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Understanding the pattern and mechanism of spatial concentration of urban land use, population and economic activities: a case study in Wuhan, China

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ABSTRACT

Quantifying the aggregation patterns of urban population, economic activities, and land use are essential for understanding compact development, but little is known about the difference among the distribution characteristics and how the built environment influences urban aggregation. In this study, five elements are collected in Wuhan, China, namely population density, floor area ratio, business POIs, road network and built-up area as the representative of urban population, economic activities and land use. An inverse S-shape function is employed to fit the elements' macro distribution. An aggregation degree index is proposed to measure the aggregation level of urban elements. The kernel density estimation is used to identify the aggregation patterns. The spatial regression model is used to identify the built environment factors influencing the spatial distribution of urban elements. Results indicates that all urban elements decay outward from the city center in an inverse S-shape manner. The business Point-of-Interest (POI) density and population density are highly aggregated; floor area ratio and road density are moderately aggregated, whereas the built-up density is poorly aggregated. Three types of spatial aggregation patterns are identified: a point-shaped pattern, an axial pattern and a planar pattern. The spatial regression modeling shows that the built environment is associated with the distribution of the urban population, economic activities and land use. Destination accessibility factors, transit accessibility factors and land use diversity factors shape the distribution of the business POI density, floor area ratio and road density. Design factors are positively associated with population density, floor area ratio and built-up density. Future planning should consider the varying spatial concentration of urban population, economic activities and land use as well as their relationships with built environment attributes. Results of this study will provide a systematic understanding of aggregation of urban land use, population, and economic activities in megacities as well as some suggestions for planning and compact development.

1. Introduction

Cities are complex dynamic systems composed of infrastructure, human activities and social connections. Over the past decades, with rapid urbanization and globalization, cities have evolved from small cities to large cities, even megacities, accompanied by urban expansion and the concentration of industry, buildings, people, roads and transportation (Schneider and Woodcock 2008; Bettencourt and West 2010; Li et al. 2017). It has been suggested that more than 54% of the world's population lived in cities in 2014, and the proportion of world's population is projected to reach 66% by 2050 (United Nations 2015). In China, since 1978, the total size of the population in cities increased from 172.45 million to 831.37 million in 2018, mainly concentrated in megacities and urban agglomerations. Megacities face the pressure of population growth. Currently, the contradiction of limited land resources and social and eco-environmental problems resulting from

urbanization and economic development has led to the valorization of spatial planning change in China. Land use strategies have experienced a transformation from "incremental planning" to "inventory planning" (Xia, Yeh, and Zhang 2020), and the compact development mode has been considered a necessity for megacities. However, compact development may lead to more concentration of urban land use, population and economic activities in urban centers, which may exert more pressure on urban areas (Ewing, Tian, and Lyons 2018). Areas with evident location advantages tend to result in an overconcentration of population and industrial activities, leading to a series of problems such as regional traffic congestion, housing congestion and serious environmental pollution (Xu et al. 2020).

The term "spatial concentration" refers to the geographic concentration distribution of the urban elements, reflecting the relationship between urban elements and geographical space in urban geography.

Urban land use, population and economic activities are interrelated in the urban development process, showing various concentration levels and patterns in cities. As compact development strategies have addressed high density, mixed land use and oriented public transport (Ben-Zadok 2005), the built environment has been influenced. Also, the built environment has changed land prices and land use (Jang and Kang 2015). As the concentration of human activities is based on the distribution of infrastructures such as built-up areas and roads, which build a foundation for business concentration in cities, the concentration patterns of urban elements are significantly influenced. Although urban researchers have long attempted to understand the concentration of distinct urban elements in cities (Bennett, Graham, and Bratton 1999; Guan et al. 2018), little effort has been devoted to evaluating the linkage and distinction between distribution patterns of different urban elements in cities, particularly the difference between vertical and horizontal elements.

The urban element was perceived as a single aspect in most previous studies, and the underlying influencing factors were examined in terms of various types of urban element concentrations, including built environment factors (Wenting, Atzema, and Frenken 2011; McMillen 2006; Kim, Pagliara, and Preston 2005). Most previous studies have only focused on the influence of built environment factors on a single urban element. As urban concentration studies have transformed from focusing on a single urban element to focusing on multiple elements, the existing concentration and the stickiness that prevents dispersal are two important factors that promote the concentration of population, buildings and human activities (Scott and Storper 2015). Recent studies have explained the spatial distribution of urban concentration based on spatial attraction and matching growth mechanisms from the perspective of the scaling law (Li et al. 2017). Although previous studies have discussed the underlying factors from various perspectives, there is limited knowledge about the impact of the built environment on the distribution patterns of various elements in cities from a geographical perspective. Moreover, micro-scale studies still need to be completed for quantifying the relationship between the built environment and urban element concentration distribution. Furthermore, various approaches and datasets have been used in quantitative urban studies, such as Points of Interest (POIs), OpenStreetMaps (OSMs), social media data (Tweets) and satellite-based impervious surface extraction (An et al. 2019; Huang, Yang, and Yang 2021; Lock and Pettit 2020; Trinder and Liu 2020; Shao, Wu, and Li 2021). Therefore, this study aims to understand the relationship between different built environment factors and various spatial distributions of urban land use, population and economic activities at the grid units through multi-source data.

The spatial structure of China's economic development is undergoing profound changes. Central cities and urban agglomerations are the core areas to promote development. With the analysis of the varying spatial concentration pattern of multiple urban elements and the mechanism from built environment perspective from a micro-scale, this study makes an incremental contribution to a deep and complete understanding of the static spatial patterns of urban elements, and fills the gap in which previous studies ignore the association between the concentration degree and pattern of various urban elements with multi-source data. Further, this study will enrich the methods of measuring the concentration degree level and deepen the understanding of the urban spatial structure. Taking Wuhan, a central city in China, as the case study, the experience can be provided as a reference for other cities. Findings from this study may help put forward suggestions for the compact development of megacities, assist urban planners in guiding the distribution of urban land use, population and economic activities.

This study examines two research questions based on multi-source data from Wuhan: (1) What is the disparity in the distribution patterns of urban land use, population and economic activities? (2) What is the mechanism of spatial concentration of urban land use, population and economic activities from the built environment perspective? In the following sections, an inverse S-shaped function is used to fit the macro distribution of the elements. Then, a concentration degree index is proposed to measure the concentration level, and kernel density estimation is used to identify the concentration patterns. Thereafter, the spatial regression model is used to reveal the mechanism of the concentration distribution patterns of urban land use, population and economic activities from the perspective of the built environment. Finally, the correlation between the concentration level and concentration patterns and some implications for planning are summarized.

