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How urban metro networks grow: From a complex network perspective

Xiaoyu Yu [a,b], Zheng Chen [c], Fang Liu [a,b,*], Hehua Zhu [a,b]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China
[b] Key Laboratory of Geotechnical and Underground Engineering (Tongji University), Ministry of Education, China, 1239 Siping Road, Shanghai 200092, China
[c] Key Laboratory of Ecology and Energy-saving Study of Dense Habitat, Tongji University, 1239 Siping Road, Shanghai 200092, China

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ABSTRACT

Metro lines emerged and developed in cities driven by various factors, and resulted in different structures as we see today. How do metro lines grow as a system? The spatiotemporal growing patterns of metro networks and their complex-network statistics may shed light on this question. Within the framework of the complex network analysis, this paper establishes a nine-metric scheme to quantify the service performance of an urban metro network from three dimensionalities i.e., accessibility, resilience, and serviceability. Accordingly, a shamrock plot is proposed as a tool to visualize the multi-dimensional maturity of a metro network as well as its growing pattern. The metrics and the visualization tool are used to reveal metro development in 42 cities of Chinese mainland. The results show that metro networks can evolve from nascent, to skeleton, and to mature forms, with their scores increasing in all dimensionalities. The choice of urban transportation between metro-dominant and automobile-dominant results from the race between metro development and car popularity. Cities may be more likely to become metro-dominant if metro develops early at a low level of car ownership. Urban metro network may develop as a response to the city's needs hierarchically from the most basic (e.g., accessibility) to more advanced (e.g., resilience and serviceability), similar to Maslow's hierarchy of individual needs.

1. Introduction

Metro lines emerged and developed in densely-populated cities to meet increasing traffic demand, forming sophisticated networks of urban public transportation with dense stations and intricate inter-station couplings (Angeloudis and Fisk, 2006). Metro lines sprawl in space and evolve over time as an outcome of accumulating infrastructure investment. The possible link between their patterns and performance in serving urban needs becomes a shared curiosity across urban planning, infrastructure engineering, and also social science. Characterizing and understanding network connections may shed light on optimizing urban public transportation networks (Von Ferber et al., 2009).

A cluster of metro lines can be considered as a complex network with the stations (as network joints) connected by line segments (as network edges), since it reveals the features of complex networks, such as small-world characteristics (Latora and Marchiori, 2002; Watts and Strogatz, 1998) and scale-free properties (Barabási and Albert, 1999) that do not exist in regular and random networks. Multiple dependent and interacting parts further complicate metro networks (Angeloudis and Fisk, 2006; Boccaletti et al., 2006; Derrible and Kennedy, 2010). They usually appear heterogeneous in space resulting from varying population density and land use across a city. Meanwhile possible changes, additions, and deletion of routes and stations during the evolution over time add to the heterogeneity. It is challenging to depict the spatiotemporal patterns of metro networks in a quantitative manner, while the complex-network theory may serve as a suitable tool for this purpose (Bar-Yam et al., 1998; Barabási, 2012).

Efforts were made to characterize metro networks with metrics developed in the framework of complex network analysis. The topological structures of metro networks are featured with a number of indicators readily defined for complex networks, such as the degree, the characteristic path length, the clustering coefficient (Seaton and Hackett, 2004), the node importance (Yang et al., 2010), the directness (Derrible and Kennedy, 2009), and the network efficiency (Latora and Marchiori, 2002; Vragović et al., 2005; Wu et al., 2018). Besides, to specify functions of metro networks as a key component of urban public transportation systems, studies were devoted to bridge the metrics to desired characteristics of metro systems, such as connectivity (Kanwar et al., 2019; Zhang et al., 2018), accessibility (J. Peng et al., 2021),

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China.
E-mail addresses: 1810745@tongji.edu.cn (X. Yu), zhengchen@tongji.edu.cn (Z. Chen), liufang@tongji.edu.cn (F. Liu), zhuhehua@tongji.edu.cn (H. Zhu).

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robustness (Angeloudis and Fisk, 2006; Chang et al., 2006; Derrible and Kennedy, 2010; Wu et al., 2018; Yang et al., 2015), reliability (Zhang et al., 2011), and resilience (Zhang et al., 2018) more recently. Accordingly, new metrics were defined for assessing particular service performance of metro lines (e.g., Huang et al., 2014; Musso and Vuchic, 1988; Wu et al., 2016).

The complex network theory is also powerful to illustrate network evolution in a subjective and quantitative manner, providing scientific support to decision-making of urban planning (e.g., González and Mota, 2021; J. Peng et al., 2021; Wang et al., 2020; Zhu and Luo, 2016). Wang et al. (2020) revisited the topological evolution of Beijing metro system in a fifty-year span to evaluate the improved service performance. Ding et al. (2015) examined the evolving topological structures of the public urban rail transit networks of Kuala Lumpur, Malaysia, and revealed that the networks grew based on the nodes with the longgest length of the shortest path. Moreover, studies were conducted for distinguishing types or phases of metro networks. For example, Yang and Chen (2018) assessed the network evolution process of Shanghai metro system from 1993 to 2020 based on topological indicators of complex network, and divided the evolution into two stages i.e., network densification and extension. Li (2016) identified three types of networks (i.e., skeleton network, growth network, and mature network) from 56 cities' metro systems according to a clustering analysis performed on six metrics. All the aforementioned studies show the potential of the complex network theory on depicting and categorizing topological organization of metro networks, which however requires more in-depth studies and empirical evidences.

This paper explores the growing patterns of urban metro networks and the possible connections to their service performance via complex-network metrics. In this study, we extend the term "metro system" to urban rail transit system with exclusive right-of-way whether they are underground, ground or elevated (Derrible and Kennedy, 2010), since rail transit across elevations is often seamlessly connected and systematically works together as a whole. We are especially curious about three fundamental questions: (1) Are there any shared spatiotemporal patterns in growing metro lines across cities, with varying geographical scales, population sizes, and economy? (2) Can the patterns interpret the service performance of metro networks? (3) Can the patterns be reduced to some critical factors? Chinese cities with rapidly growing metro systems provide ideal empirical data to examine the above questions. A total of 240 metro lines with overall mileage of ca. 8,300 km have been launched in 42 cities of Chinese mainland by the end of 2021 to serve an annual passenger volume of 24,146.794 million (China Association of Metro, 2022). With this data set, this study is designed to contribute as follows: (1) to develop a set of metrics based on the complex network analysis; (2) to identify the growing patterns of metro networks by their network service performance using the developed metrics; and (3) to explore the relationship between the growing patterns and city factors, e.g., GDP, population of city, private cars in city, and to discuss the correlation between metro growing patterns and city maturity.

Following this introduction, Section 2 displays the descriptive statistics of metro lines in cities of Chinese mainland, and proposes a nine-metric scheme from the complex network perspective to evaluate network performance in three dimensionalities. Section 3 develops a nine-metric plot as a tool and visualizes the spatiotemporal growing patterns of metro networks in the cities with the tool. Section 4 discusses the relationships between the growing patterns of metro networks and city factors. Conclusions are given in Section 5.

2. Data and methodology

2.1. Metro lines in Chinese mainland cities

Forty-two cities in Chinese mainland are currently operating metro lines, of which the basic data lay the foundation of this study. The data set is from the publicly accessible statistics provided by transit authorities on the Internet and yearbooks of the cities (National Bureau of Statistics, 2022).

Table 1
The statistics of the metro lines in 42 Chinese mainland cities as of year 2021.

Parameters	Mean	Standard deviation	Min	Max
Operating mileage (km)	197.76	195.24	20	831
Number of stations	111	93	10	408
Average daily passenger	155×10^4	236×10^4	2×10^4	978×10^4

Table 1 summarizes the statistical parameters of the data set. Out of the 42 cities, 9 cities currently operate a metro mileage of over 300 km, while 15 cities serve an average daily passenger volume of over one million. As revealed in Fig. 1, the cities with more metro stations and longer mileage tend to support a larger daily passenger volume in general as we expected, except some cities (e.g., Shenzhen city, Xi'an city, and Changsha city) relatively "overloaded" as indicated by larger blue circles compared to their "neighbors" in Fig. 1(a). As shown in Fig. 1(b) to (d), the distributions of the operating mileage, the number of stations and the average daily passenger volume all approximately resemble lognormal distributions.

