

Urban Three-dimensional Expansion and Its Driving Forces —A Case Study of Shanghai, China

SHI Longyu^{1,2}, SHAO Guofan³, CUI Shenghui¹, LI Xuanqi^{1,2}, LIN Tao¹, YIN Kai^{1,2}, ZHAO Jingzhu¹
(1. Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361003, China; 2. Graduate University of Chinese Academy of Sciences, Beijing 100049, China; 3. Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN47907, USA)

Abstract: Urban expansion is a phenomenon of urban space increase, and an important measuring index of the process of urbanization. Taking Shanghai as an example, the changes of urban average height and built-up area were studied to represent city's vertical and horizontal increases respectively, and statistical methods were used to analyze the driving forces of urban expansion. The research drew following conclusions: 1) The urban expansion process of Shanghai from 1985 to 2006 had a clear periodic feature, and could be divided into three stages: vertical expansion in dominance, coordinated vertical and horizontal expansion, and horizontal expansion in dominance. 2) The average height and quantity of buildings in core city were significantly bigger than those in suburbs, but the changing speed of the latter was faster. And 3) urbanization process was the major driving force for the city's horizontal expansion, while industrial structure improvement was the key driving factor for the vertical expansion. Those two driving forces were simultaneously affected by city's political factors.

Keywords: urban expansion; three-dimensional space; urbanization; urban vertical expansion; urban horizontal expansion; Shanghai; China

1 Introduction

Urban expansion is a phenomenon of urban space increase, and an important measuring index of the process of urbanization (Zeng et al., 2004). The characteristics and driving mechanism of urban expansion in Europe and North America have been widely studied (Aguilar, 1999). Alig et al. (2004) indicated that there was an increase of 34% in the area of urban construction land between 1982 and 1997 in the United States. This increase came predominantly from the conversion of arable land and forestland, and the driving forces for land transformation significantly increased both in population density and personal income. The process of urban expansion in Chinese cities was also investigated (Xiao et al., 2006). Seto and Fragkias (2005) used the landscape ecology method to conduct a research on the process of land use change of four cities in Guangdong Province of China between 1988 and 1999. They found that although

with different economic development and policy history, the similar characteristics were shown in their urban expansion and speed patterns. Fan (1999) believed that economic factors might not be the leading forces contributing to the China's urban growth; in contrast, social and political factors could have played a more important role during the forming of China's current urban structure.

The research on urban expansion was mostly referred as an abstract or summary of a series of different urban space orders in a certain period and geographical environment (Cheng and Masser, 2003). Most of the researches about urban expansion focused on the horizontal expansion, but relatively little concerned about the process of vertical expansion. Urban expansion was a three-dimensional process including both horizontal and vertical expansion. Current researches about three-dimensional expansion were still at an exploration period. A few studies had been made about the height (Thomson,

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Corresponding author: ZHAO Jingzhu. E-mail: jzhao@rcees.ac.cn

1966), layout structure (Wright, 1971) and the environmental effects of urban three-dimensional expansion (Hoch, 1968). Johann Kohl was the first to bring up the idea of spherical shape city (Peucker, 1968). He believed if we could build houses on top of each other as easily as side by side, and light and fresh air as well as traffic communications could be provided at considerable depths underground as easily as at upper town levels, then every town would take on spherical shape and extend its roads in all directions like a cupola (Peucker, 1968). Alfred (1890) analyzed the building height using diminishing marginal return and land rent. He believed that the height of buildings cannot increase endlessly, because at last it is found that the extra expenses for foundation and thick wall, and for his lift, together with some resulting depreciation of the lower floors, which make it stand to lose more than it gains by adding one more floors.

The horizontal urban expansion pattern in China was similar to that in USA and Europe, but there were big differences in their vertical patterns. For instance, groups of single- and double-floored houses could be seen almost everywhere in America and Europe cities. However, in China, under the pressure of huge population, citizens commonly resided in tall buildings, which led to the Chinese cities' distinct feature of vertical expansion. Therefore, this paper took Shanghai as an example to analyze the three-dimensional urban expansion process from 1985 to 2006, using the change of buildings' average height to represent the vertical increase. For horizontal expansion, the research mainly considered the expansion of built-up area. Furthermore, we investigated the socio-economic driving forces affecting Shanghai's spatial expansion, such as population growth, economic increase, industrial structure improvement, social development and transportation extension, aiming to accelerate the development of quantitative study on urbanization, and explain the actual urban structure comprehensively.

