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Classification of Metro Station Areas Using Multi-Source Big Data: Case Studies in Beijing

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Abstract Large-capacity public transportation systems, represented by urban metro lines, are the key to alleviating the significant increase in urbanization and motorization in China. But to improve the agglomeration effect of metro stations in a more accurate and targeted way requires scientific evaluation and classification of the surrounding areas of metro stations. As spatial and functional design are the core factors for urban renewal design, this study took Beijing as an example, using multi-source data to evaluate the morphology and functional composition surrounding areas of metro stations, and the Boston Consulting Group (BCG) matrix was used to classify and characterize each type of surrounding areas from morphological-functional dimensions. It shows a negative correlation of the mix-use index with the floor area ratio, and only about 20% of the areas achieve the ideal situation of high construction intensity with high mix-use diversity. Hoping to provide a reference for city managers and designers in dealing with the surrounding metro stations with different construction intensities in a more precise way.

Keywords BCG Matrix, Beijing, High density, Mixed-Use, Metro Station Area, Reachable Area

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1. Introduction

With the significant increase in urbanization and motorization in China, urban and traffic problems such as traffic congestion, environmental pollution, and urban sprawl are becoming increasingly serious, and large-capacity public transportation systems, represented by urban railways, are the key to alleviating these problems (Xie DQ, 2019). As an important public transportation system, the metro lines not only solve many commuting trips in big cities, but also drive the value and comprehensive development of the city around the metro stations. The built environment is closely related to the daily travel of urban residents. Improving the agglomeration effect of metro stations in a more accurate and targeted way requires scientific evaluation and classification of the neighborhoods around metro stations, and there is still a great potential for research on the built environment of metro stations in the present time with advanced big data.

Previous studies have concluded that the integrated development of station areas plays a crucial role in optimizing the urban spatial structure and improving traffic conditions (Tianshu, 2012). These have typically focused on the mutual influence relationship between slow travel and medium- and micro-urban spatial morphology, establishing a spatial morphology index system, and proposing spatial optimization measures and transformation suggestions for four aspects: road traffic network, transportation facilities, spatial functions and environmental facilities (Chen et al., 2020). A “node–functionality–place” model was constructed in the form of a cube as the theoretical basis for classifying transit-oriented development (TOD) typologies. The degree and intensity of TOD, although it varies from city to city, presents a similar spatial pattern, with a general tendency to decline from the central core to the outskirts (Jian et al., 2022). Concordance between regional functions and mobility features was evaluated, using datasets of dockless bike-sharing (DBS) use and land use near metro stations (Yi, 2022), which provide a referenceable research basis for this study.

In terms of functional studies around metro stations, Pan H. et al. (2003) found through a travel behavior survey that mixed land use has a significant impact on residents' travel characteristics. Mercado et al. (2019) studied the relationship between travel patterns and travel distance in Hamilton, Canada, and found that the degree of land use mixing was negatively related to travel distance. Baoyu (2016) evaluated the degree of land-use mixing, subject

data on land-use from the City of Shenzhen to entropy and phase-difference indices. Wenwen Suo (2019) studied the development of mixed functions in the Upper Waterfront District of Shanghai, based on point of interest (POI) data, and concluded that higher building density and neighborhood scale can promote the development of mixed functions. After analyzing the mix of land uses around 95 Hong Kong MTR stations using POI data, Lingzhu et al. (2020) concluded that the land-use mix index should be added to the evaluation index of TOD stations, which can provide assessment support for station selection and land-use layout optimization. In addition, some scholars have used urban POI data to study the mix of urban functions around MTR stations and to classify and categorize the areas around MTR stations accordingly (Zeng. et al., 2020; Li, 2021).

Regarding the study on the influence area and classification of the metro station surrounding area, Calthorpe proposed the concept of transit-oriented development (TOD), development principles, and related guidelines in 1993. He proposed that the scope of the TOD area is determined by the radius of 500 meters of an urban railway station, and the land within this area is developed with high intensity, so as to build a core commercial area, office area, residential area and so on. This development model makes the transit station a strong attraction point, around which a mixed functional area of work, leisure, and residence are formed, and at the same time creates a premium for the land (Baldwin, 1993). Kim (1995) classified the impact areas of subway stations into three classes according to the level of impact: less than 200-meter radius, 200- to 500-meter radius, and 500- to 1,000-meter radius. Pan et al. (2007) categorized stations according to the nature of land use of metro stations as residential, public facility, green space, road traffic, and industrial. Duan Degang et al. (2013) classified metro stations according to their regional, transportation, and land use functions. Under "regional function," he classified metro stations into the urban and neighborhood types; under "transportation function," stations were classed as comprehensive hub, large connecting, and general interchange type. Under "land use function," the classifications were residential, public, commercial service, industrial, and mixed. Lin Yanyu (2015) defined the urban space where pedestrian behavior is influenced by urban rail transit stations - the station influence domain. Zhao Guihua et al. (2016) classified metro stations mainly based on the integrated development mode of metro stations and surrounding underground space, in terms of development subject, cooperation mode, station area and type, property development form, connectivity mode, integrated development scope, and development time sequence. Zhang Zheng et al. (2019) used methods and techniques such as Internet data collection, multi-source data fusion, and spatial statistics to study the influence range of rail transit stations, proposing the concepts of "direct influence range" and "indirect influence" of rail transit. Seventeen rail transit lines in Beijing were used as research objects to analyze the influence of the difference in influence range on the passenger flow prediction results. It was verified that the refined description of the influence range of stations can improve the accuracy of passenger flow prediction.

As an overview, it can be seen that big data, refined research, and human orientation are the main concerns of urban research around metro station areas in recent years, but as for urban renewal design, spatial and functional design are undoubtedly the core factors, and thus these are the main objectives of this paper.

(1) Taking Beijing as an example, using multifaceted big data, the coverage area around the metro station's reachable area is calculated and presented based on the walking isochronous circle; the coverage area is defined for 74 subway stations within the third ring road of Beijing.

(2) Based on urban data and POI data, the indexes of 5- and 10-minute walking areas around metro stations were calculated, and the ground cover and floor area ratios were calculated. The degree of mixed use within reachable areas was evaluated using POI data.

(3) The BCG matrix was used to classify and characterize each type of metro coverage area in terms of morphological-functional dimensions for 74 reachable areas.