Since the growth of metro lines reflects more or less urban development, a correlation between the scale of metro lines and the scale of the operating city (e.g., in terms of population and GDP) could be expected (Lin et al., 2021a, 2021b). As illustrated in Fig. 2, the metro mileage is positively correlated with the population, indicating that metro development is probably driven by growing urban population. The only "outlier" is Chongqing city with a significantly low mileage compared to its population size. This deviation could be attributed to the city's mountainous topography that introduces additional challenges to underground development in the city. A strong correlation is also found with the daily passenger volume of metro lines and the GDP per capita. This can be generally noted from increasingly sized circles in warmer color towards longer mileage as well as larger population, indicating sufficient usage of metro systems in cities.

2.2. Characterizing metro lines as complex networks

A large number of studies found that urban metro networks are one kind of complex networks, since they do reveal some properties that regular and random networks do not exhibit, such as the small-world and scale-free properties (Zhu and Luo, 2016). Therefore, we used complex network metrics to evaluate metro systems in this study. A metro network was modeled as a non-direction and non-weighted network with L-space, represented as $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is a set of nodes, i.e., metro stations herein, and $\mathbf{E}$ is a set of edges, i.e., metro tracks connecting two successive metro stations (Kanwar et al., 2019).

A set of metrics is required to depict the characteristics of metro networks in a quantitative manner. There is no established or widely accepted set of metrics for all aspects of metro networks, although a variety of measures have been developed from the theory of complex networks. As a public transportation means, the priority of a metro system is to provide passengers with accessible, reliable, and comfortable commute (Su et al., 2015). Accordingly, we constructed a metric set covering three dimensionalities, i.e., accessibility, resilience, and serviceability, each of which is measured with three metrics, which are either already well-defined or amended from the well-defined metrics of complex networks. Table 2 summarizes the nine metrics and their mathematical definitions. They are selected based on the principles of relevance, independence, and comprehensiveness. However, this nine-metric set is not the only solution but one of the rational solutions that can be iteratively improved as our knowledge accumulates. Note that the choice of the metrics is largely limited by data availability, and

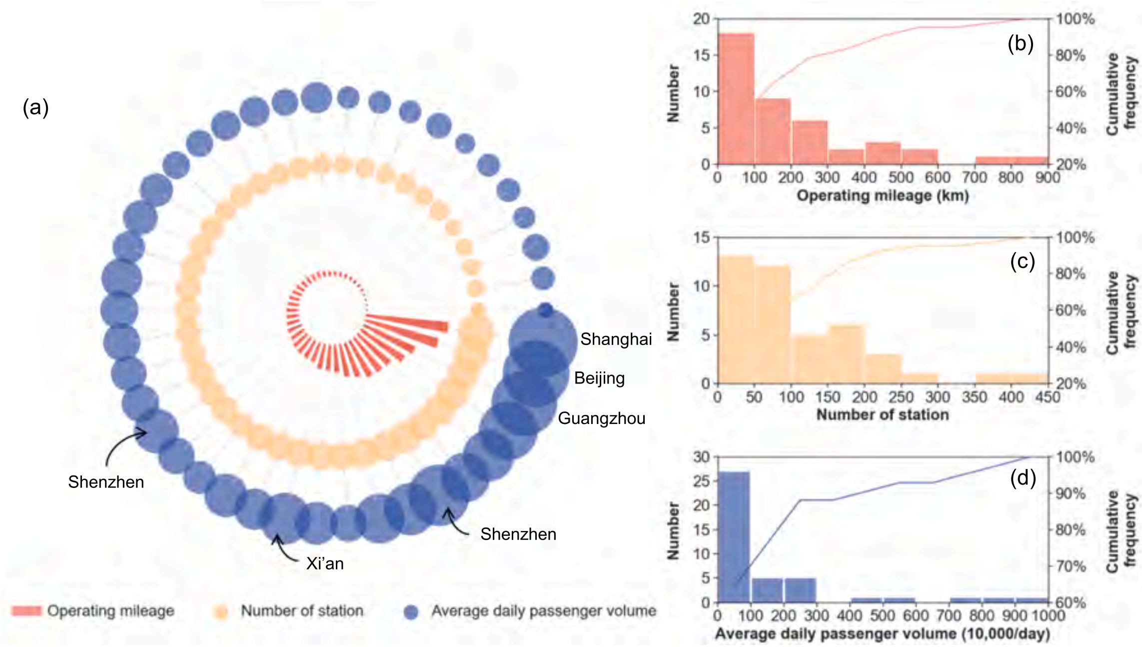

Fig. 1. The statistics of metro lines in 42 Chinese mainland cities as of year 2021: facts of the cities arranged by ascendant operating mileage counterclockwisely (a), and the histograms and cumulative frequencies of the operating mileage (b), the number of stations (c), and the average daily passenger volume (d).

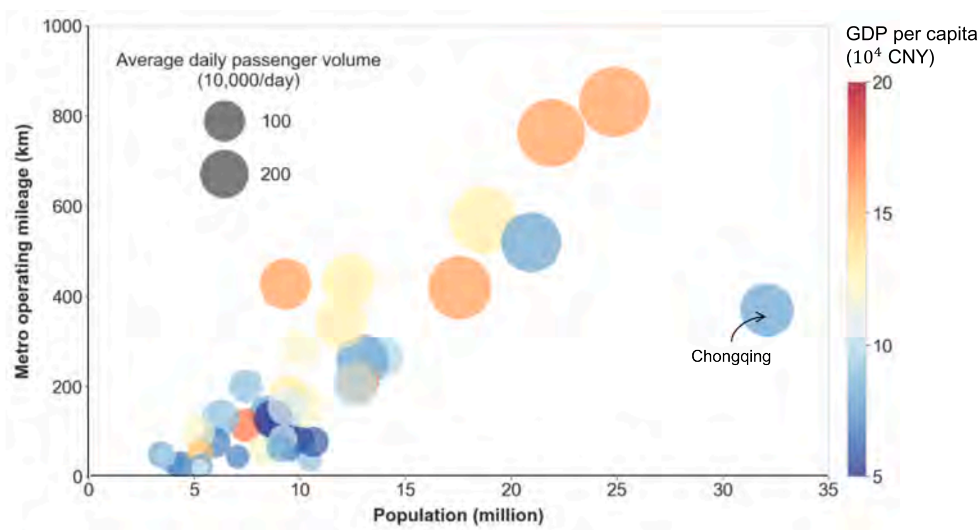

Fig. 2. The relationship between the operating mileage and the population size across 42 Chinese mainland cities in year 2021. Each city is represented with a bubble color-coded according to the GDP per capita and sized according to the average daily passenger volume.

we only consider metrics defined for non-weighted networks due to the lack of in-depth operational data. Nevertheless, the proposed methodology remains valid with appropriate redefinitions of measures in the future. Meanwhile, we did not consider the variation in the land-use types due to data paucity, although the land-use types certainly affect the layout of metro networks.

The dimensionality of accessibility accounts for the basic function of metro lines as to fulfill passengers' need to travel from one station to another. No express metro line with reduced stops is ever operated in Chinese mainland, so all stations in the data set are equally evaluated. As an essential aspect of metro networks, accessibility is quantified with three metrics: the directness (Derrible and Kennedy, 2009), the network connectivity (Angeloudis and Fisk, 2006), and the scaled global network efficiency (Chang et al., 2006). The directness reflects the ability to avoid transfers, and is often oppositely related to the maximum number of transfers. However, a large network tends to have a large value in the maximum number of transfers but still performs adequately, given network structure being complicated with the increasing network scale. Hence, the directness should take the scale into account, for instance, using the number of lines as an modifier (Derrible, 2010). The network connectivity relates to the ability to travel freely within the network. It is associated with the degree of mobility, or density of transfer possibilities (Gonźalez and Mota, 2021). A network with high connectivity would provide adequate paths to meet the basic requirement of reachability. The network efficiency represents transportation efficiency in metro networks, and is determined by the system's inherent structural property that allows passengers to move from one station to another with minimum effort (Wu et al., 2018). Here, we choose the scaled global efficiency as the metric, which modifies the network efficiency index by multiplying the number of stations to remove the effect due to variance

Table 2
A metric set to assess the performance of urban metro networks in three dimensionalities.