2. Literature review

2.1. Concentration distribution of urban land use, population and economic activities and compact development

Urban development patterns, such as urban sprawl and compact development, have been widely debated in previous studies (Ewing 1997; Tsai 2005; Schneider and Woodcock 2008). Urban sprawl is often related to concepts such as low density, commercial strip development, scattered development and leapfrog development (Tsai 2005; Sim 2010). Researchers have indicated

that as urban sprawl has resulted in various environmental problems, compact development has been advocated (Batty 2013). In contrast to urban sprawl, compact development strategies are mainly related to high-density and mixed land use (Ben-Zadok 2005).

High-density urban areas can accommodate more people and buildings and prevent urban sprawl (Jenks and Burgess 2000). High density is often accompanied by a concentration distribution of urban land use, population and economic activities in urban areas. At the same time, population concentration also leads to intensive land use and high-density buildings (Yue et al. 2021). The concentration of employment, population, housing and the amount of land developed can reflect the compactness (Ewing 1997; Galster et al. 2001; Tsai 2005). The concentration of urban activities in high-density urban areas of developed and developing countries varies with the stages of economic development (Lv and Qi 2008). The economic development of developed countries is mainly realized by the development of the service and financial industries, which is more beneficial to the development of high-density cities. In the transition period of economic development in developing countries, megacities are facing the pressure of growing urban populations, supporting the compact development of high-density urban centers and focusing on urban functional concentration. Urban interior spaces have been constantly reconstructed, and businesses, workplaces and housing are concentrated or close to urban centers (Jenks and Burgess 2000). Although the concentration of urban activities in high-density urban areas in developing countries is a characteristic of compact cities, the implementation of over-concentrated development in high-density urban areas should not be advocated in the case of inefficient policies (Li et al. 2015). The development of compact cities is prone to over-concentration, but the compactness differs from over-concentration (Yang et al. 2012a). The high density advocated by the development strategy of compact cities will affect urban land use, population, and economic activities distributed in urban centers, and the differences in their concentration levels will also have different effects on the sustainable development of compact cities.

2.2. Built environment and distribution of urban land use, population, and economic activities

The term "built environment" has been widely used in different disciplines (Lopez 2012). "Density, design, and diversity(3D)" were the components of the built environment first proposed by Cervero and Kockelman (1997). Later, "3D" was extended to include the factors of "destination accessibility and distance to transit" by Ewing and Cervero (2010).

The impact of the built environment dominates the research frontiers of urban geography theory worldwide. Given the objective of this study, our review mainly focuses on four components of the built environment: destination accessibility, transit accessibility, design, and diversity of land use.

The impacts of destination accessibility on urban elements distribution can be reflected from the impact of city centers. "Distance to city center" reflects the central agglomeration of city centers (An et al. 2019). Burgess's concentric ring model, Hoyt's sector model, Harris and Ullman's multiple-nuclei model and the bid rent theory have explained the distribution of commerce and industry (Alonso 1960). Current studies have shown that city centers and sub-centers have a significant impact on the distribution of the manufacturing industry and the production and service industry (Yang et al. 2012b; Li, Zhu, and Wang 2015; Lagonigro, Martori, and Apparicio 2020). Clark model, Newling's quadratic exponential model, and Smeed's negative power model have clearly described the impact of city centers on population density (Clark 1951; Newling 1969; Smeed 1964). Recent studies have also proved that the population distribution is positively impacted by distances to the nearest subcenter (Huang et al. 2017). Moreover, the floor area ratio tend to decrease from the city center and change with time (McMillen 2006; Cao, Shi, and Liu 2016; Barr and Cohen 2014). The closer to the core area, the lower the transportation cost, the higher the land rent, and the higher the floor area ratio (McMillen 2006). Besides, Jiao (2015) quantified the urban impervious surface density decline outward from the city center with an inverse-S shaped model. Further, Jiao (2021) proposes a geographic micro-process model and observes the urban land density changes from the city center outwards.

The link between the urban element distribution and transit accessibility has shown that the ring road and rail transit system facilitate people's travel, increase employment surrounding subway stations, and significantly impact nearby business formation (Kim, Pagliara, and Preston 2005; Zhao, Lu, and Liu 2020; Gao et al. 2020; Jin and Kim 2018; Li, Zhu, and Wang 2015; Wang et al. 2016; TTan et al. 2019; Tsai 2014; Tu et al. 2019; Zeng, Cui, and Liu 2019; Yao and Hu 2020; Sun et al. 2021). The ring road has had a significant impact on the distribution of manufacturing industry, production and service industry (Li et al. 2015). Classical economics theory has shown that the more intense the land-use investment near the train station, the higher the development intensity.

In terms of the association between urban element distribution and design, several studies have stated that public facilities have a significant impact on the distribution of manufacturing,

production and service industry, as they reshape the distribution of urban land use and floor area ratio (Kim, Pagliara, and Preston 2005; Tan et al. 2019; Zhao, Lu, and Liu 2020; Saxena, Jat, and Clarke 2021; Tsai 2014). Public sites, shorter commuting times and lower transportation costs facilitate people's travel (Kim, Pagliara, and Preston 2005). Schools, public libraries, educational institutions, medical services, social services and leisure services (parks and sports facilities) are related residence and industry locations (Frenkel 2007; Orsi 2018; Tu et al. 2019). High-rise living creates a short distance to access open spaces and natural environments and benefits the quality of life of residents (Bardhan, Kurisu, and Hanaki 2015).

As for the link between urban elements distribution and diversity of land use, Jacobs (1961) has argued that mixed land uses increase activity intensities at the neighborhood level, which is supported by many researches (Hoppenbrouwer and Louw 2005; Jacobs- Crisioni et al. 2014). However, mixed residential and industrial land use has a negative impact on the living environment (Tian, Liang, and Zhang 2017). Evidence has shown the effects of mixed land use on population and urban activities, but the impact of mixed land use on road density, built-up density and floor area ratio still needs to be explored.

3. Materials and methods

3.1. Study area and data descriptions

Wuhan locates in the northeast of Jianghan Plain, with a permanent population of 1.089 million and gross domestic product of 1,341.03 billion RMB in 2017. The urban area is divided by the Yangtze River and Han River into three parts including Hankou, Wuchang, and Hanyang, (Figure 1). It is a typical polycentric city that contains 13 administrative regions. This study focuses on the main urban area (Figure 1)including seven administrative regions as follows: (1) Jiangan, (2) Jianghan, (3) Qiaokou, (4) Hanyang, (5) Wuchang, (6) Qingshan, and (7) Hongshan. Wuhan has been considered as a mega-city since the "outline of Yangtze River economic belt development plan" initiated in 2016, resulting in more concentration of industrial, buildings, people and roads.

