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Architecture Performance-Related Design Based on Graphic Parameterization

Wenzhe Li, Xiaoyu Ying, Grace Ding

***Abstract*—**Architecture plane form is an important consideration in the design of green buildings due to its significant impact on energy performance. The most effective method to consider energy performance in the early design stages is parametric modelling. This paper presents a methodology to program plane forms using MATLAB language, generating 16 kinds of plane forms by changing four designed parameters. DesignBuilder (an energy consumption simulation software) was proposed to simulate the energy consumption of the generated planes. A regression mathematical model was established to study the relationship between the plane forms and their energy consumption. The main finding of the study suggested that there was a cubic function relationship between the depth-ratio of U-shaped buildings and energy consumption, and there is also a cubic function relationship between the width-ratio and energy consumption. In the design, the depth-ratio of U-shaped buildings should not be less than 2.5, and the width-ratio should not be less than 2.

***Keywords*—**Graphic parameterization, green building design, mathematical model, U-shaped buildings.

I. Introduction

WITH the rapid development of urban construction and people's increasing requirements for the built environment, building energy consumption continues to increase. In 2017, the total commodity energy consumption (standard coal) for building operations was 906 million tons, accounting for about 20% of the total national energy consumption [1]. Reducing the building energy consumption in operation to meet building energy efficiency, on the basis of meeting the requirements of the building environment, has become one of the most important subjects for sustainable development of buildings. A large number of researches show that the greatest potential for energy efficiency in buildings comes from the conceptional stages, in which the decisions made by architects have a great impact on building performance in many ways. For example, by changing shapes, orientation, and envelope, an optimized scheme can save 40% energy consumption compared with the original one [2], [3]. As the design process progresses, the room for building performance optimization becomes smaller and smaller, and the cost of getting the same benefits is getting higher and higher.

Wenzhe Li is with the Department of Architecture, Zhejiang University, Hangzhou, 310058 China (phone: 86-15700187213; fax: 057188018345; e-mail: mit600_lee@163.com).

Xiaoyu Ying is with Zhejiang University City Collage, Hangzhou, 310015 China (phone: 86-057188285746; fax: 057188018345; e-mail: evanyxy@qq.com).

Grace Ding is with School of the Built Environment, University of Technology Sydney, Sydney NSW, 2007 Australia (phone: 61295148659; e-mail: grace.ding@uts.edu.au).

At the beginning of the design, the building form is one of the most important considerations, because the building form directly determines the building scale and the orientation. The building form can affect the building performance in many aspects such as energy saving efficiency, construction cost and aesthetic effect. Wang et al. used genetic algorithm to study the influence of building plane shape on building performance in green building design, and concluded that the variability of building plane will cause multiple effects on building performance [4]. According to the research in Sensible City Laboratory of MIT and the University of Cambridge, the four major factors affecting building energy consumption are: building design, urban geometry, systems efficiency, and occupant behavior [5], [6]. The occupant behavior is usually random, and the system efficiency is improved by equipment engineers. The urban geometry is fixed for each region. So the building design plays an important role in reducing building energy consumption.

The shape coefficient of buildings is a main factor to affect the energy consumption of buildings and the incremental cost of building energy efficiency. In general, the lower the shape coefficient, the lower the energy consumption, but this is only applicable in cold areas [7], [8]. It is worth to mention that there is no absolute proportional relationship between them, even in cold areas [9], but the specific shape of buildings has a significant impact to building performance. In the hot summer and cold winter areas, there are two problems needed to solve in summer: cooling and dehumidification. The higher the shape coefficient of buildings, the more solar radiation the buildings absorbed, causing higher indoor temperature. However, higher shape coefficient of buildings can improve the indoor ventilation, decreasing the indoor humidity. If the shape coefficient is used to consider the building plane form, the balance between shading and ventilation is difficult to realize for designers. Some studies showed that the higher the shape coefficient of office buildings in hot summer and cold winter areas, the greater the potential of using natural resources, and the lower building energy consumption can be realized [10]. It can be concluded that the absolute value of building shape coefficient makes little sense in the hot summer and cold winter areas. Wei et al. analyzed the influence of building shape on the air conditioning cooling load, and pointed that the shape coefficient of buildings in hot summer and cold winter areas only need to be controlled within a certain range rather than the lower the better [11]. Xia discussed the performance of several building layouts in Shanghai, China, concluding that the relationship between heating energy consumption, cooling energy consumption and building layouts showed the opposite trend; no building layout can simultaneously reduce heating energy consumption and cooling energy consumption when the layout changes [12]. To sum up, their researches all indicated that the shape coefficient should not be used as a direct control factor for the formation of building forms. It is complicated to figure out the mechanism of building forms on energy consumption.