Notation	Metric	Mathematical definition	Description
A1	Directness	$\tau = \frac{N_L}{\delta}$	To reflect the ability to avoid transfers whilst accounting for the network size via the number of lines (Derrible, 2010).
A2	Network connectivity	$\gamma = \frac{E}{3N-6}$	To reflect the degree of connectivity of the network.
A3	Scaled global efficiency	$E' = \frac{N}{N(N-1)}\sum_{i\neq j}\frac{1}{d_{ij}}$	To reflect travel efficiency whilst accounting for the network size via the number of stations (Latora and Marchiori, 2002; Zhu and Luo, 2016).
R1	Clustering coefficient	$C = \frac{1}{N}\sum_{i=1}^{N}\frac{e_i}{e_i^{max}}$	A larger value denotes better tolerance to fault of the network (Derrible and Kennedy, 2010).
R2	Average node connectivity	$\overline{\kappa} = \frac{\sum_{i,j}k(i,j)}{\binom{N}{2}}$	The average of local node connectivity over all pairs of nodes of a network, and local node connectivity for two nodes is the minimum number of nodes that must be removed to disconnect them (Beineke et al., 2002).
$R3$	Circle availability	$\alpha = \frac{E-N+q}{2N-5}$	A greater value indicates more options passengers have to travel through the metro networks if any station is temporarily compromised (Musso and Vuchic, 1988).
S1	Coverage of walkable neighborhoods	$CLC = \frac{NS_i}{S_u}$	To reflect the availability of metro services within 15-minute walking distance (Musso and Vuchic, 1988).
S2	Convenience of station	$\mathrm{CS} = \sqrt{\frac{\pi N}{S_u}}$	To approximate the service area of the metro as a circular area (Mao et al., 2019; Wu et al., 2016).
S3	Service degree of population	$\mathrm{SDP} = \frac{P_{er}}{P}$	To reflect the service degree of population of the metro.

Note:
A1-3 are the metrics for accessibility; R1-3 are the metrics for resilience; S1-3 are the metrics for serviceability
E — the number of edges
N — the number of nodes
N_L— the number of metro lines
δ— the maximum number of transfers
d_{ij} — the shortest path between nodes v_i and v_j
e_i— the total number of existing edges within the neighborhood of node i
e_i^{max}— the maximum number of edges that could exist
q — the number of connected graphs in the network
$k(i,j)$— the maximum value of k for which nodes v_i and v_j are k-connected
S_u— the urban built-up area
S_i— the area around the metro station with a radius of 500 m
P_{er}— the average daily passenger volume
P — the population of the served area

introduced by network scales and to facilitate scale-independent comparisons.

The dimensionality of resilience reflects the security requirement in metro networks. The resilience of a metro network is the ability to resist unexpected failures and to maintain basic operation during failures (Kanwar et al., 2019), or more straightly, the ability to offer alternative routes during failures, accidents or even targeted attacks (Derrible and Kennedy, 2010). Hence the resilience of a network is strongly related to the redundancy of the network that characterizes the ability to provide alternative routes in the network. Three metrics are considered meaningful for characterizing resilience: the average clustering, the average node connectivity, and the circle availability. The average clustering reflects the redundant ability of a node to the adjacent nodes, representing the local redundancy at the node scale. The average node connectivity is the averaged minimum number of removal nodes required to disconnect any node pair, representing the redundant ability of all node pairs in the network. The circle availability reflects the redundant level achieved by comparing the current network to an ideal state of the optimal resilience, representing the network redundancy level.

The dimensionality of serviceability evaluates the quality of the service provided by a metro network in the context of urban life. This dimensionality mainly focuses on the capacity in delivering comfortable and convenient transportation within the city. The serviceability of a metro network is measured from three aspects: the coverage of walkable neighborhoods (Moreno et al., 2021; Weng et al., 2019), the convenience of station, and the service degree of population. The coverage of walkable neighborhoods is the proportion of the areas accessible within 15-minute walking distance apart from a metro station, and therefore it reflects the rationality of metro planning for shortening the commute time and cutting down the need for private transportation means. The walkable neighborhood here in the computation (a metro station catchment) is set to a circular area with a radius of 500 m, which is referred to the recommendation table of service elements allocation of community life circle from the Ministry of Natural Resources of China (The Office of the CPC Wuhai Municipal Committee, 2022). As addressed in He et al. (2018), the decay in the preference of walking slows down as the distance to metro stations increases up to 500 m, a comfortable walking distance. The convenience of station measures the availability of a metro station to the neighborhood, and it is defined as the averaged radius of service circles of stations required for a full coverage of the built-up area in a city. A decrease in the radius indicates an increasingly convenient network. The service degree of population reflects the proportion of urban population served by metro.

2.3. Correlation analysis of the network-based metrics

Being independent is the basic requirement of the selection of a metric set. A correlation analysis was performed to examine the dependence of the proposed three-dimensional metric set. To facilitate data processing, calculation and visualization for this entire study including the correlation analysis, we developed a set of scripts with Python libraries for complex network characterization and analysis, e.g., *networkx* (NetworkX developers, 2021), *numpy*, and *scipy*.

As shown in Fig. 3, the selected metrics are generally independent, except for a strong correlation between the coverage of walkable neighborhoods (S1) and the convenience of station (S2). For simplicity, the coverage of walkable neighborhoods is computed by simply accumulating the service areas of stations without removing the overlapping areas due to the difficulty in spatial analysis. Hence, this measure is inherently dependent on the convenience of station. Nevertheless, we include it in the metric set with the hope of refining the calculation method, considering the increasing impact of the concept of 15-minute walkable neighborhoods in urban planning.

3. Results

3.1. The shamrock plot

Cities develop at different speeds conditioned by geographical, economical, and cultural factors, so do their metro networks. It may be possible to identify a number of distinct patterns of metro networks that imply maturity levels of cities where the metros are being operated. However, a rational and feasible method is required to reach this goal.

Inspired by radar plots, we proposed a visualization tool, a shamrock plot, to identify metro network patterns of different maturity levels. As illustrated in Fig. 4, the shamrock-like plot organizes the nine metrics into three leaflets. Each leaflet formed by three isosceles triangles

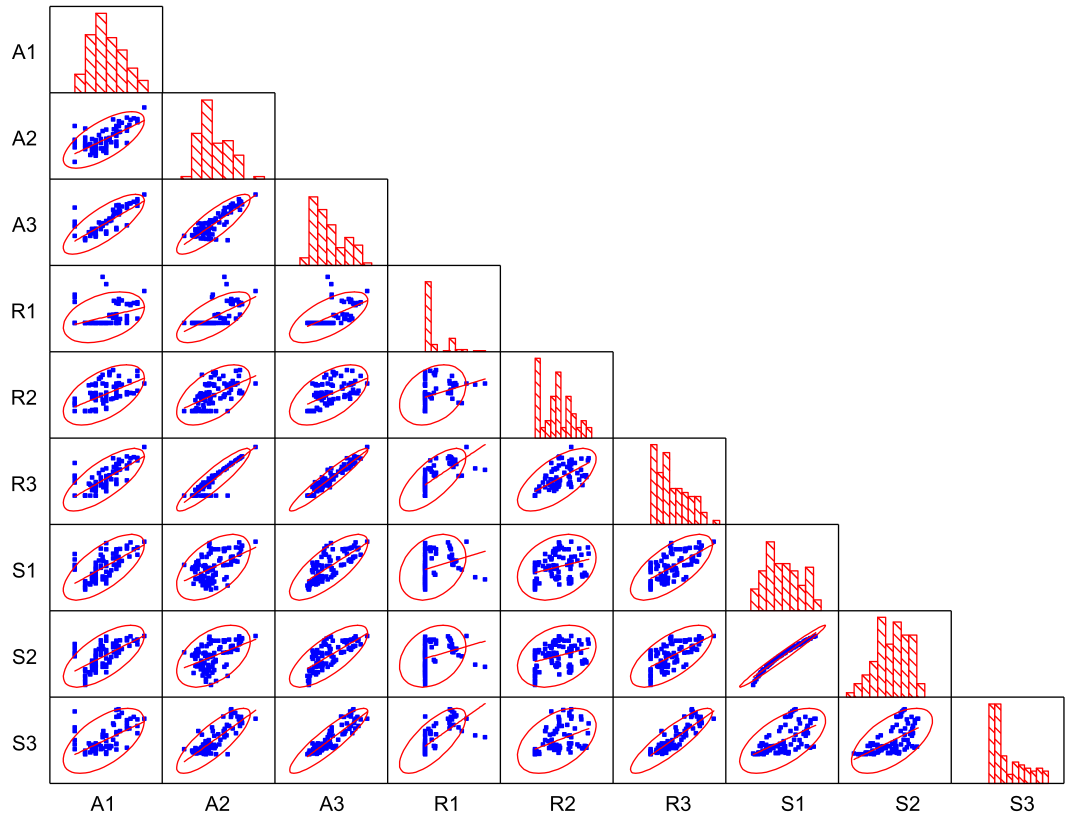

Fig. 3. Correlation analysis of the selected metrics. The 95-percent confidence levels are depicted as red confidence ellipses in the matrix scatter plots, and the histograms of the metrics are in the diagonal cells. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