2. Methodology

2.1. Study Areas and Data Preparation

According to the "Beijing Urban Master Plan (2016-2035)", Beijing has entered a stage of reduced and high-quality development. On September 30, 2022, Beijing issued the "Guiding Opinions on the Revitalization and Utilization of Existing State-Owned Construction Land (Trial Implementation)," which aims to coordinate and promote the revitalization and utilization of the existing state-owned construction areas and provide effective land-use guarantees for the high-quality development of the capital. Eight supporting policies are proposed, including the formulation of building scale indicators that will give priority to three-dimensional complex development projects such as high-tech, urban rail transit micro-centers, etc. Therefore, the surrounding area of the metro station in the built-up area has the possibility of further improvement.

Based on this, this study selects the central area within the third ring road of Beijing as the research object, in which the urban form and urban function are complex, including a large number of low-density historical building protection blocks, commercial centers, financial centers and administrative office centers, which need to be sorted out and classified more comprehensively. The study area contains a total of 74 subway stations, covering an area of 157.598 km^2 and a perimeter of 48.1 km (Figure 1).

The research data consist of open-source map data, including the reachable area around metro stations, the

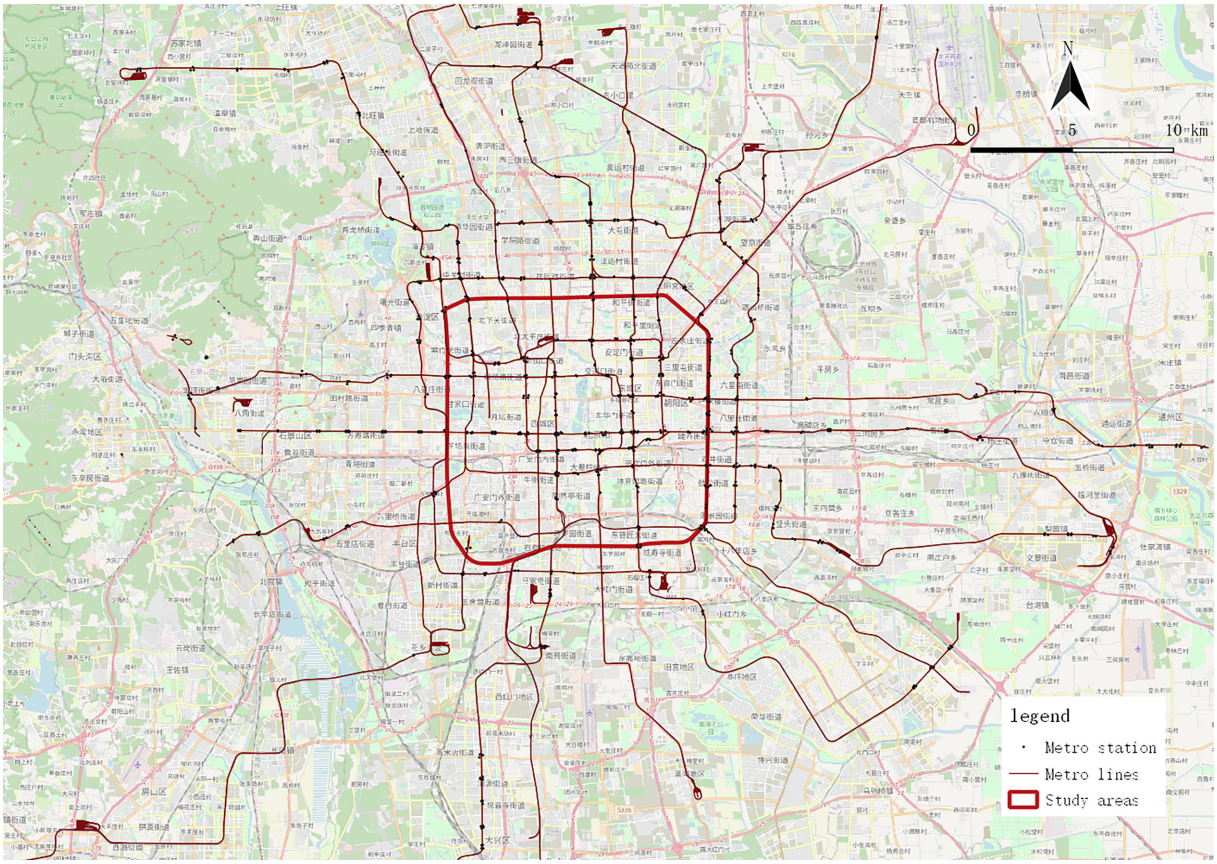


Figure 1. Areas of Beijing included in tudy areas

Table 1. Data base

Data	Source	Collection time
Reachable area of metro stations	Openrouteservice API	2022.11.3
Building footprint Number of building floors	OpenStreet Map	2019.7.1
POI data	Baidu map	2022.7.13

layout of buildings and the number of building floors in Beijing, and the POI data in Beijing (Table 1).

2.2. Measurement of Reachable Area and Morphological Indices

The methods of defining the reachable area include defining the station as the center and expanding outward with different distances as the radius, but the influence of the urban road network on reachability is not considered (Zhang et al. 2019). Further, the method of calculating the service area based on the road network lacks the definition of pedestrians, bicycles, and other transportation modes (Wu et al. 2020). In this study, the Openrouteservice API is used to obtain real-time route planning time consumption data, calculate isochronous circles, and define the reachable range around metro stations. Openrouteservice is being developed and provided by Heidelberg Institute for Geoinformation Technology (HeiGIT) and offers Routing services by using user-generated, collaboratively collected free geographic data from OpenStreetMap (OSM). Reachability has become a crucial component for many organizations from all different kinds of domains. Through Openrouteservice, researchers can obtain isochrones, which will determine which areas and objects are reachable within given times or distances.

