International Journal of Geo-Information

MDPI

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Measuring Metro Accessibility: An Exploratory Study of Wuhan Based on Multi-Source Urban Data

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Abstract: Metro accessibility has attracted interest in sustainable transport analyses. Hence, the accuracy of metro-accessibility measures have become increasingly vital. Various spatiotemporal factors, including by-metro accessibility, land-use accessibility and to-metro accessibility, affect metro accessibility; however, measuring metro accessibility while considering all these components simultaneously is challenging. By integrating these factors into a unified analysis framework, this study aims to strengthen the method for metro-accessibility assessment. Specifically, we proposed the "By metro–Land use–To metro" model to conduct a metro-accessibility index and develop an accessibility-based station typology. The results show that Wuhan metro system accessibility presented a "high-medium-low" spatial disparity from the urban center to the periphery. Meanwhile, the variety of metro-accessibility characteristics and typologies in Wuhan will equip urban planners and policymakers with a useful tool for better organising by-metro accessibility, land-use accessibility and to-metro accessibility.

Keywords: metro; accessibility; multi-source urban data; typology; Wuhan

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Citation: Wu, T.; Li, M.; Zhou, Y. Measuring Metro Accessibility: An Exploratory Study of Wuhan Based on Multi-Source Urban Data. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 18. https://doi.org/10.3390/ijgi12010018

Academic Editor: Wolfgang Kainz

Received: 15 November 2022
Revised: 5 January 2023
Accepted: 8 January 2023
Published: 10 January 2023

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1. Introduction

Rapid global urbanisation and population growth have caused many urban problems, including traffic congestion, carbon emissions and environmental pollution [1]. This has urged urban planners and policymakers to consider public transportation in order to potentially address these problems and build more sustainable urban transport systems [2,3]. Rapid and efficient urban metro systems represent an inexorably significant role in urban commuting and are widely regarded as the backbone of public transportation in large cities [4,5]. China is currently experiencing rapid growth in its metro system and many metropolises have built and expanded current metro networks in quantity [6]; 45 Chinese cities had constructed urban rail transit systems, totalling 244 lines and 7969.7 km in length, by the end of 2020, of which 78.8% comprised metro systems with 6280.8 km of combined length (China Statistical Yearbook, 2021). To strengthen the sustainability benefits of metro systems, metro-accessibility measures are becoming increasingly important in metro planning, urban geography and sustainable development [7]. Evaluating metro accessibility contributes to the assessment of metro construction and helps urban planners and policymakers to optimise metro and urban planning.

However, owing to the various spatiotemporal dimensions of metro accessibility, it is relatively difficult to find a measurement that can accurately capture all these components [7]. Geurs and van Wee (2004) [8] recognized the following four components: land-use, transportation, temporal and individual. Similarly, four primary methods have been identified for accessibility measurement: cumulative opportunity-, gravity-, utility- and person-based [9]. Currently, researchers have shed light on scores of metro accessibility indices, each of which has different data requirements, methodological approaches and application areas [10]. The diversity and complexity of these methods lead to different

interpretations of accessibility, thereby hindering their application by urban planners and policymakers [11]. Therefore, a fine balance between improving the accuracy of these metro-accessibility approaches and keeping them simple and practical is needed [12]. Planning a metro system with a good degree of accessibility might result in social, environmental and financial benefits. However, few have integrated multi-dimensions of metro accessibility characteristics and quantitatively examined the degree of metro accessibility and its correlates.

This paper aims to fill this gap and develop a conceptual framework for metro accessibility measurement by using a set of indicators. The proposed methodology considers by-metro travel characteristics, land-use distribution characteristics and to-metro travel characteristics as impact dimensions in metro accessibility measurement. By incorporating the aforementioned three dimensions, this paper develops the "By metro–Land use–To metro" model which could help to generate more insights into metro accessibility characteristics and to make appropriate policy decisions. Moreover, current innovations in geospatial big data and computing techniques can provide new opportunities for researchers to quantitatively investigate metro accessibility. Compared to traditional data, geospatial big data has several advantages such as higher variety, larger volume and lower data-collection costs [13]. Using Wuhan as a case study, this research makes an effort to integrate multi-source urban data, including traditional and non-traditional data, to develop a comprehensive accessibility index to measure and classify metro accessibility.

2. Literature Review

Accessibility is crucial for achieving sustainable urban transport and development; further, urban planners and policymakers have prioritized provision of sufficient and equal accessibility [14]. Although accessibility is a widely used concept in transportation literature, it has no consistent definition or measurement [15]. The concept of accessibility was first proposed by Hansen (1959) [16] and was defined as "potential of opportunities for interaction". Bertolini (2005) [17] defined it as "the number and diversity of places that can be reached within a given travel time and/or cost". Van Wee (2016) [18] described it as an incorporation of the scope of opportunities offered at destinations and the resistance to reaching them.

Metro accessibility has a similar definition but the mode of travel is restricted to metro-based travel. A variety of approaches have been proposed to measure metro accessibility based on different situations and purposes. In general, metro accessibility measures can be classified into two categories, namely by-metro accessibility and to-metro accessibility [19]. By-metro accessibility assesses the level of metro service given the ease of using the metro system [19]. Metro station operational attributes of the metro network are frequently used to measure by-metro accessibility, including number of directions, departure intervals and reachable stations by metro [20,21]. Recent literature shows that network centrality, such as the integration or betweenness variables of metro network topological connectivity, have become more important in spatial network analysis [2]. On the other hand, to-metro accessibility describes the convenience of using a metro service and examines either access to metro stations from a trip origin or egress from metro stations to a trip destination [10]. To-metro accessibility is normally measured by walkability factors, such as intersection density, the length of walking path and street connectivity [22,23]. Lahoorpoor and Levinson (2020) [24] discussed that station entrance and exit locations could affect to-metro accessibility and exposing the exiting system might increase ridership. Recent studies show that by-metro accessibility and to-metro accessibility cannot cover all of the analysis dimensions of metro accessibility. There is one more dimension as necessary as by-metro accessibility and to-metro accessibility, which concerns opportunities a metro station can access. Land-use accessibility refers to the spatial distribution of activity opportunities around metro stations and can be measured by the built environment variables, such as commercial facilities, public facilities and residential facilities [11].