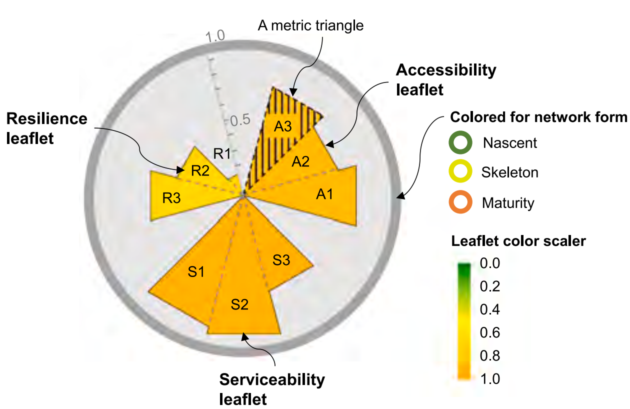

Fig. 4. The shamrock plot visualizes the nine metrics of a city's metro network. Every leaflet is colored according to the average score of the represented dimensionality. The plot is outlined in color to distinguish three morphological types of metro networks indicating different maturity levels: nascent network in green, skeleton network in yellow, and mature network in orange. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

represents a single dimensionality with three metrics. To present all metrics at a visible scale at once, the metrics are normalized as follows:

$$\widetilde{x_{ij}} = \frac{x_{ij} - x_{i_{min}}}{(x_{i_{max}} - x_{i_{min}})}, \; i = 1 \; 9, \; j = 1 \; 42 \quad (1)$$

where $\widetilde{x_{ij}}$ is the normalized value of the i^{th} metric of the j^{th} city, i.e., x_{ij}, and $x_{i_{min}}$ and $x_{i_{max}}$ are the minimum and maximum values of the i^{th} metric in the entire dataset, respectively.

The equal sides of every triangle in the plot are normalized ranging from zero to one. Every leaflet is color coded according to the averaged value of the normalized three metrics denoted by the leaflet. The growth of the "shamrock" indicated with increasing size and goldening color mimics the development of a metro network. The advantage of the shamrock plot is to visualize the multidimensional performance of metro networks in a single plot, and to ease the visual comparison over time and across cities via the variation in size, color and morphology of the shamrock.

3.2. Various maturity levels of metro networks

Fig. 5 displays the shamrock plots of 42 Chinese mainland cities ordered by descending accessibility. Given the selected metrics, the metro network in Shanghai city exhibits the most matured and balanced growth along all three dimensionalities especially with the best performance in accessibility and serviceability. It is interesting to note that good performance in serviceability could be still gained from a network with relatively low accessibility. For instance, Dalian city has a relatively high score in serviceability, despite its lowest score in accessibility. Compared with the other two dimensionalities, resilience could be the most challenging or costly performance in the metro networks. A total of 14 cities reveal no or extremely low scores in resilience, indicating that few redundant routes are available in these cities for passengers during destructive attacks to the metro networks. In contrast, serviceability scores are relatively high in most cities, especially in the two metrics, i.e., the coverage of walkable neighborhoods and the convenience of station.

It would be useful to group the metro networks into categories according to a certain rule. We employed the K-means cluster analysis, an unsupervised data classification method (MacQueen, 1967), to distinguish morphological forms of the metro networks. As shown in Fig. 6(a),

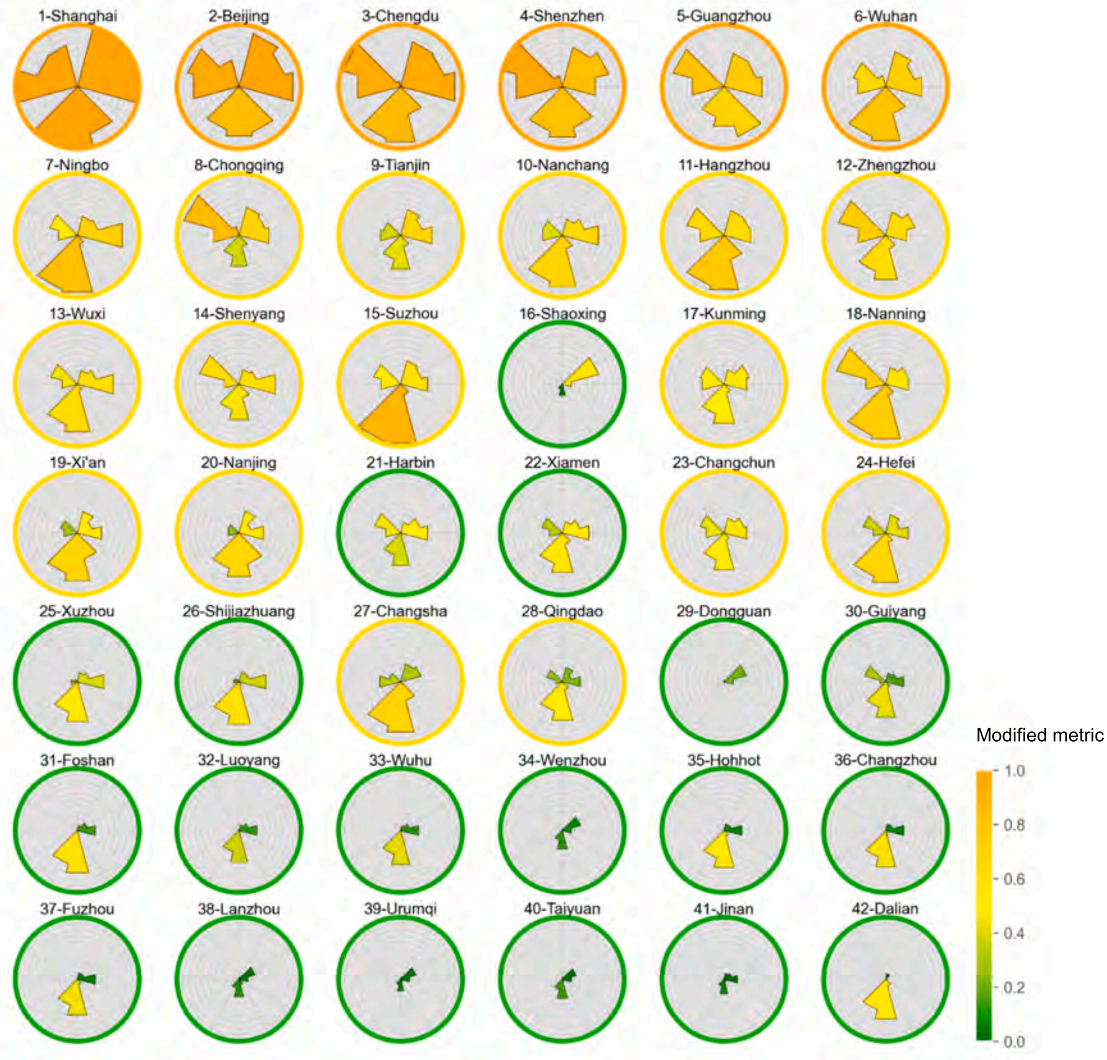

Fig. 5. Various performance of metro networks in 42 Chinese mainland cities revealed from various forms of the shamrock plots. The plots are ordered in descending scores of accessibility.