Parameterization is an effective method for considering building performance in building form design. Extending building shape coefficient to building shape parameters will facilitate an in-depth study of the relationship between building form and energy consumption. Some researchers proposed a multiple linear regression model to predict the energy consumption of office buildings under different standard plane shapes [13], [14]. The simulation in the study was conducted in cold- dry climate and warm-humid climate separately, considering the building's thermal load under seven shapes of office buildings (rectangular, H-shaped, L-shaped, polygonal, triangular, T-shaped, U-shaped). It showed that the difference between the prediction of regression model and the simulation results is within 5%. A parametric modeling process for building design, combined evolutionary algorithms and energy simulation, was prompted to help designers to evaluate building performance in conceptual design stages [15]. This method first sets the variables and constraints among the building parameters, then modeling, optimizing, and simulating. Li transformed the design problem into a mathematical model, and obtained the optimized model by genetic algorithm [16]. It can be seen that it is a reliable method to express the relationship between the building form and energy consumption in the form of parameters by means of mathematical analysis and computer model.

In hot summer and cold winter areas, U-shaped layout of buildings is widely distributed. The semi-enclosed plane form is beneficial to ventilation, and is relatively compact without excessive heat loss. The inner courtyard space is conducive to the construction of landscape gardens. Therefore, this paper takes U-shaped buildings as an example to study the correlation between the proportion of building planes and building energy consumption. The parametric models of buildings were built by MATLAB language, and the data of energy consumption of different building layouts were gained by DesignBuilder simulation. Regression analysis was conducted between the evaluation parameters of building planes and building energy consumption. According to the regression model, we can predict appropriate design parameters in a lower-energy U-shaped building.

II. Research Methodology

A. Parametric Model of U-Shaped Buildings

After investigating the existing buildings in the hot summer and cold winter areas, it was found that the common orientation of U-shaped office buildings was southwest40° -southeast40°, and the entrances to the buildings were mostly located on the notch side. Therefore, positive south ± 40° is used as a constraint for the orientation of the building model.

On the basis of retaining the main features of the U-shaped building form, the plane is simplified and its mathematical model is constructed. The diagram is shown in Fig. 1. The building 3D model is shown in Fig. 2 and Table I shows the model's parameters.

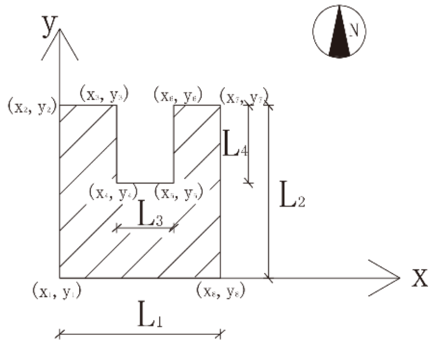

Fig. 1 Diagram of parametric model of U-shaped buildings

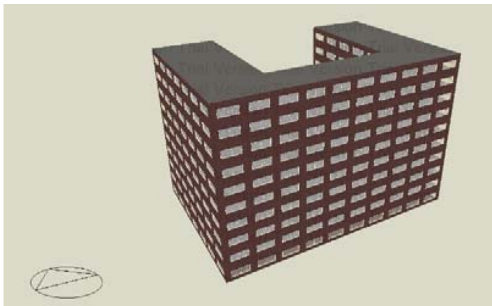

Fig. 2 Building 3D model

TABLE I
PARAMETERS OF BUILDING 3D MODEL

Building type	Office building
Gross floor area	$12000m^2$
Floor area	$1200m^2$
Total height	36m
Layer height	3.6m
Layers	10
Window-wall ratio	0.3

Above, U-shaped building plane form will be determined by four parameters: width L_1, depth L_2, notch width L_3, notch depth L_4 and they satisfy the boundary conditions below:

TABLE II
BOUNDARY CONDITIONS OF L_1, L_2, L_3, L_4

$L_1 \times L_2 - L_3 \times L_4 = 1200$
$L_1 \times L_2 > 1200$
$L_1 > L_3 > 0$
$L_2 > L_4 > 0$

16 layouts are shown in Fig. 3, and Table III shows the layout's parameters. For each layout, three kinds of orientation are conducted: S, SW40°, SE40°, as shown in Fig. 4.