2 Study Area and Methodology

2.1 Study area

Shanghai (31°12'N, 121°30'E) is the largest city in China in terms of population, with 13.68×10^6 registered permanent residents and more than 3×10^6 of a floating population by the end of 2006. Located in China's central eastern

coast at the mouth of the Changjiang (Yangtze) River, contiguous to Jiangsu Province and Zhejiang Province, the municipality as a whole consists of a peninsula between the Changjiang River and Hangzhou Bay, Chongming Island—China's third largest island, and a number of small islands (Fig. 1). The vast majority of Shanghai's land with an area of $6,340 \text{ km}^2$ is flat, apart from a few hills in the southwest corner, whose average elevation is 4m. Shanghai has a humid subtropical climate and experiences on average 1,778 hours of sunshine per year, with the mean annual temperature 18.4°C . The average number of rainy days is 112 per year, and the average annual precipitation is 1,042mm, with the wettest month being June. The average frost-free period is 276 days.

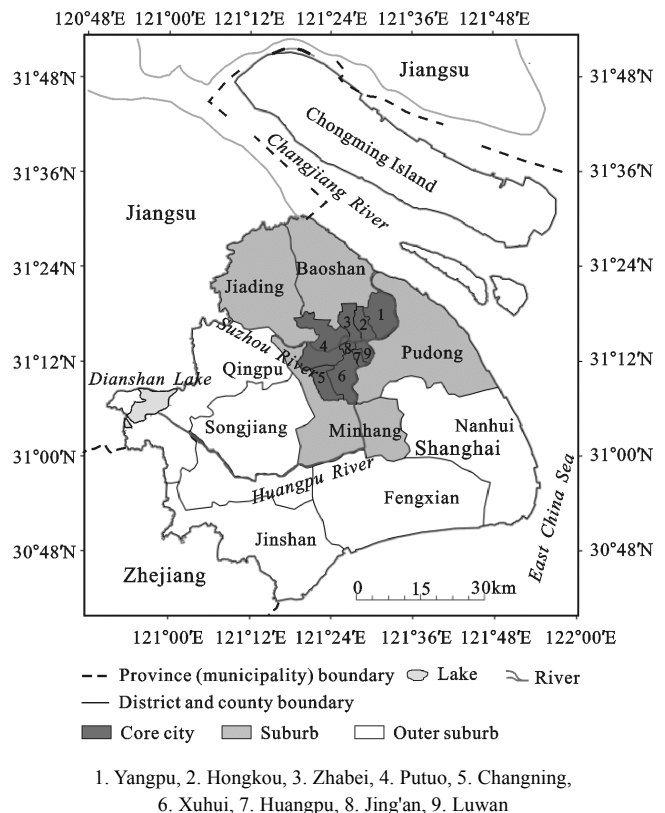


Fig. 1 Location and administrative division of Shanghai

Shanghai is administratively equal to a province and is divided into 19 county-level divisions: 18 districts and one county. Nine of those districts are collectively referred to Shanghai Proper or the core city, including Huangpu, Luwan, Xuhui, Changning, Jing'an, Putuo, Zhabei, Hongkou and Yangpu districts. Four districts are in the suburbs, which are Jiading, Baoshan, Minhang, and Pudong New District. The outer suburbs are governed by Qingpu, Songjiang, Jinshan, Fengxian, and

Nanhui districts, as well as Chongming County.

Originally a fishing and textiles town, Shanghai grew to an important city in the 19th century due to its favorable port location. As a result of economic reforms in the 1970s, urban development was stimulated to roar at very fast speed, and since 1992 Shanghai has recorded a double-digit growth for 15 consecutive years. In 2006, Shanghai nominal GDP (sum of real GDP and inflation rate) posted a 13.1% growth to 1.04×10^{12} yuan (RMB). As many other areas in China, Shanghai is undergoing a building boom, where the bulk of buildings being constructed are high-rise apartments of various height, color and design. There is now a strong focus by city planners to make sensible countermeasures about urbanization issues, such as to develop more "green areas" (public parks) among the apartment complexes in order to improve the quality of life for Shanghai's residents, quite in accordance to the theme of "Better City—Better Life" of Shanghai's Expo 2010.