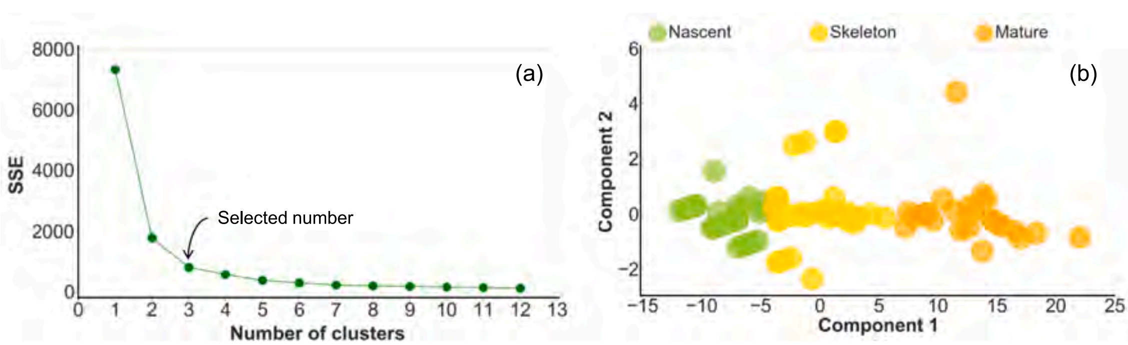

Fig. 6. Clustering analysis for identifying various forms of metro networks: (a) the number of clusters determined from the elbow method; and (b) the resulting three clusters of cities marked in different colors.

the sum of squared error (SSE) sharply drops with the increasing number of clusters, and the drop slows down as the cluster number is larger than 3, indicating that three clusters could be a reasonable target according to the elbow method (Shi et al., 2021). Fig. 6(b) shows a scatter plot obtained from the principal component analysis of the K-means clusters, and the plot groups 42 cities into three clusters marked in different colors. The same color scale is used to render the outline of every shamrock plot in Fig. 5.

As illustrated in Fig. 5, the three clusters are somehow connected with three levels of maturity, as the shamrock plots are well seated in groups of clusters while the “shamrock” generally enlarges. Thus, it could be meaningful to name the three clusters as the nascent network,

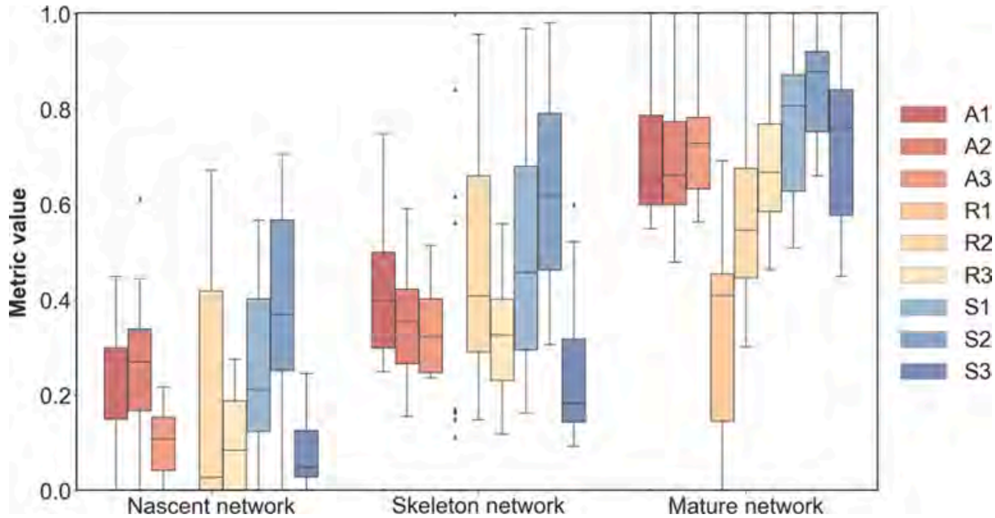

Fig. 7. Metric distributions in different forms of metro networks. Every box with error bars roughly represents the distribution of a normalized metric from a single form of metro networks.

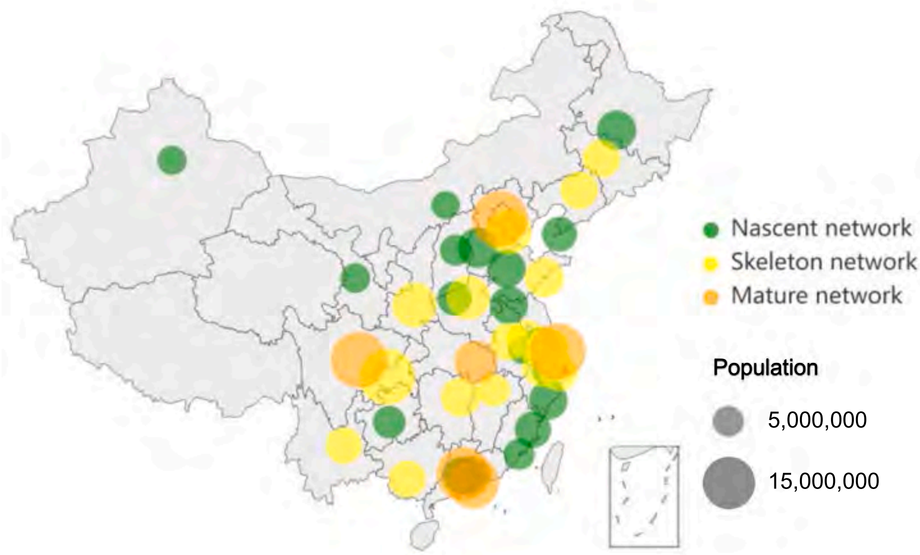

Fig. 8. Geographical distribution of different forms of metro networks. The bubbles color-coded according to the form of the metro networks and sized proportionally to city population.

the skeleton network, and the mature network, representing three forms of metro networks at various maturity levels from low to high. Fig. 7 presents the box plots of each metric in groups to reveal quantitative distinction among various forms of metro networks. The boxes are grouped in forms and colored in distinct schemes for different dimensionalities. As we expected, the boxes in all color schemes ascend as the form evolves from nascent to mature. In particular, the nascent networks have no local redundancy (R1), indicating that it is difficult for a person to reach an adjacent target station only by passing other adjacent stations. The skeleton networks are improved with higher scores than the nascent ones in all dimensionalities, especially performing better in traffic efficiency (A3). Only 6 out of 42 cities reach the mature network that provides high-quality service in the cities indicated by much higher scores in serviceability. Resilience seems the most "expensive" feature and remains in relatively low scores even in some mature networks. Nevertheless, the local redundancy is gradually gained in mature networks.

It would be interesting to explore the geographical distribution of the forms of metro networks. Fig. 8 locates metro network forms by cities on the map. Mature networks are mostly located in eastern China except Chengdu city, a western city with relatively high population. The skeleton networks are scattered and sprawl towards inland areas particularly in populated cities, where the traffic demand could be the primary driven force for the development of metro lines. The majority of cities with nascent networks are located along or near the eastern coastlines of the country that approximately coincides the developed areas. Although these cities are generally less populated, the development of metro lines is well supported by economic growth while the development scale remains limited due to less demanding traffic need.