Therefore, metro accessibility should be interpreted as a combination of by-metro accessibility, to-metro accessibility and land-use accessibility. This paper considered all these three dimensions to create our "By metro–Land use–To metro" model to evaluate metro accessibility. The model provides a new contribution to metro accessibility measurement, equipping urban planners with a progressive and beneficial tool for planning more targeted strategies. The coordination between by-metro accessibility, land-use accessibility and to-metro accessibility influences metro accessibility degree and accessibility-based station typologies in knowing which stations have achieved a state of coordinated development.

3. Methods and Data

3.1. Overall Framework of Methodology

Figure 1 shows the method structure of the present study. In the first stage, three critical dimensions: by-metro accessibility, land-use accessibility and to-metro accessibility, were presented to evaluate metro accessibility. Sub-indicators of each dimension were selected based on the previous studies, expert advice and data available. Metro lines and stations, information on metro operation, point of interests (POIs) and street network data were collected. All the data were imported into ArcGIS to be analyzed. Before calculating the indicator values, we geographically delineated the metro station catchment area for analysis. In the second stage, we quantified and integrated these indicators based on the "By metro–Land use–To metro" model to evaluate metro accessibility characteristics. The analytic hierarchy process (AHP) method was used to determine the weight of each indicator. In the final stage, cluster analysis was then applied to obtain different accessibility performance categories. A hybrid hierarchical K-means++ (H-K-means++) algorithm was performed here. Therefore, a metro-accessibility measurement framework was created to generate more insights into metro-accessibility characteristics and provide urban planners with a progressive and beneficial tool for designing targeted strategies.

3.2. Metro Catchment Area

As the land-use and to-metro dimension indicators were calculated for a certain spatial threshold, the metro-accessibility analysis outcomes were directly linked to the metro catchment area (MCA) size. Previous studies have demonstrated the diversity of case-specific distance thresholds, but no fixed criteria have determined a specific MCA value. For example, most European scholars have proposed a distance of 700 m from transit stops [25–28], while American researchers have proposed distances ranging from 400 to 800 m [29,30]. Since metros have smaller distances between stations compared to rail transit systems, a smaller MCA is required to reflect the varied willingness to walk to the metro. As recommended by our previous study [31], we selected 600 m as the delineation threshold to define the MCA in this study.

3.3. Indicator Selection

We selected the indicators according to the theoretical logic of the By metro–Land use–To metro model, previous studies, expert advice and data availability. Table 1 depicts the detailed definition and calculation method as well as the positive and negative effects of the indicators on metro accessibility.

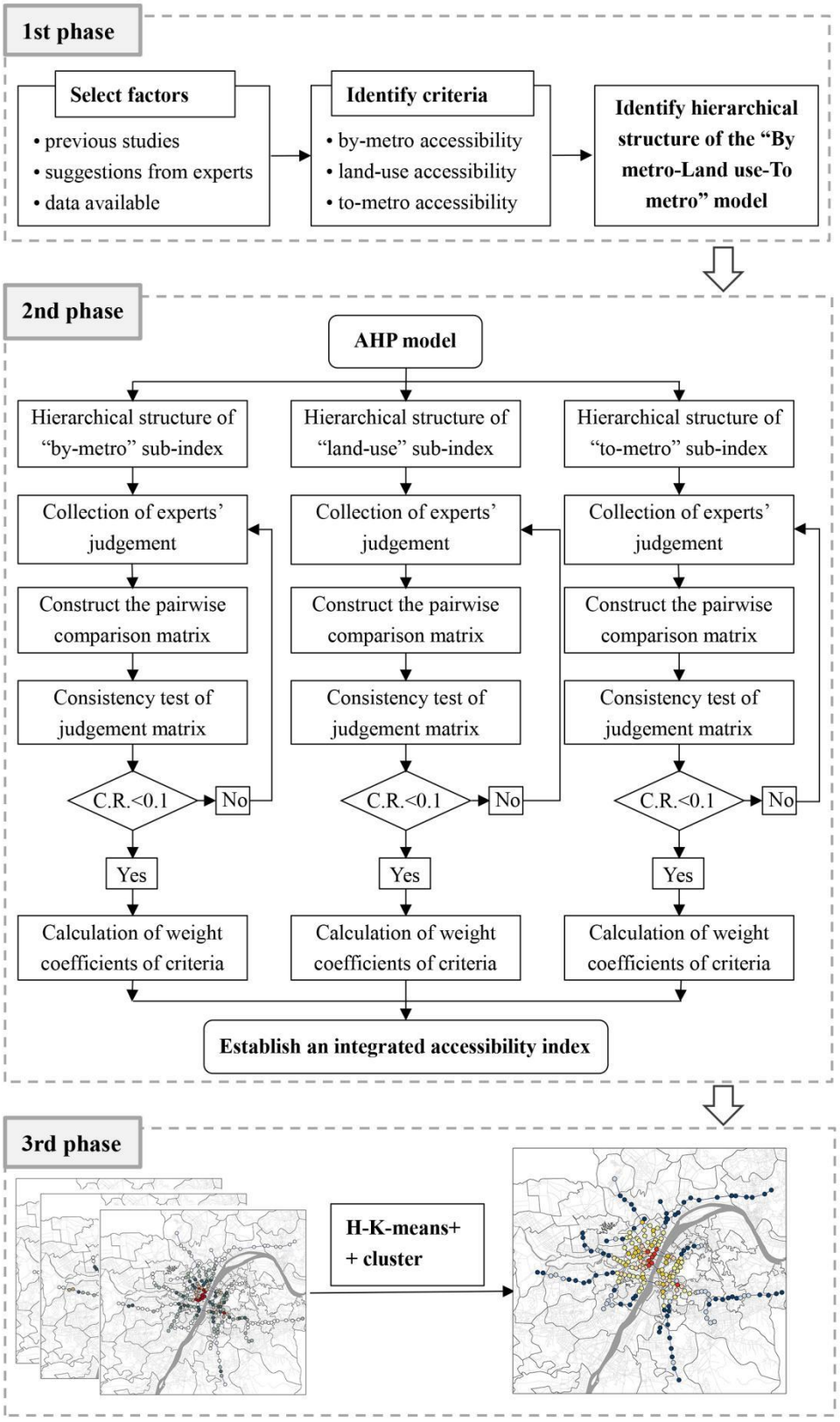


Figure 1. Flow chart of the present study.