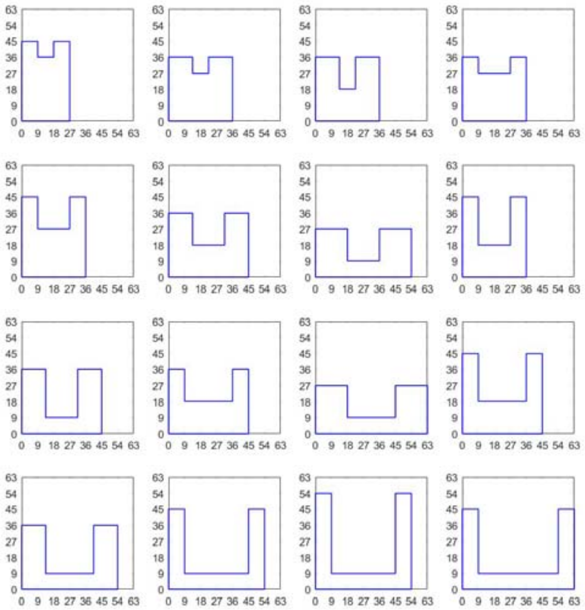

Fig. 3 16 layouts formed by programing

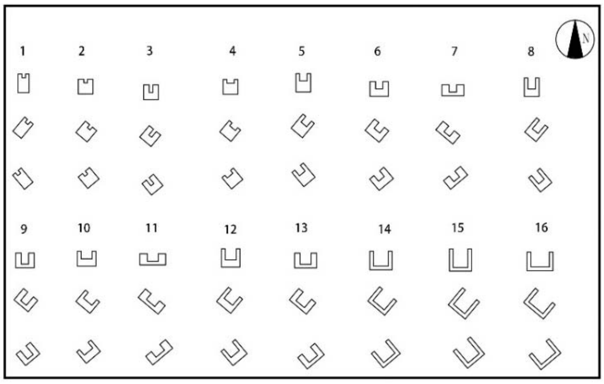

Fig. 4 48 layouts considering orientation

TABLE III
PARAMETERS OF LAYOUTS

No.	L_1/m	L_2/m	L_3/m	L_4/m	Orientation
1	27	45	9	9	SW40°, S, SE40°
2	36	36	9	9	SW40°, S, SE40°
3	36	36	9	18	SW40°, S, SE40°
4	36	36	18	9	SW40°, S, SE40°
5	36	45	18	18	SW40°, S, SE40°
6	45	36	18	18	SW40°, S, SE40°
7	54	27	18	18	SW40°, S, SE40°
8	36	45	18	27	SW40°, S, SE40°
9	45	36	18	27	SW40°, S, SE40°
10	45	36	27	18	SW40°, S, SE40°
11	63	27	27	18	SW40°, S, SE40°
12	45	45	27	27	SW40°, S, SE40°
13	54	36	27	27	SW40°, S, SE40°
14	54	45	36	36	SW40°, S, SE40°
15	54	54	36	45	SW40°, S, SE40°
16	63	45	45	36	SW40°, S, SE40°

B. Simulation of Building Energy Consumption

Internal functions of the building models are shown in Fig. 5, meeting the normal functions of office buildings. As an activity template, "Office_OpenOff_Occ" was determined. The work mode in workdays is shown in Fig. 6. Other activity setting is shown in Table IV. Annual dynamic simulation of building energy consumption was conducted in Designbuilder under the weather condition in Hangzhou, China. The results are shown in Table V.