The distribution of urban land use, population and economic activities reflect the concentration characteristics of a city (Liu et al. 2019). Urban elements are broad concepts including roads, populations, businesses and buildings (Li et al. 2017). For this study, "urban elements" refer to population density, road density, business point-of-interest (POI) density, floor area ratio and built-up density, whereas most studies only focus on one of these five elements. Vertical elements are defined as business POI density,
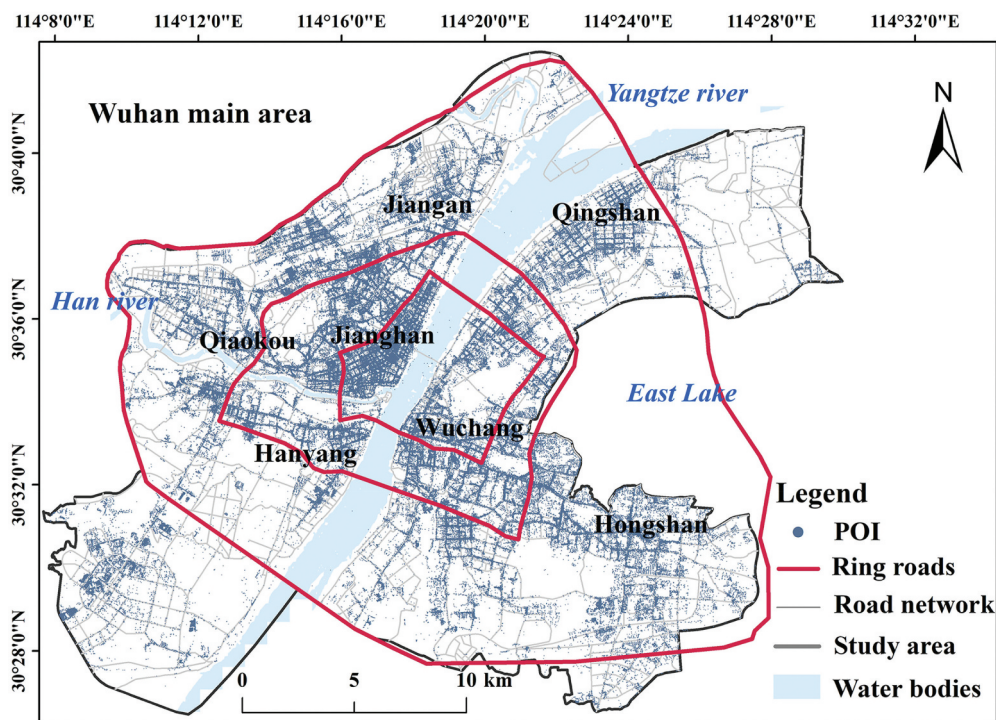
Figure 1. The spatial extent of the study area and the spatial distribution of POIs in Wuhan city.

population density and floor area ratio, whereas horizontal elements refer to road density and built-up density. As these elements are typical representatives of urban land use, population and economic activities, they are selected to comprehensively understand the distinction between urban land use, population and economic activity distribution patterns, and to examine the relationships between urban concentration and built environment.

We collected the road networks data of 2013 from Open Street Map (http://www.openstreetmap.org/), which provides global vector data. The road networks data in Open Street Map covers the main roads in Wuhan. The population data is drawn from the sixth censuses on the population level conducted in 2010. The floor area ratio data is collected from the Wuhan Municipal Bureau of Natural Resource and Planning in 2013. The built-up area data of 2010 is extracted from a cloud-free Landsat TM/ETM+ images in summer months by using the maximum likelihood classification method in ENVI 4.5, with the accuracies of the classification results up to 87%. The POI data of 2014 is derived from AMaps (http://ditu.amap.com/), with a total number of 0.51 million. According to the Code for Classification of Urban Land Use and Planning Standards of Development Land (GB50137-2011), the initial nineteen POI types are reclassified into six broader categories (Table 1).

3.2. Methods

3.2.1. Kernel density estimation and gradient analysis

With the increasing decentralized concentration of human and economic activities, Wuhan has become increasingly polycentric over time which requires a careful identification of the new Wuhan spatial structure. The gradient analysis and the calculation of element density start with the identification of the city (sub) centers. In this study, a kernel density estimation module is used to identify primary and secondary city centers, as it accurately reflects the law of distance decay (Le, Liu, and Lin 2020). Furthermore, the kernel density estimation method is used to analyze the spatial concentration characteristics of different urban elements. The kernel density estimation formula is defined as follows:

$$f(x) = \frac{1}{nh} \sum_{i-1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{1}$$

where $f(x)$ denotes the kernel density; h indicates the bandwidth; $x-x_i$ represents the distance from the estimation point to the sample x_i.

In this study, the kernel density is estimated using the default grid size and bandwidth of ArcGIS 10.2 (ESRI, Inc., Redwoodds, USA). The natural break

Table 1. POI data type classification.

ID	Land use classes	POI data type	Percentage (%)
1	Residential	Commercial residential-related, commercial residential areas	6.74
2	Administration, public services, public utilities	talent market, government agencies and social organizations, sports and leisure, science, education and cultural services, Medical care (inclusive the commercial services facilities), public facilities	10.06
3	Commercial and business	Catering services, company, shopping services, financial insurance, car maintenance, automotive services, car sales, life services, accommodation services, business residences (buildings), resorts, golf, leisure venues, entertainment venues, ice rinks, racecourses, media institutions, driving schools, training institutions, science and education cultural venues have some data, pet clinics, clinics	78.26
4	Industrial, manufacturing	factories, metallurgy, miners, industrial park	0.53
5	Road, street, and transportation	Road ancillary facilities, transportation services	3.83
6	Green space and square	Land of scenic spots	0.57

method is used to divide the results of kernel density analysis into 10 levels, and the top four levels of kernel density are identified as the alternative area. Considering urban planning and social and economic development conditions, the city center structure is finally identified, which includes one major center and seven sub-centers in Wuhan. The main center is in Jianghan Road, whereas seven sub-centers are identified as Simenkou, Zhongjiacun, Zhongnan, Jiedaokou, Guanggu Square, Xudong, and Jianshe Avenue centers (Figure 2). Figure 2 shows that the Jianghanlu center has a saturated development. Compared with some conventional city structures in traditional urban planning methods, Wuhan city has grown around city centers. Traditional city centers mainly include the Simenkou, Zhongjiacun and Jianghan Road center. Zhongnan, Jiedaokou, Guanggu square, Xudong, and Jianshe Avenue centers also have a more saturated development and are important in people's lives.