Table 1. Detailed explanation of metro-accessibility indicators.

Category	Code	Indicator	Explanation	Desirability
By-metro accessibility	B1	Reachable stations within 20 min	The number of metro stations reachable within 20 min by metro	Positive
	B2	Number of directions	The starting value was two for each station and increased by two for each additional transferable line.	Positive
	B3	Departure interval (minutes)	A pause in time between each of the two metro trains as they enter the station	Negative
	B4	Metro network integration	Integration of Wuhan metro network as measured by space syntax theory	Positive
	B5	Metro network betweenness	Betweenness of Wuhan metro network as measured by space syntax theory	Positive
Land-use accessibility	L1	Public facilities	The number of public facilities (cultural facilities, schools and hospitals) inside the 600 m MCA	Positive
	L2	Commercial facilities	The number of commercial facilities (leisure, tourism, amenities and shops) inside the 600 m MCA	Positive
	L3	Residential facilities	The number of residential facilities inside the 600 m MCA	Positive
	L4	Offices and services facilities	The number of offices and services facilities inside the 600 m MCA	Positive
	L5	Variety of POIs	Variety of POIs inside the 600 m MCA	Positive
To-metro accessibility	T1	Intersection density	The number of street network intersections in each MCA	Positive
	T2	Accessible network length	Length of the accessible street network (metres)	Positive
	T3	Street integration	Following angular analysis, mean integration values in a 700 m area	Positive
	T4	Street betweenness	Following angular analysis, mean betweenness values in a 700 m area	Positive

3.3.1. By-Metro Accessibility Indicators

The by-metro accessibility dimension measures the ease and directness of inter-station metro travel and includes indicators used by Li et al. (2019) [32] and several other studies. We integrated operational attributes and network centrality indicators and selected five indicators to measure by-metro accessibility (Table 1). B1 measured the number of stations that can be reached within 20 min via the metro system, which was calculated by Direction API. B2 measured the number of metro directions at a station. Each station was assigned a value of two and an additional score of two was added for each transfer line. B3 measured how long it took for two metro trains to pass the station, assuming the shortest interval between departures when there are multiple lines. Lastly, to describe the metro network centrality, we referred to the integration centrality (B4) and betweenness centrality (B5). Using a topology-based model to capture the prominence of each node in the metro network, both of the indicators were calculated using the Depthmap software (UCL, London, UK). B4 measured the average shortest paths of a station to all other stations in the metro network, reflecting the centrality and prominence of a station. B5 measured the proportion of a station to be passed through between any two stations by the shortest paths, reflecting the penetrability of a station.

3.3.2. Land-Use Accessibility Indicators

For land-use accessibility, we considered built environment features that refer to the accessible opportunities of each station (Table 1). All five indicators were calculated based on the point of interests (POIs) collected from Geode Map. L1 measured the number of public facilities (cultural facilities, schools and hospitals); L2 measured the number of commercial facilities (leisure, tourism, amenities and shops); L3 measured the number of residential facilities; and L4 measured the number of offices and service facilities within the MCA. L1–4 presented land density and vitality at each station, including possible points and areas that might be trip attraction points [33] and L5 measured the variety of POIs based on the classification of L1, L2, L3 and L4.

3.3.3. To-Metro Accessibility Indicators

As walking is the most important way for first- and last-mile travel services to and from a station, to-metro accessibility measures how walking is facilitated by streetscape (e.g., physical attributes and amenities). The indicators are shown in Table 1. Indicator T1 describes the number of intersections in each MCA. T2 measures the street-line density in each MCA, which represents the total length of an accessible street network [34]. In reference to the work of Wu and Zhou (2022) [23], we used street integration (T3) and street betweenness (T4) to describe street network topological connectivity. While T3 measured the closeness of each street to all others in the given network, T4 calculated the ease of access for pedestrians to reach the station without taking too many turns. A station's potential (the selection of a destination from a place of origin) for to-move increased if the surrounding streets network were better connected, whereas a higher betweenness indicated more through-move potential (the choice of the transitional areas which can be crossed to get from one place to another). The spatial design network analysis (sDNA), a package of GIS, was used to quantify T3 and T4. As such, the following four significant steps were taken:

1. Street network data were obtained from the open street map (OSM) and were imported into sDNA.
2. Angular choice analyses were performed for a low metric radius (600 m).
3. The station areas (radius: 700 m) were cut from the angular choice map. A pedestrian's ideal walking radius is 600 m. This radius was increased by 100 m to lessen the edge effect caused by cutting.
4. Average integration and betweenness values were determined for each station.

3.4. Indicator Integration

As every indicator did not have the same influence on the results, we standardised, normalised and weighed these indicators before aggregating them into integrated indices. Based on the ranking assigned by experts, an integrated index was obtained by aggregating the indicators with the help of the AHP method via the following steps:

1. Standardising and normalising the indicators

Before integrating the indicators, we normalised and standardised all indicators, as follows:

$$X'_{ij} = \begin{cases} \frac{X_i - \min X_{ij}}{\max X_{ij} - \min X_{ij}} & \text{positive} \\ \frac{\max X_i - X_{ij}}{\max X_{ij} - \min X_{ij}} & \text{negative} \end{cases} \quad (1)$$

where X_{ij} is the value of indicator i for station j, max X_{ij} is its highest value and min X_{ij} is its lowest value of indicator i for all stations. Positives represent a greater value with a positive contribution and negatives denote a higher value with a negative contribution.