TABLE IV
SIMULATION PARAMETERS

Activity	value
Occupancy density	0.1110人/m^2
Lighting density	400lux
Cooling setpoint temperature	24°C
Cooling setback temperature	28°C
Heating setpoint temperature	22°C
Heating setback temperature	12°C
Equipment energy consumption	11.77w/m^2
Domestic hot water	0.2L/m^2-day

TABLE V
TOTAL ENERGY CONSUMPTION OF BUILDINGS IN AIR CONDITIONING

No.	Orientation / Building energy consumption					
1	S	91	SW	91	SE	91
2	S	89	SW	90	SE	90
3	S	91	SW	92	SE	92
4	S	90	SW	91	SE	91
5	S	92	SW	92	SE	92
6	S	91	SW	92	SE	92
7	S	92	SW	94	SE	94
8	S	95	SW	95	SE	95
9	S	95	SW	95	SE	115
10	S	94	SW	94	SE	94
11	S	94	SW	94	SE	94
12	S	94	SW	94	SE	94
13	S	95	SW	95	SE	95
14	S	100	SW	100	SE	100
15	S	100	SW	100	SE	100
16	S	100	SW	100	SE	100

III. RESULTS AND ANALYSIS

The depth and width of buildings affect the absorption of solar radiation by the building skin, indoor ventilation, indoor lighting, etc., so the building form directly affects building energy consumption. In addition, it is necessary to predict the energy consumption of different building shapes in the conceptional stages. Therefore, width-ratio (M_1) and depth-ratio (M_2) of U-shaped buildings are selected as a performance object in this paper. $M_1=L_1/L_3$; $M_2=L_2/L_4$

A. The Relationship between Layouts and Energy Consumption in Different Building Orientation

The relationship between building layouts and energy consumption is shown in Fig. 7. The results show that: 1) Under the common orientation (positive south ± 40°), there is no obvious correlation between building energy consumption and building orientation azimuth. 2) The energy consumption

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corresponding to each building layout is: layout 1-7 <Layout 8-13 < Layout 14-16. There is a large deviation in layout SE9, and we eliminate it as an outlier when doing regression analysis.

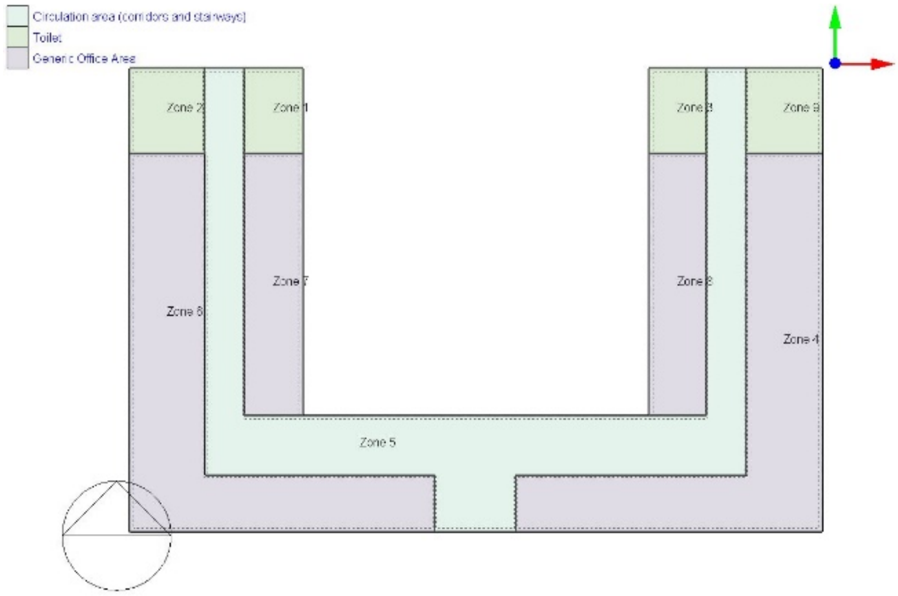
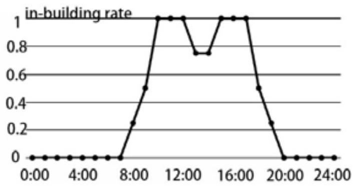
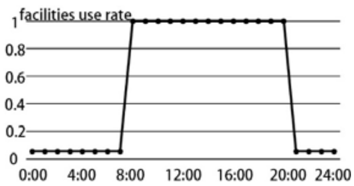


