circular the building shape, the lower the building energy consumption in hot-summer and warm-winter areas. On the other hand, Mei et al. (2013) studied the psychrotolerant performance of public buildings including building with in-line-shape plane, building with rectangular-ambulatory-plane and building with U-shaped plane in cold regions under the low energy consumption target. However, their research lacked the introduction of effective parameter tools and the conclusions were not deep enough. At the present, there is no parametric design research on high-rise buildings with L-shaped plane which are common in Hangzhou, China because of great adaptability to the site. Therefore, this paper addressed the relationship between the shape and the energy consumption of high-rise buildings, and the application of this relationship in an actual design project, with L-shaped buildings as an example.

In conclusion, there is not a direct proportional relationship between building body-type coefficient and building energy consumption, but there is a strong relationship between specific shapes of buildings and building energy consumption. Therefore, it is necessary to introduce effective parameter tools to the research on low-energy buildings based on shape optimization. In this article, an energy consumption simulation software, the DesignBuilder, was implemented to study the influence of specific shapes of standard floors in high-rise buildings on building energy consumption by using MATLAB language. Through encoding the simplified L-shaped plane of standard layers in high-rise buildings and simulating the energy consumption of building models in experiment, the relationship between width ratio and depth ratio of L-shaped layouts and the energy consumption of buildings was obtained, which may provide reference and evaluation indicators for shape optimization in green building design.

2. Research methodology

2.1 Model setting

For a single building, energy-saving design can be implemented by controlling the parameters such as building shape, size, height, the number of floors, and window-wall ratio. All other things being equal, the quantitative relationship between building shape and energy consumption was studied in this paper. Based on the investigation of existing public buildings in Hangzhou, the experimental model data was set as follows: floor area of 1200m^2, 10 layers, layer height of 3.6m, gross floor area of 12000m^2, and total height of 36m. It is very important to notice that the public building is rich in shapes such as rectangular, L-shaped, rectangular-ambulatory-plane, oval, or polygon as shown in Fig. 1. For research convenience, typical architectural planes have been simplified to models with major characters.

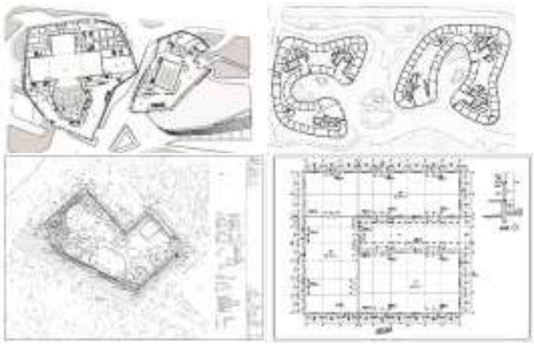


Fig. 1. Typical public building planes in Hangzhou city

The simplified building with L-shaped plane was programmed by establishing mathematical models using MATLAB language for parametric design. The southwest corner of the building was defined coordinate origin denoted as (x_1, y_1). Connecting the remaining 5 points clockwise with the line segment, a closed L-shape was obtained. It is necessary to consider building area as the constraint condition in the model because it tends to be determined before conceptual design in an actual design project. Under the above conditions, the simplified building with L-shaped plane was determined by three design variables: west side length L_1, north side length L_2 and east side length L_3, as shown in Fig. 2.

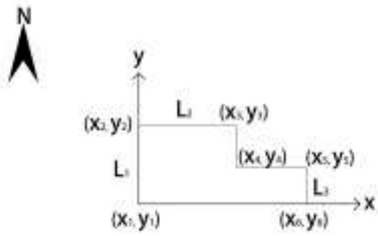


Fig. 2. Sketch of building with L-shaped plane in parametric design

In this article, width ratio and depth ratio were considered as shape feature functions to study the relationship. M_1 represented the width ratio, and M_2 represented the depth ratio. The values of length variables and corresponding shape feature functions were shown in Table 1.

$$M_1 = L_2 / X_5 \quad [1]$$

$$M_2 = L_1 / L_3 \quad [2]$$

Table 1. Modeling data of buildings with L-shaped plane in parametric design.