2. Building the evaluation hierarchy.

As indicated in Figure 2, the index evaluation system covers three levels: the integrated metro-accessibility index; the by-metro, land-use and to-metro accessibility sub-indexes; and their indicators. The indicator weights were calculated by paired comparisons at the same level [35]. Notably, measuring the degree of metro-accessibility and the classification of accessibility-based station typologies required interdependence among the three dimensions. Therefore, AHP was conducted separately to integrate the by-metro, land-use and to-metro sub-indices. Finally, the three sub-indices were assigned equal weights to establish an integrated metro-accessibility index.

3. Calculating indicator weights

The evaluation team comprised 25 experts. They included professors in urban planning (N = 6), transport geography (N = 7), land-use (N = 5) and academic staff from the Wuhan Metro Group (N = 3) and Planning Bureau (N = 4). When the in-pair comparison matrix passed the consistency test with a consistency ratio (CR) below 0.1, it was possible to

convert the subjective opinions of experts into the objective weights of each indicator [36]. Overall, to come to a consensus, all specialists had taken four cycles of feedback. Table 2 summarises the pairwise matrix with CRs and Figure 2 displays the evaluation hierarchy and determined weights of each indicator.

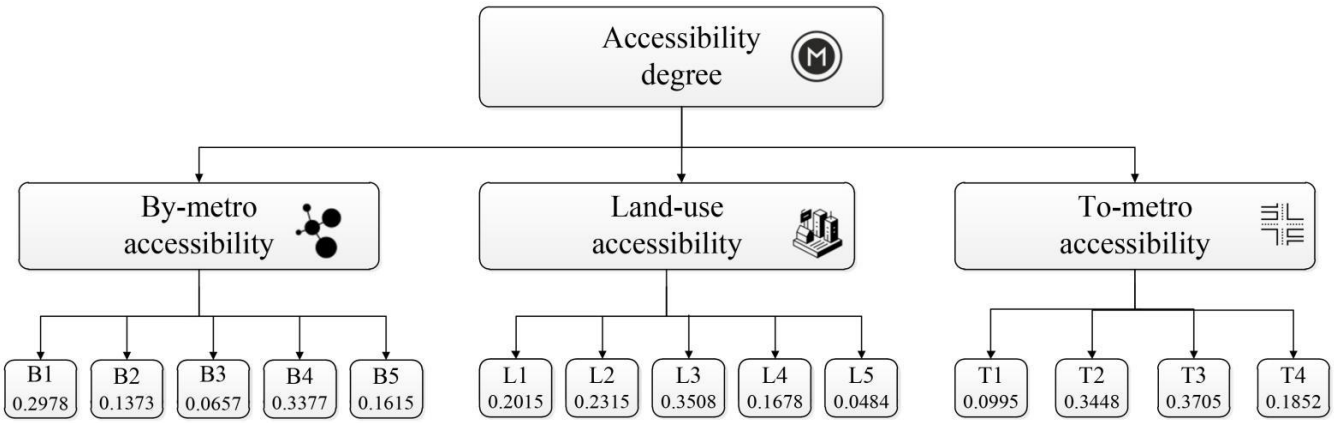


Figure 2. The evaluation hierarchy and determined weights of each indicator by AHP.

Table 2. Pairwise matrix and ranking of indicators.

	Indicator	M1	M2	M3	M4	M5	Weight
B1	Reachable stations within 20 min	1	2	4	1	2	0.2978
B2	Number of directions	1/2	1	2	1/3	1	0.1373
B3	Departure interval	1/4	1/2	1	1/5	1/3	0.0657
B4	Metro network integration	1	3	5	1	2	0.3377
B5	Metro network betweenness	1/2	1	3	1/2	1	0.1615
			CR = 0.007				
	Indicator	**E1**	**E2**	**E3**	**E4**	**E5**	**Weight**
L1	Public facilities	1	1	1/2	1	5	0.2015
L2	Commercial facilities	1	1	1/2	2	5	0.2315
L3	Residential facilities	2	2	1	2	5	0.3508
L4	Offices and services facilities	1	1/2	1/2	1	4	0.1678
L5	Variety of POIs	1/5	1/5	1/5	1/4	1	0.0484
			CR = 0.0219				
	Indicator	**S1**	**S2**	**S3**	**S4**		**Weight**
T1	Intersection density	1	1/3	1/4	1/2		0.0995
T2	Accessible network length	3	1	1	2		0.3448
T3	Street integration	4	1	1	2		0.3705
T4	Street betweenness	2	1/2	1/2	1		0.1852
			CR = 0.0039				

3.5. Station Classification

For a better perception of the degree of accessibility, the symbiosis of three dimensions and the typologies of metro stations, the stations were divided into clusters with similar attributes using the H-K-means++ method. The main process of this approach can be summarised into two stages. First, hierarchical cluster analyses generated trees and helped decide the optimal number of clusters. Second, all stations were clustered according to their by-metro, land-use and to-metro accessibility values using the K-means++ clustering algorithm. K-means++ can choose the initial cluster centres as far away from each other as possible [1].

3.6. Study Area

Wuhan, the largest metropolitan area in Central China, is the study area of this paper. Wuhan has not been extensively explored in comparison to cities such as Beijing and Shanghai, which have been explored in previous research. With a population of over ten million, Wuhan is now among the most populated cities in China. In 2004, Wuhan launched its first metro line, making it China's seventh city to run an urban rail transit system. Wuhan has accelerated the development of metro systems in recent years. In December 2020, the Wuhan metro system had nine operating routes (i.e., lines 1–4, 6–8 and 11), with a total length of 338.4 km, as shown in Figure 3. With an initiative launched, Wuhan's municipal government try to transform Wuhan into a "metro metropolis", aiming for massive and continuous metro construction developments and integrating regional spatial development with the metro network [37], which propelled this empirical study of the city.