The study takes 5- and 10-minute walks as inputs, and each entrance of the metro station as the starting point, to obtain the isochronous circle, and then takes the area merge to obtain the reachable range around the metro station (Figure 2). By crawling and organizing the data, the service coverage of the metro stations within the study area is calculated as follows:

$C_i = S_i/S$

Ci = service coverage of the metro station within i minutes' walk

Si = service area of the metro station within i minutes' walk

S = study area

The 5-minute reachable area (RA-5) by walking is calculated to be 35.027 km^2 and the service coverage is

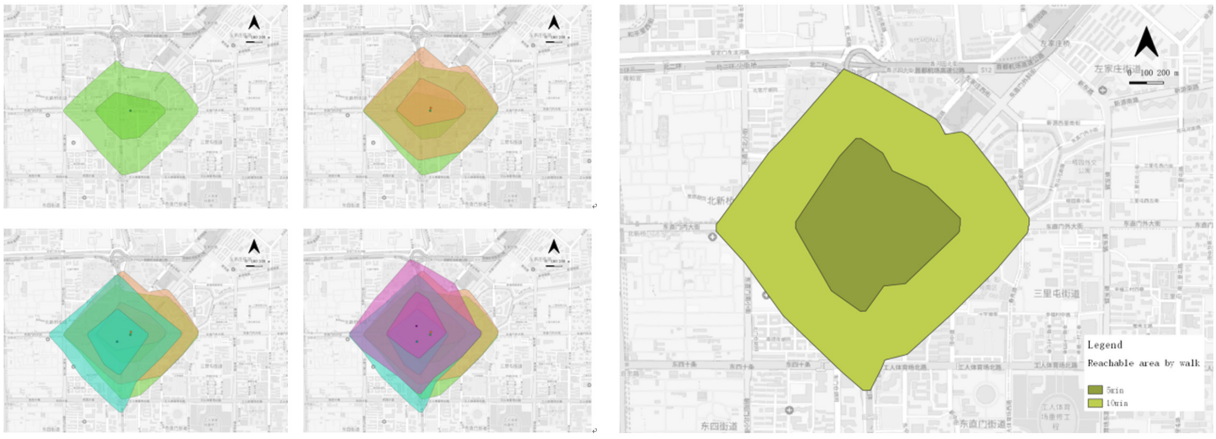
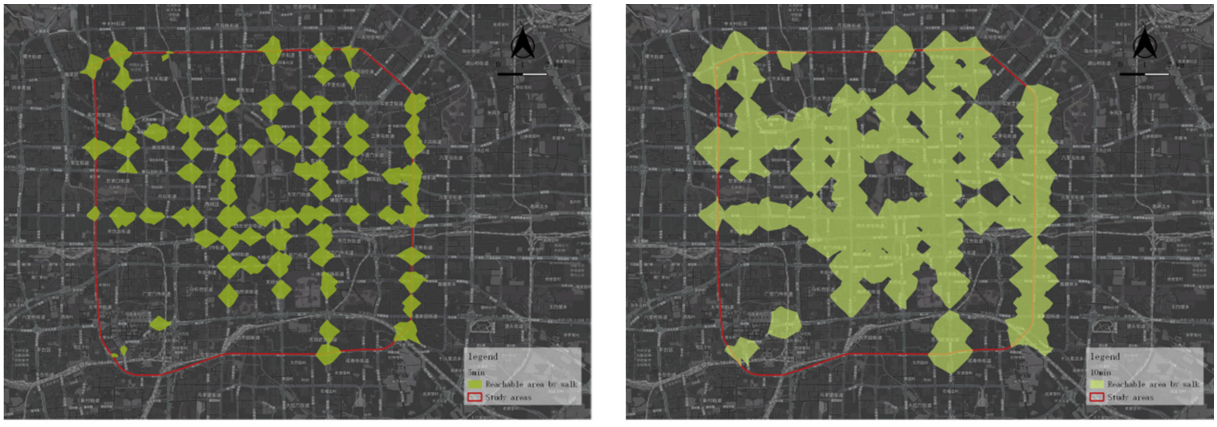


Figure 2. Obtain the isochrones of each railway entrance and exit, and merge into the walking reachable area (5min/ 10min) to the metro station.



(a) 5-minute reachable areas by walking (b) 10-min reachable areas by walking

Figure 3. Reachable areas by walking.

22.2 percent. The 10-minute reachable area (RA-10) by walking is 95.684 km^2 and the service coverage is 60.7 percent (Figure 3).

The metro station's reachable area has a high value for development and uses due to its high accessibility (Li, 2016). However, metro stations are located in different functional areas of the city, and the surrounding blocks show different layout patterns, with corresponding construction intensity requirements. To describe the urban morphology of the metro station reachable area more comprehensively, the study used OSM map data to obtain the building footprint and the floor number and calculated the ground cover ratio and floor area ratio.

It is calculated that the ground cover ratio in the RA-5 ranges from 0.001 to 0.844, and the floor area ratio lies between 0.002 and 2.43, while the ground-cover ratio in the RA-10 is between 0.019 and 0.427, the floor area ratio is between 0.033 to 2.379, and the numerical distribution is shown in Figure 4.

2.3. Mixed-Use Index Measurement, Based on POI Data

The POI (Point of Interest) method abstracts the physical location of geospatial data as point data, with only location and no size (Gao, 2013), which portrays the location information of various facilities of the city. It has the advantages of simple structure, good openness, large sample size, and complete information coverage (Li, 2021). This study obtains 1,576,000 various POI data points of Beijing from the Baidu Map platform. Through the analysis of POI data, the functional characteristics of blocks around metro stations and the spatial distribution of facilities are revealed.

Due to the complexity of the original classification of POI data, this sample set was classified into six categories: Administrative offices; road and transportation facilities; scientific, educational and cultural services; commercial residences; leisure and entertainment; and commercial services, according to the <Urban land classification and planning and construction land standards> (GB50137-201). Then the POI data in the reachable area (RA-10) were

