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Monitoring the Different Types of Urban Construction Land Expansion (UCLE) in China's Port City: A Case Study of Ningbo's Central City

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Abstract: The internal structure of urban construction land expansion (UCLE) is closely related to urban sustainability, and the UCLE in China's port city has a unique pattern. This study attempted to monitor the internal structure evolution of UCLE based on construction land transfer data in Ningbo's central city from 2002 to 2015. Equality fan analysis and kernel density analysis were applied to characterize the spatial–temporal dynamics of different types of UCLE and to summarize their evolution patterns. The results revealed that in the whole study area, the rank of the expansion size and intensity of construction land was: industrial land > traffic land > residential land > public land > commercial land. The dominant directions of all types of UCLE were the directions of the port zones. In the port zones, there were more apparent expansion trends and higher expansion intensities of industrial, traffic and public lands, which meant that the port had significant impact on UCLE, especially in terms of industrial land. Additionally, commercial and residential land expansions showed a circle-shaped gradient pattern; industrial land sprawl was in a leapfrog pattern; public and traffic land sprawl was illustrated in a bi-centric pattern. In the future, local government should encourage the development of residential and public land rather than industrial land, and shift the present industry structure which dominated by industry to a more balanced structure, in order to achieve sustainable development.

Keywords: urban construction land expansion; internal structure; spatial–temporal analysis; evolution pattern; industry structure; Ningbo; port

1. Introduction

Urban construction land expansion (UCLE) is the key research area of urban planning and urban geography which has attracted the attention of many decision makers, planners and scholars [1]. The internal structure of UCLE is the reflection of urbanization quality [2]. Meanwhile, the evolution of land use structure is strongly linked to urban socio-economic development and ecological environment protection [3,4]. Therefore, creating a suitable internal structure of UCLE is beneficial to effective allocation of urban land resources, as well as social and economic sustainable development [4,5].

In recent years, western developed countries have entered into the post-industrial era, which has generated many new urbanization problems, such as imbalanced urban land use structure, inner city decay and traffic congestion. In order to alleviate these problems, many scholars have carried out numerous studies, which cover the following aspects: urban spatial extension and sprawl [6–11], industrial spatial layout [12,13], urban land use changes [14–17], and traffic organization [18,19], all of which has provided an important theoretical support for the study of UCLE.

China is now undergoing a period of rapid urbanization, which has brought about a fast reconstruction and expansion of urban construction land. In this context, UCLE showed the characteristics of diversification and complexity [20–22]. Common problems such as imbalanced urban land use structure, traffic congestion, and unordered sprawl exist in metropolitan area, which has resulted in the low efficiency of urban production–living–service space formation and urban operation [4,23–26]. As an aspect of empirical research of UCLE, most of the domestic scholars had either studied the expansion, the morphological characteristics and spatial patterns of urban overall construction land [27–29] or concentrated on the research of a single type of urban construction land, e.g., industrial land, residential land and business service land [30–33]. Hence, the studies on the internal structure, and the spatial–temporal characteristics and evolution pattern of UCLE are insufficient.

The basis of urban land allocation in China has been the transfer system of construction land use right, which attempted to form a reasonable internal structure of UCLE. This system derived from the "State-owned land access rules of invitation for bid, auction and hanging out shingle" (implemented from 1 July 2002). According to this regulation, all kinds of profit-oriented lands such as business, tourism, entertainment and commodity residential lands must be transferred through bidding, auction or listing [34,35]. It was conducive to give the market the significant role in optimal allocation of land resources [4,26]. Meanwhile, the study of UCLE can be enhanced by classification of the expanded construction land into different sub-types. This will help to uncover the internal structure of the land and subsequently improve the overall efficiency of the urban land.

UCLE has similar situations in port cities and general cities. However, due to the special status of ports, ports play a significant role in UCLE. Therefore distinct spatial–temporal characteristics and evolution pattern of UCLE emerge in port cities [36]. In this study, we took a famous port city in Eastern China—Ningbo's central city as our study area. From the 1990s, the Ningbo government overemphasized and focused on industrial development, especially harbor industry development, rather than the improvement of a high quality service sector [37], which has resulted in slow growth of GDP and a low contribution of service sector (tertiary industry) to GDP. In comparison to a neighboring major city such as Hangzhou, as of 2015, the contribution of the tertiary industry to GDP was nearly 20% greater than the secondary industry [38]. However, for Ningbo, the contribution of the tertiary industry was 1.6% less than the secondary industry [39]. Moreover, overestimating the industrial sector will sacrifice environmental quality and reduce the livability of the city, as well as obstruct human capital which is required for the development of service sector [40]. Hence, it is important to generate suitable internal structure of UCLE, which will guide more reasonable industry development. The industry development should be transformed from an industry-dominated mode into a service industry-dominated mode, in order to form new and green industry structure. This new industry structure will better protect Ningbo's natural environment, create good quality urban living and promote a shift from production city to livable city [37]. In short, the suitable UCLE along with the new industry structure will make the city and human settlements more harmonious and sustainable.

This study attempted to monitor the internal structure evolution of UCLE based on construction land transfer data in Ningbo's central city from 2002 to 2015. Three major goals were as follows: (a) characterizing the spatial–temporal dynamics of different types of UCLE in the whole central city and the port zones; (b) summarizing evolution pattern of each type of UCLE and (c) revealing the impact of port on UCLE, and to promote sustainable UCLE and sustainable development of social economy in a port city. The results of this study will provide benefit to optimizing the internal structure and space layout of UCLE, as well as provide reference and support for the formulation of urban master plan and relative development policies.

2. Materials and Methods

2.1. Study Area

Ningbo City is located in the middle of China's coastline and the southern part of Yangtze River Delta. Ningbo Port consists of Beilun Port Zone, Zhenhai Port Zone, Ningbo Port Zone, Daxie Port Zone and Chuanshangang Port Zone; it is an important foreign trade port and shipping transit hub in the history of China. Ningbo is the fourth largest port city in the world, and is one of the fifteen strongest comprehensive and competitive cities in the Chinese mainland. It is also among the five regional centers in Yangtze River Delta. According to The General Report of Ningbo City Development Strategy to 2030, one of the development goals is transforming Ningbo from the port city into the Asia–Pacific international gateway city through strengthening the construction of an integrated transportation hub, and reinforcing the cultivation of core functions, such as trade and service industry. Another goal is creating a more ecological and livable city through protecting distinctive and superior natural environment (e.g., mountains, sea, rivers, lakes, islands), and improving the quality of urban life [37,41].

Ningbo City consists of six districts (i.e., Haishu, Jiangdong, Jiangbei, Zhenhai, Beilun and Yinzhou), two counties (i.e., Ninghai and Xiangshan) and three county-level cities (i.e., Yuyao, Cixi and Fenghua). Ningbo's central city covers the scope of six districts with an area of 2560 km^2 (Figure 1). Central city is located in Ningshao Plain; the terrain is high in southwest part and low in northeast part. Haishu, Jiangdong and Jiangbei districts are located in the center of the city, and these districts are the core carriers of the urban functions, namely they are political, economic and cultural centers. Zhenhai is one of the important ports for China's foreign communication. Beilun is a crucial part of the international shipping center in northeast Asia, and is an important manufacturing base in East China. It is also a modern logistics center in the region. Yinzhou has developed high-end manufacturing and modern service industries. Furthermore, Yinzhou is the incubator of new industries; the comprehensive economic strength ranks first in Ningbo.