Fig. 5 Internal functions of the building models



(a) In-building rate



(b) Facilities use rate

Fig. 6 Work mode in workdays of office buildings

B. The Relationship between Width-Ratio and Energy Consumption of U-Shaped Buildings

The mathematical regression model between energy consumption and width-ratio is obtained by fitting the data, as shown in Fig. 8 and Table VI. The results show that: (1) The cubic function fitting can obtain a regression model with a coefficient higher than 0.8. (2) When width-ratio of U-shaped buildings is greater than 2 and less than 3.5, the changes of building energy consumption are not obvious and remain at a low level. (3) When width-ratio of U-shaped buildings is less than 2 or greater than 3.5, the building energy consumption decreases as the width-ratio increases, in other words, the closer the notch width of U-shaped buildings is to the intermediate range, the lower the energy consumption. Neither too wide nor too narrow notch is not conducive to reduce building energy consumption.

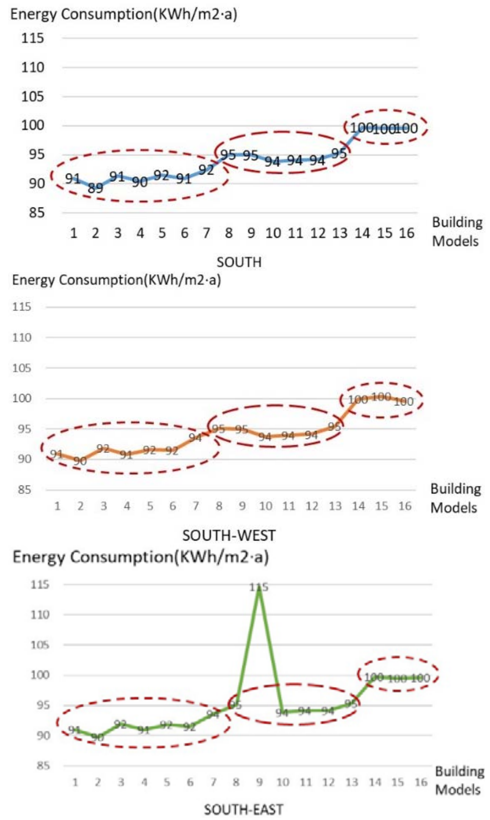


Fig. 7 The relationship between layouts and energy consumption in different building orientation