L_1	L_2	L_3	M_1	M_2
30	30	30	0.75	1.00
		20	0.67	0.67
		10	0.50	0.33
	20	30	0.50	1.00
		20	0.40	0.67
		10	0.25	0.33
	10	30	0.25	1.00
		20	0.18	0.67
		10	0.10	0.33
20	30	30	0.60	1.50
		20	0.50	1.00
		10	0.33	0.50
	20	30	0.43	1.50
		20	0.33	1.00
		10	0.20	0.50
	10	30	0.23	1.50
		20	0.17	1.00
		10	0.09	0.50
10	30	30	0.50	3.00
		20	0.40	2.00
		10	0.25	1.00
	20	30	0.38	3.00
		20	0.29	2.00
		10	0.17	1.00
	10	30	0.38	3.00
		20	0.15	2.00
		10	0.08	1.00

By using data visualization in MATLAB, it can be seen that nine of the twenty-seven experimental models were rectangular layouts. The remaining eighteen L-shaped layouts were regarded as research objects, as shown in Fig. 3.

Fig. 3. Eighteen kinds of L-shaped layouts in parametric design

2.2 Building Energy Consumption Simulation

The relationship between building shape and energy consumption cannot be studied by means of test instruments because of the long period, high costs, large user individual difference, and uncontrollable process. Therefore, the graphical software DesignBuilder based on the energy consumption simulation software Energyplus was used to analyze the energy consumption of the building models. For research convenience, the data of building models was set up according to the survey results of public building shapes of major cities in hot-summer and cold-winter areas, as shown in Table 2. The purpose of changing the building shape was achieved by changing length variables with the same gross floor area. The energy consumption analysis data of building models was shown in Table 3.

Table 2. Data setting of building models.

Gross floor area	12000m^2
Floor area	1200m^2
Total height	36m
Layer height	3.6m
Layers	10
Window-wall ratio	0.3
Cooling setpoint temperature	24℃
Heating setpoint temperature	22℃

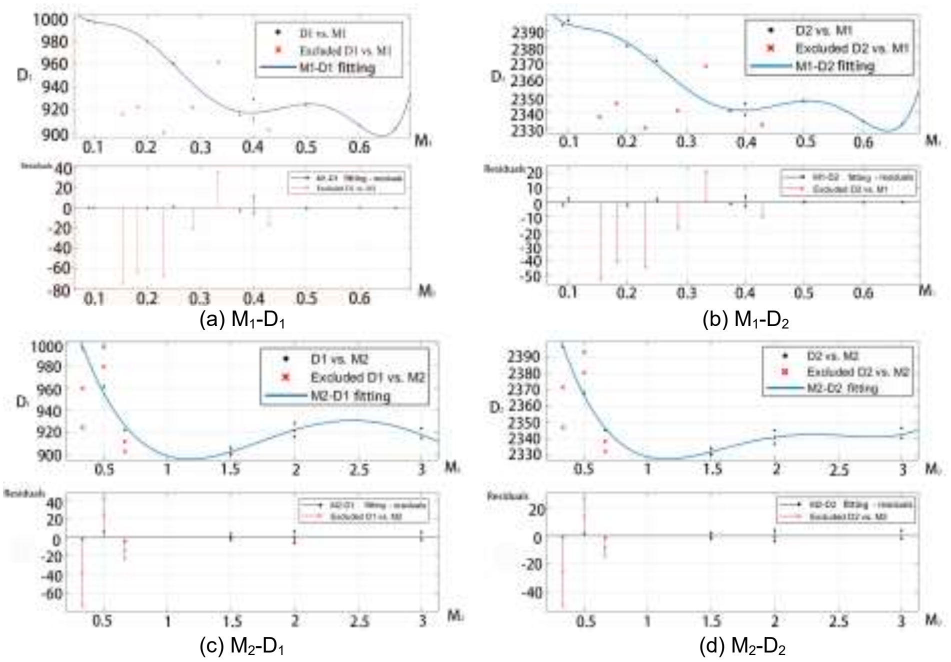
Table 3. Energy consumption statistics of building models (under the weather condition in Hangzhou).

No.	L_1	L_2	L_3	M_1	M_2	Cooling (MW·h)	Total (MW·h)
1	30	30	20	0.67	0.67	903.31	2332.77
2			10	0.50	0.33	924.74	2347.7
3		20	20	0.40	0.67	912.05	2338.4
4			10	0.25	0.33	960.26	2371.45
5		10	20	0.18	0.67	922.41	2345.44
6			10	0.10	0.33	996.22	2396.19
7	20	30	30	0.60	1.50	906.46	2334.49
8			10	0.33	0.50	961.58	2368.11
9		20	30	0.43	1.50	902.67	2332.11
10			10	0.20	0.50	979.47	2380.49
11		10	30	0.23	1.50	900.02	2330.4
12			10	0.09	0.50	997.55	2393.22
13	10	30	30	0.50	3.00	924.04	2346.78
14			20	0.40	2.00	928.63	2345.31
15		20	30	0.38	3.00	915.41	2340.82
16			20	0.29	2.00	922.05	2340.9
17		10	30	0.38	3.00	915.41	2340.82
18			20	0.15	2.00	916.4	2337.23