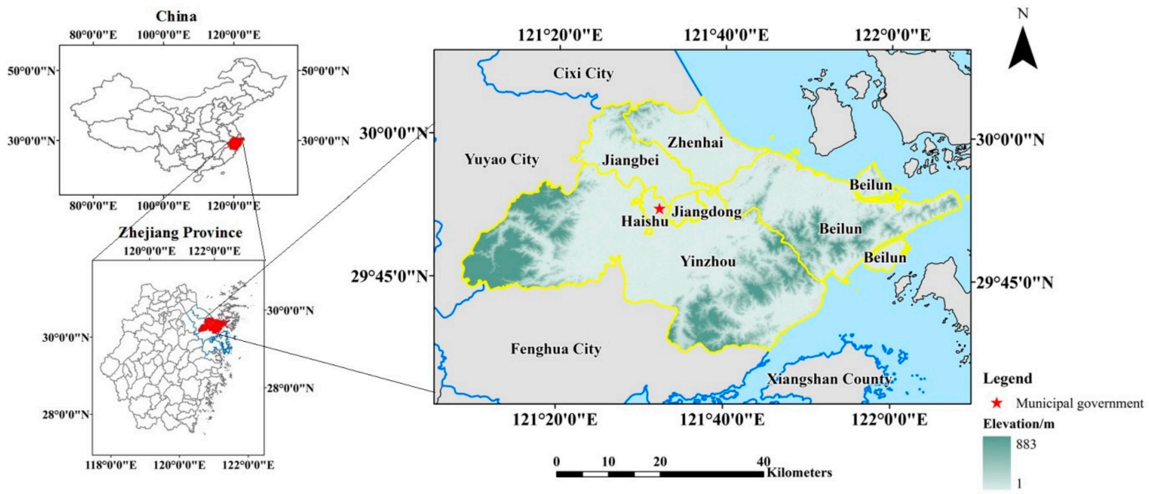


Figure 1. Location of Ningbo's central city; the yellow line area: the central city; the blue line area: the surrounding counties and cities. Note: the administrative division within Ningbo's central city was adjusted in 2016, but the overall administrative region of the central city was not changed. As the study period in this paper was 2002–2015, we used the old administrative division.

2.2. Data Preparation

Urban construction land transfer data in our study were obtained from the Ningbo Municipal Bureau of Land Resources. The land transfer records from 2002 to 2015 included the names and numbers of development projects, processing time, land areas, land prices and so on. The construction land data were imported into ArcGIS 10.1 software (Esri Inc., Redlands, CA, USA), and time division and land classification were implemented. Urban construction lands in this paper were divided into the following six categories: commercial land, residential land, industrial land, public administration and service land (public land), traffic land and other land. In order to maintain the integrity of the data, other land was included in this classification. However, because other land was relatively stable and it was not the research focus, the other five types of UCLE were mainly analyzed in this paper. The description, corresponding industry type and land area of each type of construction land can be found in Table 1. The corresponding industry types were displayed to help understand the situation of industry development along with the different types of UCLE.

Table 1. Urban construction land classification system.

The Type of Construction Land	Description	Corresponding Industry Type	Expansion Area in 2002–2015 (ha)	The Proportion of Total Expansion Area (%)
Commercial land	Land used for trade, tourism, entertainment and other services	Tertiary industry: wholesale and retail, accommodation and catering, financial industry, commercial service industry, culture, sports and entertainment	1711.93	5.21
Residential land	Land used for commercial housings and rural residential lands	Secondary industry: construction industry; Tertiary industry: real estate	6827.35	20.76
Industrial land	Land used for factories, storage and logistics	Secondary industry: manufacturing industry, production and supply of electricity, gas and water; Tertiary industry: storage and logistics	11,304.85	34.37
Public administration and service land	Land used for government agency, charity, science and education, public facilities, parks and green spaces	Tertiary industry: public facilities management, education, health, social security and social welfare, public management and social organization	3875.34	11.78
Traffic land	Land used for highways, railways, ports and piers, streets and alleys	Tertiary industry: transportation industry	7639.66	23.23
Other land	Land used for water conservancy facilities, special use areas (e.g., religious lands and burial lands)	Tertiary industry: water conservancy and other services	1528.16	4.65

Other geographical spatial data included existing urban construction lands vector data before 2002 and port zones vector data, which were sourced from the Ningbo Municipal Bureau of Land Resources. In addition, social and economic statistical data from 2002–2015 were derived from Ningbo Statistical Yearbooks [42] and Statistical Bulletins of Ningbo's National Economy and Social Development [43].

2.3. Methods

2.3.1. Equality Fan Analysis

Equality fan analysis was used to reveal the spatial–temporal differences of urban expansion through analyzing anisotropy of UCLE. This meant the spatial–temporal differences of urban expansion can be shown by increased areas, expansion speeds and expansion intensities of construction lands in different orientations [24,44,45]. The specific steps were as follows: (1) in ArcGIS 10.1 software, the municipal government was set as center and the orientation of east by north (22°50′) was chosen as the starting point to draw 16 equal fans with proper radius size (60 km); (2) the line file was transformed to the shape file, and "Analysis Tools/Overlay/Intersect" was applied to divide 16 sector areas; (3) the expansion areas of each type of construction land in each sector area were extracted; (4) the expansion intensity index of each type of construction land in each sector area was calculated. Expansion intensity index was applied to analyze and describe the extended status of urban construction land. The intensities, speeds and trends of UCLE in different orientations and different periods could be compared by this index [46–48]. Expansion intensity index was expressed in Formula (1):

$$\mathrm{EI} = \Delta U_{ij} / \left(\Delta t_j \times TLA_i\right) \times 100 \tag{1}$$

where ΔU_{ij} refers to the expansion area of construction land in ith research unit in jth period; Δt_j refers to time span of jth period; TLA_i refers to the total land area of ith research unit.

In order to highlight the dominant direction of urban expansion, Nature Breaks was used for determining five spatial expansion types based on the values of expansion intensity index (i.e., >0.08 was high-speed extension, 0.04–0.08 was fast-speed extension, 0.02–0.04 was medium-speed extension, 0.01–0.02 was slow extension, 0–0.01 was basic stability) [44]. If the spatial expansion types of adjacent orientations were high-speed extension and/or fast-speed extension, these adjacent orientations were combined together to form the urban dominant extension wing.

2.3.2. Kernel Density Analysis

Kernel density analysis was used to embody the gathering of construction land parcels based on some land attributes (e.g., land area) and generated hotspot maps [49]. In this analysis, firstly, a symmetrical surface was set over each point (i.e., mass center of each land parcel); then the distance from the surface to a reference position was calculated according to a Gaussian kernel function; finally, the distances from all the surfaces to that reference position were summed [50]. This analysis could evaluate local probabilities and degree of tectonic activities in the region [4,26]. Moreover, this analysis enabled us to show the spatial morphological changes of UCLE, and to reveal urban development process and the succession degree of functional space. Kernel density was expressed in Formula (2):

$$\mathrm{f}(x,y) = 1/\left(nh^2\right)\sum_{i=1}^{n} K(d_i/h) \quad (2)$$

where $\mathrm{f}(x,y)$ refers to the density in the position (x,y); n refers to the number of observation objects, h refers to bandwidth or kernel size, K refers to kernel function (i.e., land size), and d_i refers to the distance from the position (x,y) to the position of ith observation object.