2.2 Data and method

The data used to demonstrate the spatial characteristics of Shanghai include the size of built-up area, quantity of high-rise buildings obtained from *Shanghai Statistical Yearbook* between 1985 and 2006 (Shanghai Statistical Bureau, 1985–2006). Social and economic indexes used for driving forces analysis are also obtained from *Shanghai Statistical Yearbook*.

2.2.1 Average high-rise building heights

The average high-rise building heights of Shanghai and each district were calculated by Equation (1):

$$H = \frac{\sum_{i=1}^n (h_i \times N_i)}{\sum_{i=1}^n N_i} \quad (1)$$

where, H is the average high-rise building height (m); h_i is the height of the building with i stories (m), assuming that each story is 4m high; N_i is the quantity of buildings with i stories; n is the number of the highest story in a certain area.

2.2.2 Extent of urban expansion

The velocity variation rate was used to evaluate the extent of urban expansion across a given period. This index was calculated by Equation (2):

$$V = \frac{X_t - X_0}{m} \times 100\% \quad (2)$$

where V is the velocity variation rate; X_t and X_0 are the last and initial values of urban space (horizontal or vertical dimension) in a given period. Horizontal space was expressed as the built-up area, and vertical space was expressed as the square value of average height, in order to be in accordance with the unit of built-up area. m is the changing period (year). It was believed that the urban space was increasing when $V > 0$; urban space was decreasing when $V < 0$. The urban space expansion types were defined according to the differences of V value: if $V > 10\%$, urban space expansion type was high-speed growth; $4\% < V < 10\%$, was low-speed growth; $0 < V < 4\%$, was slow growth; Similarly, when $V < -10\%$, $-10\% < V < -4\%$, and $-4\% < V < 0$, urban space expansion types corresponded to high-speed decline, low-speed decline and slow decline respectively.

2.2.3 Three-dimension spatial variation

A three-dimension spatial index was introduced to describe the three-dimension spatial variation of a city. The index expressed a proportional relationship between urban vertical expansion and horizontal expansion, which can be calculated by Equation (3):

$$C = \frac{(1000 \times H)^2}{A} \quad (3)$$

where C is a three-dimension spatial index, dimensionless; H is the average high-rise building height (m); A is the built-up area (km^2). During a given period, if the value of C increases, it means that the urban space expands more in the vertical direction, but if the value of C decreases, it means that the urban space expands more in the horizontal direction.

3 Results

3.1 Urban expansion process

Figure 2 showed the composition structure of high-rise buildings in Shanghai from 1985 to 2006. The total amount of high-rise buildings rose from 225 to near 12,000 in 1985–2006, increasing 53 times. From 1985 to 1992, the construction speed of high-rise buildings was slow; however, it began to speed up after 1992. From 1992 to 1999, the increase of high-rise buildings concentrated in the skyscrapers with the height range from 80m to 120m; during 1999 and 2006, the growth of buildings over 80m slowed down, but the 40–60m buildings expanded rapidly. This alteration in component structure of high-rise buildings has brought obvious

change in buildings' average height (Fig. 2).

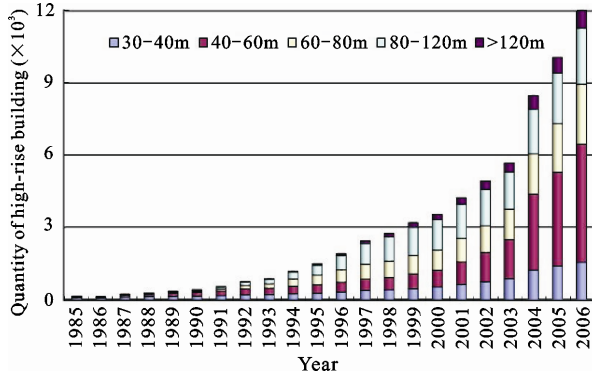


Fig. 2 Composition of high-rise buildings in Shanghai in 1985–2006

According to Equation (1), the average high-rise building heights of Shanghai from 1985 to 2006 were calculated (Fig. 3). Shanghai's horizontal expansion was gradually increasing, but the vertical expansion was steadily declining after reaching the peak (74.8m) in 1999. With the assistance of the velocity variation analysis, the process of Shanghai urban expansion was divided into 3 stages.