3. Results and analysis

In the initial analysis of the data, above 40% of building energy consumption was used for cooling in hot-summer and cold-winter areas, and there was significant difference in different shapes of buildings. This study obtained the quantitative relationship among depth ratio, width ratio, cooling energy consumption, and total energy consumption by applying the mathematics regression analysis method. M_1 represented the width ratio of building with L-shaped plane, and M_2 represented the depth ratio. D_1 represented the cooling energy consumption of buildings, and D_2 represented annual total energy consumption. By invoking the curve fitting toolbox of MATLAB, two-dimensional regression fitting analysis to M_1-D_1, M_2-D_1, M_1-D_2, M_2-D_2 and three-dimensional regression fitting analysis to M_1/M_2-D_1, M_1/M_2-D_2 was presented as follows.

By excluding outliers, regression models were fitted with high coefficient of determination (R^2) and low steady residual error (RMSE). Most of the coefficient of determination was over 0.98. Fig. 4 showed the fitting plots and corresponding residuals plot in MATLAB.



(a) M_1-D_1 (b) M_1-D_2 (c) M_2-D_1 (d) M_2-D_2

Fig. 4. Fitting results of side length ratio and energy consumption in MATLAB (fitting plot, residuals plot)

3.1 M_1-D_1

The confidence coefficient of regression models was at least 95% by the 6-degree polynomial function at M_1-D_1. Considering the consistency of fitting curve and real data, the regression model was selected as the final model. The liner model poly6 of M_1-D_1 was shown in Table 4.

Table 4. Fitting results of M_1-D_1.

Polynomial function	$f(x) = (4.12x^6 - 9.22x^5 + 7.97x^4 - 3.35x^3 + 0.71x^2) \times 10^5 - 7331x + 1282$ [3]
Goodness of fit	Sum of square error (SSE) = 125.42
	Coefficient of determination (R^2) = 0.9914
	Adjusted R^2 = 0.9811
	Root mean square error (RMSE) = 5.008
Conclusion	The polynomial can be accepted

The fitting plot was shown in Fig. 4 (M_1-D_1). Some of the conclusions were as follows: (1) When the width ratio of building with L-shaped plane was at the interval of $0<M_1<0.4$, the cooling energy consumption decreased as M_1 increased remarkably. (2) When the width ratio of building with L-shaped plane was at the interval of $M_1>0.4$, the cooling energy consumption fluctuated slightly with M_1, increased with M1 increased at the interval of $0.4<M_1<0.5$ and decreased with M_1 increased at the interval of $0.5<M1<0.67$. (3) At the interval of $0<M_1<0.67$, the cooling energy consumption reached its minimum 897.2MWh when M_1=0.64.

3.2 M_1-D_2

Excluding the same outliers as situation for M_1-D_1, the regression model for M_1-D_2 was obtained. The liner model poly6 of M_1-D_2 was shown in Table 5.

Table 5. Fitting results of M_1-D_2.

Polynomial function	$f(x) = (2.05x^6 - 4.42x^5 + 3.65x^4 - 1.44x^3 + 0.28x^2) \times 10^5 - 2647x + 2491$ [5]
Goodness of fit	Sum of square error (SSE) = 45.73
	Coefficient of determination (R^2) = 0.9922
	Adjusted R^2 = 0.9829
	Root mean square error (RMSE) = 3
Conclusion	The polynomial can be accepted

The fitting plot was shown in Fig. 4 (M_1-D_2). Compared with Fig. 4 (M_1-D_1), it can be seen that both showed the same trend, and there were only minor differences in individual numerical value: the inflection point shifted from M_1=0.4 to M1=0.37 left; the maximum descending rate changed from 225MWh to 180MWh; the minimum point was still at M_1=0.64, but the numerical value was 2329MWh. Some of the conclusions were as follows: (1) The key to reducing building energy consumption in hot-summer and cold-winter areas by shape optimization was to reduce the cooling energy consumption. (2) The best width ratio of building with L-shaped plane was 0.64 considering only the relationship between the width ratio and annual total energy consumption of high-rise building with L-shaped plane. (3) For low-energy buildings, it was important to guarantee that the width ratio of building with L-shaped plane was not less than 0.33.

3.3 M_2-D_1

Excluding six outliers, the regression model whose confidence coefficient was at least 95% by the 4-degree polynomial function at M_2-D_1 was obtained. The liner model poly4 of M_2-D_1 was shown in Table 6.