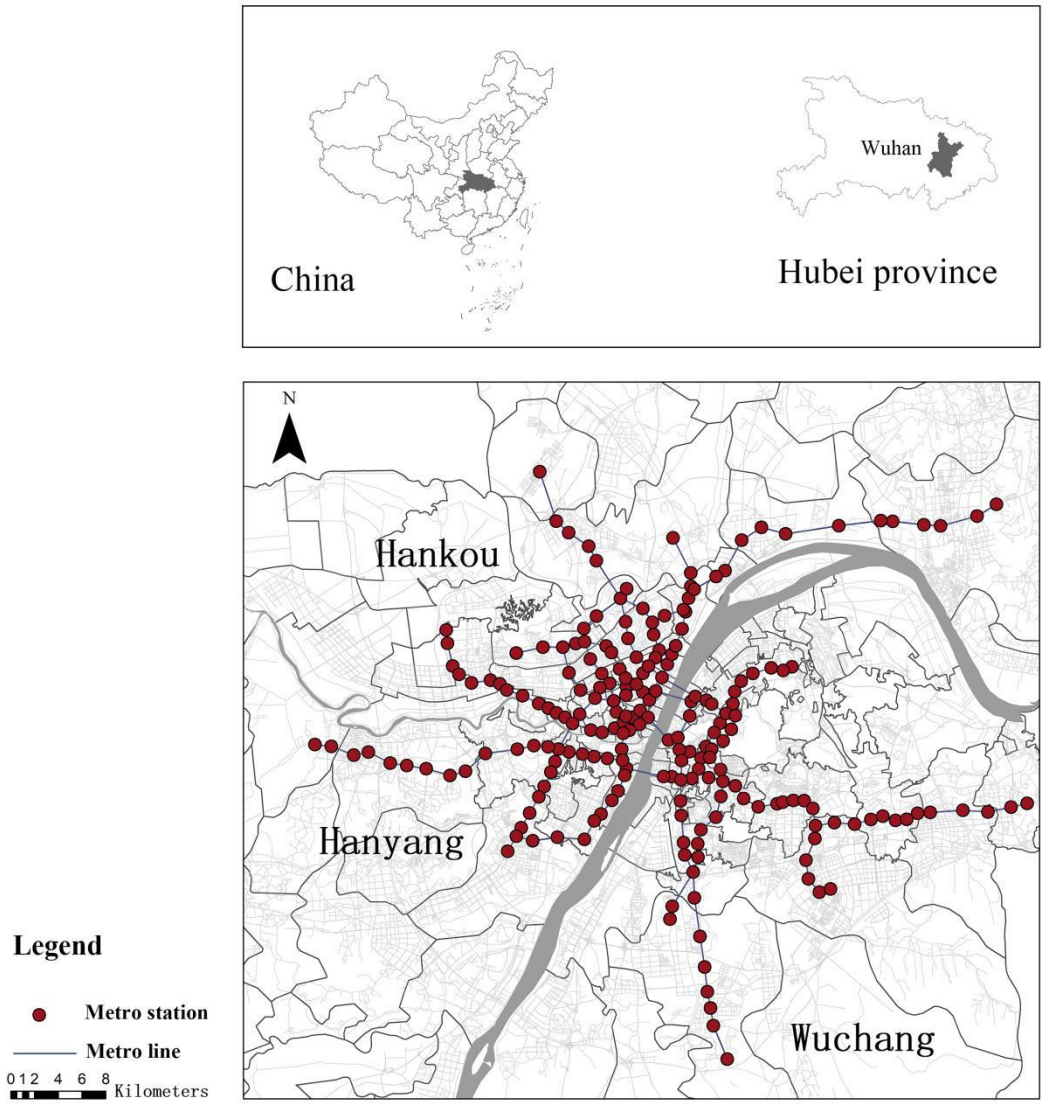


Figure 3. Map of the study area.

Furthermore, as a waterfront city, the urban core of Wuhan is divided by the Yangtze and Han Rivers into three towns, that is, Hankou, Wuchang and Hanyang. With the rapid development of cities, these former "town centres" have turned into regional centres or sub-centres. In Wuhan, these factors have caused the emergence of a polycentric urban spatial structure. Therefore, an empirical study of Wuhan could shed light on how metro accessibility contributes to such development.

3.7. Data Collection

This study used multi-source urban data, including traditional and non-traditional data, to quantify the indicators mentioned above. Traditional data, such as the metro departure interval, the number of directions and the transfer information, were obtained from the government website to represent the physical characteristics of the metro system. For non-traditional data, street polylines data were acquired from Open Street Map (OSM) and POIs data were collected by a web crawler through the Geode Map. The obtained street polylines data were imported into ArcGIS to describe physical attributes and analyzed by sDNA to represent topological connectivity. The obtained POI data included names, locations and classification types and were classified into four major types to measure land use accessibility: public facilities, commercial facilities, residential facilities, offices and services facilities. Metro operation data were collected from Geode Map API and the Direction API was used to calculate reachable stations within 20 min.

4. Results

4.1. Metro-Accessibility Degree

Figure 4 shows the spatial patterns of the by-metro, land-use and to-metro sub-indices and the integrated accessibility index. The integrated accessibility index values for the stations present clear spatial disparities, declining from the city's core to the outskirts. The sub-indices' patterns were analogous to those of the integrated accessibility index. In particular, stations with higher by-metro accessibility values were observed in the central network assembled by lines 1–8. The transfer stations' by-metro accessibility value was very good, with a declining rating-circle structure. With respect to land-use accessibility, metro stations in the Hankou District's central part presented larger values, while those situated in Wuhan's outer ring exhibited lower values. The Hankou District possessed the most stations with higher to-metro accessibility sub-index values, whereas stations featuring lower to-metro accessibility values frequently appeared in suburban areas. It was universal to witness metro stations with larger integrated accessibility index scores in the central core, especially in the central part of Hankou District. By contrast, stations located in the Hanyang District exhibited lower values for either the integrated accessibility index or the three sub-indexes. The Jianghan Road Station had the highest accessibility, followed by the Dazhi Road, Hong Kong Road, Xunlimen, Sanyang Road and Jiedaokou stations.