A concentric ring-based gradient analysis method is chosen to explore the impact of spatial gradients on urban elements(Jiao 2015). The position of the lowest point of the built-up density between the sub-centers and the main center is identified and the two centers are buffered separately at a radius of 1 km, merging the subsequent buffers that met at the lowest urban land density location. In sequence, serial buffers are successively established for the main center and sub-centers. Finally, the entire buffer is integrated (Figure 2).
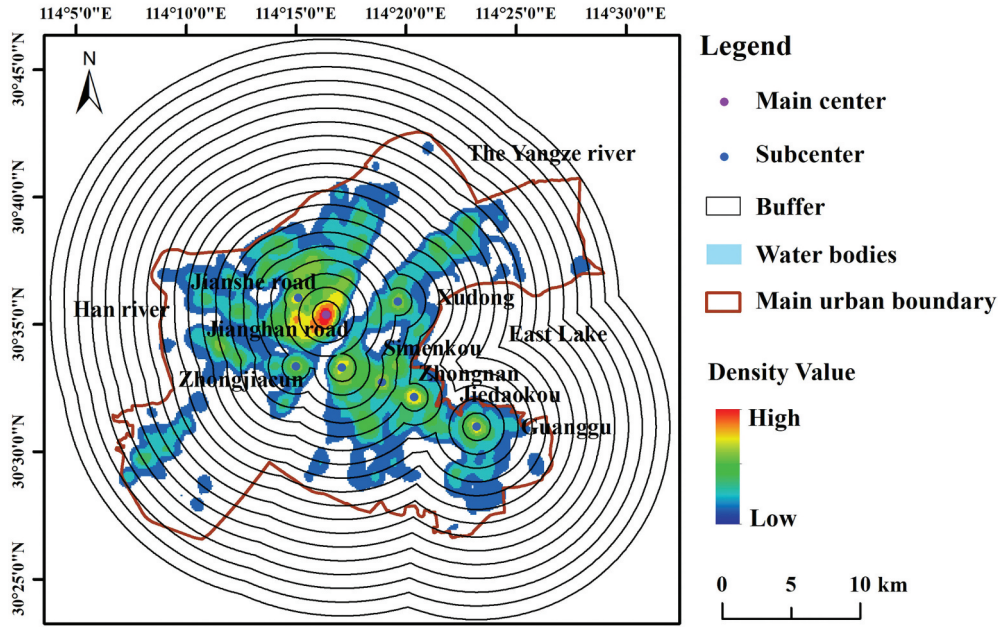
Figure 2. The polycentric structure and concentric ring partitioning in Wuhan, China. The one main center and seven sub-centers were identified based on the Kernel density estimation of all POIs.

The ring density of the urban element is calculated separately based on the ring partitioning of the study area. Equation (2) is employed to calculate the ring density of business POIs, roads and built-up areas.

$$D_i = \frac{P_i}{S_i} (i = 1, 2 \ldots n) \tag{2}$$

where D_i represents the element density of the ith ring; S_i denotes the ring area minus the water area, and P_i is the number of business POIs or the total road length or the built-up area of the ith ring.

Considering the spatial unit characteristics of the floor area ratio and population density, the ring density of the floor area ratio and population are calculated using Equation (3).

$$D_i = \sum_{j-1}^{n} \frac{S_j D_j}{\sum_{j-1}^{n} S_j} (i = 1, 2 \ldots n; j = 1, 2 \ldots n) \tag{3}$$

where D_i denotes the average value of the element in the ith ring, S_j is the area of the jth unit contained in the ith ring; D_j is the value of the element in unit j, and n is the total number of spatial units of elements contained in each ring.

3.2.2. Inverse S-shape function and concentration degree indicator

Jiao (2015) observed a universal inverse S-shaped pattern of decreasing urban land density from the city center to the outside, and proposed an inverse S-shaped function to fit the urban land density distribution. Since the function can be also used to characterize the macro spatial distribution of other urban

elements, the inverse S-shaped function is used in this study to fit the distribution of urban elements in Wuhan (Jiao 2015). The function is defined as:

$$f(r) = \frac{1 - c}{1 + e^{\alpha\left(\frac{2r}{D}\right) - 1)}} + C \tag{4}$$

where f denotes the density of urban elements, r is the distance to the city center, e is the Euler number, a is a parameter that controls the slope of the inverse S curve, D represents the urban area radius, and c represents the density of urban elements in the urban fringe. The slope of the density distribution curve reflects the concentration of the urban elements. A steeper slope indicates the significant influence of the city center on the distribution of elements, and the density of elements rapidly decreases outward from city centers.

Based on the function on Equation (4), the Concentration Degree Index (CDI) is established to describe the level of concentration, which is defined as the ratio of the concentration radius of urban elements to the number of buffers. The concentration radius of an urban element is determined by the parameter D ($D_{elements}$). The higher the concentration degree of the urban element, the smaller the CDI value. The index can be written as:

$$CDI = \frac{D_{elements}}{D_{buffer}} \tag{5}$$

where $D_{elements}$ is the concentration distance of the element to the city center, and D_{buffer} is the number of buffers that cover the study area. Based on the CDI value in this study, the quantile method in ArcGIS,

Table 2. The description of five elements and independent variables.

Types	Categories	Variables	Descriptions	Abbreviation
Intensity of urban elements concentration	Business POI density kernel density	Business POI density	The kernel density of Business POI density	BPDKD
	Road density kernel density	Road density	The kernel density of Road density	RDKD
	Population density kernel density	Population density	The kernel density of Population density	PDKD
	Floor area ratio kernel density	Floor area ratio	The kernel density of Floor area ratio	FARKD
	Built-up density kernel density	Built-up density	The kernel density of Built-up density	BUDKD
Built environment	Destination accessibility	The distance to the nearest city center	The distance to nearest city centers(meters)	TDTNCC
	Transit accessibility	Subway and bus station count	Total number of subway and bus station POI in the grid	SBSC
Design	Number of green space and square	Total number of green squares and parks POI in the grid		NOGSS
		Education and culture facilities density	The kernel density of education and culture facilities POI in the grid	ECFD
		Medical service facilities density	The kernel density of medical service facilities POI in the grid	MSFD
		Sports and leisure facilities density	The kernel density of sports and leisure facilities institution POI in the grid	SLFD
		Government and administration density	The kernel density of government and administration POI in the grid	GAD
		Building height	Building height in the grid	BH
	Diversity	Mixed land use	Land use mix in the grid	LUM
Open space	The nearest distance to Yangtze River recreation space	The nearest distance to Yangtze River recreation space (meters)		TNDTYRRS
	The nearest distance to East Lake scenic area	The nearest distance to East Lake scenic area(meters)		TNDTELSA

which can ensure that the extreme and middle classes have the same number of values, are used to divide the CDI values into three types: high concentration (CDI ≤ 0.315900), moderate concentration (0.315901 < CDI ≤ 0.43300), and low concentration (CDI > 0.433401).