Table 6. Fitting results of M_2-D_1

Polynomial function	$f(x) = 11.59x^4 - 117.4x^3 + 400.8x^2 - 531x + 1135$ [4]
Goodness of fit	Sum of square error (SSE) = 202.14
	Coefficient of determination (R^2) = 0.9725
	Adjusted R^2 = 0.9610
	Root mean square error (RMSE) = 5.37
Conclusion	The polynomial can be accepted

The fitting results as shown in Fig. 4 (M_2-D_1) indicated that D_1 decreased monotonically as $0<M_2<1.15$, increased as $1.15<M_2<2.5$, and began to decrease as $M_2>2.5$. At the interval of $0<M_2<0.67$, D_1 had a large variation range and the maximum descending rate reached 215MWh, small variation range in other interval. D_1 reached its minimum 896.1MWh when M_2=1.18. Compared with situation for M_1-D_1, it can be concluded that: (1) The relationship between width ratio of building with L-shaped plane and the cooling energy consumption of buildings had the same trend as that of depth ratio and the cooling energy consumption. Its main feature was a critical point that divided the relationship curve into two noteworthy parts, a part of it changed dramatically, and the other changed slowly. (2) By optimizing the depth ratio of building with L-shaped plane, it can save 10% electric energy for a high-rise building with ten stories.

3.4 M_2-D_2

Excluding the same outliers as situation for M_2-D_1, the regression model whose confidence coefficient was at least 95% by the 4-degree polynomial function at M_2-D_2 was obtained. The liner model poly4 of M_2-D_2 was shown in Table 7.

Table 7. Fitting results of M_2-D_2.

Polynomial function	$f(x) = 15.02x^4 - 122.1x^3 + 352.2x^2 - 416x + 2501$ [6]
Goodness of fit	Sum of square error (SSE) = 64
	Coefficient of determination (R^2) = 0.9814
	Adjusted R^2 = 0.9690
	Root mean square error (RMSE) = 3.26
Conclusion	The polynomial can be accepted

The fitting plot was shown in Fig. 4 (M_2-D_2). Compared with Fig. 4 (M_1-D_2) and Fig. 4(M_1-D_2), it can be seen that M_1-D_2 was convex function which appeared slowly first and fast afterwards, while M_2-D_2 was concave function which appeared fast first and slowly afterwards before reaching the critical point. The minimum annual total energy consumption was 2329MWh when M_2=1.18. D_2 decreased rapidly as $0<M_2<1.18$, and changed slowly as $M_2>1.18$. Based on the above data, conclusions may be reached as follows: (1) If other conditions remain the same, in terms of building energy consumption, the width ratio of building with L-shaped plane had the same variation trend as the depth ratio, but for the width ratio, the variation rate on energy consumption reached the maximum when approaching the critical point. For the depth ratio, that was an infinity point. (2) With the above data setting, the minimum cooling energy consumption was 896.1MWh, the minimum annual total energy consumption was 2329MWh, and the corresponding optimum was width ratio at 0.64 and depth ratio at 1.18, as shown in Fig. 5.

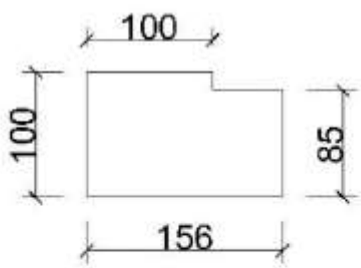


Fig. 5. The optimum of high-rise building with L-shaped plane aiming at low energy consumption

3.5 M_1/M_2-D_1

The analysis of the relationship between individual variables and energy consumption brought us to a conclusion that width ratio and depth ratio had almost the same impact on energy consumption, obtaining the regression with great coefficient of determination by excluding some outliers. Furthermore, three-dimensional fitting regression models were generated as follows, and that make sense: (1) compared with two-dimensional fitting results, the influence of the length ratio of high-rise buildings with L-shaped plane on energy consumption was verified; (2) the appropriateness of excluding these outliers was examined; (3) the generated contour plot can provide help and support for architects in low-energy building design.