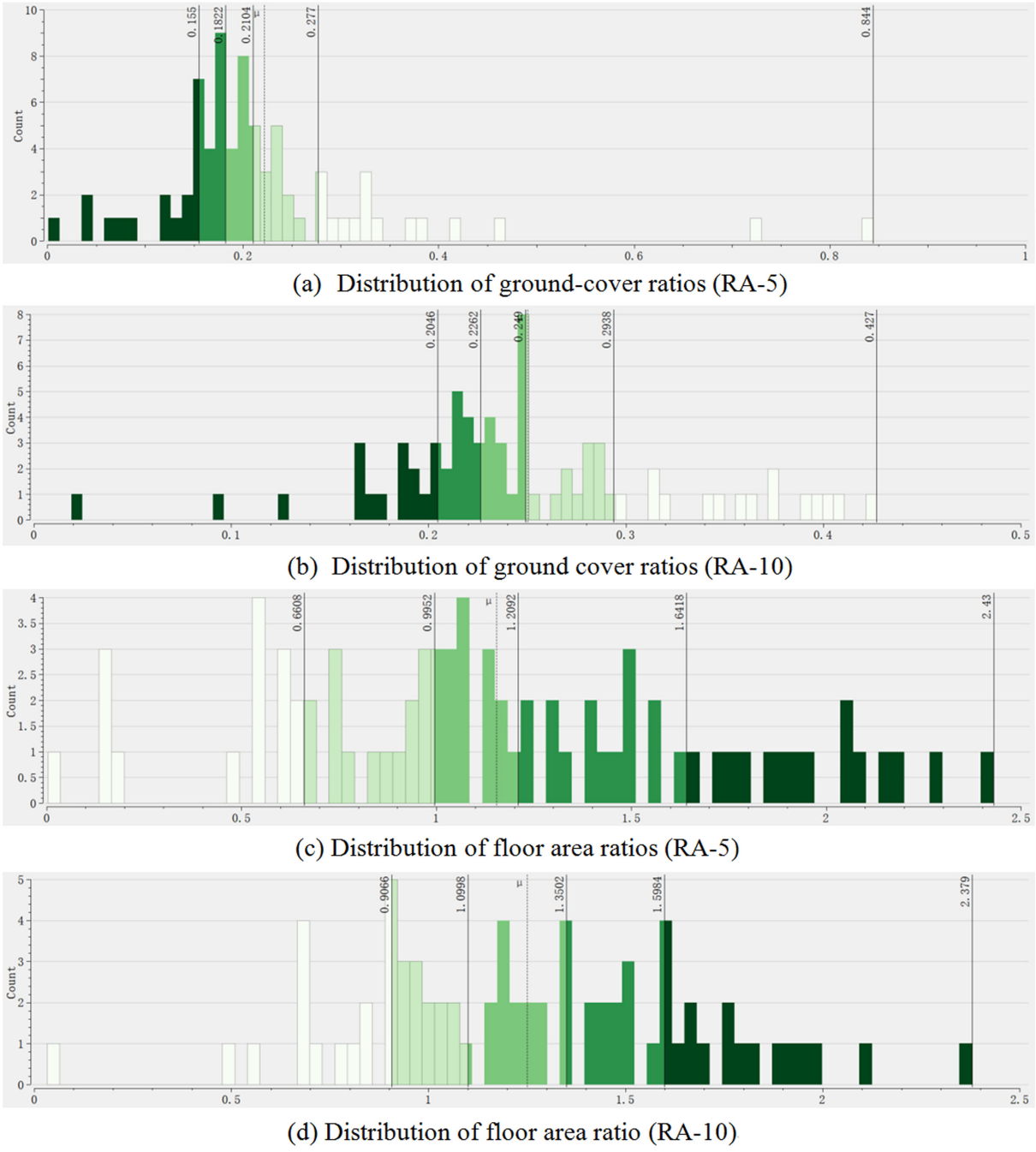


Figure 4. Distribution of morphological indices.

extracted and classified, and a total of 88396 POI data were screened, as shown in Table 2. The POI frequency density was calculated based on the total number of POI and area in each reachable zone, as demonstrated in Fig. 5, which shows that the POI frequency density of RA-5 was distributed between 0.0001 and 0.0025, and the POI frequency density of RA-10 was distributed between 0.0002 and 0.002, reflecting the degree of functional aggregation in each reachable area.

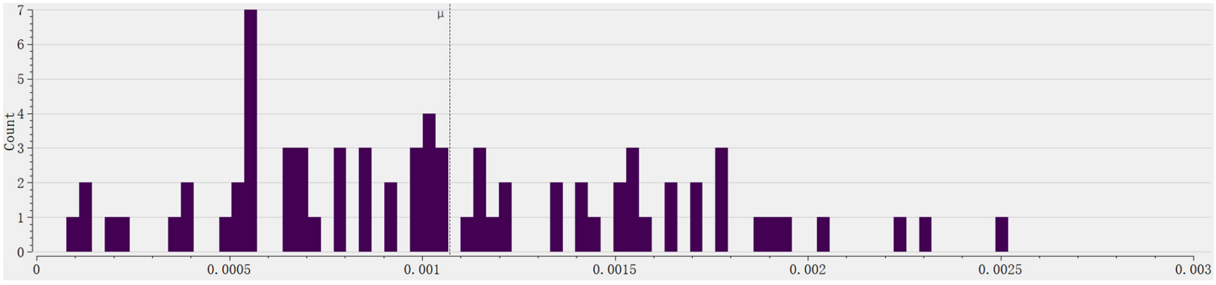
$$P_i = \frac{n_i}{N} \times 100\% (i = 1,2,\ldots,6)$$

p_i = Frequency density of POI of category i; n_i = POI number of category i; N = Total number of POI.

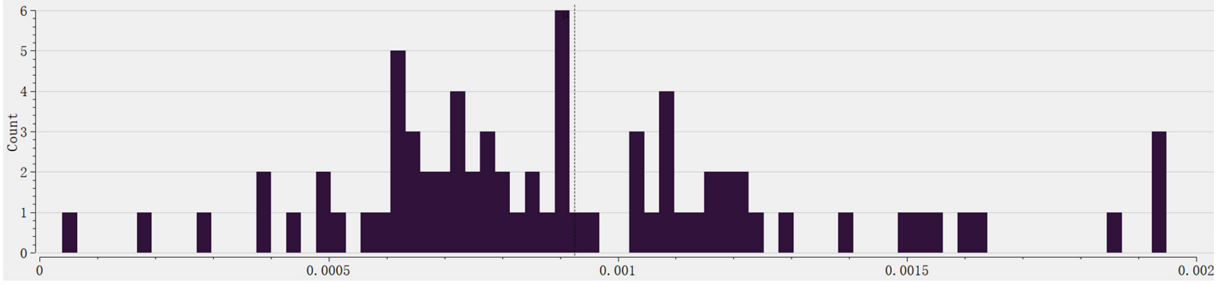
The land-use index is mainly used to evaluate the degree of mixing of the types and the proportion of different land-use functions in a region. Studies have shown that