3.2.3. Spatial regression modeling

The first law of geography emphasizes the spatial dependence and similarity of adjacent objects (Tobler 1979). Urban concentration reflects spatial dependence and heterogeneity. Therefore, spatial regression is employed instead of traditional linear regression to determine the influencing factors of various concentrations. Our study area is divided into 684 grid cells of 1 km × 1 km, and the values of the influencing factors for each grid are calculated using ArcGIS. All variables are normalized and transformed into natural logs.

Concentration presents spatial autocorrelation. After examining the spatial auto-correlation of all five elements in GeoDa (Anselin 2005), the spatial error model (SEM) according to Equation (6) and Spatial Lag Model (SLM) according to Equation (7) are used to better understand the mechanism of the urban concentration. The SEM and SLM can be defined as follows:

$$Y = \alpha + \beta X + \rho W_r + \varepsilon \tag{6}$$

$$Y = \alpha + \beta X + e, e = \lambda W_e + \varepsilon \tag{7}$$

where Y is the dependent variable, X is a matrix of explanatory variables, β is the coefficient for explanatory variables, ρ and λ denote spatial lag and error coefficients, respectively; ε and e are spatial error terms, and W is a spatial weight matrix.

3.3. Explanatory variables

In this study, built environment variables at the grid units include destination accessibility, transit accessibility, design and diversity of land use (Table 2). Since the Yangtze River recreation space and the East Lake scenic area are two famous open spaces in Wuhan, which provide tourism and recreation (Jiao and Liu 2010), both are considered to reflect the role of scarce landscape resources on the distribution of urban elements. The description of the dependent and independent variables in the spatial regression model is presented in Table 2.

The kernel density of business POI density, road density, population density, floor area ratio and built-up density are used as dependent variables to measure the intensity of urban element concentrations.

Destination accessibility reflects the advantages of location, which can be attractive to human and economic activities in cities. Researchers have considered the distance to the nearest city center as a proxy for destination accessibility which reflects the dependence of urban elements on city centers (Yin and Sun 2018). The number of subway and bus stations reflects transit accessibility.

Based on the literature review, design factors in this study refer to the building height, density of medical service facilities, density of government and administration, density of education and culture facilities, density of sports and leisure facilities and number of green spaces and squares (Chen et al. 2019). Urban amenities can attract more attention to the development of cities. Researchers have considered buildings as proxies for the most important elements of urban landscapes (Xia, Yeh, and Zhang 2020). As the
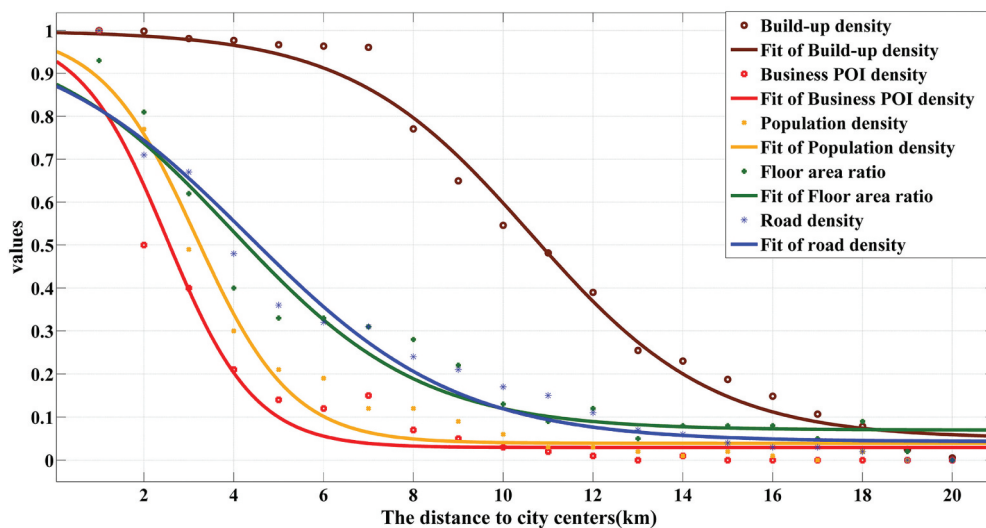

Figure 3. The curves of fitted inverse S-shaped functions of urban land use, population, and economic activities in Wuhan city.

city tends to have more three-dimensional space development, building height is used to represent the level of vertical development by city.

Diversity reflects multifunctional land-use (Pagliarin 2018). Thus, it may be a powerful driving factor for the distribution of urban elements, measured by the land use mix. Land use mix is defined as the mixed use of residential, public services and utilities, commercial and business, industrial, road, street, transportation, green space and square POI in each grid. It is calculated based on the entropy function (Yue et al. 2016).

Cities with more open spaces are expected to benefit people's lives and work. Urban parks, green paths and natural resources such as water bodies provide entertainment and influence health, business, residential commercial development and floor area ratio distribution (Wen, Xiao, and Zhang 2017; Ekkel and Vries 2017; Park and Kim 2019; Jang and Kang 2015; McMillen 2006; Tsai 2014). Open space factors include the nearest distance to the Yangtze River recreation space and the East Lake scenic area.

Table 3. The parameters of fitted inverse S-shaped functions and concentration degree of urban land use, population and economic activities in Wuhan city.

Category	a	c	D	R-square	CDI
Business POI density	2.9720	0.0293	5.0220	0.8918	0.2511
Population density	2.9710	0.0393	6.3190	0.9686	0.3159
Floor area ratio	1.8810	0.0696	7.9290	0.9453	0.3965
Road density	1.8720	0.0430	8.6670	0.9349	0.4334
Built-up density	5.2620	0.0500	21.2400	0.9899	1.0620

4. Results

4.1. Concentration degrees and spatial patterns of urban land use, population, and economic activities

In this study, the fitted curves are shown in Figure 3 and the estimated parameters for five elements are shown in Table 3. The adjusted R^2 values for all urban elements are over 0.85, indicating that the inverse S-shape function can well characterize the spatial pattern of five urban elements. Figure 3 shows that the densities of five urban elements present an inverse S- shape decrease outward from the city center. All the declining patterns can be divided into three categories. The steep curves indicate that the densities of urban elements, such as POI density and population density, rapidly decrease with the distance from city centers. The fitted curves of the floor area ratio and road density show that they gradually decline in contrast to the business POI density and population density. The fitted curves of the built-up density show that it slowly decreases and then declines rapidly. In addition, it can be seen from Figure 3 that the density of floor area ratio and road show local undulating morphological characteristics from the city center to the outside, which indicates that the concentration phenomenon also occurs outside the main city center and sub-centers.

