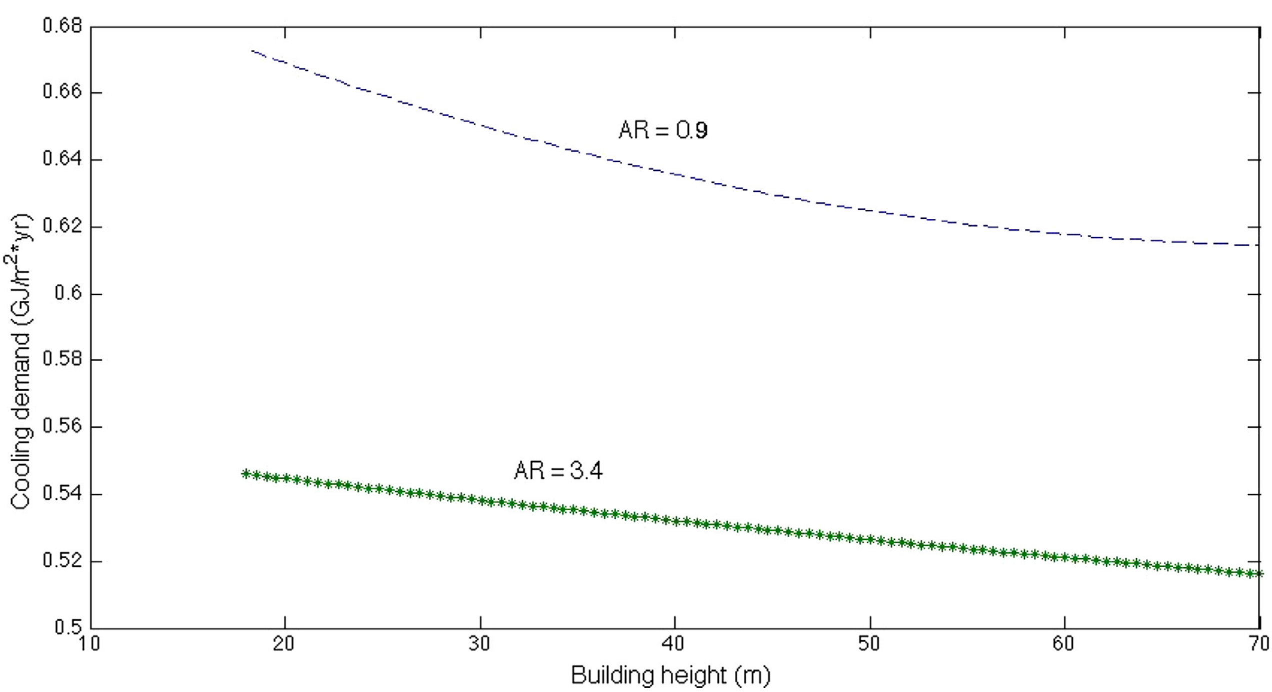

Fig. 9. Impact of height on cooling demand (young couple family).