3. Results

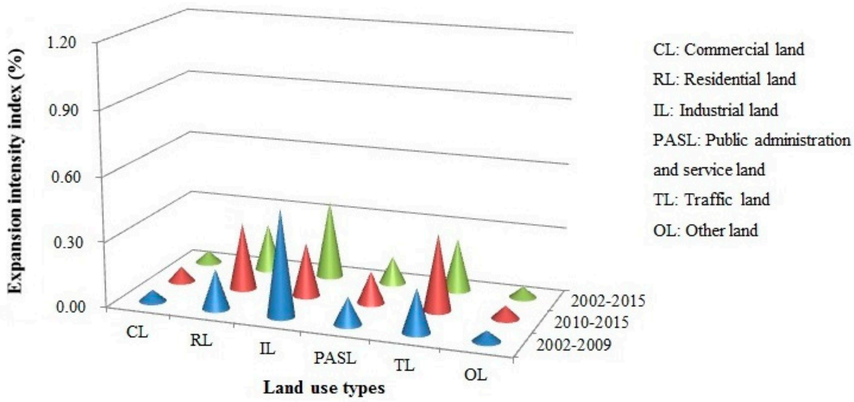
3.1. Spatial–Temporal Characteristics of UCLE

3.1.1. The Whole Central City

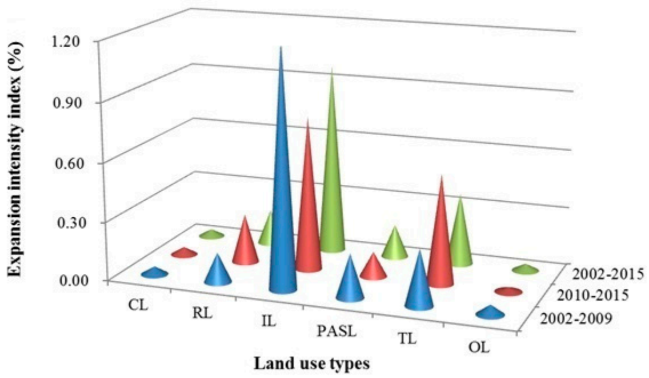
In terms of temporal characteristic, urban construction land expanded drastically throughout the whole study period with the area of 32,887.29 ha and the expansion intensity of 1.06% (Table 2). The extended areas and intensities of industrial, traffic and residential lands were much larger than that of public, commercial and other lands. Industrial land had the largest and strongest expansion in Ningbo's central city in 2002–2015. Although the extended area of total construction land in the period of 2010–2015 (14,247.63 ha) was less than that in the period of 2002–2009 (18,639.66 ha), the expansion intensity from 2010 to 2015 (1.19%) was larger than that from 2002 to 2009 (1.11%). It was interesting that, except for industrial land, the expansion intensities of other types of construction land in the latter period was greater than that in the previous period, especially residential and traffic land (Figure 2a).

Table 2. Area and expansion intensity index of urban construction land expansion (UCLE) in the whole central city.

The Type of Urban Construction Land	Area (ha)			Expansion Intensity Index (%)		
	2002–2009	2010–2015	2002–2015	2002–2009	2010–2015	2002–2015
Commercial land	889.98	821.95	1711.93	0.0530	0.0686	0.0549
Residential land	3114.94	3712.41	6827.35	0.1856	0.3097	0.2191
Industrial land	8324.68	2980.17	11,304.85	0.4961	0.2486	0.3627
Public administration and service land	2105.59	1769.75	3875.34	0.1255	0.1476	0.1243
Traffic land	3390.95	4248.71	7639.66	0.2021	0.3545	0.2451
Other land	813.52	714.64	1528.16	0.0485	0.0596	0.0490
Sum	18,639.66	14,247.63	32,887.29	1.1107	1.1886	1.0553



(a)



(b)

Figure 2. Figures of expansion intensity indices of UCLE in (**a**) the whole central city and (**b**) the port zones in the three periods of 2002–2009, 2010–2015 and 2002–2015.

In terms of spatial characteristics, the entire spatial pattern of UCLE is shown in Figure 3. UCLE was mainly adjacent to the existing construction land and presented a pattern of outward expansion from the center. Urban sprawl mainly occurred in the middle and east part of central city during the entire study period. Yinzhou, Zhenhai and Beilun Districts had a clear trend of construction land diffusion, while the urban expansion in the traditional urban center (i.e., Haishu, Jiangdong and Jiangbei Districts) was relatively compressive. However, it was noteworthy that all types of construction lands mainly expanded in Yinzhou, Zhenhai and Beilun Districts from 2002 to 2009, while they increased slowly in these three districts and maintained steady expansion in the traditional urban center from 2010 to 2015. Industrial, traffic, residential and public lands had wider extended scopes of expansion than that of commercial land in 2002–2015. The extended scope of commercial land was mainly concentrated in the traditional urban center and its surrounding areas.

3.1.2. The Port Zones

In terms of temporal characteristics, there was a significant urban sprawl in the port zones in the study period, and the area and the expansion intensity of UCLE was 7286.54 ha and 1.77%, respectively (Table 3). The increased trend of different types of construction lands in the port zones was similar to that of the whole central city. However, the expansion intensities of industrial land in the three periods (i.e., 1.26%, 0.79% and 0.98% respectively) were all much larger than that (i.e., 0.5%, 025% and 0.36% respectively) of the whole study area (Figure 2a,b). Traffic and public lands also had higher expansion intensities when compared to the situation in the whole central city. It was worth noting that the extended area and intensity of total construction land in the period of 2010–2015 had an obvious decreasing tendency, while residential and traffic lands showed a rising trend (Figure 2b).

In terms of spatial characteristics, the spatial pattern of UCLE in the port zones is displayed in Figure 3. UCLE were adjacent to the existing construction land in the port zones of Beilun District, while the expansion of new and isolated construction lands occurred in the port zones of Zhenhai District. There were prominent expansions of industrial, traffic, public and residential lands in 2002–2009, especially industrial land, while there was less expansion scope of construction lands in 2010–2015.

Table 3. Area and expansion intensity index of UCLE in the port zones.