The proposed CDI index is calculated to measure the concentration degree of urban land use, population and economic activities according to Equation
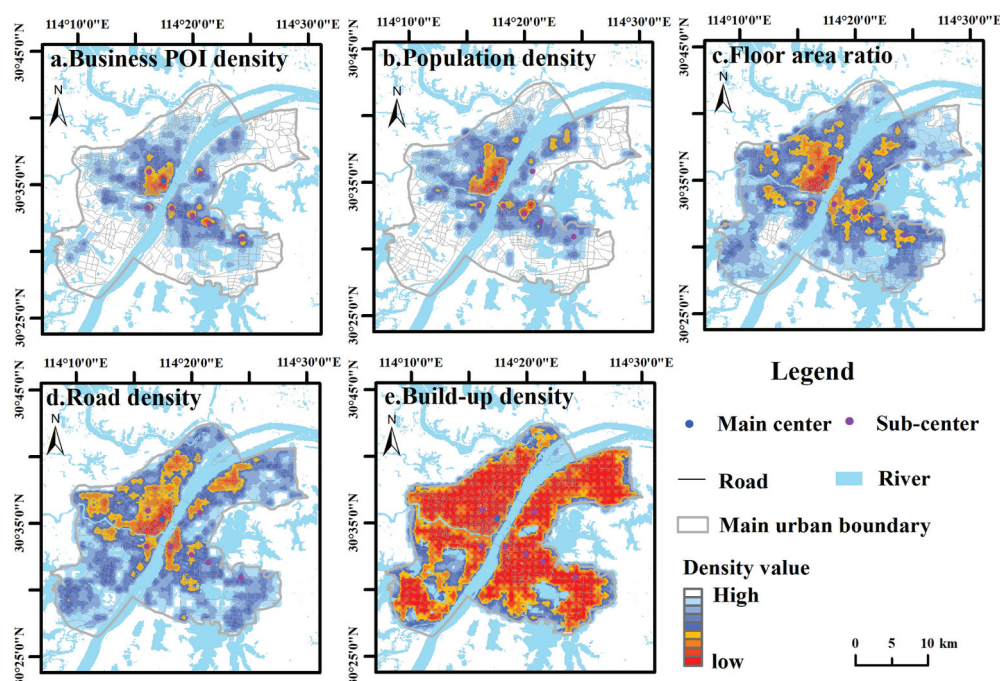
Figure 4. Spatial distributions of Kernel density estimations of urban land use, population, and economic activities in Wuhan city. (a) Business POI density; (b) Population density; (c) Floor area ratio; (d) Road density; (e)Built-up density.

(5), as shown in Table 3. The CDI values of the business POI density and population density are found to be less than 0.35, corresponding to high geographical concentration. The floor area ratio and road density are moderately aggregated. However, the concentration level of the built-up density is relatively low, which suggests a spreading pattern of built-up density in the main city area.

The spatial concentration patterns of urban land use, population, and economic activities are further examined using kernel density estimation (see Figure 4). Three types of spatial concentration patterns are identified: a point-shaped pattern, an axial pattern, and a planar pattern. Large areas with the top four levels of kernel density refer to planar patterns, which decrease from the city center to the outer ring. The built-up density is the most typical element with a large planar pattern. The planar pattern of business POI density, floor area ratio, population density, and road density generally occur in the Jianghan Road main city center. A small area with the top four levels of kernel density refers to a point-shaped pattern, which is observed in the center of the sub-centers and communities. Business POI density, floor area ratio, population density and road density are observed in Zhongnan Center, Simenkou Center, etc. Many small areas along urban roads and urban rivers with the top four levels of kernel density form the entire axial pattern. The floor area ratio is evidently aggregated along the Luoyu Road and the Yangtze River recreation space.

4.2. Effects of built environment on the distribution of urban land use, population, and economic activities

After conducting spatial dependence testing, the SLM is employed to explore the influencing factors of population density, whereas the SEM is applied to examine the influencing factors of other elements. For the spatial error and spatial lag regressions, the kernel density values of the elements are the dependent variables, whereas the independent variables are shown in Table 2. Table 4 demonstrates the influencing factors of the different aggregated urban elements. From Table 4, the explanatory variables account for more than 69% of the concentration of urban elements.

Destination accessibility crucially influences urban land use, population, and economic activities. For every 1% increase in the distance to the nearest city center, the concentration of business POI density, floor area ratio and road density is expected to increase by 0.5212%, 0.1650% and 0.1849% respectively. This can be explained by the fact that the attraction of city centers provides more access to socioeconomic activities. Classical studies in urban geography have defined the central business district as having the highest central activities. As for transit accessibility, the number of subway and bus stations positively influence the concentration of business POI density, built-up density and road density, which is consistent with our expectations.

For design factors, differences in influence are observed in public service facilities on various urban elements. Business POI density, floor area ratio and road density are positively associated with medical service facilities. Education and culture facilities have shown a positive relationship with built-up density, whereas sports and leisure facilities are positively associated with business POI density. Population density, road density and floor area ratio are positively affected by the government and administration. The number of green spaces and squares is negatively associated with the concentration of road density and business POI density. In addition, it is observed that building height positively impacts the floor area ratio and built-up density. For every 1% increase in the building

Table 4. Standardized coefficients for exploratory urban aggregated elements variable obtained by spatial regression.