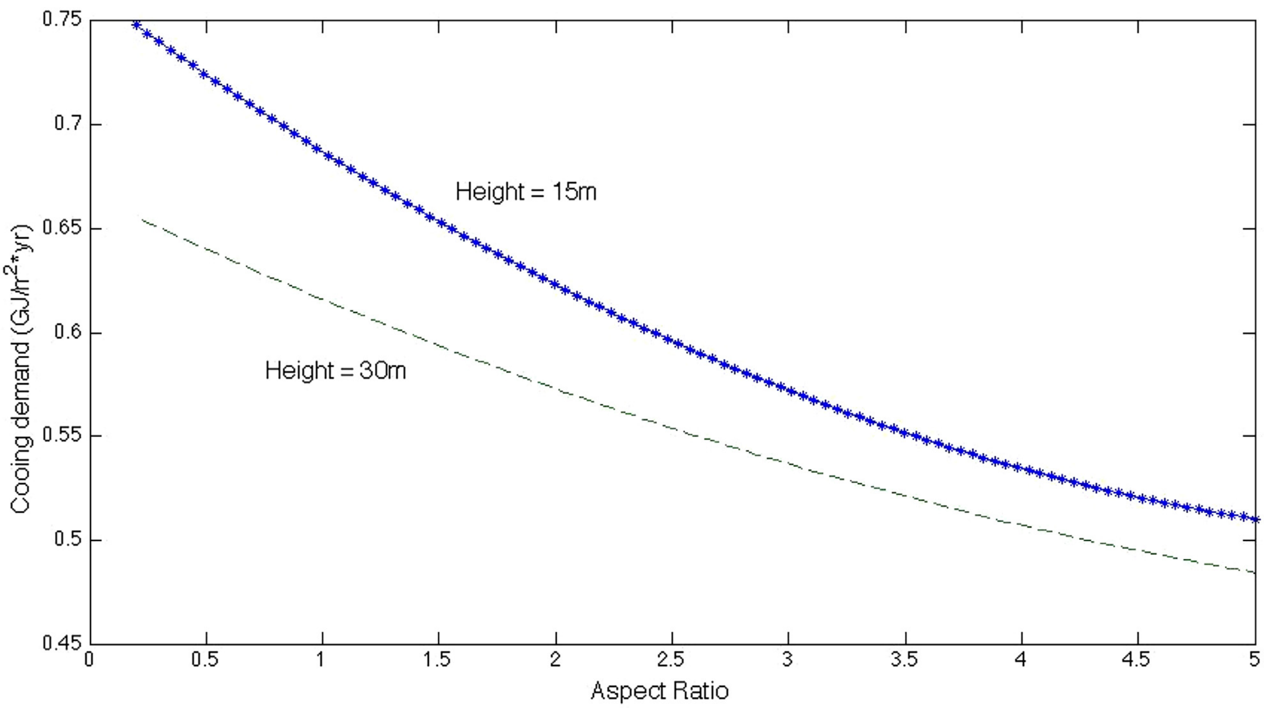

Fig. 11. Impact of aspect ratio on cooling demand (young couple family).

Table 11
Linear regression analysis results.

	Heating (young couple)	Heating (old couple)	Heating (couple with parents)	Cooling (young couple)	Cooling (old couple)	Cooling (couple with parents)
Constant	0.16	0.20	0.19	0.69	0.67	0.85
Coefficient of height	−3.14e-4	−4.44e-4	−4.45e-4	−3.89e-4	−5.7e-4	−5.2e-4
partial correlation coefficients of height	−0.55	−0.58	−0.55	−0.44	−0.42	−0.33
Coefficient of AR	6.1e-3	1.5e-2	1.3e-2	−3.4e-4	−5.2e-2	−6.2e-2
partial correlation coefficients of AR	0.48	0.72	0.65	−0.88	−0.88	−0.88
Goodness of fit	0.40	0.60	0.52	0.79	0.79	0.85

cooling demand. It is also noted that after aspect ratio reaches a certain amount, further increasing aspect ratio is less effective.

Combining Figs. 10 and 11, it is clear that larger aspect ratio increases heating demand and decreases cooling demand. Thus, to achieve a minimal energy consumption for space cooling and heating, it is critical to balance cooling and heating by choosing an optimal aspect ratio.

5.2.3. *Combined effects of height and AR*

To understand how height and AR together determine the heating and cooling demands of the three types of families, a linear regression analysis is performed. In this analysis, the input variables (height and AR) are kept the same, and the response variable is switched from heating to cooling for each type of family. The constant, coefficient of height, and coefficient of AR are solved using the minimal squared error approach. The partial correlation coefficient is the correlation between one input variable and the response variable when the second input variable is controlled, therefore reflects the importance of the input variable. All results are shown in Table 11.

For all three types of families, height and AR are significant factors to cooling and heating demand. Compared with height, AR is more significant. Except for heating demand in young couple family, the importance of AR exceeds height in all cases. The coefficients for heating demands in old couple family and couple with parents family are close, suggesting these two family structures have similar heating demand profiles. The goodness of fit values for heating demands are in general smaller than those for cooling demands, suggesting that cooling demands are better described by the linear regression models.