The Type of Urban Construction Land	Area (ha)			Expansion Intensity Index (%)		
	2002–2009	2010–2015	2002–2015	2002–2009	2010–2015	2002–2015
Commercial land	91.43	62.62	154.05	0.0412	0.0395	0.0374
Residential land	338.57	398.07	736.64	0.1526	0.2511	0.1787
Industrial land	2785.33	1248.09	4033.42	1.2552	0.7874	0.9787
Public administration and service land	494.25	201.51	695.76	0.2227	0.1271	0.1688
Traffic land	632.92	887.08	1520	0.2852	0.5597	0.3688
Other land	110.61	36.06	146.67	0.0498	0.0227	0.0356
Sum	4453.11	2833.43	7286.54	2.0067	1.7876	1.7681

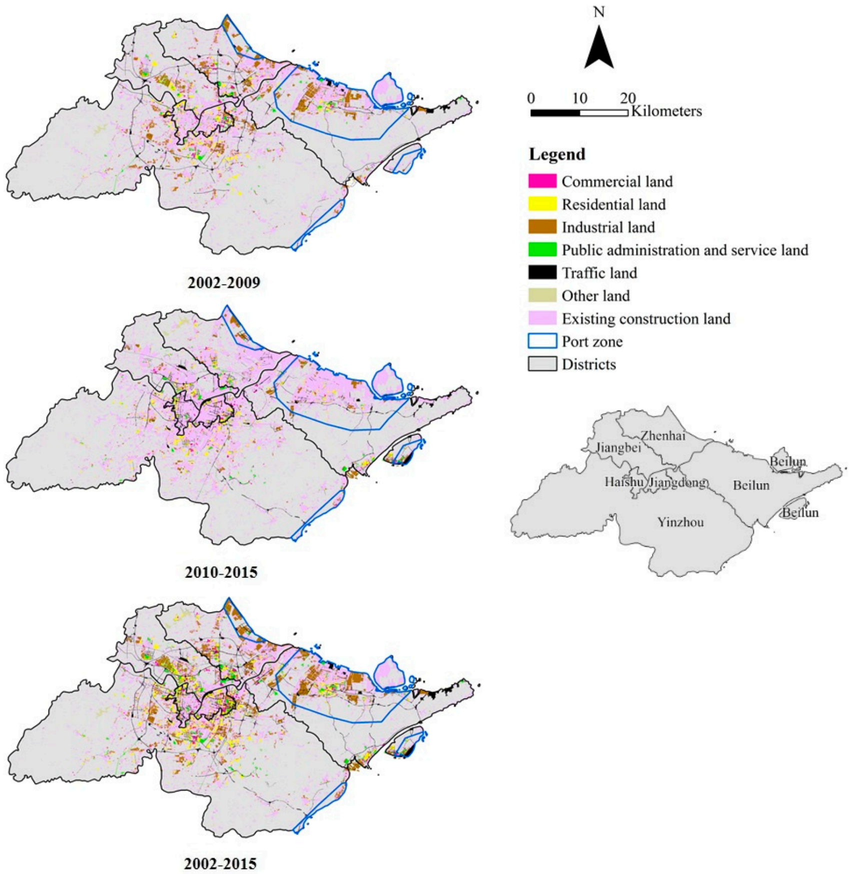


Figure 3. Figures of UCLE in the three periods of 2002–2009, 2010–2015 and 2002–2015.

3.2. Spatial Differentiation of UCLE

The sector zoning map and the results of equality fan analysis were shown in Figure 4 and Table A1. In order to show spatial anisotropy and the dominant direction of urban development more intuitively, we drew radar maps and summarized five spatial expansion types of UCLE, which can be found in Figure 5 and Table A2. During the period of 2002–2009, only industrial and traffic land had obvious directional expansions. The dominant extension wings of industrial land were N-NNE and NE-NEE-E, and the traffic land's dominant extension wing was NEE-E-SEE. Between 2010 and 2015, except for commercial land, four other types of UCLE had significant directional expansions. The dominant extension wings of these construction lands were as follows: (a) residential land: NEE-E-SEE and N-NNE; (b) industrial land: NNE-NE and NEE-E-SEE; (c) public land: NNE-NE-NEE-E-SEE; (d) traffic land: NE-NEE-E-SEE and NW-NNW. During the entire study period, NEE-E-SEE was the major expansion wing of all five types of construction land, which covered most of the port zones in the Beilun District. Moreover, another major expansion wing of industrial land was N-NNE-NE, which was the orientation of the port zone in the Zhenhai District.

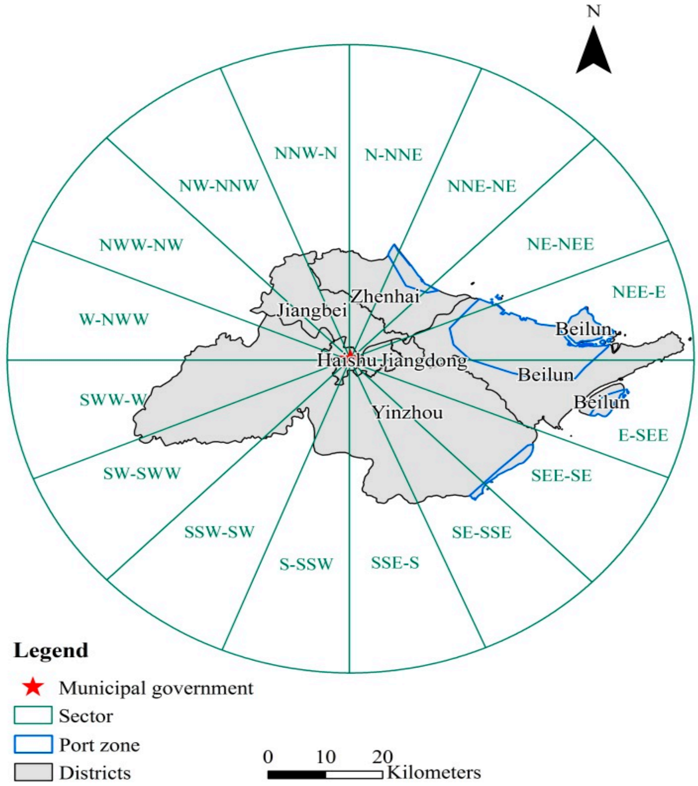


Figure 4. The sector zoning map of equality fan analysis.

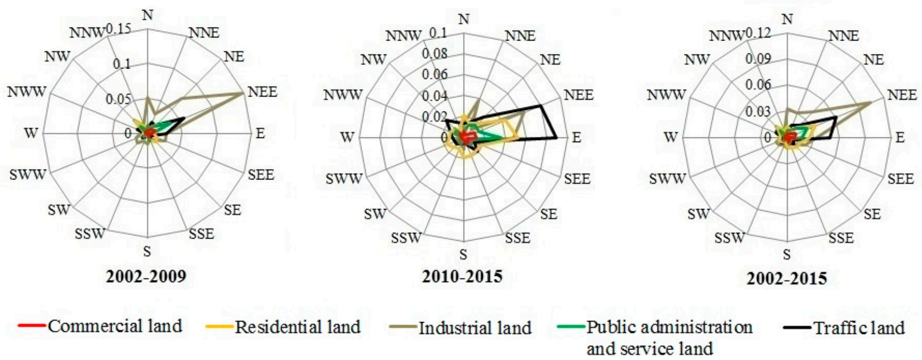


Figure 5. Rader maps of expansion intensities of urban construction lands in the three periods of 2002–2009, 2010–2015 and 2002–2015.