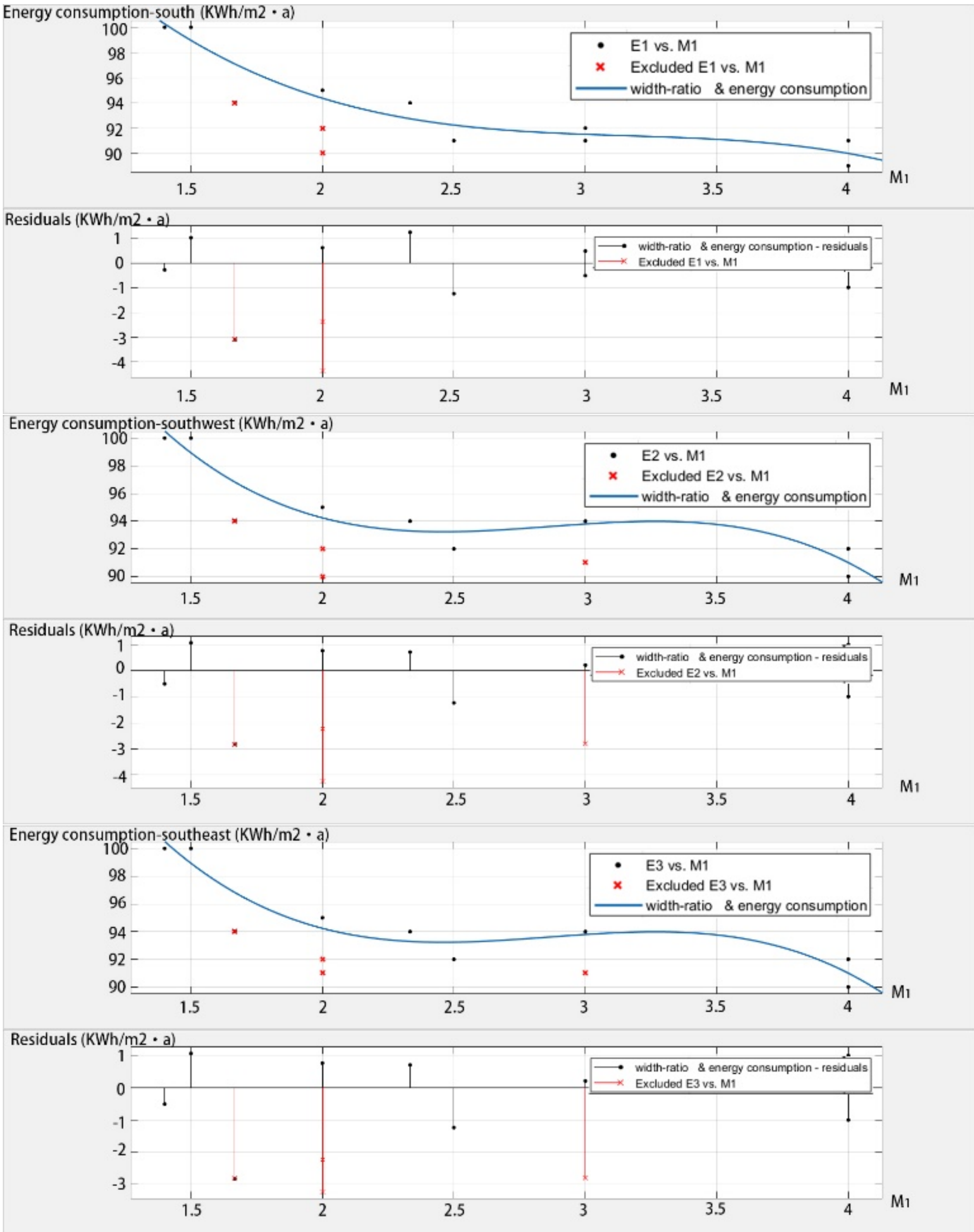


Fig. 8 Regression fitting of width-ratio and energy consumption of buildings

TABLE VI
REGRESSION FITTING OF WIDTH-RATIO AND ENERGY CONSUMPTION OF BUILDINGS

M_1-E_1: $f(x) = -1.4x^3 + 13.4x^2 - 43x + 138$
SSE=18.2, R^2=0.89, Adjusted R^2=0.85, RMSE=1.5
M_1-E_2: $f(x) = -2.8x^3 + 24.53x^2 - 68x + 156$
SSE=15.75, R^2=0.87, Adjusted R^2=0.81, RMSE=1.5
M_1-E_3: $f(x) = -2.8x^3 + 24.53x^2 - 68x + 156$
SSE=15.75, R^2=0.87, Adjusted R^2=0.81, RMSE=1.5

C. The Relationship between Depth-Ratio and Energy Consumption of U-Shaped Buildings

The mathematical regression model between energy consumption and depth-ratio is obtained by fitting the data, as shown in Fig. 9 and Table VII. The results show that: (1) The cubic function fitting can obtain a regression model with a coefficient higher than 0.9. (2) When depth-ratio of U-shaped buildings is greater than 2.5, the changes of building energy consumption are not obvious and remain at a low level. (3) When depth-ratio of U-shaped buildings is great than 1 and less than 2.5, the building energy consumption decreases as the depth-ratio increases, in other words, the shallower the notch of U-shaped buildings, the lower the energy consumption.