5.3. *Optimal residential community layout parameters*

From the above analysis, it is clear that height has a negative effect on both cooling and heating demand. Due to this impact, taller buildings are preferred since their less energy demands for space cooling and heating. In reality, Floor Area Ratio (FAR) is often controlled for a particular area. However, Building Coverage Ratio (BCR) can be adjusted by planners during the design stage. Therefore, given a FAR, it is suggested to reduce BCR and increase building height. On one hand, reducing BCR helps increase green Area Ratio (GAR), therefore ameliorate the effect of urban heat island. On the other hand, increased building height help reduce building energy consumption both in winter and summer. It should be noted that, this discussion is mainly from the space cooling and heating perspective, some adverse effects of tall buildings (such as higher energy demand for domestic water supply) should be also considered in practice.

While the effect of height on space cooling and heating demand is quite straightforward, the effect of AR is more complex. While AR has a negative effect on the cooling demand, it has a positive effect on the heating demand. Obviously, to achieve annual minimal energy consumption for heating and cooling, there might exist an optimal AR.

Table 12
Optimal Aspect Ratio for Different Scenarios.

Building height	Cooling and heating system	Young couple	Old couple	Young couple with parents
15m	centralized heating and cooling	5	4.1	5
	centralized heating and decentralized cooling	0.2	0.2	0.2
	decentralized heating and cooling	5	3.9	4.8
30m	centralized heating and cooling	5	5	5
	centralized heating and decentralized cooling	0.2	0.2	0.2
	decentralized heating and cooling	5	5	5

With the above assumptions, the optimal AR value for various building height, family structure and cooling/heating scenarios are calculated and shown in Table 12. It can be seen that the type of HVAC system has a significant impact on the optimal AR value. For buildings with centralized heating/cooling or decentralized heating/cooling system, a large AR value is preferred. However, for buildings with centralized heating and decentralized cooling system (such as Qingdao), a small AR value is more favoured from the energy perspective. In general, old people prefers warmer environment, therefore needs more heating energy than young people. As a result, the optimal AR for old people is smaller than that for young people (as shown in Table 12). However, in districts with centralized heating and decentralized cooling system, the difference of optimal AR values for different family structures diminishes, since space heating is the primary energy demand. It is also found that increasing height helps reduces the difference of optimal ARs among various family structures, due to the quickly reduced heating demand.

6. Conclusion

In this study, three community planning parameters (Floor Area Ratio, Building Coverage Ratio, and Aspect Ratio) are studied in terms of their impacts on energy demands of residential communities, considering the difference of HVAC system (centralized and decentralized) and the type of family structure (young couple, old couple, and young couple with parents). It is found that average building height (determined by FAR and BCR together) and AR are the key parameters affecting building energy consumption. While increasing height can decrease building heating and cooling loads, the impact of AR is more complex. The optimal AR value depends on the type of HVAC system and family structure. In general, communities served by district heating system and decentralized cooling system (such as the cases studied in Qingdao city) needs significantly lower AR than those served by decentralized heating and cooling system, mainly due to the different energy consumption behaviour. However, in both cases, the optimal AR value is significantly different from the current value, which is around 1 in the surveyed communities. Regarding the family structures, as old couple family needs more heating energy in winter and are more energy saving in summer, a lower AR value is more suitable. For the surveyed samples, the optimal AR value for young couple, old couple, and young couple with parents family are found to be the same, at a level much lower than the current value.

The findings of this paper suggests that, space cooling and heating energy consumption behavior depends on the type of HVAC system, the service fee charging mechanism, as well as the type of family structures. From the energy perspective, current aspect ratio in most Chinese residential communities is not optimal. In northern Chinese cities whose heating system is primarily centralized system and cooling system is decentralized, the optimal AR value should be lower than the current value. In southern Chinese cities where summer cooling load is comparable with winter heating load, and both heating and cooling systems are decentralized, the optimal AR value should be higher than the current value.

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