3.3. Evolution Pattern of UCLE

To further reveal the dynamic evolution pattern of UCLE, we used kernel density analysis to evaluate the sprawl tendency of five types of construction lands (Figure 6): (a) Commercial and residential lands showed an increasing trend from the traditional urban center extended to Yinzhou, Zhenhai and Beilun Districts from 2002 to 2015 (Figure 6a–f). The hotspot areas of these two types of construction lands were distributed in the middle and east of the central city, which included some part of the port zones in the Beilun District; (b) Industrial land expansion clustered outside the urban center and located mainly in Zhenhai, Beilun and Yinzhou Districts (Figure 6g–i). In the period of 2002–2009, industrial land sprawled mainly in the west and the east, the eastern part of hotspot areas covered the most of the port zones in Zhenhai and Beilun Districts (Figure 6g); and in the period of 2010–2015, the hotspot areas only aggregated in the port zones (Figure 6h); (c) Public land sprawl moved from the middle to the east and the south, and the hotspot areas were located in the middle and the east (i.e., the port zones of Beilun District) of the central city between 2002 and 2015 (Figure 6j–l); (d) The directions of traffic land expansion were west, north and east, and the hotspot areas were mainly distributed in Yinzhou and the port zones of Zhenhai and Beilun Districts from 2002 to 2009 (Figure 6m). However, traffic land sprawl was concentrated in the traditional urban center from 2010 to 2015 (Figure 6n). Hence, the hotspot areas of traffic land expansion contained the traditional urban center and the port zones of Beilun District during the entire study period (Figure 6o).

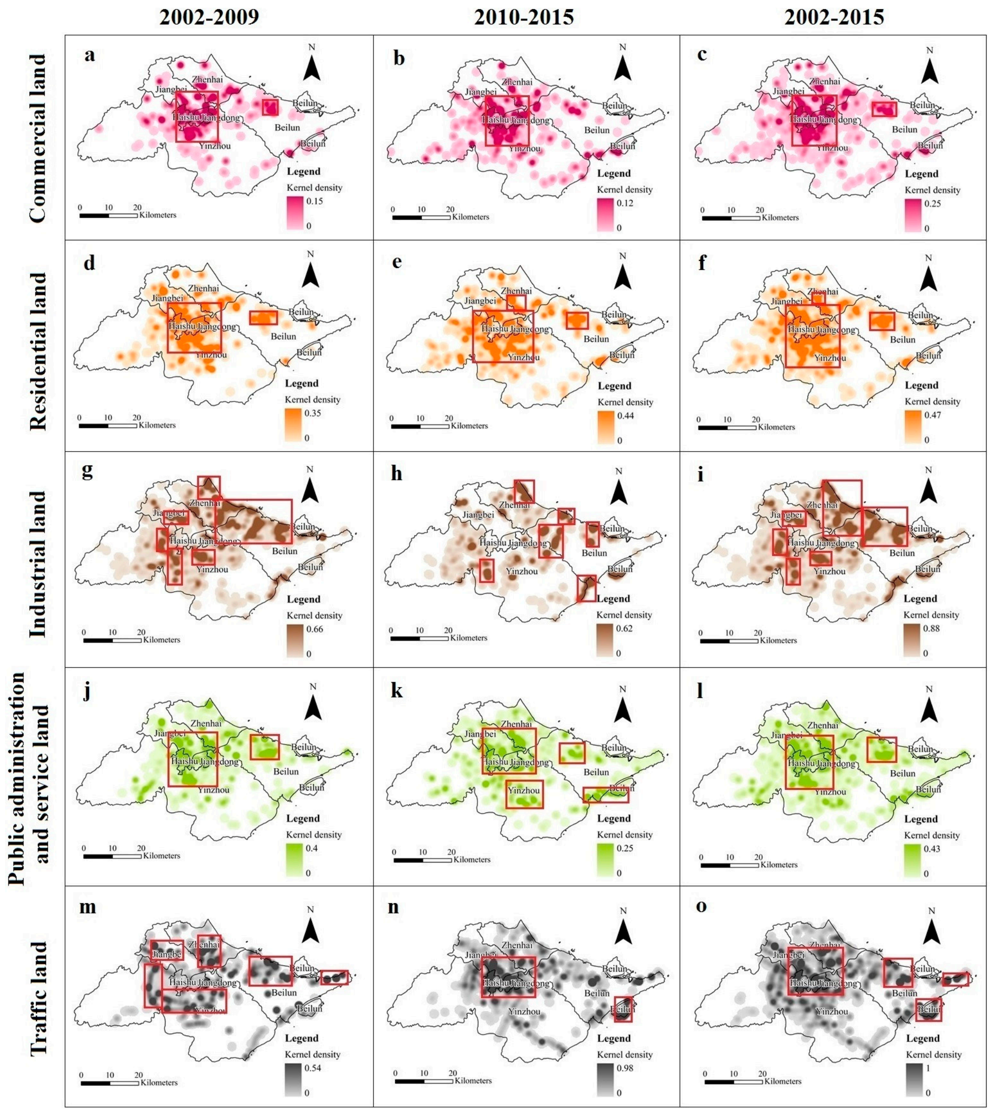


Figure 6. Hotspot maps of UCLE in the three periods of 2002–2009, 2010–2015 and 2002–2015; the red rectangle regions represent the hotspot areas with high expansion densities and large expansion areas. Note: the red rectangles were drawn through visual judgment and Photoshop CS5 software (Adobe, San Jose, CA, USA).

4. Discussion

4.1. Spatial and Temporal Variation of UCLE

4.1.1. Temporal Variation

Ningbo is a famous industrial and commercial city in East China; its industry and commerce have been booming since the commercial port was opened. At the same time, Ningbo is the chemical industry base of Yangtze River Delta. Hence, along with the rapid development of economy, construction land showed sustained expansion in 2002–2015, especially industrial land.

In the period of 2002–2009, in order to overcome the global economic crisis, the Chinese government was committed to reinforcing infrastructure construction and promoting the prosperity of the real estate industry, modern service industry and other emerging industries [51]. In this background, all types of constructions lands in Ningbo's central city sprawled drastically, especially residential and industrial land. According to the Ningbo City Master Plan (2006–2020) (revised in 2015) (NCMP), the development direction of Ningbo was to become an advanced manufacturing base and an important foreign trade port. Additionally, in the NCMP, logistics parks and cargo hubs would be in centralized distribution, which combined with port, highway, railway, the aviation field and a large industrial park. For instance, the NCMP projected to place the main logistics center in the rear area of Beilun Port. These planning contents accelerated the rapid expansions of industrial, traffic and public lands, especially in the port zones.

In the period of 2010–2015, because of the staged adjustment of economy and industrial structure, the expansion areas of construction land were less than that in the previous period, both in the whole central city and in the port zones. However, the expansion intensity remained high, which derived from the large land demand with rapid economic development. Industrial upgrading encouraged the development of commercial land and limited the unordered sprawl of industrial land, which led to the steep drop of the expansion area and intensity of industrial land. In this period, although the Chinese government enacted some policies and measures to regulate and control the hyped real estate market and outrageous home prices, such as "Housing Restriction Policy" (issued in 2010) [22], the expansion area and intensity of residential land maintained a high level due to the enormous housing demand. The significant expansion of traffic land was consistent with the development idea of the central city in NCMP, the content of which was strengthening the connection between the central city (included the port zones) and the peripheral areas by rail transit, highway and expressway, and by building an open network system.