Variables	Population density	Business POI density	Floor area ratio	Road density	Built-up density
Model	Spatial Lag model	Spatial error model			
TDTNCC	0.0361	−0.5212*	−0.1650*	−0.1849*	−0.1838
SBSC	−0.0267	0.0296**	0.0180	0.1665*	0.2838*
NOGSS	0.0242	−0.0385*	−0.0238	−0.0510**	−0.0291
ECFD	0.0818	−0.0224	−0.0211	0.0013	0.1689**
MSFD	0.0849	0.0937*	0.2498*	0.1778*	0.0710
SLFD	−0.0975	0.1218*	−0.0176	0.0127	−0.0222
GAD	0.1895*	0.0022	0.0817*	0.1151*	0.1035
BH	0.0715	−0.0075	0.4428*	0.0421	0.2172*
LUM	0.0313	−0.0345*	−0.0035	−0.044**	0.1512*
TNDTYRRS	−0.0348	0.1384*	0.0548	0.1110**	0.2920*
TNDTELSA	−0.0074	0.0978**	−0.1148**	0.1665**	0.3726*
Constant	0.0871	0.2249	0.1490	−0.0265	−0.1686
REME	0.6305	-	-	-	-
REMS	-	0.7162	0.6195	0.6081	0.6505
R^2	0.7031	0.7896	0.8644	0.6972	0.7115

** Correlation is significant at the 0.05 level (two-tailed).
* Correlation is significant at the 0.01 level (two-tailed).

height, floor area ratio and built-up density are expected to increase by 0.4428% and 0.2172% respectively.

From Table 4, the diversity of land use is found to have a negative impact on the concentration of business POI density and road density, which is opposite to the finding of Jacobs (1961). An 1% increase in land mix use is expected to result in a 0.0345% and 0.044% decrease in business POI density and road density respectively, resulting in a 0.1512% increase in the concentration of built-up density. The distribution of land use mix has spread, whereas the distribution of business POI density is more concentrated in city centers.

Among the open space factors, the nearest distance to the Yangtze River recreation space and the East Lake scenic area has a positive effect on the concentration of business POI density, road density and built-up density, whereas the nearest distance to the East Lake scenic area negatively influences the concentration of floor area ratio. This result may be largely attributed to biodiversity conservation. Landscape layout and special environmental protection of the East Lake and the Yangtze River, land use and road construction are subject to strict control. The development intensity in the area surrounding the East Lake and the Yangtze River is reducing.

5. Discussion

5.1. Understanding the association between the concentration degree and concentration pattern

The distribution of five urban elements in this study have indicated that urban land use, population and economic activities are unevenly distributed. Three types of concentration levels are an important finding in this study. The comparison of the concentration level of urban land use, population and economic activities yield results similar to those of Li et al. (2017). In addition, this study further finds that the floor area ratio is moderately aggregated whereas the built-up area is poorly aggregated. The concentration level of vertical elements is found to be higher than that of horizontal elements. This may be ascribed to the horizontal and vertical growth of urban growth (Zhang et al. 2017). Compact development strategies that address high density and high rise in urban areas promote vertical growth; thus, they impact on the concentration of human and economic activities in core areas, which leads to more road and land expansion (Cuberes 2011).

The concentration patterns of urban land use, population and economic activities are another important finding in this study. Point-shaped concentration mainly occurs in the main center and sub-centers, with an axial concentration always along the main traffic routes and landscape resources. It is coherent with the study of Yuan et al. (2017) and Li et al. (2015). Further, from the perspective of horizontal and vertical elements, the distribution pattern can be divided into two types: the combination of point-shaped and axial, and planar patterns is observed for vertical elements, whereas horizontal elements are associated with planar patterns. Vertical elements tend to present a more complex distribution pattern than horizontal elements. In addition, this study provides an evidence that areas with higher road density correspond with higher built-up density and floor area ratio, which is also found in previous studies (Cai, Wu, and Cheng 2013).

Our finding also indicate the association between the concentration degree and concentration pattern of urban land use, population and economic activities. The association can be divided into three types: highly concentrated urban elements such as business POI density and population density are combined with point and planar patterns; medium aggregated urban elements such as floor area ratio and road density are a mixture of point-shaped, axial and planar patterns; and weakly aggregated urban elements such as built-up density present planar patterns. The first type shows that the planar pattern occurs in the main city center, and the point pattern is clustered in the sub-centers, indicating that the polycentric structure has a significant influence on the concentration of urban land use, population and economic activities. The second type reflects that urban elements are not only significantly dependent on the main center and sub-centers, but also largely rely on the main traffic routes and landscape resources. The third type shows a spreading pattern. Studies by Liu et al. (2019) from the perspective of agglomeration centrality reveals the distribution of streets in most city areas with low aggregation, which reflects a spreading distribution. In the Wuhan Urban Master Plan (2010–2020), the main urban area is designed for the important public service functions of the city, constructing high buildings of residential living, advancing land use intensity and strengthening the construction of the secondary road network. Zoning control over development intensity has more potential to influence the association between spatial concentration level and patterns which reflects concentric urban development. As the concentric expansion model is currently a development model in megacities (Sun, Zheng, and Ma 2014), the traditional location theory and the Alonso land rent model significantly influence the development patterns. In this study, urban elements present an inverse S-shaped decrease outward from the city center in Wuhan, which also verifies concentric urban development. The association between the concentration degree and concentration pattern from a complete perspective is important for understanding the static spatial patterns of urban elements, as it has been underestimated in previous studies.

5.2. Factors influencing the distribution of urban land use, population, and economic activities

Analyzing the influencing of built environment factors on the distribution of urban elements can help planners and decision-makers with reasonable spatial allocations of urban land use, population and economic activities. Multi-source data have been used to relate to build environment factors. The findings of this study reveal the differences between the effects of built environment factors on urban land use, population and economic activities.

Our findings verify that city centers are important for the concentration of road density, floor area ratio and economic activities. Better destination accessibility attracts more economic activities and increases land values, resulting in land use and floor area ratio change (Jang and Kang 2015; McMillen 2006). Unexpectedly, our study reveals that city centers have no impact on population density, which is not consistent with previous studies (Troy and Grove 2008; Huang et al. 2017). Such an inconsistency may be ascribed to the polycentric structure of Wuhan. Compact development strategies address the high-density mode, in which high -density tends to concentrate on urban centers. The improvement of infrastructure and living conditions in sub-centers has decentralized the living and working of people, which may lower the impact of city centers on population density. Besides, city centers also have no impact on the built-up density in this study. Since city centers in Wuhan are developed regions, built-up area is distributed evenly around city centers, rendering the influence of city centers neglectable for built-up density.

As for the transit accessibility, consistent with previous studies, bus and subway stations play a crucial role in the distribution of business POI density, built-up density and road density. These findings agree with previous studies which reveal that business centers heavily rely on subway stations and light rail lines (Shi, Wu, and Wang 2015), metro station sites have a significant impact on the surrounding business development (Green and James 1993), the rail transit is related to the change in land use patterns for the surrounding non-construction land (TTan et al. 2019). The more bus and subway stations there are, the denser the road network and the higher the road density. Different from our common understanding, subway and bus stations are found to be insignificant for the distribution of floor area ratio and population density. That may be attributed to the limited external influnce distance of subway and bus stations.