Table 2. Classification of POI

Original categories of POI data	Classified categories of POI data	Total number of POI in RA-10	Percentage of POI by category
Administrative office	Administrative office	8116	9.18%
Road and transportation facilities	Road and transportation facilities	12353	13.97%
Scientific, educational and cultural services	Scientific, educational and cultural services	9426	10.66%
Commercial residence	Commercial residence	5073	5.74%
Sports and leisure services Public facilities Scenic spots	Leisure and entertainment	6943	7.85%
Healthcare services Financial and insurance services Shopping Corporate Enterprise Daily life services Food services	Commercial services	46485	52.59%



(a) Distribution of POI frequency density in RA-5



(b) Distribution of POI frequency density in RA-10

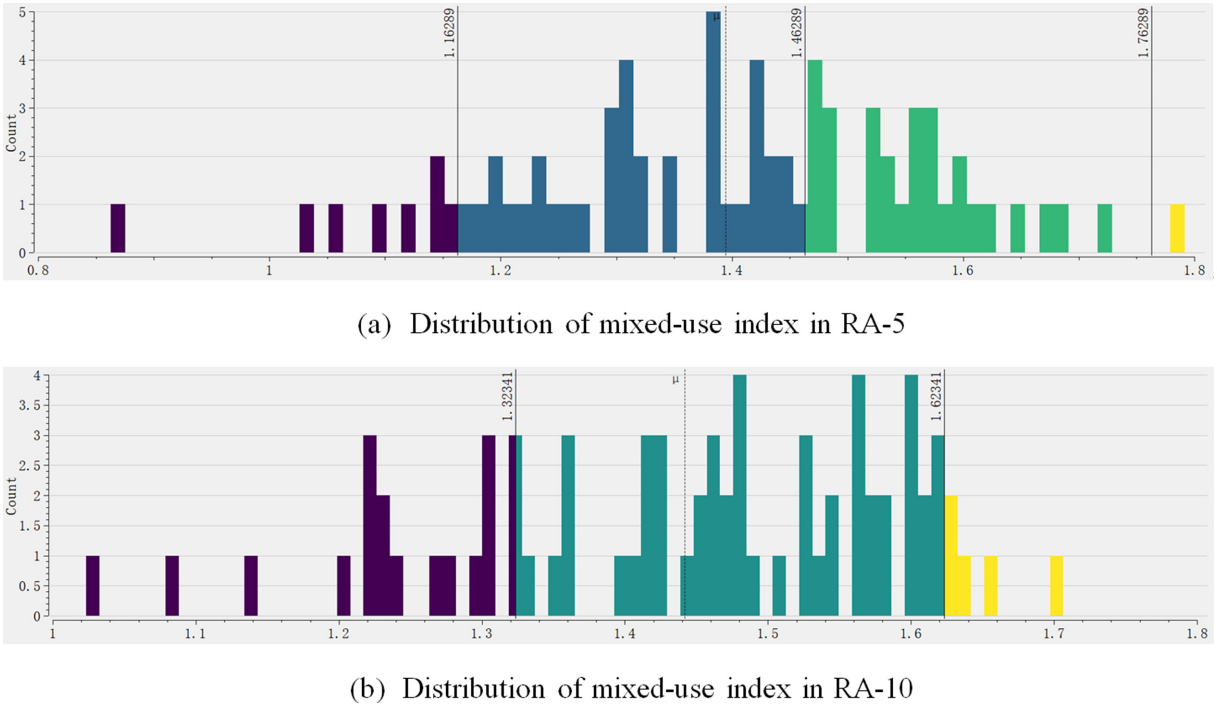
Figure 5. Distribution of POI frequency density.

the more land use types and the more balanced distribution in a region, the more it can promote a mutually beneficial symbiotic relationship between various functional facilities in the region and avoid high-intensity and high-cost travel (Gutierrez et al., 2021; Yin et al., 2018) Entropy indices are often used to evaluate the degree of land-use mixing, and commonly used indices include the Shannon-Wiener Index, which can judge the index of mixing of a sample, weighing the importance of each type (C.J. et al., 2005):

$$D_{(x)} = -\sum_{i=1}^{s} (p_i ln p_i)$$

$D_{(x)}$ = the Shannon-Wiener index; x = random variable; $P(i)$ = the probability of an occurrence of the random variable.

In this study, based on the analysis of POI data, the



(a) Distribution of mixed-use index in RA-5

(b) Distribution of mixed-use index in RA-10

Figure 6. Distribution of mixed-use index.

mixed-use index is calculated for each reachable area to characterize the degree of functional mix around the metro station (Suo, 2019; Bao, 2016). The percentage of each type of POI in the reachable region was calculated as the value of P(i), and the mixed-use index distribution was obtained as shown in Figure 6, which ranges from 0.86 to 1.79 in RA-5, while in RA-10 the index lies between 1.02 and 1.71.

2.4. BCG Matrix

The BCG Matrix method, founded by management scientist and founder of the Boston Consulting Group Bruce Henderson in 1963, is a method to help differentiate and manage investment projects by analyzing sales growth rates (an indicator of responsive market gravity) and market share (an indicator of corporate strength) to determine a company's product mix. Using the framework and simplicity of a 2 x 2 matrix (Table 3), the BCG Matrix identifies so-called "stars," "question marks," "cash cows," and "dogs" (Tilles, 1966):

(1) Star products: High growth and high market share, good development prospects, competitive; need to increase investment to support their development.

(2) Problem products: High growth but low market share; good development prospects but insufficient market development; needs to be a cautious investment.

(3) Cash Cow products: Low growth but high market share, mature market leaders; should reduce investment to maintain market share and delay the decline.

(4) Lean Dog products: Low growth and low market share, low theoretical rate or even loss; should adopt a retreat strategy (Dag, 2017).

Table 3. The BCG Matrix (Dag, 2017)

	High market share	Low market share
High market growth	Star	Question mark
Low market growth	Cash cow	Dog

In this study, the analysis logic of BCG matrix is used to classify 74 metro-station-reachable areas in terms of urban morphology (ground-cover ratio and floor-area ratio), functional composition (POI frequency density-mix-use index) and morphology-function (floor area ratio-mix-use index) to explore potential strategies for the future development of different metro station areas (Table 4).