4.1.2. Spatial Variation

According to the current situation of land available for development being mainly located outside the traditional urban center, major expansions of construction land occurred in Yinzhou, Zhenhai and Beilun Districts (i.e., the areas cover the whole port zones) from 2002 to 2009. However, in recent years (i.e., 2010–2015), for the sake of protecting land resources and achieving sustainable land use, the local government converted the extensive land use pattern to an intensive and economical land use pattern, and concentrated on improving the utilized efficiency of the stock lands in the traditional urban center. So the construction lands maintained steady expansion in the urban center during this period. The traditional urban center was positioned as the complete and functional administrative and business center in NCMP, so financial, commercial service, culture and entertainment industries were encouraged, as opposed to traditional and heavy industries. It resulted in the situation where commercial land had larger sprawl than industrial land in this area between 2002 and 2015.

In the port zones, the prominent expansions of industrial, traffic and residential lands during the period of 2002–2009 corresponded with the planning layout of Beilun and Zhenhai Districts in the NCMP. The content of the planning layout was the banded and grouped development of living-dwelling zone and coastal industrial storage zone, which were connected by rapid transit.

A mass of industrial land expansion was closely related to the developed chemical engineering industry in the port zones. Ningbo Petrochemical Economic and Technological Development Zone (in Zhenhai District), Ningbo Economic and Technological Development Zone and Daxie Development Zone (in Beilun District) were vital chemical industry bases in Ningbo. There was less expansion scope for industrial land and other construction land during the period of 2010–2015, due to industrial upgrading and the transformation of land use pattern, which indicated that it would improve the comprehensive benefits of lands in the future. In addition, equality fan analysis proved that the located azimuths of port zones were the dominant extension wings of urban development in 2002–2015. It indicated that the actual urban sprawl in Ningbo was biased toward the port zones.

4.2. Spatial Evolution Pattern of UCLE

(a) Commercial and residential land expansions showed a circle-shaped gradient pattern from the traditional urban center to surrounding areas. However, commercial land gathered more centripetally than residential land. This may be because commercial lands were primarily sited in the areas with high land prices and good land use revenues, which was influenced by urban land prices. So the density of commercial land was the highest in the traditional urban center. Residential land also aggregated centripetally, and expanded outward with relatively high densities. It demonstrated that with the deepened degree of urbanization, the prosperity of the population and the economy has caused a huge housing demand. Furthermore, commercial and residential land also had an obvious sprawl in the port zones along with the growth of port trade and immigration; (b) Industrial land sprawled towards west and east and showed a leapfrog pattern, which was in accordance with the spatial distribution of major industries: high-end manufacturing and new industries in the Yinzhou District, and the chemical industry in the Zhenhai and Beilun Districts; (c) Public lands sprawled mainly around the traditional urban center and in the major port zones, which may have derived from the growing concerns of humanism and ecological harmony, thus local government aimed to reinforce the life service function and to build “Beautiful Ningbo”; (d) Traffic lands sprawled in the west, north and east of the central city in the previous period because the beltways of the traditional urban center and rapid transit in the port zones were constructed. In the latter period, traffic lands sprawled in the tradition urban center because of renewal projects of streets and alleys. The spatial evolution pattern of public and traffic land can be summarized as a bi-centric pattern, namely, two types of UCLE mainly agglomerated around the traditional urban center and in the port zones.

4.3. Sustainable Development in a Port City

4.3.1. Sustainable UCLE

The vision of sustainable UCLE involves decreasing the proportion of industrial land; increasing the proportions of residential land and public green space; guiding the balanced development of other types of construction lands [52]. Similarly, in order to respond to the call for intensive land use, and to avoid the problem of “value production space and despise living space”, local government should gradually reduce the quantity index of new industrial land and reserve sufficient residential and public land. It will not only conform to the principle of being “people-oriented”, but will also adapt to the rising level of economic and social development in Ningbo. At the same time, local government should improve the conditions of housing, transportation, education, culture, health and environment, expand the urban residential space and public life space, and steadily improve the quality of people’s life space.

The internal structure of UCLE in Ningbo was unreasonable, which was reflected by excessive industrial land expansion and insufficient residential and public land expansions. For the achievement of sustainable UCLE, local government should control the scale of industrial land in Yinzhou, Zhenhai and Beilun Districts, and increase the investment intensity, volume rate and building coefficient of industrial land. Residential land should be properly increased in and around the traditional urban center through activating the urban stock land and promoting the efficiency of land. Public land should be increased and equally allocated in the whole central city. Meanwhile, the public green space system should be improved and urban ecological landscapes should be beautified. Commercial land can be strengthened and appropriately increased in the traditional urban center and the port zones, so as to improve the business and service functions in the urban center and the port zones. Traffic land construction should be focused on the construction of a comprehensive intercity transportation network, based on the existing transportation lines and shipping hubs. These suggestions can provide reference and support for the formulation of an urban master plan and subsequent development policies.

4.3.2. Sustainable Development of the Social Economy

As an important port city, Ningbo's maritime transport and trade has become a significant driving force of economic development in industry and service sectors [40]. The positive correlation between port development and GDP growth is shown in Figure 7. Based on the continuous development of maritime transport and technology, Ningbo Port has played an important role in international trade and service, and the throughputs of cargo and containers increased rapidly in the two periods. However, the composition of GDP was suboptimal because the contribution of the secondary industry to GDP was excessive and the contribution of the tertiary industry needed to be improved. In addition, the GDP of secondary industry in Ningbo mainly came from heavy industry, such as steel, chemical engineering and petroleum industries, which would affect environmental quality and city's livability. It will create a dilemma of economic growth and environmental protection in the long term. Therefore, shifting the industry-dominated industry structure to a more balanced or a new service sector-dominated structure will reduce the environmental impact, as well as promote sustainable development of the social economy.

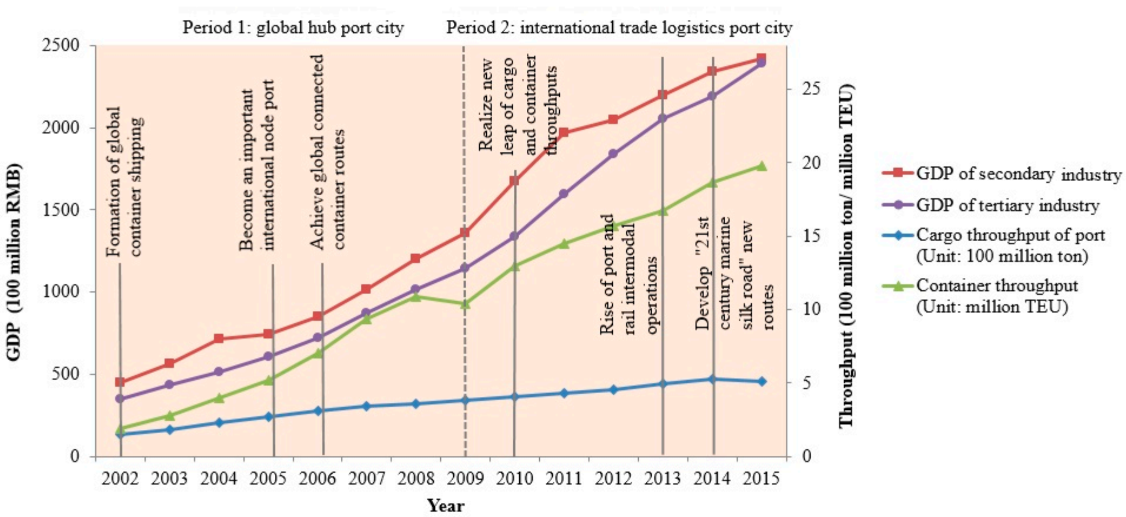


Figure 7. Diagram of economy and port developments from 2002 to 2015.