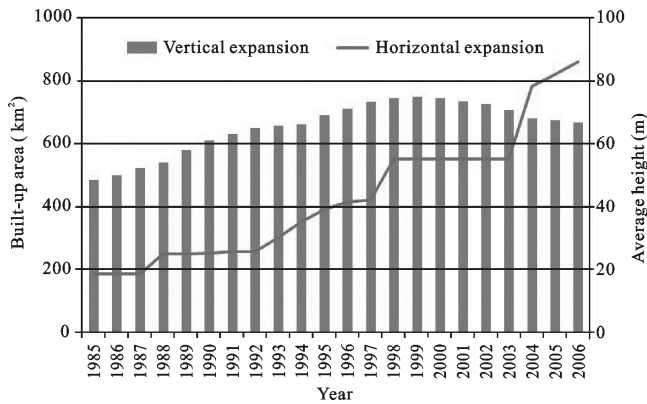


Fig. 3 Urban vertical and horizontal expansion in 1985–2006

3.1.1 Stage I (1985–1992): vertical expansion in dominance

This period was the beginning stage of Shanghai's urban construction, not long after the Reform and Open-up Policy of China in 1978. The built-up area increased merely 70km² in the seven years, from 184km² to 254km², with an average velocity variation rate of 5.43% yearly, which was a figure of low-speed growth range. Comparatively, the average height increased 16.5m, from 48.4m to 64.9m, resulting in a velocity variation rate of 12.45%

for vertical expansion, a figure of highspeed growth range.

3.1.2 Stage II (1992–1999): coordinated vertical and horizontal expansion

Horizontal space expanded rapidly during this period. The built-up area doubled in the seven years, from 254 to 550km², with a velocity variation rate of 17.12%, moving into high-speed growth stage. In contrast, the average growth of urban height slowed down, with the velocity variation rate of 7.68%, from 64.9 to 74.8m, which was a relative low-speed growth. It was named coordinated expansion because the horizontal space accelerated its expansion speed, while the vertical space was still increasing anyway.

3.1.3 Stage III (1999–2006): horizontal expansion in dominance

The speed of horizontal expansion slowed quite a bit in this period, from 550 to 860km², with an average annual growth of 8.07%. With entering the low-speed growth range, Shanghai's urban construction entered a stable period. The vertical expansion during this period showed a slow decline, from 74.8 to 66.7m, with an average annual growth rate of -2.98%. Despite both the two expansion was slowing down, Shanghai's expansion expressed a stable phenomenon, and the main feature of space expansion direction was horizontal comparatively. Using Equation (3), we can get the trend of three-dimension spatial index (C) (Fig. 4). It could be found that the three-dimension expansion of Shanghai was featured by fluctuating decline in general. From 1985 to 1992, the value of C increased, indicating that vertical expansion was the major process in this period. In the following periods (1992–1999 and 1999–2006), however, the C value decreased gradually, suggesting the main spatial expansion type was horizontal expansion. By combining Fig. 4 and Table 1, two features of Shanghai's three-dimension expansion were concluded: the first is that the direction of urban three-dimension spatial expansion changed from vertical expansion to horizontal one; the second is that the speed of the three-dimension expansion became slow gradually.