3.3. Temporal patterns of metro networks and improved performance

Three cities (i.e., Shanghai city, Beijing city, and Chongqing city) are examined in details to track their metro growth and performance improved over time. These three cities operating metro lines over 15 years constitute good case studies with geographical and contextual

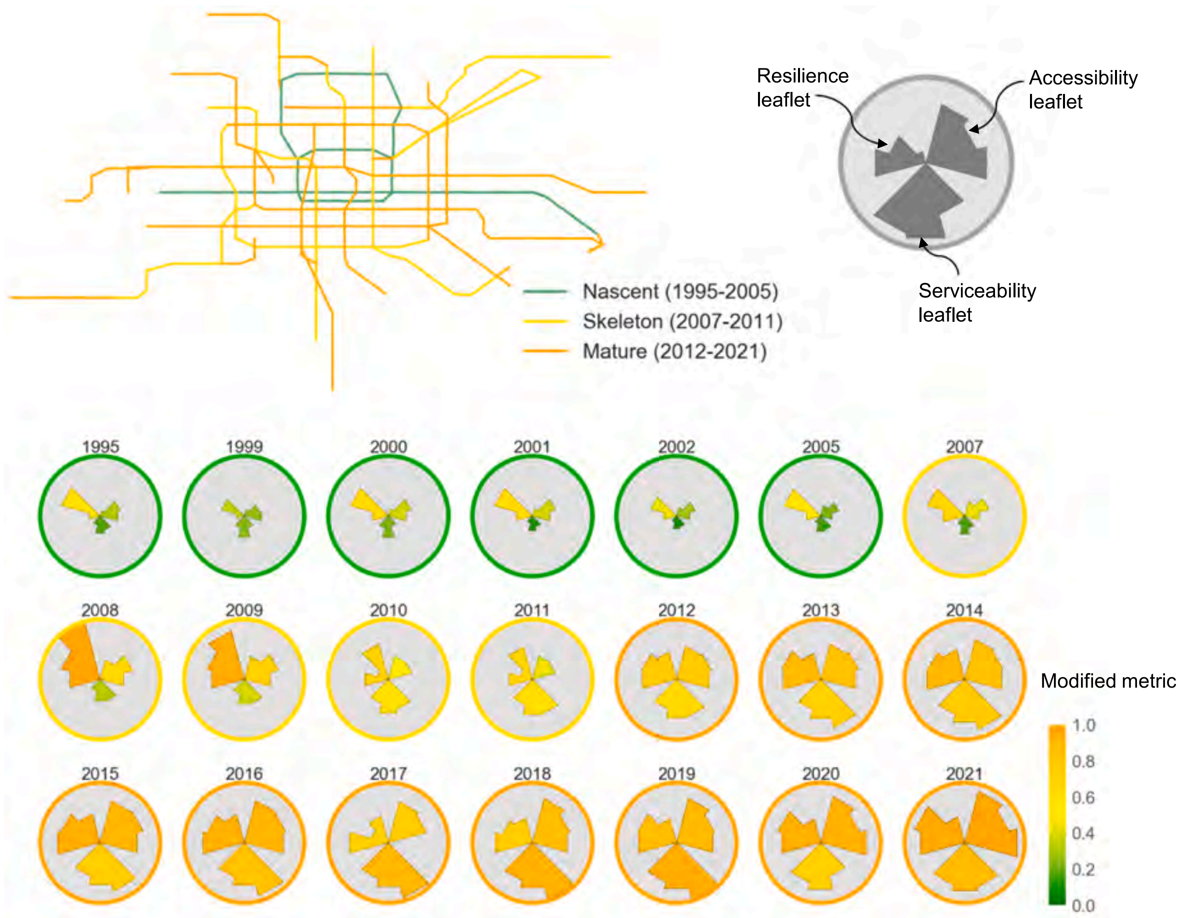

Fig. 9. The growing metro network in Beijing city since 1995. The map above is a deformed topology map.

representativeness.

Figs. 9 and 10 compare the growing patterns of metro networks in Beijing city and Shanghai city, both of which currently operate large-scale metro networks. Although the first metro line in Chinese mainland was launched in 1971 in Beijing, we only plot the data after 1995 due to poverty of earlier data. Although they both reached the maturity form, we do notice differences in the evolution paths of the two cities. Shanghai reached the maturity form sooner than Beijing, though Beijing has a much longer experience in operating urban metro lines. More importantly, Beijing developed its metro resilience even in the early phase of development before 2007, indicated by a relatively large leaflet of resilience during the entire process of development since 1995 as illustrated in Fig. 9. This could be attributed to the fact that security is of prior importance in this capital city of the country. In contrast, as a commercial center of the country, Shanghai values relatively less on resilience but more on serviceability; the leaflet of resilience stopped growing or even shrank until 2015, while the growth of leaflet of serviceability gradually caught up. Implied by the evolving shamrock plot, Shanghai metro seems to favor towards serviceability after 2010. With a lagged growth in resilience, the metro network in Shanghai has developed in a less balanced manner than that in Beijing. Another interesting finding is that the evolving shamrock plots capture the significant impact of the recent epidemic. As illustrated in Fig. 9, the leaflet of serviceability in the plot of Beijing dramatically reduced in size in year 2020 with the outbreak of COVID-19. Pervasive health concern and consequential interruptions in urban activities caused significant reduction of passenger flow in public transportation including metro system, thus affected serviceability scores (Yang et al., 2022). Similar reduction, although less significant, is also noted in Shanghai.

Fig. 11 presents the metro network growth in Chongqing city, an example of skeleton networks. The city entered the skeleton phase after 9-year operation. The resilience leaflet began to develop fast ever since, while the other two leaflets grew slowly, exhibiting obvious uneven development across the three dimensionalities. Due to less developed accessibility and serviceability, the system remains in the skeleton form for more than 8 years.

As shown in Fig. 12, the metro growth in three cities over time shows an overall upward trend in all metrics as displayed. The resilience of Beijing and Shanghai metro reached a small peak in the early stages of development, and subsequently the network resilience declined with the expansion of lines. The resilience dimensionality of Chongqing metro received a huge boost at the latest development stages, which could be followed with a decline as already happened in the other two cities. To elaborate the reasons causing variations and difference requires more data that support in-depth analysis, which however is beyond the scope of this study.

As inspired in the temporal patterns analysis in this section, we find that a mature network may be equipped with the characteristics, e.g., high directness, high circle availability, and high coverage of walkable neighborhoods, which may need to be considered at the early stage. At the specific operational level, measures like increasing the number of loop lines, appropriately reducing the distance between adjacent stations of metro lines, and keeping a balanced development of all the dimensionalities, may help enhance the maturity level of metro lines. Nevertheless, the above conjectures may require subsequent verification.

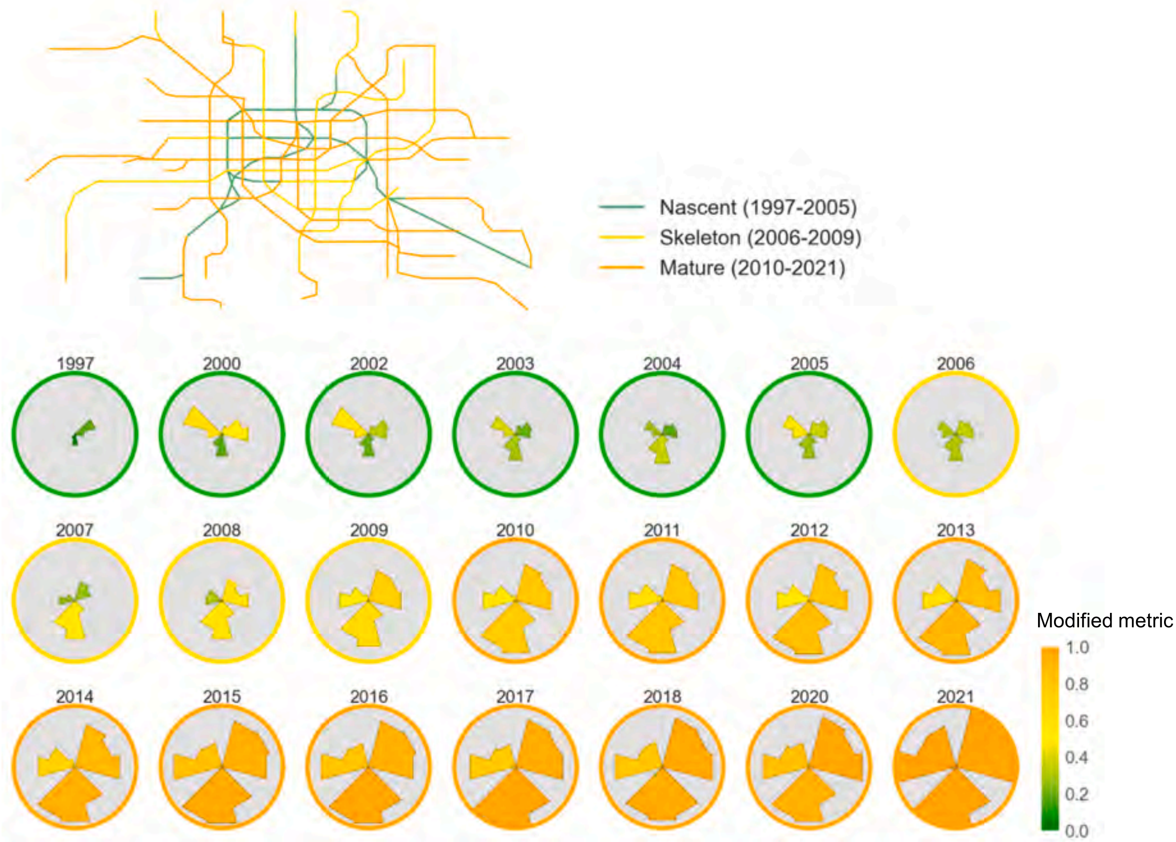

Fig. 10. The growing metro network in Shanghai city since 1997. The map above is a deformed topology map.