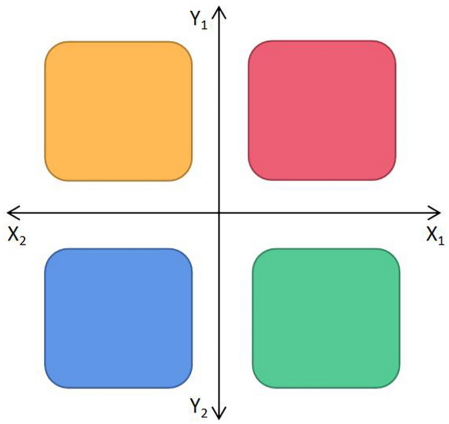
3. Results

According to the classification method of Table 4, the calculated ground cover density, floor area ratio, POI frequency density, and mixed-use index within the reachable range are standardized by Z-score, then classified and visualized by QGIS to obtain the distribution of various types of metro stations' reachable area.

3.1. Classification of Reachable Areas Based on Urban Morphology

Ground cover ratio and floor area ratio can reflect the characteristics of urban form, based on which the reachable area of metro stations can be divided into four categories:

Table 4. Metro Station Reachable Area Classification Method

	Urban morphology X_1=High ground cover ratio; X_2=Low ground cover ratio Y_1=High floor area ratio; Y_2=Low floor area ratio
	Functional composition X_1=High POI frequency density X_2=Low POI frequency density Y_1=High mix of uses; Y_2=Low mix of uses
	Morphology-function X_1=High floor area ratio; X_2=Low floor area ratio Y_1=High mix of uses; Y_2=Low mix of uses

High ground-cover ratio / High floor-area ratio, Low ground-cover ratio / High floor-area ratio, Low ground-cover ratio / Low floor-area ratio, and High ground-cover ratio / Low floor-area ratio, respectively. As can be seen in Figure 7, the distribution of RA-5 is more concentrated and similar, while the distribution of RA-10 is looser, with greater differentiation between the various categories of urban forms.

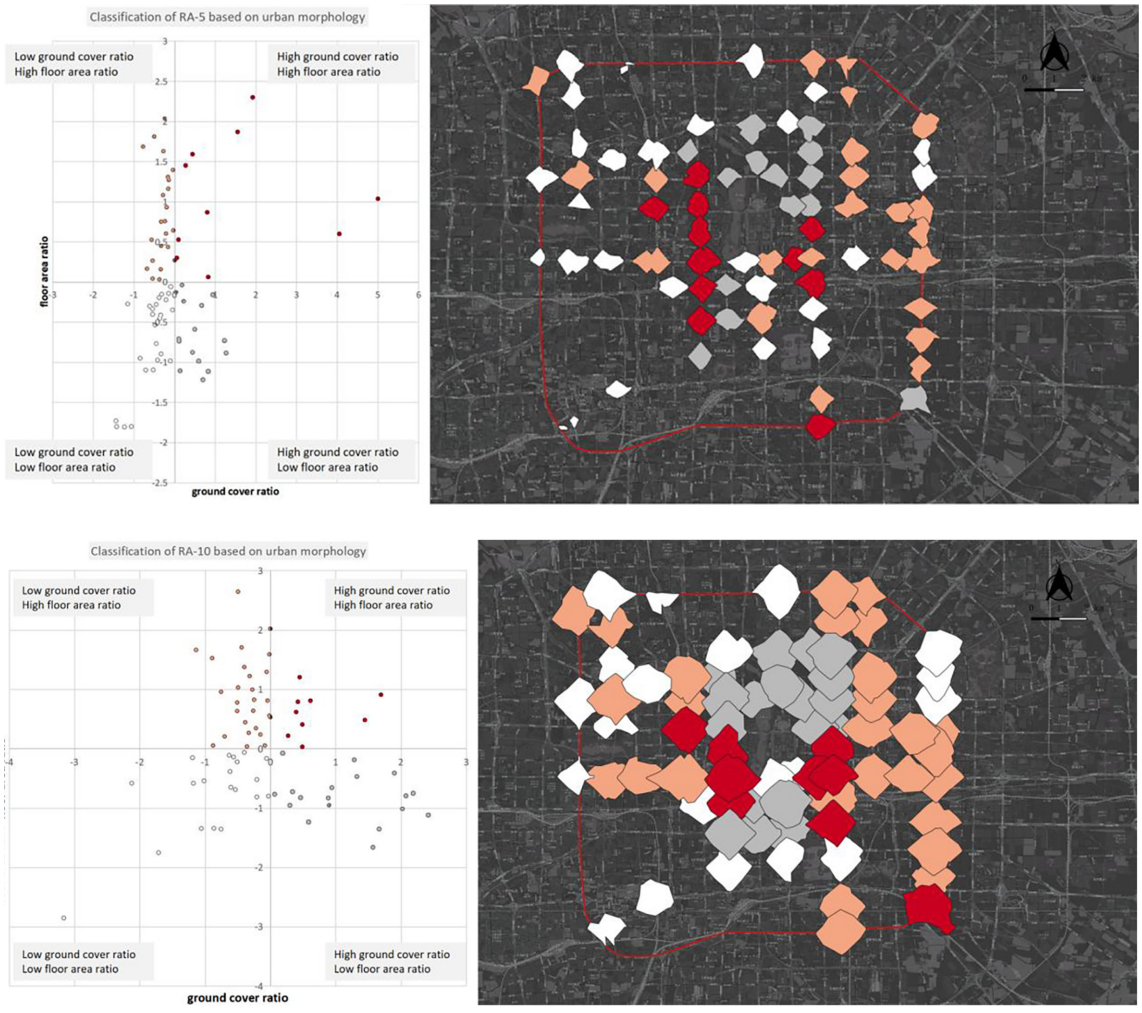


Figure 7. Classification of reachable areas based on urban morphology.

In the RA-5 area, Low ground-cover ratio / High floor-area ratio and Low ground-cover ratio / Low floor-area ratio account for the largest proportions, which are 31.10 and 36.49 percent, respectively. In terms of spatial distribution, Low ground-cover ratio / High floor-area ratio zones are concentrated between the 2nd and 3rd ring road on the east, while Low ground-cover ratio / Low floor-area ratio zones are concentrated in the northeast area within the 2nd ring road.

In the RA-10 area, the four categories are more balanced, which are 12.16, 36.49, 27.03, and 24.32 percent, respectively, and it can be seen that some areas show completely different categories from RA-5, indicating that the urban form around the metro station displays completely different characteristics at different radius. For example, Ping'anli station is a High ground-cover ratio / High floor-area ratio zone in RA-5 with a building density of 0.726 and a floor-area ratio of 1.486, while in RA-10 it becomes a High ground-cover ratio / Low floor-area ratio type, with a building density of 0.402 and a floor-area ratio of 0.911, with a significant reduction in the average number of building stories.