5. Conclusions

The previous studies mainly researched UCLE as a whole; and the internal structure of UCLE was not fully recognized. However, the various sprawls of different types of construction lands have great effects on retaining preponderant function and promoting sustainable development of the city. Furthermore, different types of UCLE in one of China's port cities represent unique spatial–temporal characteristics and pattern, so it is necessary to supplement this current study with other relevant studies in important port cities. Based on the methods of equality fan analysis and kernel density analysis, our study revealed spatial–temporal characteristics and spatial differentiation of five types of UCLE, and summarized their evolution patterns in Ningbo's central city during the period of 2002–2015. The main conclusions of these analyses were as follows:

(1) The overall UCLE in Ningbo's central city from 2002 to 2015 was huge and maintained a fast growth trend. The rank of the expansion size and intensity of construction land was: industrial land > traffic land > residential land > public land > commercial land. These UCLE were mainly adjacent to the existing construction land and presented a pattern of outward expansion from the urban center.
(2) The UCLE in the port zones was prominent and the expansion intensity was higher than that of the whole central city, especially industrial land. UCLE was adjacent to the existing construction land in the port zones of the Beilun District, while the expansion of new and isolated construction lands occurred in the port zones of the Zhenhai District.
(3) The dominant extension wings of all five types of construction lands were NEE-E-SEE and N-NNE-NE, which covered most of the port zones in the Zhenhai and Beilun Districts. It indicated that the actual urban sprawl in Ningbo was biased toward the port zones.
(4) Commercial and residential land expansions showed a circle-shaped gradient pattern from the traditional urban center to surrounding areas. Industrial land sprawled outside the traditional urban center and in the port zones, which showed a leapfrog pattern. Public and traffic lands expansions illustrated bi-centric pattern, which meant that these two types of UCLE mainly agglomerated around the traditional urban center and in the port zones.
(5) The internal structure of UCLE in Ningbo was unreasonable. Industrial land expansion should be controlled while residential and public lands should be increased to achieve sustainable UCLE. Additionally, the present industry structure, which was dominated by industry should be transformed to a more balanced structure to promote sustainable development of social economy.

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Appendix A

Table A1. The results of equality fan analysis.

Urban Construction Land	Fan Section	Area (ha)			Expansion Intensity Index (%)		
		2002–2009	2010–2015	2002–2015	2002–2009	2010–2015	2002–2015
Commercial land	N-NNE	47.83	65.67	113.50	0.0029	0.0055	0.0036
	NNE-NE	56.32	33.74	90.06	0.0034	0.0028	0.0029
	NE-NEE	123.85	36.59	160.44	0.0074	0.0031	0.0051
	NEE-E	195.03	136.96	331.99	0.0116	0.0114	0.0107
	E-SEE	117.61	142.64	260.25	0.0070	0.0119	0.0084
	SEE-SE	24.73	48.54	73.27	0.0015	0.0040	0.0024
	SE-SSE	34.74	80.42	115.16	0.0021	0.0067	0.0037
	SSE-S	99.51	77.76	177.27	0.0059	0.0065	0.0057
	S-SSW	13.3	23.84	37.14	0.0008	0.0020	0.0012
	SSW-SW	6.56	20.24	26.80	0.0004	0.0017	0.0009
	SW-SWW	27.6	29.9	57.50	0.0016	0.0025	0.0018
	SWW-W	35.23	17.22	52.45	0.0021	0.0014	0.0017
	W-NWW	7.08	13.96	21.04	0.0004	0.0012	0.0007
	NWW-NW	27.77	26.01	53.78	0.0017	0.0022	0.0017
	NW-NNW	38.24	51.68	89.92	0.0023	0.0043	0.0029
	NNW-N	34.58	16.78	51.36	0.0021	0.0014	0.0016