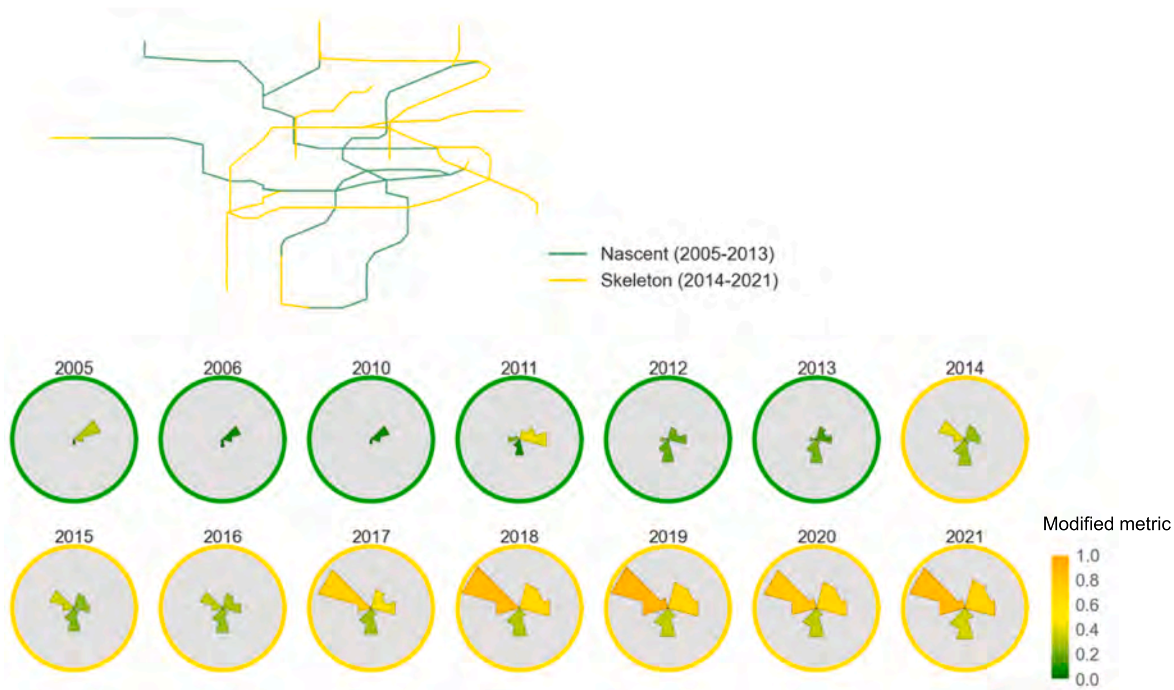

Fig. 11. The growing metro network of Chongqing city since 2005. The map is a deformed topology map.

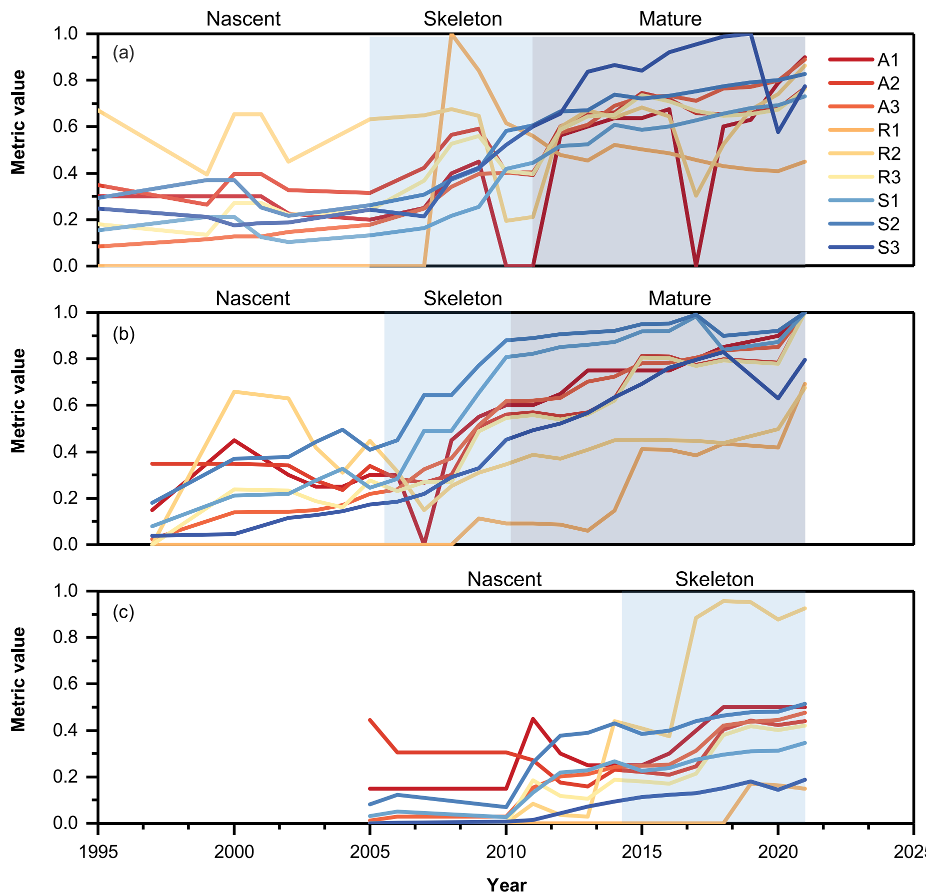

Fig. 12. The time-dependent variation of the normalized metrics of the metro networks in (a) Beijing city, (b) Shanghai city, and (c) Chongqing city.

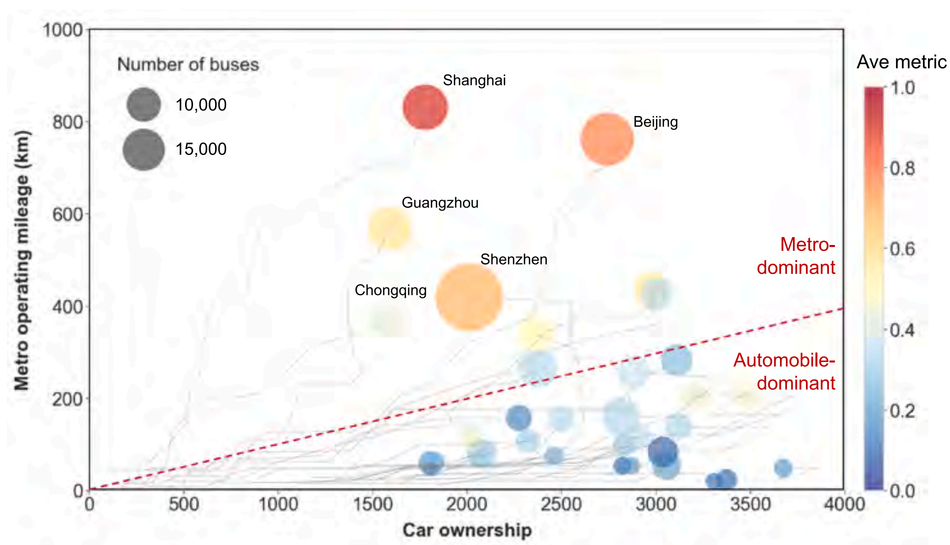

Fig. 13. The competing growth of metro lines and automobiles in different cities.

4. Discussion

4.1. Do the metro lines compete with the private cars in a city?

Metro lines and private cars are important transportation means to accommodate urban life. As an alternative, the supply of metro lines may reduce the demand of private transportation, or vice versa. Therefore, it is reasonable to expect a competition between the two, which raises a question: Does the growth of metro systems impact this competition? We explored this question by comparing the metro growth of 42 cities with their car ownership.