3.2. Classification of Reachable Areas Based on Functional Composition

The POI frequency density and mixed-use index can describe the degree of functional mixing in urban neighborhoods (Bao, 2016). As shown in Figure 8, the overall trend shows a negative correlation between POI frequency density and the mixed-use index; that is, as the POI frequency density increases, the mixing degree index decreases, and is more significant in the RA-10 areas.

Within RA-5, the Low POI frequency density / High mixed-use areas account for 44.60 percent of the total, mainly distributed in the western and central areas. High POI frequency density / Low mixed-use areas account for 33.78 percent, mainly in the eastern area along the third ring road, showing a stronger functional dominance.

In the RA-10 classification matrix, the distribution of points is more concentrated, with the Low POI frequency

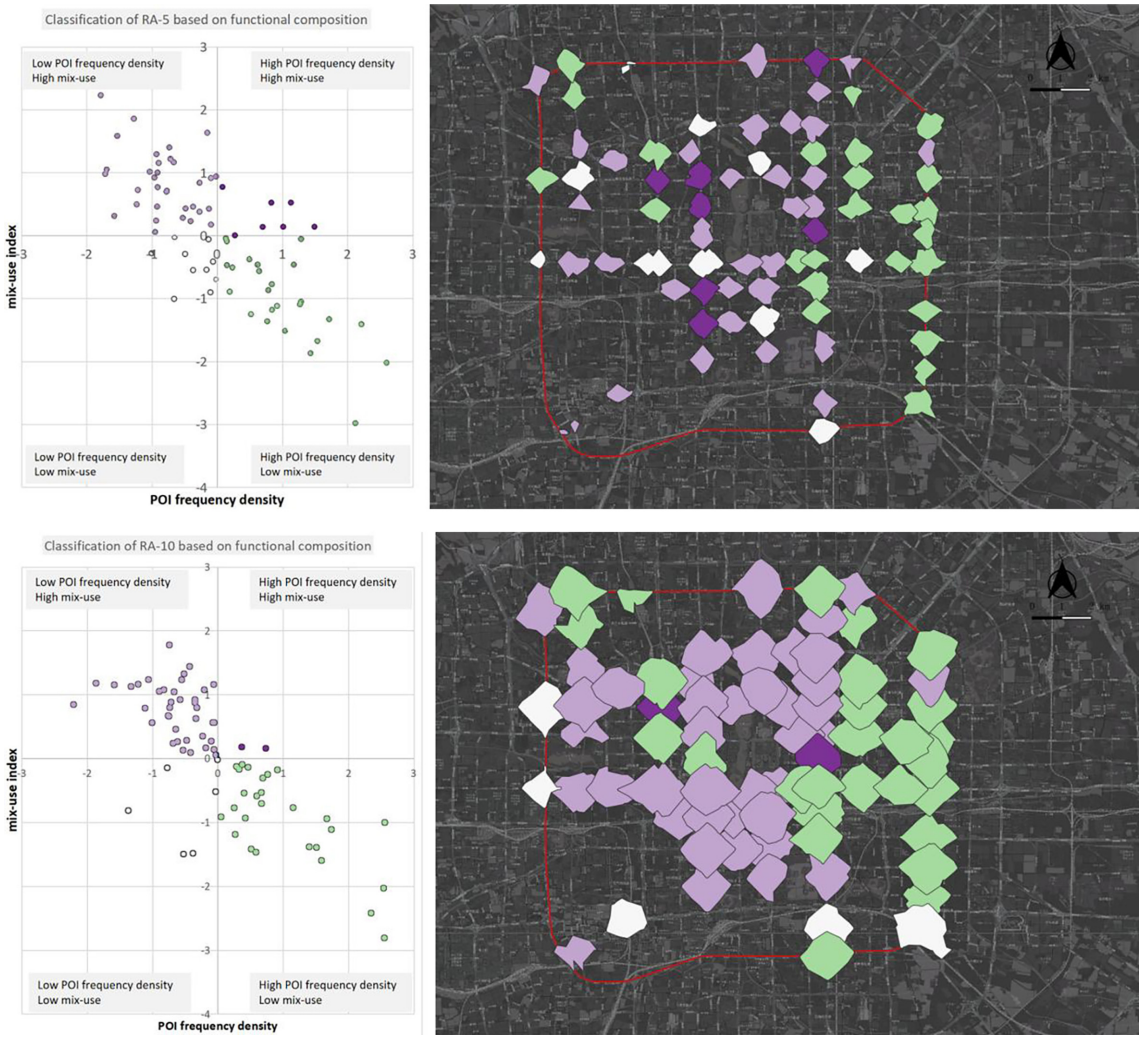


Figure 8. Classification of reachable areas based on functional composition.