3.2 Regional difference

The average heights of high-rise buildings in different districts or counties were presented in Table 1. Both the average height and quantity of high-rise buildings in core city were the highest, followed by the suburbs and outer

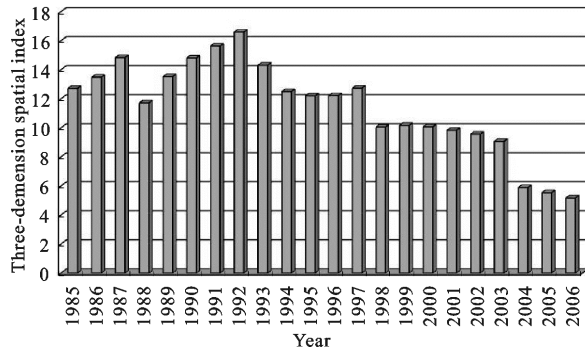


Fig. 4 Three-dimension spatial index in 1985–2006

suburbs, forming a strong gradient feature. In different periods of urban expansion, it showed significant regional differences. In 1992, the urban construction occurred mainly in core city, and more than 90% of high-rise buildings were concentrated in city centre (705 in the core city and 43 in the suburbs). The increase rate was also faster in the core city than that in suburbs. The average height of buildings in the core city increased 13.8m, but only increased 8.0m in suburbs (those build-

ings in outer suburbs were not recorded in *Shanghai Statistical Yearbook* before 1992). During 1992–1999, the average height of buildings in suburbs started to heighten up, and reached the peak of 74.4m in 1999, near the height of 77.0m in the core city. Compared to the period of 1985–1992, the increase rate in the core city began to descend in this period with 4.0% to 3.4% per year. In contrast, the increase rate in the suburbs ascended by 7.7% per year, more than that in the core city (3.4%), which reflected a kind of suburbanization feature of Shanghai. From 1999 to 2006, urban construction expanded to entire administrative region. As far as the increase rate of high-rise buildings' quantity was concerned, the outer suburbs made the fastest growing of 11 times, in contrast to 8 times in the suburbs and 2 times in core city. Meanwhile, the average heights decreased in every region, indicating a falling tendency of urban vertical space, mainly because of the slow-down construction of high-rise buildings over 80m in the whole city.

Table 1 Average height and quantity of urban buildings at different time

Period	Average height of building (m)			Quantity of high-rise building		
	Core city	Suburb	Outer suburb	Core city	Suburb	Outer suburb
1985	48.9	40.0	–	221	4	–
1992	62.7	48.0	–	705	43	–
1999	77.0	74.4	62.9	2,900	551	78
2006	74.2	61.2	55.0	6,918	4,208	863
Increase rate						
1985–1992	4.0%	2.9%	–	31.3%	139.3%	–
1992–1999	3.4%	7.7%	–	38.2%	160.5%	–
1999–2006	–0.6%	–2.5%	–1.7%	23.9%	100.0%	161.8%

4 Driving Forces of Urban Three-dimensional Expansion

4.1 Driving factors

Historical studies indicated that urban expansion was the result of the joint effect of social, economic, and political factors (Verburg et al., 1999; Moreira et al., 2001; Fang et al., 2002; Liu and Shen, 2006). An index system of driving factors was developed by choosing factors mainly from five aspects: population growth, economic increase, industrial structure improvement, social development and transportation extension. Statistical methods such as principal component analysis and correlation coefficient analysis were applied to explaining the driving mechanism of urban expansion.

In this article, the driving force index system of urban expansion developed in this paper consisted of 16 indexes (Table 2). Firstly, by using SPSS13.0 software, correlation analysis was carried out, and the results showed that all the selected indexes had significant relationship with both vertical and horizontal expansion of Shanghai (significant level over 95%). Then, through the principal component analysis, after the rotation method of Varimax with Kaiser Normalization, the rotated component matrix with two principal components was extracted (Table 2), and the cumulative variance explained by the two principal components was 97.37%. As shown in Table 2, the principal component I had significant relationship (such as A_2 , A_3 , A_4 , A_5 , A_7 , A_8 , A_{15} and A_{16} , variable loading over 0.8) with the indexes from three types: economic increase,

population growth and transportation extension, which could be summarized as urbanization factor. The principal component II could be connected with the indexes of

industrial structure improvement (such as A_9 , A_{10} , A_{11} , variable loading over 0.8), so, it might be seen as industrial structure factor.