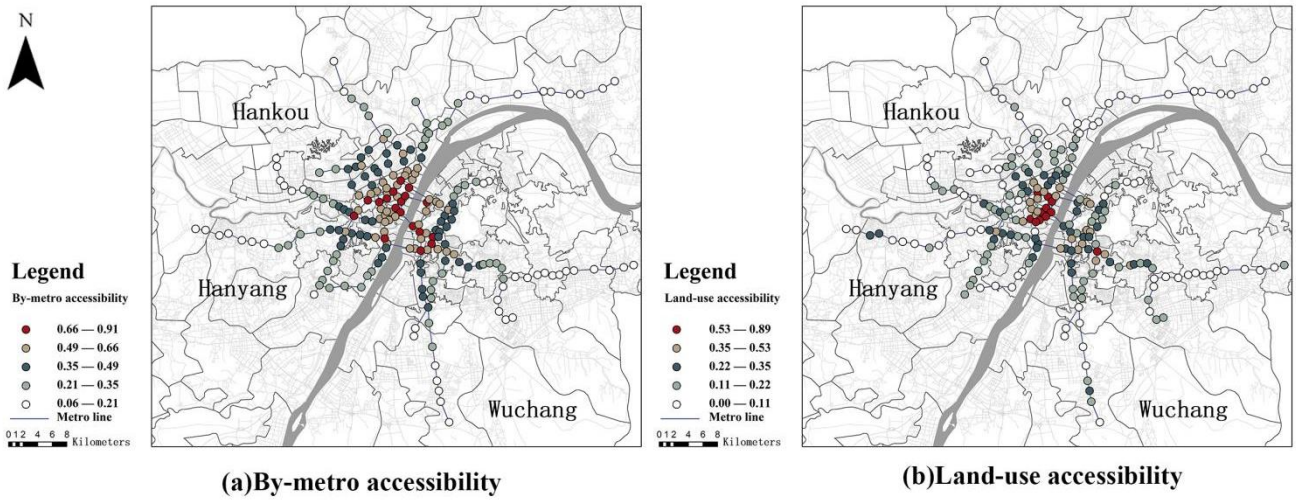


Figure 4. *Cont.*

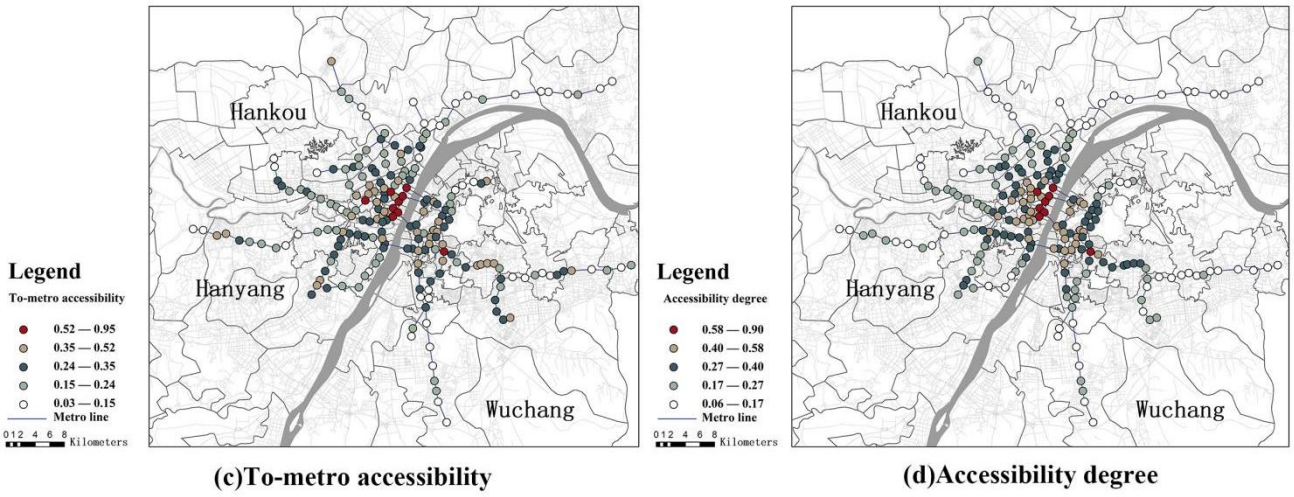


Figure 4. Spatial patterns of different sub-indices, including (**a**) 'by-metro', (**b**) 'land-use', (**c**) 'to-metro', as well as (**d**) the integrated accessibility index.

4.2. Accessibility Typology

Table 3 summarises the statistics and six cluster solutions for the metro station accessibility typologies based on the H-K-means++ cluster analyses. Each of the six typologies has distinct characteristics. The location and scatter plots of the specific accessibility typologies are shown in Figures 5 and 6.