The three-dimensional fitting result was plotted by linear interpolant for M_1/M_2-D_1, as shown in Fig. 6. SSE=2.5849×10-26 and R-square=1. Compared with two-dimensional fitting plot, some conclusions can be obtained as follows: (1) The minimum cooling energy consumption was 895.1MWh when M_1=0.23 and M_2=1.5. Compared with M_1-D_1 (0.64, 897.2) and M_2-D_1 (1.18, 896.1), it shows that the minimum cooling energy consumption remained unchanged but the corresponding length ratio had certain changes; (2) A critical point of the relationship existed between the length ratio and cooling energy consumption dividing the relationship curve into two noteworthy parts, a part of it changing dramatically, and the other changing slowly with low energy consumption; (3) M_1 can be obtained through M_2 aiming at low energy consumption by consulting the contour plot. For example, at M_1=0.25, the cooling energy consumption was low as $1.3<M_2<1.8$, and it was high as $0<M_2<0.6$ which should be avoided.

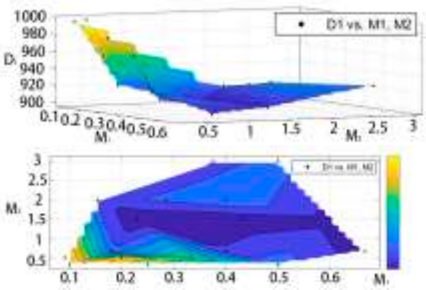


Fig.6. Three-dimensional fitting result of the length ratio and cooling energy consumption in MATLAB (fitting plot, contour plot)

3.6 M_1/M_2-D_2

Three-dimensional fitting result was plotted by linear interpolant for M_1/M_2-D_2, as shown in Fig. 7. SSE=2.0680×10-25 and R^2 =1. The minimum energy consumption was 2332MWh when M_1=0.23 and M_2=1.5. Compared with the situation for M_1/M_2-D_1, the minimum point was the same. It can be found that the low energy consumption area became larger in this contour plot. For example, when M_1=0.25, the low energy consumption was extended with M2, from the interval of $1.3<M_2<1.8$ to the interval of $1.3<M_2<2.3$, indicating that the depth ratio could be increased properly for this situation.

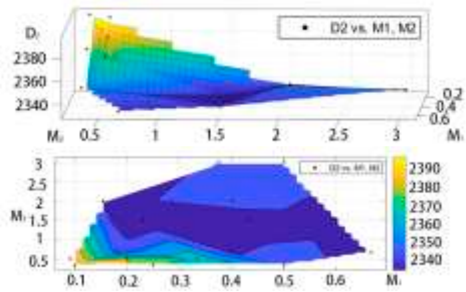


Fig.7. Three-dimensional fitting result of the side length ratio and energy consumption in MATLAB (fitting plot, contour plot)

4. Conclusions

In this article, eighteen kinds of L-shaped layouts were obtained by changing the length parameters of building with L-shaped plane, and the annual energy consumption dynamic simulations were conducted on them by using DesignBuilder. Regression and variance analysis were done on the relationship between the length ratio and energy consumption. The critical point, the optimum and the contour plot of building shape under low energy consumption target were discovered. Hence, this article is original in that:

① The parametric design of building shape was conducted by introducing MATLAB language, and the shape was combined with energy consumption simulation data by data visualization feature in MATLAB. The research methodology is applicable to buildings with all kinds of shapes.

② Multidimensional regression analysis and curve fitting were conducted by taking curve fitting toolbox of MATLAB into consideration in the analysis, obtaining the critical point and the optimal point of building shape for low energy consumption and the contour plots of shape parameters. The results can be directly used in architectural shape speculation for low energy buildings.

The specific conclusions are as follows:

[1] The north-south and depth ratio of building with L-shaped plane have an important influence on energy consumption of buildings, and there is a critical point dividing the relationship curve into two noteworthy parts. One part of it changed dramatically, and the other part changed slowly. For the width ratio, it is 0.4, and for the depth ratio, it is 0.67. Between the length ratio of plane and energy consumption of buildings, there exists a functional relation, such as the situation for M1-D1:

$$f(x) = (4.12x^6 - 9.22x^5 + 7.97x^4 - 3.35x^3 + 0.71x^2) \times 10^5 - 7331x + 1282 \quad [3]$$

[2] The key to reducing building energy consumption in hot-summer and cold-winter areas by shape optimization is to reduce the cooling energy consumption and it can save more than 10 percent of electric energy for a high-rise building with ten stories.

[3] The result shows that both the width ratio and depth ratio influence energy consumption of buildings, which means it is equal important to consider both them in design.

[4] With the low energy consumption target, the optimum is width ratio at 0.64, and depth ratio at 1.18 for building with L-shaped plane in hot-summer and cold-winter areas.

[5] This article gives the range of energy consumption of L-shaped high-rise buildings with width ratio and depth ratio in contour plots which offer designers a set of references at the conceptual design stage.

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