Table 2 Correlation coefficient among urban expansion driving factors

Index type	Social-economic index	Correlation coefficient		Variable loading	
		Vertical	Horizontal	I	II
Population growth	Total population (A_1)	0.788**	0.918**	0.653	0.694
	Urban population (A_2)	0.657**	0.980**	0.809	0.572
	Urbanization rate (A_3)	0.623**	0.985**	0.834	0.542
Economic increase	Total GDP (A_4)	0.577**	0.979**	0.860	0.509
	GDP per capita (A_5)	0.589**	0.981**	0.851	0.528
	Output of primary industry (A_6)	0.838**	0.937**	0.590	0.795
	Output of secondary industry (A_7)	0.569**	0.978**	0.866	0.496
	Output of tertiary industry (A_8)	0.578**	0.977**	0.855	0.513
Industrial structure improvement	Proportion of primary industry (A_9)	-0.802**	-0.863**	-0.527	-0.801
	Proportion of secondary industry (A_{10})	-0.910**	-0.860**	-0.421	-0.897
	Proportion of tertiary industry (A_{11})	0.901**	0.877**	0.454	0.885
Social development	Fixed assets investment (A_{12})	0.674**	0.975**	0.761	0.620
	Real estate investment (A_{13})	0.620**	0.962**	0.796	0.563
	Dwellers wages (A_{14})	0.666**	0.981**	0.789	0.610
Transportation extension	Total road length (A_{15})	0.522*	0.945**	0.872	0.459
	Total road area (A_{16})	0.463*	0.927**	0.898	0.397

Notes: **Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)

Finally, built-up area (horizontal space, Y_1) and average height (vertical space, Y_2) were designed as dependent variables, as well as the two principal components (X_1 and X_2) obtained from principal component analysis as independent variables. X_1 denoted urbanization factors and X_2 represented industrial structure factor.

Using forward stepwise model selection method, two linear regression equations were obtained. Table 3 indicated that urbanization process was the major driving force for the city's horizontal expansion, while industrial structure improvement was the key driving factor for vertical expansion.

Table 3 Regression equation of urban expansion in Shanghai

Spatial type	Regression equation	Adjusted R^2	F value	Significance
Horizontal space	$Y_1=428.903+164.927X_1+121.903X_2$	0.963	272.632	0.00
Vertical space	$Y_2=65.355+8.037X_2$	0.945	359.992	0.00

4.2 Driving mechanism of urban expansion

The driving mechanism of urban expansion affected by urbanization and industrial structure improvement of Shanghai could be demonstrated by four phenomena. 1) Construction of industrial zones. By the end of 2006, there had been 842 national development zones and 2,859 municipal development zones in Shanghai, such as Shanghai Hongqiao and Minhang Economic & Technological Development Zones, Jinqiao Export Processing Zone, Caohejing High & New Technological Development Zone, Jinshan and Caojing Chemical Industry Bases and so on. Only in 2006, the total industrial product value of those industrial zones was 860×10^9 yuan (RMB), accounting for 83.2% in Shanghai's total GDP. The industrial zones were mainly established in

the suburbs, which could easily lead to the expansion of built-up area. Figure 3 showed that from 1992 to 1999, the horizontal space (built-up area) expansion velocity began to accelerate. 2) Influences of differential land rent. With the increased land price in city center, the industrial layout presented a diffusing phenomenon from the core city to suburbs. The heavy industries and traditional industries with low efficiency per unit land in central area tended to migrate towards the suburbs or outer suburbs, where land price was lower than that of core city. 3) Population migration. On the one hand, old-city reconstruction along with the fast development of real estate business in the core city reduced the living space of floating population, thus compelled them to spread to the suburbs. On the other hand, with thriving

economy in the suburbs, urban infrastructure and living situations were improved, attracting large number of population migrated from surrounding provinces. Based on the Fifth National Population Census data from Shanghai Statistical Bureau (Shanghai Statistical Bureau, 2000), in the 1990s, the population growth in core city was much slower than that of the suburbs. The core city's population increased only 234×10^3 in the 10 years, by contrast, the population reached 2.6×10^6 in the suburbs. As Table 1 showed the increase rate of high-rise buildings in the suburbs was faster than that of the core city from 1992 to 1999, which was an embodiment of the suburbanization process from other side. 4) Transportation expansion. The development of transportation systems boosted the improvement of traffic condition in each district, thereby changed the distribution of building construction and affected urban spatial expansion (Wang et al., 2007). The promotion of efficiency in transportation system could also encourage the transformation of urban growth pattern from centralization to suburbanization, and enhance the business communication among districts. In the 1990s, Shanghai's urban expansion was developed along the main traffic arteries that fan out from the city centre. The allocation of town groups with close economic relationship and complementary function also followed the line of traffic corridor (Liu and Shen, 2006).