Fig. 13 presents the growing paths of the two competing transportation means by plotting the metro mileage against the car ownership (measured by the average number of automobiles owned per 10,000 persons) of each city. Metro mileage and car ownership simultaneously increased in most cities, probably because they both developed as a

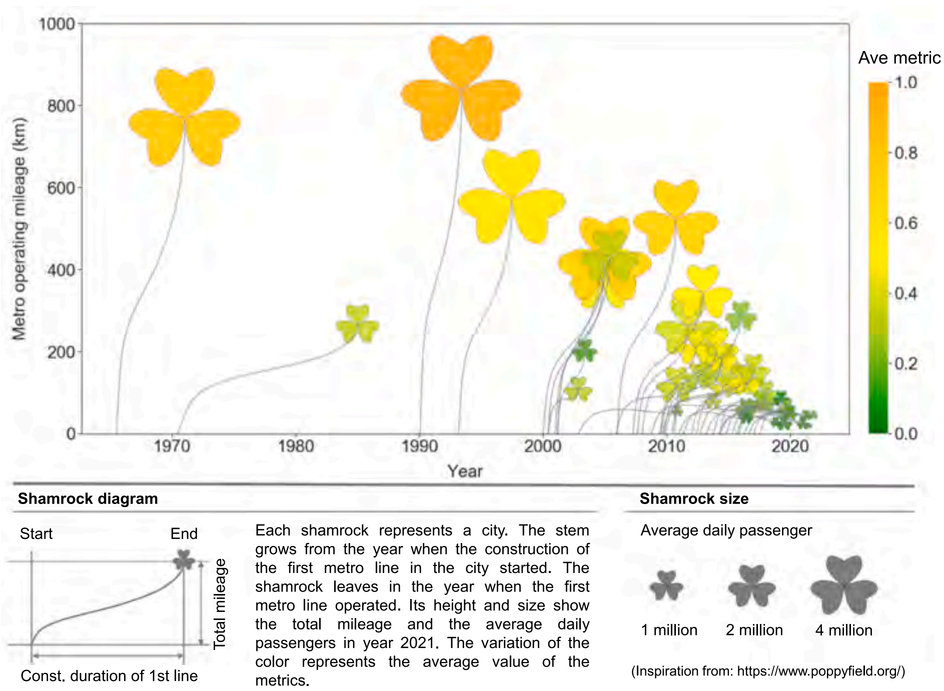

Fig. 14. Growing metro networks in 42 cities of Chinese mainland. Each shamrock represents a city operating metro. The stem grows from the year when the construction of the first metro line in the city started. The shamrock leafs in the year when the first metro line was accomplished. Its size shows the average daily passengers, and the variation of the color represents the average value of the nine metrics. Inspiration of this plot comes from the project of Poppy Field (https://www.poppyfield.org/).

result of economic growth. However, the growing rate of metro mileage does vary across different cities and under different levels of car ownership. The growing paths can be roughly grouped into automobile-dominant and metro-dominant. Automobile-dominant cities have a relatively high level of car ownership, which could largely alleviate the demand for public transportation means and therefore inhibit the growth in metro mileage. For metro-dominant cities (e.g., Beijing city, Shanghai city, and Guangzhou city), the metro lines expanded at a relatively high speed compared with the car ownership. Interestingly, an accelerated increase in the metro mileage appears in these cities as the car ownership reaches a certain threshold (e.g., about 1500 and 2400 automobiles per 10,000 persons in Beijing and Shanghai, respectively). This may indicate that the dominancy of metro lines in a city could be further strengthened, when automobiles approach certain constraints such as the traffic capacity the whole road system can carry. The timing for introducing metro lines to a city could significantly impact the destiny of the city being metro-dominant or automobile-dominant. Metro could have a better chance to flourish in a city if it is introduced at a lower number of the car ownership. As shown in Fig. 13, the cities with metro lines initiated at the car ownership below about 1000 mostly become metro-dominant later. Besides, metro-dominant cities tend to have a higher number of buses, indicating that a mutually beneficial relationship exists among different forms of public transport. We also notice a regression of car ownership in some of the cities (e.g., Shenzhen), in which the number of automobiles shrank likely due in part to the new strategy of low-carbon economy development that encourages public transportation in China.

4.2. Does the metro network of a city grow to pursuit hierarchical needs of the city?

Maslow's hierarchy of needs states that humans are motivated to fulfill their needs in a hierarchical order from the most basic to more advanced, including physiological, safety, belonging and love, esteem, and self-actualization (Maslow, 1943). Similarly, the metro network in a city may also develop to pursuit the city's needs in a hierarchical order (Lin et al., 2022), as our understanding on better life in cities is continuously improving, and reshaping our planning and construction decisions of urban infrastructure including metro lines.

The three dimensionalities of a metro network could be ordered from the most basic needs to more advanced ones in analogy to Maslow's hierarchy of needs. Accessibility may be the most basic need that a metro network would pursue to ensure its priority as a public transportation means. Thus, it is intensively valued during the early stage of metro growth. Resilience is the ability of a metro network to maintain sufficient accessibility even during natural or manmade attacks. It could be compared to the human need for safety. Serviceability is the ability to provide people with convenient and comfortable travel services, and it may be attributed to livability of a city. The significance of resilience and serviceability of a metro network could be gradually realized and therefore given increasing attentions as the network evolves towards more mature forms such as the skeleton and mature networks, which would continue to pursue accessibility but less prioritized.

5. Concluding remarks

This paper presents an attempt to quantitatively specify the spatio-temporal growth patterns of metro networks with the tools of the complex network theory by using the empirical data from 42 Chinese mainland cities that operate metro lines. Three essential dimensionalities (i.e., accessibility, resilience, and serviceability) are recognized to evaluate a metro network. Nine metrics grouped in three dimensionalities are proposed derived from complex network statistics to quantify the metro's performance in pursuing the city's hierarchical needs. A new tool of multi-dimensional data visualization, i.e., the shamrock plot, is developed to identify different patterns and maturity levels, while delineating temporal growing patterns of metro networks.

Cities differ, so do the metro lines in them. Such differences may be driven by different develop rates under combined effects of geographical, economic and social factors. It would be interesting to depict a holistic landscape on how metro networks grow in 42 Chinese mainland cities. Inspired by the Poppy Field project that visualizes war fatality (https://www.poppyfield.org/), we developed a plot of "shamrock field" shown in Fig. 14. Each shamrock depicts a city operating metro. The stem grows from the year when the construction of the first metro line in the city started. The shamrock leafs in the year when the first metro line was accomplished. Its size shows the average daily passengers, and the variation of colors represents the average value of the nine metrics. The height of the shamrock depicts the current mileage. As shown in Fig. 14, the cities with a longer history in metro operation transformed the metro networks to larger and more mature systems (represented by high and golden shamrocks), which may be consistent with the conclusion in Fig. 12 that the metro of one city tends to grow in a relatively even manner in all the nine-network metrics over time. Younger metro systems (represented by shorter and greener shamrocks) were boosted particularly in the past decade in more cities, indicating a flourishing development of metros in Chinese mainland.

We do believe that the theory of complex networks provides a handy yet scientific tool to quantitatively depict the spatiotemporal growing patterns of metro networks which seem unmeasurable. However, the nine-metric representation is our first trial and may receive further improvement as we progress. In the future work, the metrics could be enriched by introducing traffic flow data to gain power to further articulate the service performance of metro networks. As the sustainable development (F. L. Peng et al., 2021) and intelligent management (Wang, 2021) constitute the essential part of a modern resilient metro system, additional dimensionalities could be also introduced in the proposed framework, which however requires more detailed data besides the topological structure of the network itself. For instance, with additional data regarding hazard possibility and land use, this study could be extended in the context of risk analysis (Kodur and Naser, 2021) to achieve more implication, e.g., warning and prevention of rainstorm induced disasters (Lyu et al., 2019a,b, 2020). The metrics and the visualization tool developed in this study can be used to evaluate the maturity and growth pattern of metro system not only restricted to the cities being studied, but extensible to other areas. Meanwhile, by obtaining and monitoring the hidden unique characteristics of the urban metro network since their early phase, the tool could assist decision makers to timely adjust planning and to optimize the service performance of metro system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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