Table A1. *Cont.*

Urban Construction Land	Fan Section	Area (ha)			Expansion Intensity Index (%)		
		2002–2009	2010–2015	2002–2015	2002–2009	2010–2015	2002–2015
Residential land	N-NNE	139.3	253.19	392.49	0.0083	0.0211	0.0126
	NNE-NE	145.05	171.93	316.98	0.0086	0.0143	0.0102
	NE-NEE	254.27	219.49	473.76	0.0152	0.0183	0.0152
	NEE-E	591.21	521.48	1112.69	0.0352	0.0435	0.0357
	E-SEE	158.97	619.15	778.12	0.0095	0.0517	0.0250
	SEE-SE	268.17	224.86	493.03	0.0160	0.0188	0.0158
	SE-SSE	301.74	214.4	516.14	0.0180	0.0179	0.0166
	SSE-S	185.54	222.88	408.42	0.0111	0.0186	0.0131
	S-SSW	120.25	231.4	351.65	0.0072	0.0193	0.0113
	SSW-SW	35.05	128.77	163.82	0.0021	0.0107	0.0053
	SW-SWW	85.18	161.58	246.76	0.0051	0.0135	0.0079
	SWW-W	80.09	210.41	290.50	0.0048	0.0176	0.0093
	W-NWW	81.24	157.73	238.97	0.0048	0.0132	0.0077
	NWW-NW	106.63	164.72	271.35	0.0064	0.0137	0.0087
	NW-NNW	389.63	115.7	505.33	0.0232	0.0097	0.0162
	NNW-N	172.62	94.72	267.34	0.0103	0.0079	0.0086
Industrial land	N-NNE	856.85	164.75	1021.60	0.0511	0.0137	0.0328
	NNE-NE	496.1	452.93	949.03	0.0296	0.0378	0.0305
	NE-NEE	1174.32	123.01	1297.33	0.0700	0.0103	0.0416
	NEE-E	2474.81	749.95	3224.76	0.1475	0.0626	0.1035
	E-SEE	470.08	575.08	1045.16	0.0280	0.0480	0.0335
	SEE-SE	483.27	212.9	696.17	0.0288	0.0178	0.0223
	SE-SSE	239.48	83.74	323.22	0.0143	0.0070	0.0104
	SSE-S	136.89	14.71	151.60	0.0082	0.0012	0.0049
	S-SSW	257.01	135.35	392.36	0.0153	0.0113	0.0126
	SSW-SW	211.05	80.75	291.80	0.0126	0.0067	0.0094
	SW-SWW	336.34	54.43	390.77	0.0200	0.0045	0.0125
	SWW-W	296.53	108.3	404.83	0.0177	0.0090	0.0130
	W-NWW	154.81	30.6	185.41	0.0092	0.0026	0.0059
	NWW-NW	107.39	36.86	144.25	0.0064	0.0031	0.0046
	NW-NNW	432.91	141.82	574.73	0.0258	0.0118	0.0184
	NNW-N	196.84	14.99	211.83	0.0117	0.0013	0.0068
Public administration and service land	N-NNE	190.26	59.64	249.90	0.0113	0.0050	0.0080
	NNE-NE	122.66	152.73	275.39	0.0073	0.0127	0.0088
	NE-NEE	242.46	188.61	431.07	0.0144	0.0157	0.0138
	NEE-E	601.75	184.23	785.98	0.0359	0.0154	0.0252
	E-SEE	106.72	432.42	539.14	0.0064	0.0361	0.0173
	SEE-SE	42.83	80.9	123.73	0.0026	0.0067	0.0040
	SE-SSE	64.27	132.74	197.01	0.0038	0.0111	0.0063
	SSE-S	190.06	61.16	251.22	0.0113	0.0051	0.0081
	S-SSW	58.01	33.99	92.00	0.0035	0.0028	0.0030
	SSW-SW	14.64	81.95	96.59	0.0009	0.0068	0.0031
	SW-SWW	115.29	73.27	188.56	0.0069	0.0061	0.0061
	SWW-W	21.76	28.78	50.54	0.0013	0.0024	0.0016
	W-NWW	30.79	22.12	52.91	0.0018	0.0018	0.0017
	NWW-NW	28.92	103.39	132.31	0.0017	0.0086	0.0042
	NW-NNW	216.95	112.45	329.40	0.0129	0.0094	0.0106
	NNW-N	58.22	21.37	79.59	0.0035	0.0018	0.0026
Traffic land	N-NNE	122.64	159.21	281.85	0.0073	0.0133	0.0090
	NNE-NE	271.17	183.11	454.28	0.0162	0.0153	0.0146
	NE-NEE	267.48	332.74	600.22	0.0159	0.0278	0.0193
	NEE-E	945.31	958.06	1903.37	0.0563	0.0799	0.0611
	E-SEE	462.26	1056.63	1518.89	0.0275	0.0882	0.0487
	SEE-SE	133.32	138.01	271.33	0.0079	0.0115	0.0087
	SE-SSE	113.97	222.49	336.46	0.0068	0.0186	0.0108
	SSE-S	143.19	77.66	220.85	0.0085	0.0065	0.0071
	S-SSW	48.27	64.90	113.17	0.0029	0.0054	0.0036
	SSW-SW	90.24	84.21	174.45	0.0054	0.0070	0.0056
	SW-SWW	157.17	110.81	267.98	0.0094	0.0092	0.0086
	SWW-W	67.87	107.41	175.28	0.0040	0.0090	0.0056
	W-NWW	43.27	121.78	165.05	0.0026	0.0102	0.0053
	NWW-NW	251.89	166.25	418.14	0.0150	0.0139	0.0134
	NW-NNW	189.10	273.19	462.29	0.0113	0.0228	0.0148
	NNW-N	83.80	192.25	276.05	0.0050	0.0160	0.0089

Table A2. Spatial expansion types of UCLE.

Urban Construction Land	Spatial Extension Type	Orientation			Dominant Extension Wing		
		2002–2009	2010–2015	2002–2015	2002–2009	2010–2015	2002–2015
Commercial land	High-speed extension				NEE-E	NEE-E-SEE	NEE-E-SEE
	Fast-speed extension						
	Medium-speed extension						
	Slow extension	NEE-E	NEE-E, E-SEE	NEE-E			
	Basic stability	Others	Others	Others			
Residential land	High-speed extension				NE-NEE-E, NW-NNW-N, SEE-SE-SSE-S	NEE-E-SEE, N-NNE	NEE-E-SEE
	Fast-speed extension		NEE-E, E-SEE				
	Medium-speed extension	NEE-E, NW-NNW	N-NNE	NEE-E, E-SEE			
	Slow extension	NE-NEE, SEE-SE, SE-SSE, SSE-S, NNW-N	NNE-NE, NE-NEE, SEE-SE, SE-SSE, SSE-S, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW	N-NNE, NNE-NE, NE-NEE, SEE-SE, SE-SSE, SSE-S, S-SSW, NW-NNW			
	Basic stability	N-NNE, NNE-NE, E-SEE, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW	NW-NNW, NNW-N	SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW, NNW-N			
Industrial land	High-speed extension	NEE-E		NEE-E	N-NNE, NE-NEE-E	NNE-NE, NEE-E-SEE	N-NNE-NE-NEE-E-SEE
	Fast-speed extension	N-NNE, NE-NEE	NEE-E, E-SEE	NE-NEE			
	Medium-speed extension	NNE-NE, E-SEE, SEE-SE, NW-NNW	NNE-NE	N-NNE, NNE-NE, E-SEE, SEE-SE			
	Slow extension	SE-SSE, S-SSW, SSW-SW, SW-SWW, SWW-W, NNW-N	N-NNE, NE-NEE, SEE-SE, S-SSW, NW-NNW	SE-SSE, S-SSW, SW-SWW, SWW-W, NW-NNW			
	Basic stability	SSE-S, W-NWW, NWW-NW	SE-SSE, SSE-S, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW, NNW-N	SSE-S, SSW-SW, W-NWW, NWW-NW, NNW-N			

Table A2. *Cont.*

Urban Construction Land	Spatial Extension Type	Orientation			Dominant Extension Wing		
		2002–2009	2010–2015	2002–2015	2002–2009	2010–2015	2002–2015
Public administration and service land	High-speed extension				NEE-E	NNE-NE-NEE-E-SEE	NE-NEE-E-SEE
	Fast-speed extension						
	Medium-speed extension	NEE-E	E-SEE	NEE-E			
	Slow extension	N-NNE, NE-NEE, SSE-S, NW-NNW	NNE-NE, NE-NEE, NEE-E, SE-SSE	NE-NEE, E-SEE, NW-NNW			
	Basic stability	NNE-NE, E-SEE, SEE-SE, SE-SSE, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW, NNW-N	N-NNE, SEE-SE, SSE-S, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW, NW-NNW, NNW-N	N-NNE, NNE-NE, SEE-SE, SE-SSE, SSE-S, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-NW, NNW-N			
Traffic land	High-speed extension		E-SEE		NEE-E-SEE	NE-NEE-E-SEE, NW-NNW	NEE-E-SEE
	Fast-speed extension	NEE-E	NEE-E	NEE-E, E-SEE			
	Medium-speed extension	E-SEE	NE-NEE, NW-NNW				
	Slow extension	NNE-NE, NE-NEE, NWW-NW, NW-NNW	N-NNE, NNE-NE, SEE-SE, SE-SSE, W-NWW, NWW-NW, NNW-N	NNE-NE, NE-NEE, SE-SSE, NWW-NW, NW-NNW			
	Basic stability	N-NNE, SEE-SE, SE-SSE, SSE-S, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NNW, NNW-N	SSE-S, S-SSW, SSW-SW, SW-SWW, SWW-W	N-NNE, SEE-SE, SSE-S, S-SSW, SSW-SW, SW-SWW, SWW-W, W-NWW, NWW-N			

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