The results about driving forces of urban horizontal expansion in this paper were similar to Liu and Shen's research, in which the development of agriculture and industry, relocation and construction of residential areas, transportation system, differential land rent, foreign investment utilization and technology import were assumed to be the main driving factors affecting Shanghai's urban expansion (Liu and Shen, 2006). They also pointed out that, in different stages, the intensity and fashion of those driving forces imposed on Shanghai's urban expansion were inconsistent. Nevertheless, little was mentioned about vertical expansion. As shown in Fig. 2, we attributed the variation of vertical space in Shanghai to the industrial structure improvement, which in some way altered high-rise building's composition structure.

4.3 Policy influence on urban expansion

Apart from economic and demographic factors, policy had predominant influence on Shanghai's urban expansion through all stages. Most obviously, the continuous

extension of Shanghai's districts in some extent explained the leaping growth of built-up area. There were five districts set up in Shanghai during 1992–1999: Pudong New District was set up in 1992; Jiading County was evacuated, with Jiading District established in 1992; Jinshan, Songjiang, and Qingpu counties were evacuated, with the corresponding districts established in 1997, 1998 and 1999, respectively.

In the 1980s, restricted by the urban development guideline of “strictly controlling large cities, rationally developing medium-size cities, and actively developing small cities and towns” (Luo, 1988), the spatial expansion of Shanghai was rather slow. The population and economic scale were at a relatively low level, and urban construction was concentrated mainly in core area.

In the 1990s, affected by the policy of “actively promoting the construction of national high and new technology industry development zone” (Xu et al., 2007), Shanghai's urban expansion gradually sped up. In August 1990, the establishment of Lujiazui Financial and Trading Zone, Jinqiao Export Manufacturing Zone and Waigaoqiao Bonded Area were considered as the start of Pudong New District's splendid development. After that, the focus of Shanghai urban construction transferred from core area to the suburbs. Along with the rapid development of residential buildings, industrial parks and university campuses, suburban agricultural land had shrunk gradually, and urban landscape had changed dramatically (Rui, 2007). In addition, the central government's gradual loose of control on household registration makes rural population transfer easier into urban population, attracting large number of immigrants to Shanghai.

In the 21th century, Shanghai has drawn up the 1966 construction plans of urban system (1 core city, 9 new cities, 60 new towns and 600 core villages), promoting the flow of current, technology and information from city center towards outskirt areas, and speeding up the space allocation and structure adjustment. From the spatial perspective, Shanghai would gradually get rid of the single cored development pattern, and enter the new phase of multi-centered, multi-layered, networked urban system development.

5 Conclusions

To grasp the complex process of urban space expansion

would help understand the nature of urbanization, also provide timely reference for decision making on sustainable urban development and construction planning. This paper took urban vertical expansion as a new breakthrough point for urban expansion research, preliminarily investigated the spatial and temporal development process and driving forces of urban expansion. Based on the Shanghai's statistical data, we described the picture of urban three-dimensional space change via two indexes: average high-rise building's height and urban built-up area, which represented vertical space and horizontal space, respectively. Furthermore, we introduced the three-dimension spatial index and velocity variation index to delimit the stages of urban space growth. The results indicted Shanghai's spatial expansion has shifted from the vertical expansion in dominance into the horizontal expansion in dominance. Shanghai is just among the transition phase: from fast growth (horizontal expansion) to slow growth (vertical expansion or inside filling). The periodic feature of economic development determined the periodical replacement of urban expansion patterns, therefore, urban vertical growth should be the leading direction in the future. Urbanization process was the major driving force for the city's horizontal expansion, while industrial structure improvement was the key driving factor for vertical expansion. These two driving forces were simultaneously affected by city's political factors. The average height of high-rise buildings could be considered as a new index of analyzing urban spatial development. The research process and method of this paper could be used in other mega cities, which might deepen the understanding of the process and regularity of urban expansion through comparison study.

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