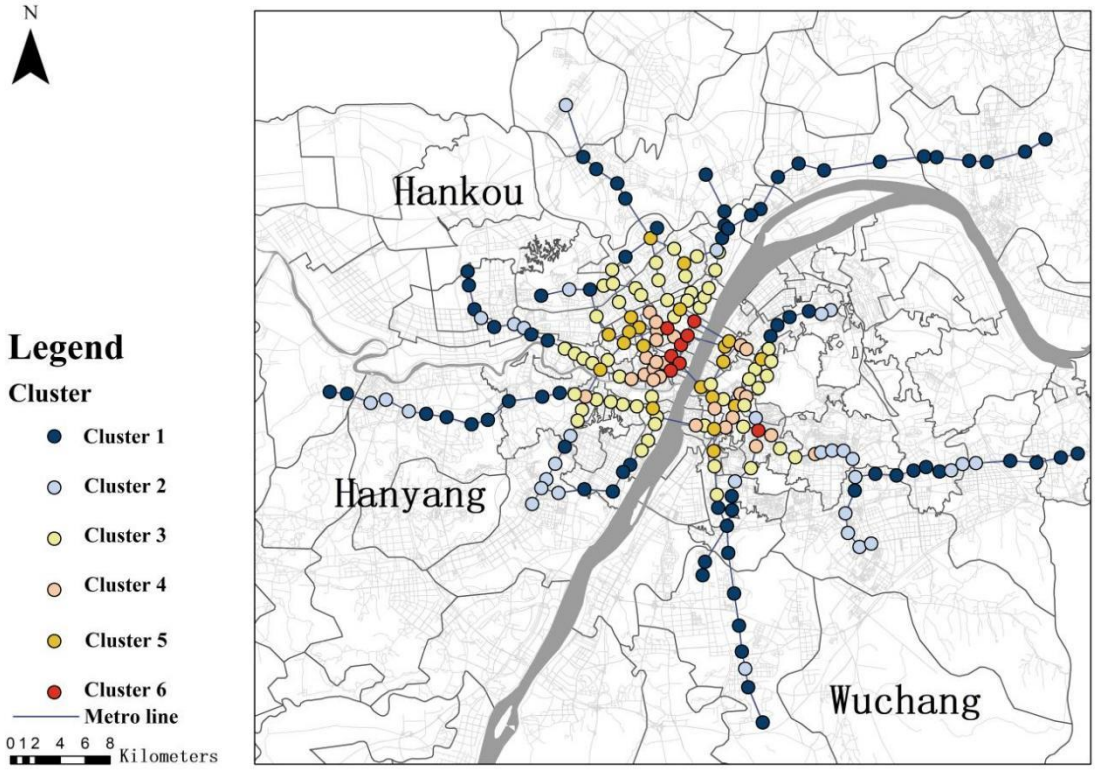


Figure 5. Classification of metro station accessibility in Wuhan.

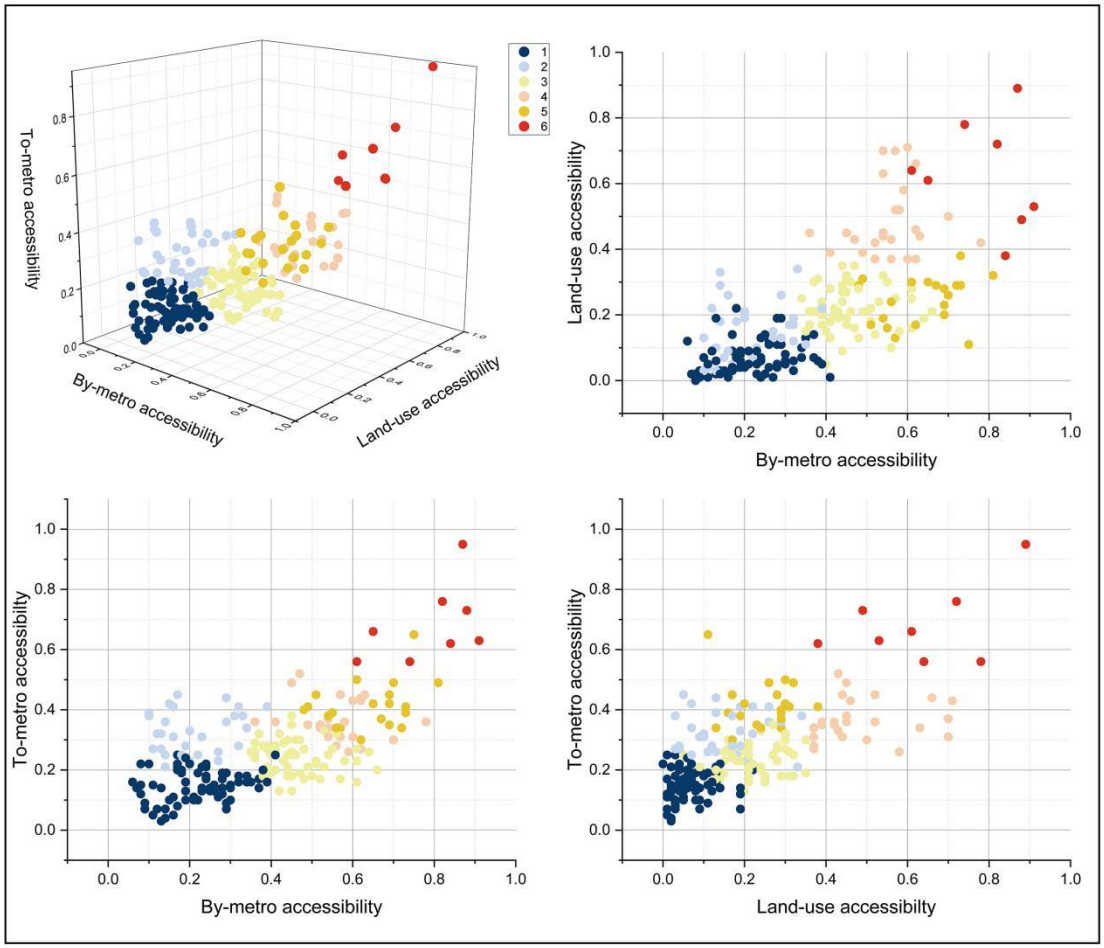


Figure 6. Scatter plots of by-metro accessibility, land-use accessibility, to-metro accessibility of Wuhan metro stations.

Table 3. Summary of cluster description.

Clusters	Number	Example of Stations	By-Metro Accessibility (Avg.)	Land-Use Accessibility (Avg.)	To-Metro Accessibility (Avg.)
C1	71	Dijiao, Jinghe	0.219	0.068	0.148
C2	32	Fozuling, Guanggu Avenue	0.222	0.151	0.323
C3	55	Baotong Temple, Qingyuzui	0.462	0.218	0.239
C4	25	Hanzheng Street, Wangjiawan	0.560	0.487	0.365
C5	20	Yuejiazui, Jiyuqiao	0.638	0.245	0.415
C6	8	Jianghan Road, Jiedaokou	0.790	0.629	0.684

Cluster 1 (71 stations) and Cluster 2 (32 stations) were located in the metro system's urban peripheries and suburban branches. Although stations in both clusters had low by-metro and land-use accessibility sub-index values, some notable differences were observed. For example, Cluster 1 comprised stations with the lowest values for all three sub-indices. Compared to Cluster 1, Cluster 2′s to-metro accessibility sub-index score was much larger, indicating that Cluster 2 station areas were more walkable. Notably, metro stations in Cluster 1 were generally situated at the terminus of the line, whereas those in Cluster 2 were relatively closer to the central city.