For design factors, Jang and Kang (2015) have shown that constructed and natural amenities influence land use changes. Our study shows the negative impact of green space and square on road density and business POI density which is not consistent with our

expectation. This can be explained by the spreading distribution of a small number of green spaces and squares. Our study finds that green spaces and squares in Wuhan do not significantly affect the distribution of population density, concurring with Jiao and Liu (2010), which may be because the influnce distance of park with external effects is limited and the relatively decentralized population density distribution. Government and administration correlate positively with population density, floor area ratio and road density which is in consistent with previous findings (Huang et al. 2017; Wu, Zhang, and Dong 2013). Government and administration provide people with livelihood services, attracting people living, and the accessibility of government and administration requires high road density. Education and culture facilities have shown a positive relationship with built-up density. Consistent with the existing findings (Wu, Zhang, and Dong 2013), education and culture facilities promote land use transitions. Sports and leisure facilities are positively associated with business POI density. Sports and leisure facilities are often attracting increasingly economic activities. There is a significant positive relationship between density of medical service facilities and road density. Medical service facilities provide convenient medical services that require high accessibility and thus having a positive impact on road density. As expected, building height has a significant positive impact on floor area ratio. The higher the buildings, the broader vision the occupants will have, and thus people enjoy sufficient sunlight and good ventilation (Jiao and Liu 2010).

Diversity factor represented by mixed land use refers to increase the intensity of land uses and the diversity of uses, integrating segregated uses (Grant 2002). It is reasonable that land use mix is positively related to built-up density. Urban spatial development is affecting built-up density. Mixing land use has become one of the key planning principles of the Smart Growth movement and other land-use planning strategies (Song and Knaap 2004). However, we find that land use mix does not always positively affect the concentration distribution of some urban elements. Land use mix has a negative impact on the concentration of business POI density, which is opposite with the finding of Jacobs (1961). This is probably because the distribution of land use mix is spreading whereas the distribution of business POI density is more concentrated in city centers. It is suggested to focus on different land use in different functional areas with different land use mix.

5.3. Advantages and the shortcomings of the methods

In this study, the kernel density estimation method is used to identify the polycentric structure in Wuhan. Wuhan Urban Comprehensive Planning (2010–2020)

indicates that Wuhan's urban structure shifts toward a layout including the Central Activities Zone, DongHu Lake scenic spot and comprehensive city cluster. The Sixin, Luxiang, and Yangchunhu sub-centers are planned. The results have shown that the development of polycentric structures in Wuhan is constantly improving. However, it is still necessary to guide the development of the Sixin and Yangchunhu sub-centers. Compared with traditional identification methods based on remote sensing mapping data, statistical data, survey data, and etc., the POI data can more accurately reflect the urban spatial structure.

Previous studies have employed a series of indicators to measure the aggregation level of urban elements. The EG index, Kd equation and accumulated M equation are proposed to evaluate industrial agglomeration (Ellison and Glaeser 1997; Duranton and Overman 2005; Marcon and Puech 2003). Ripley's K function based on spatial distance is often used to analyze the distribution pattern of a type of point event and the influence of one type of event distribution pattern on other types of events (Wang et al. 2016). Cuthbert and Anderson (2002) used the function of a single variable and double variable K to measure the spatial dependence and agglomeration between residential and business land. Road network agglomeration is used to measure the concentrated distribution of roads, rather than the uniform distribution in the landscape area (Albers et al. 2012). However, these indices may fail to comprehensively reflect the aggregation levels of multiple urban elements. Using such indices may lead to an incomplete quantification of urban aggregation and a poor understanding of the distinction between multiple elements in urban development. Compared with previous indices, the aggregation degree index in this study is proposed to effectively measure the spatial aggregation level of different elements at the same time, which is beneficial to the comparison of spatial aggregation of different factor levels. However, such aggregation degree index may be limited due to it is based on the inverse S-shape function, not a single independent indicator.

5.4. Implication for spatial planning and compact development practices

The results from this study can inform spatial planning and compact development practices in cities of China. Some effective policies and planning recommendations may help to reasonably allocate urban land use, population and economic activities.

First, planners should focus on the concentration level and patterns of urban land use, population and economic activities. A high concentration of elements around the main city center should be considered to achieve maximum advantages. The distribution of the medium concentration of elements should be more balanced to meet the needs of different people, which can achieve sustainable and compact urban form. A low concentration of elements should be more compact, resulting in less dispersion. The association between the concentration level and concentration pattern should be considered in the development strategies.

Second, urban land use, population and economic activities can be integrated into the development strategies according to different built environments. Enhancing the balanced development of multiple centers is helpful in narrowing the inequality of spatial accessibility. More favorable policies should be provided, such as better public infrastructure and improved accessibility. It is essential to develop a balanced mix of land use and built-up area intensification for achieving urban vitality.

6. Conclusions

The concentration pattern of urban land use, population and economic activities, and the potential concentration mechanisms need to be systematically investigated. In this study, we find that the business POI density, population density, floor area ratio, road density and built-up density generally exhibit an inverse S-shaped decrease tendency from the city center outward with three distinct declining patterns. A concentration degree index is proposed to quantify aggregation level of urban elements. We reveal that population and economic activities are highly aggregated, whereas land use is more sprawled. Urban elements are associated with point-shaped, axial and planar patterns. The spatial regression modeling shows that the built environment is associated with the distribution of urban land use, population and economic activities. Destination accessibility factors, transit accessibility factors and land use diversity factors shape the distribution of business POI density, floor area ratio, road density, and particularly the destination accessibility factor. Design factors have different impacts on land use and economic activities, positively associated with population density, floor area ratio and built-up density. The results of this study may promote the consideration of characteristics and mechanisms of urban concentration among urban land use, population and economic activities, providing assist in sustainable urban spatial development practices.

Although this study considers five elements to examine the distribution pattern and the concentration degree of urban land use, population and economic activities in

Wuhan City, other elements should be analyzed in multiple cities. The association between the concentration level and concentration pattern is evaluated from a static point of view. It is thus desired to examine whether it is suitable to use this association to better understand urban land use, population and economic activities from a dynamic perspective in future studies. Due to the data availability, different data production time of the data employed in this study may affect the final results. Different types of urban land use, population and economic activities can interact with each other. However, this study can't identify any interaction between them. The study of the interaction between urban land use, population and economic activities is clearly an area for the future research. Furthermore, our study reveals the concentration level and patterns, but can't reveal whether the urban elements are overconcentrated, which needs to be further explored.

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Data availability statement

The data that support the findings of this study are available on reasonable request from the corresponding author.

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