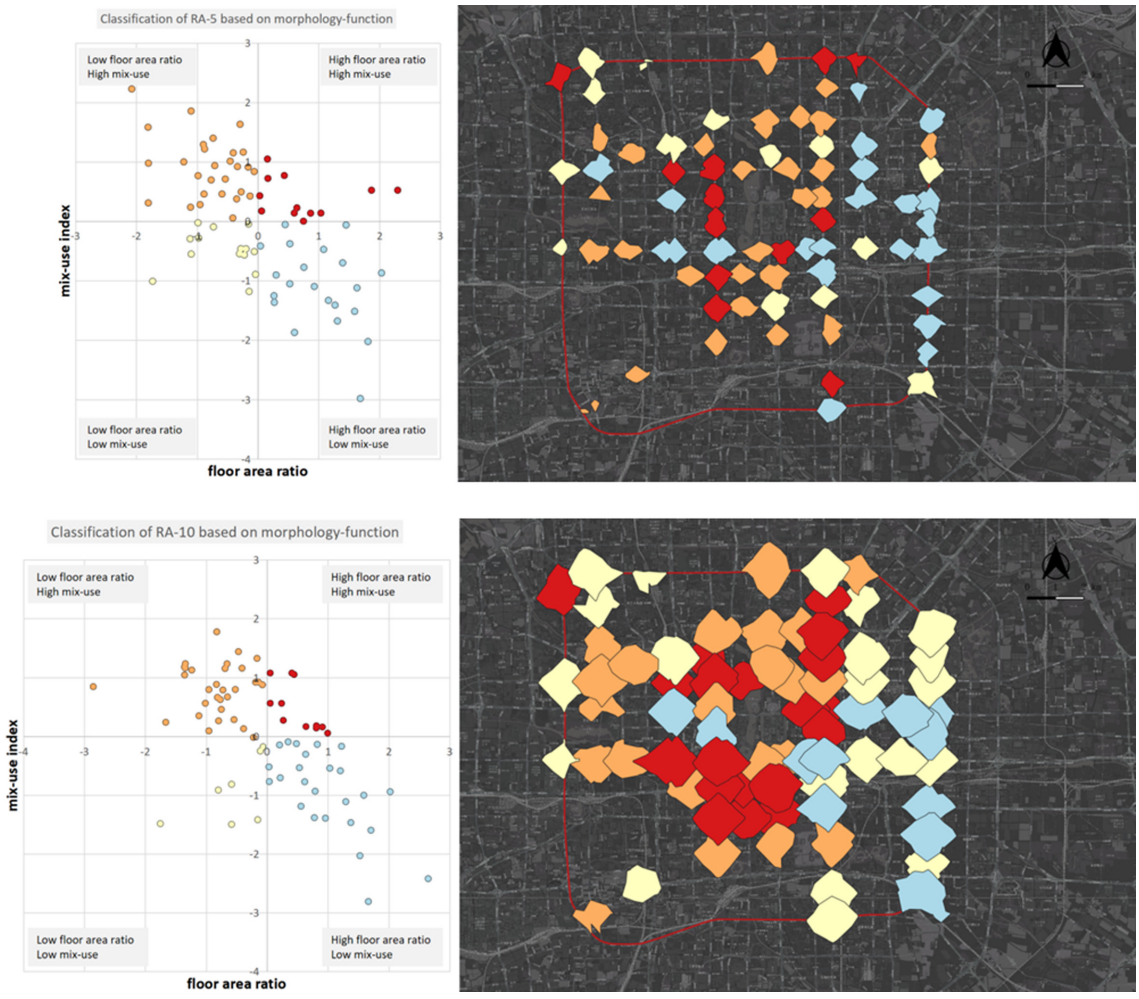


Figure 9. Classification of reachable areas based on morphology-function.

density / High mixed-use areas accounting for 54.05 percent of the overall dataset, and the spatial distribution covers the central and western regions of the study area. There are only two subway stations in the area that become High POI frequency density / High mixed-use, namely Chegongzhuang metro station (POI frequency density = 0.0012; mixed-use index = 1.47) and Dengshikou metro station (POI frequency density = 0.0011; mixed-use index = 1.47).

3.3. Classification of Reachable Areas Based on Morphology-Function

The classification based on floor-area ratio and mixed-use index can reflect the degree of coordination between urban construction intensity and functional distribution in the reachable areas. As shown in Figure 9, there is a trend that the higher the building floor-area ratio, the lower the functional mix, and the distribution of points is more concentrated in the RA-10 areas, and the trend of negative correlation is more significant.

In RA-5 areas, only 16.22 percent reached High floor area ratio / High mixed-use, mainly distributed in the Cai Shi Kou - Ping An Li stations of Metro Line 4; while Low -floor-area ratio / High mixed-use accounted for 37.84 percent, and High floor-area ratio / Low mixed-use accounted for 28.38 percent, mainly distributed in the eastern area, which needs to make full use of the built space and implant diversified urban functions.

Among the RA-10 areas, the four types of areas are more balanced, with 25.68 percent achievig a High floor-area ratio / High mixed-use balance; 29.73 percent are Low floor-area ratio / High mixed-use. The above two types are mainly distributed within the second ring road, and in more mature development areas. Meanwhile, 28.38 percent are Low floor-area ratio / Low mixed-use, and 16.22 percent are High floor area ratio / Low mixed-use types; the above two types are mainly distributed along the third ring road

4. Discussion

In terms of the reachable area of metro stations, the RA-5 area ranges from 41,229.25 m² to 703,742.37 m², with an average value of 476,059.61 m² and an average radiation radius reaching 389.27 m. The RA-10 walkable radiation

range ranges from 575,024.42 m² to 2,330,279.19 m², with an average value of 1,697,772.24 m², and the average radiation radius reached 735.13 m. In contrast to previous studies (K.C.L. K., 1995), in this study more precise access to the subway station walkable areas was obtained, to provide the basis for subsequent studies.

Comparing the floor-area ratios of RA-5 and RA-10, the average floor-area ratio in the RA-5 area is 1.15, and the average floor-area ratio in the RA-10 area is 1.25. Unlike the general transit-oriented development (TOD) model, the closer the subway station is, the higher the construction intensity is. The characteristics of the TOD model are not prominent. Possible reasons include that the study area is the core urban area of Beijing, and most of the construction predates the metro line, so the TOD characteristics are not obvious enough.

In terms of functional composition, through the classification and calculation of POI data, 55.41 percent of the RA-5 areas and 45.95 percent of the RA-10 areas, the commercial service function accounts for more than 50 percent. Part of the reason for this phenomenon is that the POI of the commercial service function is relatively dense, and many POI points correspond to a smaller space, which cannot represent the actual functional space share. In future research, it is necessary to further optimize the classification and analysis of POI point data. The optimization design strategy should be different for areas with different functional characteristics.

5. Conclusion

Based on multiple source data, this study calculated and evaluated the morphology and function of 74 metro station-reachable areas in Beijing's Third ring road region, focusing on the urban morphology and functional composition within the pedestrian reachable area of the metro station domain, and classified the reachable areas using the BCG matrix approach. The results show that in terms of urban morphology, there is no significant difference between the construction intensity of RA-5 and RA-10 in the reachable area, which does not yet show the circle-type construction intensity distribution of TOD. The function distribution shows the association of higher POI frequency density with lower mixed-use diversity, and the dominance of commercial service functions is obvious. In the classification matrix of form and function, it shows a negative correlation of decreasing mix-use indices with increasing floor-area ratios, and only about 20 percent of the areas achieve the ideal situation of high construction intensity and high mix-use diversity. It provides a reference for city managers and designers in dealing with the space surrounding metro stations with different construction intensities and functional characteristics, and optimizes the urban morphology and functional layout more precisely.

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