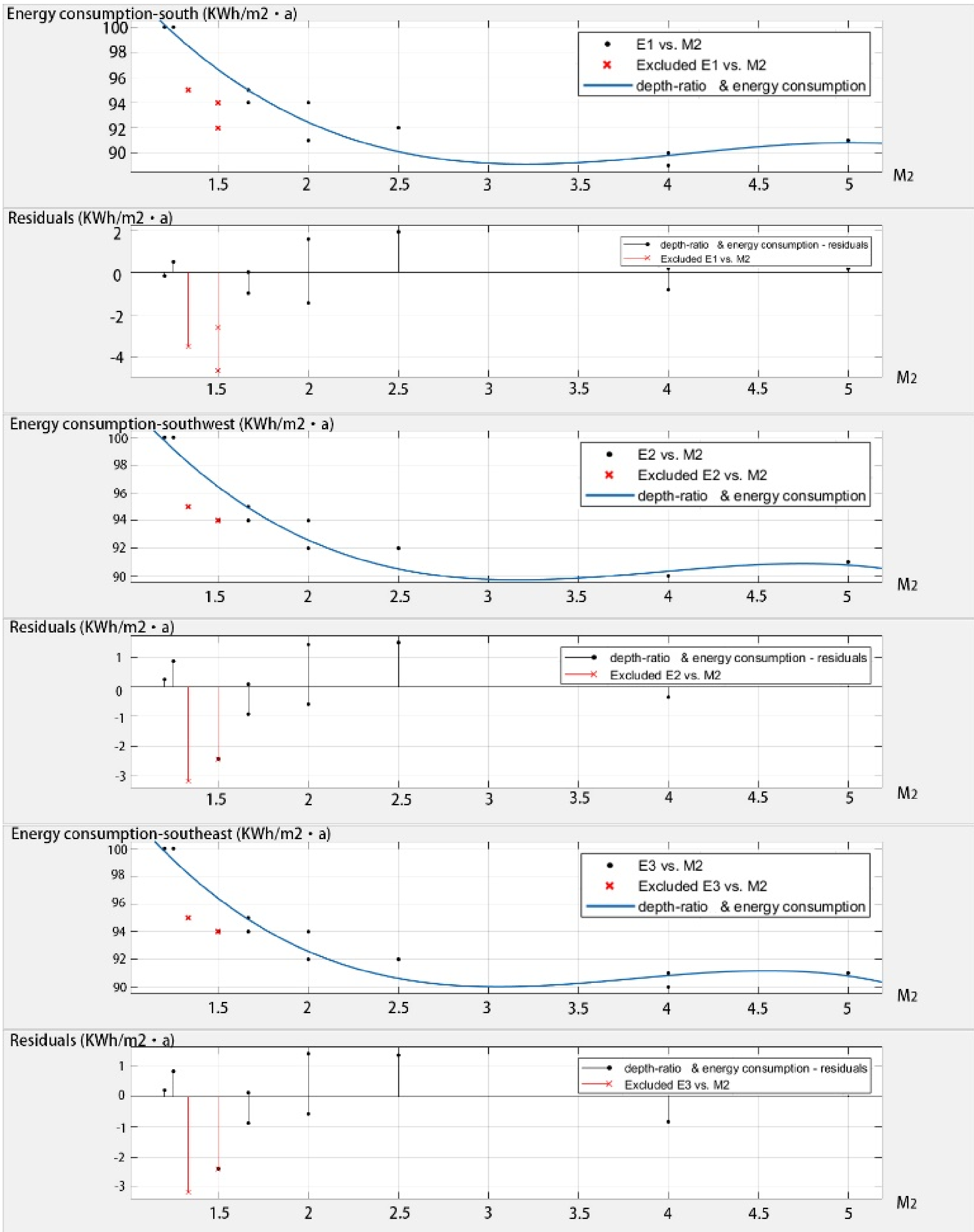


Fig. 9 Regression fitting of depth-ratio and energy consumption of buildings

IV. Conclusion

1) Within positive south ±40°, the effect of orientation on building energy consumption is not significant. The energy consumption of south buildings is slightly lower than that of southwest buildings and southeast buildings.
2) The influence of depth-ratio of U-shaped buildings on the energy consumption is greater than width-ratio.
3) The critical point of depth-ratio of U-shaped buildings is

2.5, and the critical point of width-ratio is 2 and 3.5.

TABLE VII
REGRESSION FITTING OF DEPTH-RATIO AND ENERGY CONSUMPTION OF BUILDINGS

M_2-E_1: $f(x) = -0.58x^3 + 7.17x^2 - 28x + 124$
SSE=12.34, R^2=0.93, Adjusted R^2=0.90, RMSE=1.24
M_2-E_2: $f(x) = -0.6x^3 + 7.12x^2 - 27x + 123$
SSE=13.44, R^2=0.91, Adjusted R^2=0.89, RMSE=1.22
M_2-E_3: $f(x) = -0.7x^3 + 7.89x^2 - 29x + 124$
SSE=13.27, R^2=0.91, Adjusted R^2=0.89, RMSE=1.21

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