In Cluster 3 (55 stations), a balance between land-use and to-metro accessibility was observed, with moderate by-metro accessibility. Most of these stations were located around the city centre, close to the transfer stations. Cluster 4 (25 stations) presented a balance between by-metro and land-use accessibility with moderate to-metro accessibility, suggesting that metro network development can be matched by surrounding urban development and that a highly connected and walkable street network could strengthen the mutual enhancement between metro transit and land-use. Scores for Cluster 5 (20 stations) were similar to those of Cluster 4 for by-metro and to-metro accessibility, but with a comparatively low score for land-use accessibility, potentially due to the higher presence of transfer stations in this cluster.

Cluster 6 (8 stations) was characterised by the three highest sub-indices, situated in the city centre, particularly concentrated within the central Hankou District, except for Jiedaokou Station, which was located in the centre of the Wuchang District. More specifically, these stations, which also have the best degree of accessibility, were well balanced and operated at maximum efficiency.

5. Discussion and Conclusions

5.1. Accessibility Degree and Typology

To stimulate a more sustainable pattern of growth and lifestyle, many cities have invested in sustainable transportation. To achieve these goals, ensuring metro accessibility is necessary. Building on existing metro-accessibility research, the present study develops a comprehensive metro-accessibility index to quantify the degree of accessibility and classify accessibility-based station typologies. We propose three dimensions to measure metro accessibility more accurately: by-metro accessibility, land-use accessibility and to-metro accessibility. This study focuses on the integration of these dimensions into a unified analysis framework and develops a "By metro–Land use–To metro" model that can be used to assess metro accessibility and develop accessibility-based station typologies.

From urban centre to urban fringe, the degree of the Wuhan metro accessibility presented a "high-medium-low" spatial disparity. Metro stations with the highest degree of accessibility were predominantly dispensed in the central urban areas along the Yangtze River. The metro line operated firstly in central Wuhan and the stations in the central core can gradually achieve greater accessibility after years of development. Notably, as a polycentric city, the accessibility of the three towns differed, with Hankou ranking first and Hanyang ranking last. The accessibility degree presented an analogous spatial pattern among the three towns, with a decline from urban center to urban suburbs. For example, the Jianghan Road Station, as the centre of the metro network structure, experienced rather mature growth within its catchment area.

We distinguished six accessibility-based station clusters representing different degrees of by-metro accessibility, land-use accessibility and to-metro accessibility. The diversity of these types highlights the uniqueness and specialisation of accessibility among Wuhan metro stations. Cluster 1, with the lowest value of by-metro, land-use and to-metro accessibility, had the most stations. Some suburban lines, such as Metro Lines 11 and 21, were far away from the city centre, because of the advance planning and construction of metro systems. Land-use and street networks along these lines are currently being planned. Clusters 3 and 5 featured unbalanced situations, due to their surroundings. Urban development greatly lags behind metro construction in these types. Stations in Cluster 6, which fulfil the cooperation between the by-metro accessibility, land-use accessibility and to-metro accessibility, were located at the core of urban areas, particularly concentrated within the Hankou District centre. The Jiedaokou Station, in the Wuchang District, was the only one belonging to this cluster, while the Hanyang District had no stations in this cluster.

5.2. Implications for Metro-Accessibility Planning

This study's accessibility-based typology of metro stations can provide valuable insights into metro development and urban planning. The internally similar but externally

distinct characteristics of accessibility may allow planners to develop targeted strategies for each typology. Generally, planners should prioritise Clusters 3 and 5 to achieve greater overall cost-to-benefit ratios. For Cluster 3, introducing new urban construction projections and improving walkability may be a practical solution to match the already high by-metro accessibility. For metro stations in Cluster 5, by-metro accessibility was relatively high, but their land-use accessibility was relatively low, suggesting that strategies to promote accessibility should focus on increasing land-use accessibility. Metro stations in Clusters 1 and 2 were located on the outskirts and connected the Wuhan centre to the suburbs; thus, efforts should be made to plan ahead and guide development around these stations. The existing high accessibility of all three dimensions for Cluster 6 provides a good opportunity for accessibility and sustainable metro transport evolution.

5.3. Strength, Limitations and Prospects

A method with characteristics of practice and flexibility is demonstrated in this study for measuring metro station accessibility and establishing accessibility typologies. We integrated the three dimensions affecting metro accessibility and established a "By metro–Land use–To metro" model using multi-source urban data that is readily accessible to the general public, such as traditional data, POIs and OSM data. The proposed approach is universal and can be applied to other global geographic contexts to assess metro accessibility after a suitable adjustment of the indicator system.

Nevertheless, there are certain shortcomings in this study which need to be addressed in the future. First, the POI data provided the type and location of each facility, not their size and patronage. Regardless of the actual size, each POI in this study was considered a single-sized facility. In future studies, detailed land-use data from Wuhan should be used to identify and model land-use development. Second, we used a circular buffer (600 m) to delineate the station catchment area without taking into account the path distance and physical obstacles. To address this limitation, future research could include metro service areas based on street networks. Third, we used the AHP approach for weight determination. As an experience-driven method, this might suffer from the subjective bias of expert opinions. In future research, we might integrate subjective and objective methods to overcome the shortcomings of using a subjective weighting method.

Author Contributions: Conceptualization, Tao Wu and Mingjing Li; methodology, Tao Wu, Mingjing Li and Ye Zhou; data curation, Tao Wu and Ye Zhou; investigation, Tao Wu and Mingjing Li, Writing-original draft, Tao Wu All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by 2022 Hubei Changjiang National Cultural Park Construction Research Project, Hubei Provincial Department of Culture and Tourism, grant number HCYK2022Y08; Wuhan Science and Technology Bureau, grant number 2022010801020310.

Data Availability Statement: POI data were obtained from Gaode Map (https://lbs.amap.com/, accessed on 10 November 2021). Street data were acquired from Open Street Map (OSM) (https://www.openstreetmap.org/, accessed on 10 November 2021). Metro operation data was from the government's official website (https://www.wuhanrt.com/public_forward.aspx/, accessed on 10 November 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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